NUGENIA
Nuclear Generation II&III Alliance

ENIQ REPORT

Proceedings of the NDE in Nuclear 2023 Conference

27th – 29th June 2023, Sheffield UK

NDE in Nuclear 2023

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Authors

Oliver Martin, EC-JRC

Alina Giesler, LGI Sustainable Innovation

Zahra Kharbouch, LGI Sustainable Innovation

ENIQ
European Network for Inspection & Qualification
NUGENIA Technical Area 8

SNETP Association

c/o EDF

Avenue des Arts 53B, 1000 Brussels, Belgium

Email: secretariat@snetp.eu

Website: www.snetp.eu

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Index

Foreword		P.4
Executive summary		P.5
1.	NDE in Nuclear 2023 Overview	P.11
2.	Plenary Session - Introduction & Keynote Presentations	P.13
3.	NDE 4.0 (I)	P.70
4.	Electromagnetic Methods	P.123
5.	Regulatory & Code Issues and Harmonisation	P.179
6.	NDE 4.0 (II) and NDE Optimisation	P.225
7.	Advanced Ultrasonic Inspections	P.277
8.	Personnel & Human Factors incl. NDE Personnel Training & Certification	P.354
9.	Automated Analysis of NDE Data incl. AI / ML (I)	P.398
10.	R&D and Application of NDE Technologies & Equipment	P.468
11.	NDE of Concrete & other Non-Metallic Materials	P.526
12.	Automated Analysis of NDE Data incl. AI / ML (II)	P.576
13.	NDE Reliability & Qualification (I)	P.623
14.	Advanced Manufacturing and NDE	P.681
15.	NDE Reliability & Qualification (II)	P.762
16.	Structural Health Monitoring (SHM)	P.815
17.	NDE of Coarse Grained Materials & NDE of Complex Geometries (I)	P.875
18.	NDE Modelling & Simulation	P.937
19.	NDE of Complex Geometries (II)	P.968
20.	List of participants	P.1002

Foreword

NDE in Nuclear 2023 was the second event of a new series of international conferences on Non-Destructive Examination (NDE) for nuclear installations. It was organised and hosted by the Sustainable Nuclear Energy Technology Platform (SNETP) in collaboration with the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC) from 27th – 29th June 2023 in Sheffield, UK. The objective of the conference was to provide a venue for NDE professionals to share and discuss advances in R&D and implementation of NDE techniques and technologies for the commercial nuclear industry. The conference numbered 174 attendees and featured a vendor exhibition with 18 vendors. These proceedings include the 76 technical programme presentations plus 3 keynote presentations from 17 countries in the topics of NDE 4.0, NDE optimisation, automated analysis of NDE data including artificial intelligence / machine learning, advanced manufacturing & NDE, structural health monitoring, NDE modelling & simulation, electromagnetic methods, advanced ultrasonic inspections, R&D and application of NDE technologies & equipment, NDE reliability & qualification, NDE of coarse grained materials, NDE of complex geometries, regulatory & code issues and harmonisation, personnel & human factors including NDE personnel training & certification, NDE of concrete & cables.

SNETP would like to thank all the authors and presenters, exhibition vendors, sponsors, programme committee members, the Nuclear AMRC and MARICK Communications for their efforts and contributions in delivering the event.

Executive Summary

The international conference NDE in Nuclear 2023 provided an opportunity for NDE professionals to share and discuss the latest advances in R&D and implementation of NDE techniques and technologies for commercial nuclear power plants. The conference comprised 76 technical presentations plus 3 keynote presentations from 17 countries. It also included a vendor exhibition with 18 vendors and technical tours of the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC).

The technical programme was divided in three parallel streams with the following topics:

The international conference NDE in Nuclear 2023 provided an opportunity for NDE professionals to share and discuss the latest advances in R&D and implementation of NDE techniques and technologies for commercial nuclear power plants. The conference comprised 76 technical presentations plus 3 keynote presentations from 17 countries. It also included a vendor exhibition with 18 vendors and technical tours of the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC).

The technical programme was divided in three parallel streams with the following topics:

- **Stream 1**: NDE 4.0, NDE optimisation, automated analysis of NDE data including artificial intelligence / machine learning, advanced manufacturing & NDE, structural health monitoring, NDE modelling & simulation;
- **Stream 2**: electromagnetic methods, advanced ultrasonic inspections, R&D and application of NDE technologies & equipment, NDE reliability & qualification, NDE of coarse grained materials, NDE of complex geometries;
- **Stream 3**: regulatory & code issues and harmonisation, personnel & human factors including NDE personnel training & certification, NDE of concrete & cables.

These proceedings contain the technical presentations and the three keynote presentations. The presentations in these proceedings describe work at varying stages of implementation and degrees of maturity and are primarily intended as informational only. Interested parties are encouraged to contact the authors of any of the presentations included in these proceedings to obtain further information about their R&D, products and services.

NDE 4.0 (I)	
NDE 4.0 for the Electric Power Industry Low Carbon Energy Future Terrill Massey (EPRI)	p. 71
Metallic Materials Fatigue Data Determined through NDE Principles as a Basis for Structural Assessment in Nuclear Engineering Christian Boller (Saarland Univ.) et al.	p. 83
New Challenges in Nuclear Power Plant ISI in Czech Republic Ladislav Horáček (UJV) et al.	p. 93
Evaluation of Techniques for Compression of Ultrasonic Data Terrill Massey (EPRI)	p. 115
Electromagnetic Methods	
Investigation of Eddy Current Arrays and Ultrasonic Techniques to Inspect Spent Fuel Pool and Transfer Canal Liners Nathan Muthu, Byungsik Yoon (EPRI)	p. 124
Modelling the Influence of the Tube Support Plate on the Eddy Current Testing of the Steam Generator: Numerical Tools and Experimental Validation Audrey Vigneron (CEA) et al.	p. 142
Use of NEWS and MMM technologies for diagnostics of NPP components Jaroslav Brom, Petr Vlček (CVR)	p. 154
Dry Storage Canister Inspection with Eddy Current Arrays Nathan Muthu (EPRI)	p. 167
Regulatory & Code Issues and Harmonisation	
Safety improvements through the use of risk-informed technologies Patrick O'Regan (EPRI) et al.	p. 180
Technical Basis for Nondestructive Examination Experience Requirements - ASME Section XI, Appendix VII Ronnie Swain, Carl Latiolais (EPRI)	p. 194
Weld Acceptance via Ultrasonic Inspection (in Lieu of Radiography) - Application to Nuclear Components David Duxbury, Dave Whitehead, Andrew Wood (Rolls Royce)	p. 200
In-Service Inspection & Repair strategy for newcleo Lead-cooled Fast Reactor Andrea Barbensi, Jean-Sébastien Genot, Simone Nardi (newcleo), Mariano Tarantino (ENEA)	p. 215
NDE 4.0 (II) and NDE Optimisation	
Nuclear NDE research progress and its integration into a data centric engineering approach Frederic Cegla et al. (Imperial College)	p. 226
Interactive Database Knowledge Visualization Platform Mike Mouchet (EPRI)	p. 239
Ultrasonic array inspection of safety critical components with complex structure Jie Zhang, Xiaoyu Sun, Paul Wilcox (Univ. Bristol)	p. 246
Investigation of Wave Propagation Pattern in a Multilayer Planar Structure Vinooth Rajendran et al. (Robert Gordon University)	p. 256
Optimization of NDE Examination Requirements - A Modern Approach Robert F. Grizzi, Do Jun (DJ) Shim (EPRI)	p. 265
Advanced Ultrasonic Inspections	
Total Focusing Method Application for Reactor Pressure Vessel Welds: Case Studies Terrill Massey (EPRI) et al.	p. 278
Using phase relationships in non-symmetric ToFD configurations Thomas Bloodworth (Bloodworth Consulting), Mikaël Debroise (Framatome)	p. 289

Laser-induced ultrasonic phased array imaging for non-contact, non- destructive evaluation of tokamak power plant welds Matthew Riding (Univ. Strathcycle) et al.	p. 298
Visualisation of Multi-Frequency Ultrasonic Data Terrill Massey (EPRI)	p. 330
LLT-tandem inspection of thick-section welds using phased-arrays Thomas Bloodworth (Bloodworth Consulting) et al.	p. 346
Personnel & Human Factors incl. NDE Personnel Training & Certification	
Using Ultrasonic Simulators to Facilitate Reliable NDE Josh Stellakis (EPRI)	p. 355
Human reliability assessment method applied to investigate human factors in NDT: The case of the interpretation of radiograms in the French nuclear sector Justin Larouze (Mine Paris), Pierre Calmon (CEA), Etienne Martin (EDF)	p. 362
Development of a Virtual and Synthetic Flaw Modification Process for Training and Qualification George Connolly (EPRI) et al.	p. 377
NDE Training and Knowledge Transfer for the Modern Workforce Scott Hamel (EPRI)	p. 388
Automated Analysis of NDE Data incl. AI / ML (I)	
Generative Machine Learning in Ultrasonic Testing – Simulation and Reconstruction Applications Daniel Algernon, Claudia Thurnherr, Aurélia Muller (all SVTI)	p. 399
Machine Vision Applications in the Nuclear NDE Industry Thiago Seuaciuc-Osorio (EPRI), Iikka Virkkunen (Trueflaw)	p. 420
Flaw Response Simulations using Flaw Profiles Obtained by Destructive Testing Richard Jacob et al. (PNNL)	p. 438
Evaluation of a deep learning algorithm trained by simulation to characterize defects from multimodal TFM images in the presence of uncertainties Roberto Miorelli, Sébastien Robert, Stéphane Leberre and Pierre Calmon (CEA)	p. 448
Leveraging Machine Learning to Improve Flaw Depth Sizing in Balance-of- Plant Components Thiago Seuaciuc-Osorio (EPRI)	p. 459
R&D and Application of NDE Technologies & Equipment	
Inspection of concrete/steel/concrete pipes affected by corrosion with ultrasound techniques Thilakson RAVEENDRAN (EDF) et al.	p. 469
Advanced ultrasonic imaging solutions for the inspection of nuclear assets Niels Pörtzgen (Applus)	p. 478
Outage Water Tank NDT inspection Francisco Javier de la Morena Martínez (Tecnatom)	p. 487
Beam characterization of a LINAC system for an NDT qualification process Sylvain Murgier (EDF) et al.	p. 499
How to research NDE in Nuclear without Nuclear Power Plants Anne Jüngert (MPA, Univ. Stuttgart)	p. 514
NDE of Concrete & other Non-Metallic Materials	
Ultrasonic Monitoring of Irradiated and Thermally Aged NPP Cable Sheets Yasemin Inc (VTT)	p. 527
Guided Wave Inspection of Inaccessible Regions of Prestressed Concrete Containment Vessels (PCCVs) Jay L. Fisher (Southwest Research Institute) et al.	p. 537

Cargo Inspection using Muon Tomography for Nuclear Security Akanchha Fnu, Pankaj Wahi, Prabhat Munshi (India Tech)	p. 546
Natural NDE for Nuclear: Muography Case Studies for Waste and Infrastructure Inspection David Mahon (Univ. Glasgow)	p. 556
Nonlinear Ultrasonic Inspection of Concrete Slabs Containing Embedded Steel Liners Subjected to Accelerated Corrosion Markus Nilsson (Lund Univ.) et al.	p. 566
Automated Analysis of NDE Data incl. AI / ML (II)	
Towards Deployment of AI-Assisted Ultrasonic Inspections in the Nuclear Power Industry Thiago Seuaciuc-Osorio (EPRI) & Iikka Virkkunen (Trueflaw)	p. 577
XAI for signal analysis of guided wave testing at pipe elbows Toshihiro Yamamoto (JAPEIC) et al.	p. 586
Evaluation of Assisted Data Analysis for Encoded Ultrasonic Examinations in Nuclear Power Plants Richard Jacob & Jared Gillespie (PNNL)	p. 597
Machine Learning Techniques for Detecting and Sentencing Surface Breaking Cracks using Ultrasonic Data Channa Nageswaran & Xuening Zou (TWI)	p. 607
Synthesizing Ultrasonic Data with Machine Learning Terrill Massey (EPRI)	p. 616
NDE Reliability & Qualification (I)	
Baffle to Former Bolts Inspection in Spain: Procedure & Ultrasonic Data Analysts Qualification Ignacio Real (Iberdrola) & Jose Ramon Gadea (Tecnatom)	p. 624
Round Robin Tests for WWER Heat Exchange Tubes Michal Benak, Roman Krajčovič (VUJE) et al.	p. 638
ENIQ Inspection Qualification for the UK Civil Nuclear New Build Chris Curtis (IVC)	p. 639
ENIQ based Inspection Qualification of novel techniques (FMC case study) Miles Weston (TWI) & Stavros Avramidis (IVC)	p. 647
Update of CEX-120 Methodology for Qualification of Non-Destructive Testing used in the In-Service Inspections of Spanish Nuclear Power Plants Ignacio Real Rubio (Iberdrola) & Francisco Javier Campaña Martín (Tecnatom)	p. 664
Advanced Manufacturing and NDE	
Exploratory Ultrasonic Testing (UT) Nondestructive Evaluation (NDE) Applied to Dissimilar Metal Components George Connolly (EPRI) et al.	p. 682
Real-Time Phased Array Ultrasonic Weld Pool Monitoring During Multi-Pass Weld Deposition Nina E. Sweeney, David Lines (Univ. of Strathclyde) et al.	p. 691
Non-destructive testing of Additive Manufactured (AM) components for the nuclear industry as well as other applications of AM Ola Johansson (Ringhals AB) & Jorge Benítez (SQC)	p. 699
In-Process Ultrasonic Inspection During Fusion Welding Charles N. MacLeod, David Lines (Univ. of Strathclyde) et al.	p. 716
Proposal of mechanical benchmarks for image-based simulation (IBSim) workflows in high-value manufacturing Llion M. Evans et al. (Swansea Univ.)	p. 730
NDE Reliability & Qualification (II)	

Challenges of Mechanized NDE at Ringhals 4 Pressurizer 2022/2023 T.Hallqvist (Dekra), O.Johansson (Ringhals NPP), P.Alzen (SQC)	p. 763
Virtual round robins – new insight into NDE reliability Iikka Virkkunen & Tuomas Koskinen (Aalto Univ.)	p. 776
Qualification of Eddy Current Inspection of WWER Steam Generator Threaded Holes Roman Krajčovič (VUJE) et al.	p. 787
HPC End-of-Manufacturing Inspections Qualification Mikaël Debroise (Framatome) & Thomas Bloodworth (Bloodworth Consulting)	p. 788
Non-destructive testing of components used in MARIA research reactor Marcin Kowal et al. (NCBJ)	p. 806
Structural Health Monitoring (SHM)	
In-service, on-stream, ultrasonics for NDE and process monitoring in Nuclear Tim Stevenson, Will Vickers, David Martin (Ionix Advanced Technologies Ltd)	p. 816
Characterization and Monitoring of ID Cracking in Pressurized Piping Using Surface Strain Measurements - Phase 1 - Unwelded Carbon Steel Piping James J Wall (EPRI) & Brian P. Hohmann (Hohmann Engineering)	p. 832
Low-cost structural health monitoring system for engineering applications Ceri A. Middleton (Univ. Liverpool) et al.	p. 843
Passive Guided Wave Tomography for Corrosion Monitoring under Varying Environmental Conditions Tom Druet (CEA) et al.	p. 853
Real-time ultrasonic measurement of component temperature gradients – development of a tool for better high-cycle thermal fatigue monitoring Laurence Clarkson & Frederic Cegla (Imperial College)	p. 865
NDE of Coarse Grained Materials & NDE of Complex Geometries (I)	
Comparison of flaw detectability of different phased array ultrasonic techniques used in centrifugally cast stainless steel Shan Lin and Shoji Hajime (both CRIEPI)	p. 876
Advanced Ultrasonics for Cast Austenitic Stainless Steel Examination Mark Dennis, Terrill Massey, George Connolly (EPRI)	p. 891
Estimation of columnar crystal orientation by machine learning for centrifugally cast stainless steel Keiji Watanabe (CRIEPI) et al.	p. 902
Geometry Measurement of Core Baffle of VVER-1000 Type Reactors of NPP Temelín Petr Vlček & Miroslav Žamboch (UJV)	p. 915
Nozzle Weld Inspection In A 3D Environment Paul Hillman, Johan Berlanger, Guy Maes (Eddyfi Technologies)	p. 928
NDE Modelling & Simulation	
TFM imaging simulations of defects near or in the weld bevel: modelling approach and advances on new hybrid finite element tools N. Leymarie (CEA) et al.	p. 938
Evaluation of Ultrasonic Simulation Software Mark Dennis, Terrill Massey, George Connolly (EPRI)	p. 949
Probabilistic Graphical Model for Sizing Assessment in Ultrasonic Testing of Dissimilar Metal Weld Mohammed Siddig (VTT)	p. 960
NDE of Complex Geometries (II)	
Robotized adaptive 3D ultrasonic technique for the inspection of a complex nuclear component with a matrix array David Roue (CEA) et al.	p. 969

Flexible wedge phased array transducers for inspecting variable-geometry or complex components Philippe Dumas et al. (Imasonic)	p. 983

Table 1.1: NDE in Nuclear 2023 Technical Programme

1. NDE in Nuclear 2023 Overview

NDE in Nuclear 2023 is the second edition of a new series of international nuclear NDE conferences that replaces the former NDE in Relation to Structural Integrity for Nuclear and Pressurized Components conference series from 1998 to 2015. The first edition of this new series, NDE in Nuclear 2019, was organized by the Electric Power Research Institute (EPRI) in June 2019 in Charlotte, NC, USA. NDE in Nuclear 2023 was organised and hosted by the Sustainable Nuclear Energy Technology Platform (SNETP) in collaboration with the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC) from 27th – 29th June 2023 in Sheffield, UK. The objective of the conference was to provide a venue for NDE professionals from nuclear utilities, service vendors, inspection equipment manufacturers, research laboratories, universities and other interested parties to discuss advancements in R&D and implementation and application of NDE technologies for the commercial nuclear industry

The conference numbered 174 attendees and 76 oral technical presentations plus 3 keynote presentations from 17 countries. The conference also featured a technology showcase event at the Nuclear AMRC that included a vendor exhibition with 18 vendors and tours through the advanced manufacturing facilities of Nuclear AMRC.

This section provides an overview of the event.

Technical Programme

Following a plenary session with three keynote presentations, the technical programme included 76 presentations divided into 18 sessions in 3 parallel streams as shown in the table below.

Table 1.2: NDE in Nuclear 2023 Technical Sessions

Stream 1	Stream 2	Stream 3
NDE 4.0 (I)	Electromagnetic Methods	Regulatory & Code Issues and Harmonisation
NDE 4.0 (II) & NDE Optimisation	Advanced Ultrasonic Inspections	Personnel & Human Factors incl. NDE Personnel Training & Certification
Automated Analysis of NDE Data incl. AI / ML (I)	R&D and Application of NDE Technologies & Equipment	NDE of Concrete & other Non-Metallic Materials
Automated Analysis of NDE Data incl. AI / ML (II)	NDE Reliability & Qualification (I)	
Advanced Manufacturing and NDE	NDE Reliability & Qualification (II)	
Structural Health Monitoring (SHM)	NDE of Coarse Grained Materials & NDE of Complex Geometries (I)	
NDE Modelling & Simulation	NDE of Complex Geometries (II)	

The full technical programme can be retrieved from the table at the end of this section. Sections 3 through 18 provide the abstracts and presentations for each of the topical sessions. Technical papers were not required as part of the conference. The papers that were optionally submitted are published online on NDT.net (https://www.ndt.net/search/docs.php3?MainSource=313).

Technology Showcase

The Technology Showcase took place at Nuclear AMRC premises in Rotherham, outside Sheffield, UK and included a vendor exhibition, tours of the Nuclear AMRC facilities and associated Tech Talks.

Vendor Exhibition

The vendor exhibition included 18 vendors and companies showcasing the newest and innovative technologies related to NDE in the nuclear industry. The organizations that participated in the exhibition are listed alphabetically below:

1. Advanced OEM Solutions (AOS)
2. Crimson Industrial Vision Ltd
3. Eddyfi Technologies
4. Electric Power Research Institute (EPRI)
5. EVIDENT
6. IMASONIC
7. IMechE Argyll Ruane
8. Ionix Advanced Technologies
9. Lavender International NDT
10. Oberon Technologies
11. PEAK NDT Ltd
12. Sonaspection International Ltd
13. Sustainable Nuclear Energy Technology Platfform (SNETP)
14. TPAC
15. Unitive Design and Analysis Ltd
16. viZaar industrial imaging AG
17. WesDyne Sweden AB (Westinghouse company)

Ringhals AB (Vattenfall) kindly sponsored the event.

Technical Tour

Tours of the facilities of Nuclear AMRC, Rotherham (Sheffield), UK provided participants with an overview of Nuclear AMRC activities on R&D and qualification of advanced manufacturing techniques for reactor components and NDE.

2. Plenary Session - Introduction & Keynote Presentations

The plenary session included three technical keynote presentations. First, Prof. Anthony Croxford from the University of Bristol provided an overview on the state-of-the-art of automated NDE data analysis with AI / ML. The Mr. Gavin Edwards from EDF HPC gave an update on the Hinkley Point C newbuild project. At last Mr. Steve Chengelis, Director R&D Future Nuclear at EPRI delivererd a keynote presentation on advanced nuclear reactors, thereby including various aspects like different reactor concepts & applications, NDE challenges and manufacturing of components.

The three keynote presentation were preceeded by an introductory presentation on SNETP and the European Network for Inspection & Qualification (ENIQ, part of SNETP and in charge of the conference programme & content) by Ms. Candice Boudet (LGI Consulting / SNETP) and Mr. Ignacio Real Rubio (Iberdrola & ENIQ chair).

The presentation materials of the introductory presentation and the three keynotes follow.

Conference Welcome	Candice Boudet (LGI Consulting / SNETP) & Ignacio Real Rubio (Iberdrola & ENIQ leader)
Automated analysis of NDE data with AI / ML	Prof. Anthony Croxford (Univ. Bristol)
Hinkley Point C - Project Update	Gavin Edwards (EDF Energy HPC)
Advanced Nuclear Reactors	Steve Chengelis (EPRI)

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NDE in Nuclear 2023

Conference Welcome

Candice Boudet & Ignacio Real

27th June 2023

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NDE in Nuclear 2023

Internal Use

Welcome to Sheffield!

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Cutlers´ Hall

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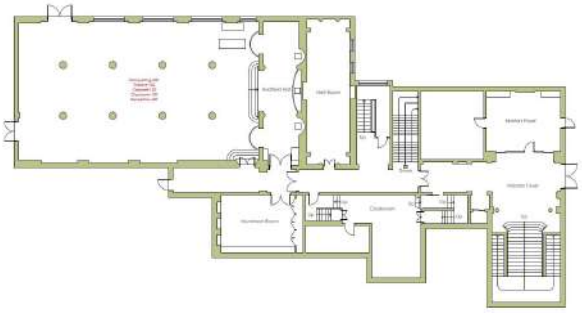
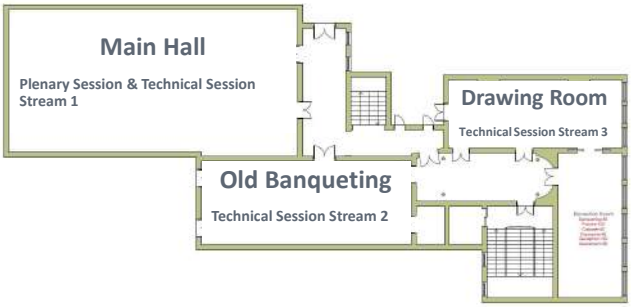


Ground Floor



First Floor

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How the Conference Is Organized

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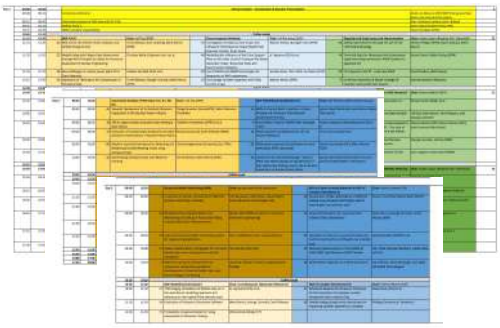

- Today, 3 Parallel Technical Sessions
- Wednesday & Thursday Mornings, 2 Parallel Technical Sessions
- Wednesday Afternoon, visit to NAMRC, Technical Exhibition & Dinner

NUCLEAR AMRC

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NDE in Nuclear 2023

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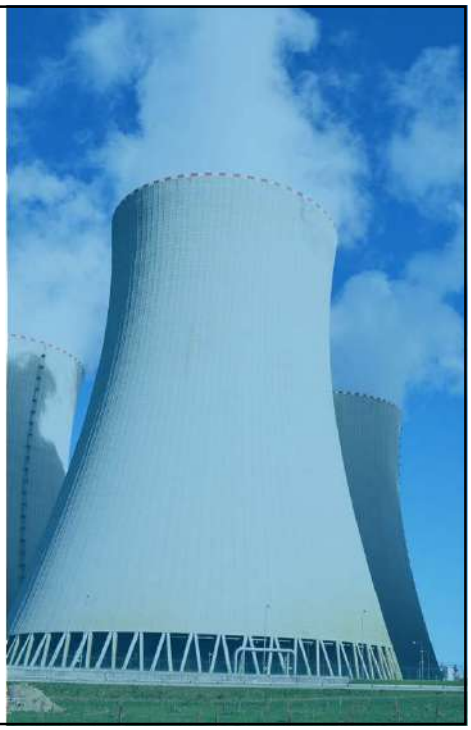
SNETP Presentation

Candice BOUDET,
LGI Sustainable energy
SNETP Secretariat representative

Internal Use

SNETP in a nutshell

- SNETP was set up in 2007 under the auspices of the European Commission with the goal to **support technological development for enhancing safe and competitive nuclear fission in a climate-neutral and sustainable energy mix**.
- In line with the objectives of the SET-Plan and the European Green Deal, SNETP aims to contribute to:
  - Lowering European greenhouse gas emissions
  - Assuring security of energy supply for Europe
  - Stabilizing electricity prices in Europe
- The association gathers various types of stakeholders: industry, research centres, safety organisations, universities, non-governmental organisations, SMEs, etc.



Internal Use

SNETP added value

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- **SNETP is the only European wide association dedicated to collaborative nuclear research.**
  - All major European R&D organisations involved in nuclear are members of the association.
  - Various events are organised and online tools are deployed to facilitate collaboration of the community on new projects proposals. Since its creation in 2007, SNETP has supported discussions on approximately 300 project ideas.
- **The specific European Technology & Innovation Platform (ETIP) status provides an important visibility to SNETP and its members**, with privileged access to relevant high-level managers within EU institutions, international organisations, and member states.
- **SNETP and its members contribute to the shaping of European energy policies**, by exchanging with peers on research priority topics, by producing reference documents (e.g. SRIA) on the state of R&D&I in Europe, by publishing position papers, etc.

Internal Use

SNETP Objectives

Promoting Scientific Excellence
- Agree on, implement and promote common R&D&I priorities within the SNETP community representing the three pillars and strenghten EU expertise and excellence

Boosting Innovation
- Facilitate industrial-driven and intersectoral innovation (digital, robotics, materials, etc.) in nuclear for current and new applications (non-power, hydrogen, etc.)

Representing nuclear fission R&D in European Affairs
- Promote SNETP expertise and research priorities towards European institutions

Strenghtening International Relations
- Promote SNETP expertise and research priorities towards international nuclear institutions (IAEA, OECD/NEA, GIF, etc.)

Providing solutions to Industry
- Foster industrial-driven research addressing the needs of SNETP industrial members in particular regarding safety, supply chain, licensing and cost-competitiveness

Cooperating closely with Regulators
- Reinforce cooperation between SNETP and the different regulatory and standardization bodies.

Supporting R&D infrastructures
- Support projects and initiatives aiming at maintaining/refurbishing/building the needed infrastructure to perform R&D&I in the nuclear field.

Sharing Experience with European Associations
- Foster & coordinate interactions with European associations in the field of nuclear, and any other sector with potential mutual interests with nuclear.

Engaging with Civil Society
- Engage with civil society and non-nuclear stakeholders to rationalize the debate on the European energy mix and enhance the acceptability of nuclear.

SNETP members

SNETP strategy based on:

- Nuclear Energy is one key element of electricity generation by 2050 according to EU long term scenarios (15% of the mix)
- Nuclear research and innovation is key to keep on strengthening safety, performance, dismantling, waste management
- The door shall be kept widely open for research and innovation on new reactors (such as SMR, Gen IV) which could provide enhanced safety, performance and waste management
- Nuclear is a transverse technology with strong impact on other fields such as medicine, but also data management, industrial software development, balanced energy mix with variable RES

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Digitalisation	Advanced manufacturing	Hydrogen

SNETP Sustainable Nuclear Energy Technology Platform

NDE Internal Use in Nuclear 2023

NUGENIA Nuclear Generation II&III Alliance

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- The association (AISBL, under Belgian law) gathers approximatively 120 stakeholders from industry, research centers, safety organisations, universities, non-governmental organisations, SMEs …

NUGENIA Nuclear Generation II&III Alliance

NC2I Nuclear Cogeneration Industrial Initiative

ESNII European Sustainable Nuclear Industrial Initiative

Gen II = existing Light water reactor
GEN III = new LWR
GEN IV = advanced (modular reactor)

SNETP is the European Technology & Innovation platform for Nuclear Energy focused on Gen II-III and IV reactors with electric and non-electric applications

SNETP Sustainable Nuclear Energy Technology Platform

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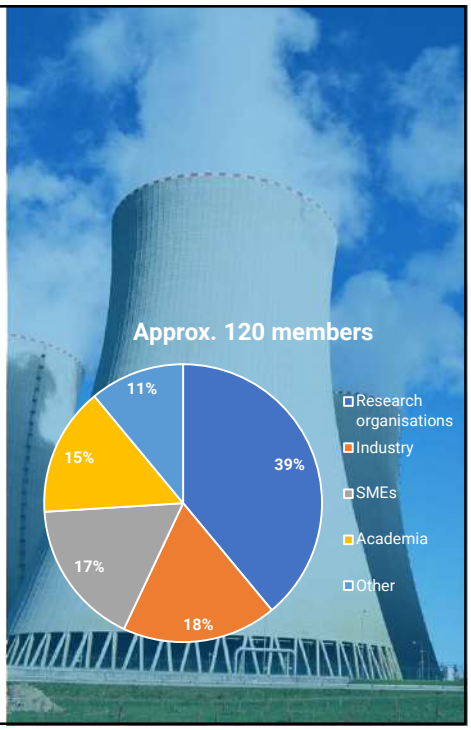

What's next ?

ENIQ
European Network for Inspection & Qualification
NUGENIA Technical Area 8

- SNETP is one the SMR pre-partnership secretariat members
- NUGENIA, ESNII and NC2I vision papers will be published in September 2023
- SNETP deployment stategy will be published in 2024
- SNETP launched calls to support the community:
  - Call for Studies
  - Booster to support SMEs
- SNETP supports OFFERR and launch calls to support European research facilities:
  - Next cut off date: 30 september 2023
  - Webinaire to explain and present the call : 4th July 9.30 to 12.00

SNETP Sustainable Nuclear Energy Technology Platform

NDE in Nuclear 2023

Internal Use

NUGENIA Nuclear Generation II&III Alliance

SNETP
Sustainable Nuclear Energy Technology Platform

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NUGENIA Technical Area 8

ENIQ Presentation

Ignacio Real
Iberdrola Energía Sostenible
ENIQ Steering Committee Chairman

NUGENIA Nuclear Generation II&III Alliance

NDE in Nuclear 2023

Internal Use

ENIQ Scope

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European Network for Inspection & Qualification
NUGENIA Technical Area 8

- ENIQ was created in 1992 as a utility-driven network dealing with the reliability and effectiveness of NDT for NPPs
- ENIQ qualification methodology was developed regarding the inspection of pressurised metallic components and is used in European LWRs and CANDU Reactors and accepted by IAEA and WENRA as recommended practice to follow
- ENIQ has two sub-areas in which the technical work is performed, the Sub Area for Qualification (SAQ), and the Sub Area Inspection Effectiveness (SAE)
- ENIQ members come from utilities, ISI vendors, Qualification Bodies (QBs) and research organisations in Europe with additional members from Canada, Japan and the USA
- The ENIQ steering committee (SC) is the decision-making body and its members come from utilities of EU member states plus observers from Canada, Japan, USA and the leaders of the two sub-areas.
- In 2012 ENIQ was integrated into NUGENIA, becoming Technical Area 8 of NUGENIA

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ENIQ Objectives

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•Addressing issues where the practice and implementation of NDT will ensure the safe and reliable operation of NPPs through inspection qualification, the application of risk-informed approaches, and other processes;

•Providing recommendations and guidance to optimise and harmonise processes;

•Continually improving the processes for inspection qualification and RI-ISI for increased effectiveness and efficiency;

•Responding to the new challenges resulting from plant life extension (PLEX), new Build, including Small Modular Reactors (SMRs), and the application of the advanced manufacturing processes;

•Promoting ENIQ approaches outside Europe and in non-nuclear industries;

•Maintaining links with other Technical Areas, especially TA4 and TA6

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ENIQ R&D Challenges

- Supporting the application of Machine Learning and Artificial Intelligence pursuant to ENIQ Recommended Practice 13 and the developments in the field.
- Use of virtual flaws on qualification: Practical trials or technical justification
- Use of structural health monitoring systems in NPP to complement ISI

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- Understand the technical barriers that preclude the transport of qualifications between countries and find methods or procedures on how to overcome these
- Evaluating the latest NDT technologies to determine the qualifiable applications for nuclear inspections.
- Review of risk-informed pre-service inspection (PSI) for new build and modifications of existing plants.
- Extension of RI-ISI to all mechanical components, i.e. beyond piping
- Benchmarking of RI-ISI approaches worldwide to harmonize them and improve credibility

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Keynote Speaker Introduction

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Keynote Speaker: Prof. Anthony Croxford

ENIQ European Network for Inspection & Qualification NUGENIA Technical Area 8

University of Bristol

Title: Automated Analysis of NDE Data with AI/ML

Bio:

- Anthony Croxford is a professor of Ultrasonics and Dynamics at the University of Bristol and a member of the Ultrasonic and Non-Destructive testing group.
- He is also a Turing fellow and founder of a spinout company, Inductosense.
- He is interested in how we ensure and understand the long term condition of structures

Keynote Speaker: Dr Gavin Edwards

ENIQ European Network for Inspection & Qualification NUGENIA Technical Area 8

eDF Energy. Technical Director HPC

Title: Hinkley Point C

Bio:

- Gavin Edwards joined EDF (BE) in 2007 after a decade working in several commercial, manufacturing, and international roles. He has worked in diverse areas supporting the NG fleet such as lifetime extension, fuel route, structural Integrity, outages, operational and event recovery safety case management
- Then in 2015 moved to nuclear new build and the Bradwell project. Developing the technical partnership with CGN to form a joint venture and take the HPR1000 reactor design through the Generic Design Assessment process. Negotiated GDA Entry with UK Gov. and taking the organisation through Step 1 and 2. Accountable for delivery of the safety, security and environment cases.
- He sits as a member of the HPC GenCo Board, and in the Principle Designer role for the project.
- He holds the SIRO role for security and have previously sat as Nuclear Safety Committee member.
- He also chairs a number of the design change and project funding committees.

Keynote Speaker: Steve Chengelis

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EPRI | ELECTRIC POWER RESEARCH INSTITUTE

- EPRI
- Title: SMRs including Inspectability
- Bio:
  - Steve Chengelis is the Director of Future Fleet at the Electric Power Research Institute (EPRI), focusing on research that supports the near-term deployment of advanced reactors and the utilization of nuclear energy to meet a clean energy future.
  - Prior to his current role, Chengelis was the Director of the Nondestructive Evaluation (NDE) and Welding and Repair Technology Center (WRTC). The Department identifies and develops technologies that can reliably and cost-effectively examine and characterize material changes in nuclear components, as well as develops and tests advanced materials, joining, and repair technologies for nuclear plant applications.
  - Previously, Chengelis led the Strategy and Execution department for the nuclear sector at EPRI
  - Chengelis joined EPRI in 2013 as a Technical Advisor for the nuclear sector. Prior to joining EPRI, Chengelis worked for Babcock and Wilcox Nuclear Energy

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Contact us

www.snetp.eu

secretariat@snetp.eu

www.linkedin.com/company/snetp

@SNE_TP

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Internal Use

University of BRISTOL

The Alan Turing Institute

RCNDE

Automated analysis of NDE data with AI/ML

Sergio Cantero-Chinchilla, Xin Tu, Richard Pyle, Rob Hughes, Jie Zhang, Kangwei Wang, Rhodri Bevan, Paul Wilcox, Anthony Croxford

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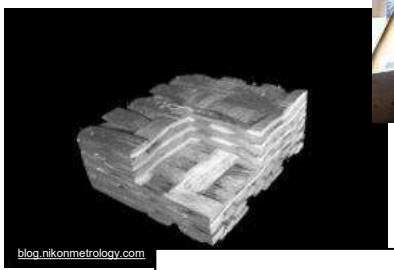
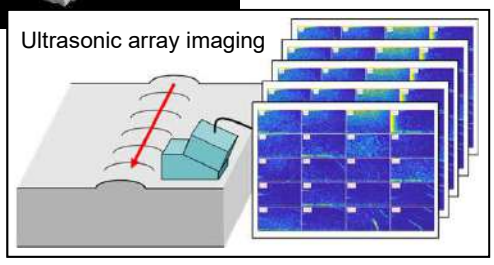
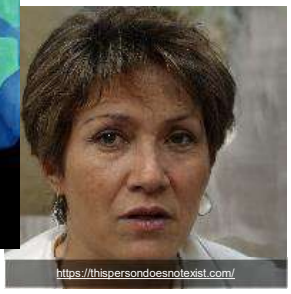
Context







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Motivation for machine learning in NDE

- Augmenting / replacing human data interpretation
  - Reducing effect of human factors
  - Dealing with high data volumes from automated inspection, permanent monitoring etc.
  - Supporting Industry 4.0
- Doing interpretation that is too complex for humans
  - Analysis that requires many steps
  - Data has more than 2 dimensions
  - Data is from multiple NDE modalities

- Increasing NDE reliability
- Reducing NDE cost
- Increasing NDE capability

Challenges for machine learning in NDE

- NDE is mostly applied to high-value and/or safety-critical plant
  - Genuine defects are rare
  - Ground-truth data about genuine defects is usually unavailable
  - Making samples with artificial defects is expensive (and difficult)

  How to deal with lack of labelled, true-positive data?

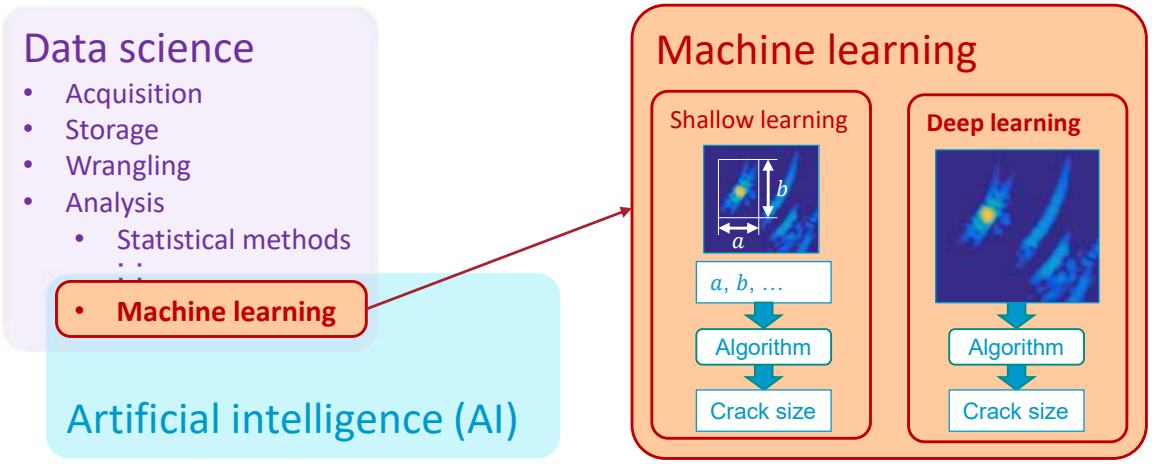
- NDE is highly regulated
  - Need to demonstrate high Probability of Detection
  - Inspection qualification procedures based on physical reasoning

  How to qualify inspections involving machine learning?

Outline of talk

- Artificial intelligence, data science, machine learning and all that
- Tools and concepts
- Examples
  1. Detection and characterisation from images
  2. Artefact suppression in Ultrasonic images
  3. Artefact suppression in guided wave signals
- Conclusions and challenges

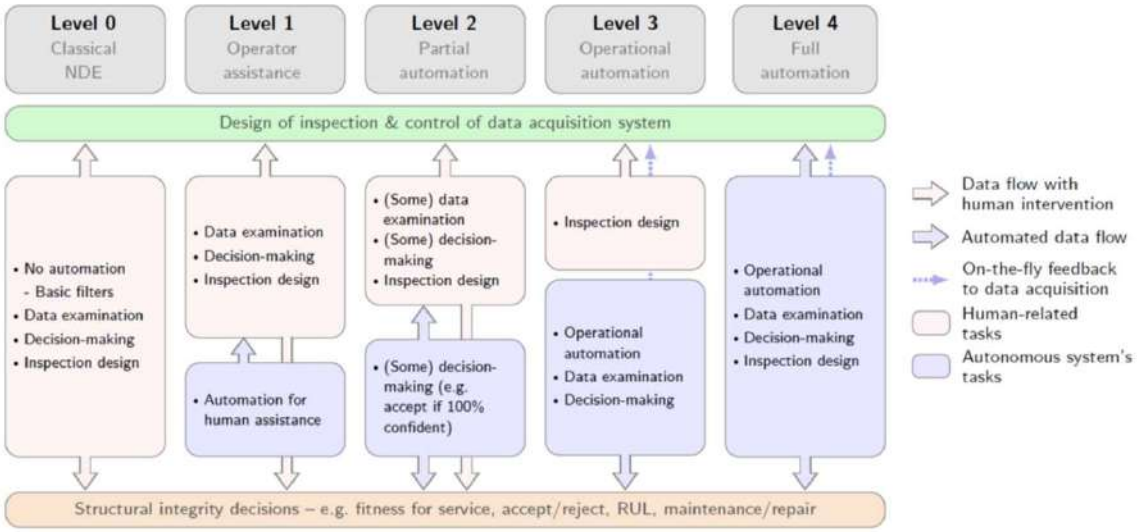
Artificial intelligence, data science, machine learning and all that



Tools and concepts

- State-of-the-art machine learning tools readily available (Tensorflow etc)
  - Training networks in reasonable time possible on decent PC with GPU
  - Designing and tuning network for a specific task is the difficult bit
- High-quality, high-volume (10^{4+}) datasets is key
  - Needs to adequately sample parameter space
- Need data for
  - Training: passed repeatedly through network for training
  - Validation: used to determine when to stop training, choose between networks etc.
  - Test: previously unseen by network to determine final performance

Levels of automation



 Cantero-Chinchilla, Wilcox, Croxford, "Deep learning in automated ultrasonic NDE –developments, axioms and opportunities", *NDT & E Int.*, 2022

Consider two problem types

1. Those with accurate defect data
   - Lots of real data including damage
   - Well validated models of defects
   - Key challenge is level of uncertainty in predictions

   Example 1

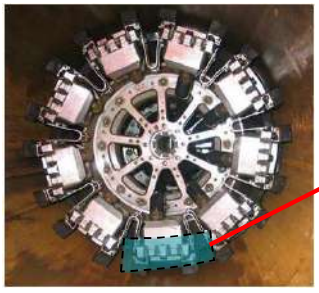
2. Limited defect data
   - Require any sentencing to be physics based
   - May be some defects but insufficient to train ML model

   Example 2
   Example 3

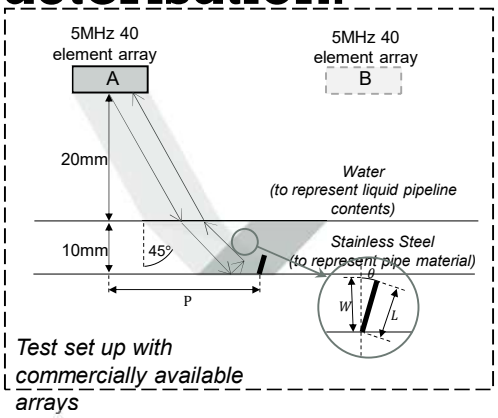
Detection and characterisation:

Inline Pipe Inspection

Pig launching

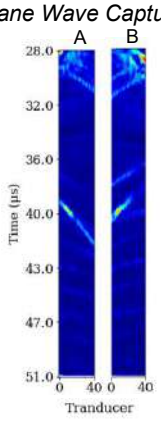


PA ring inside a pipe

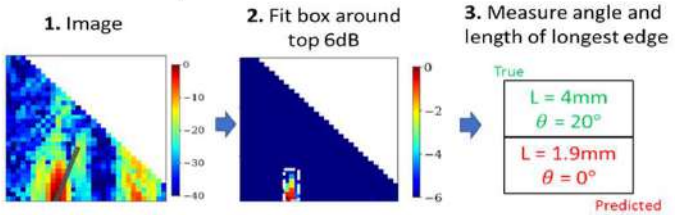


Test set up with commercially available arrays

Plane Wave Capture (PWC)

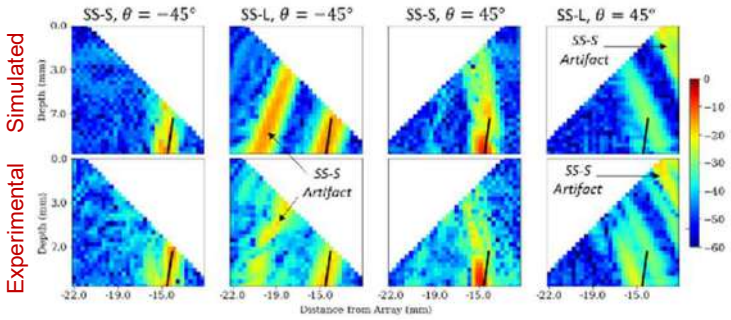


Sizing



Detection and characterisation

- Simulated data for training
  - Hybrid FE / ray-tracing model of defect responses
  - Superposition onto experimentally-measured 'noise'
  - **25,625** crack datasets (25 lengths, 41 positions, 25 angles)
  - 85/15 train/validation split
- Experimental data
  - **999** datasets (21 samples, 27 positions and flips)
  - 75/25 validation/test split

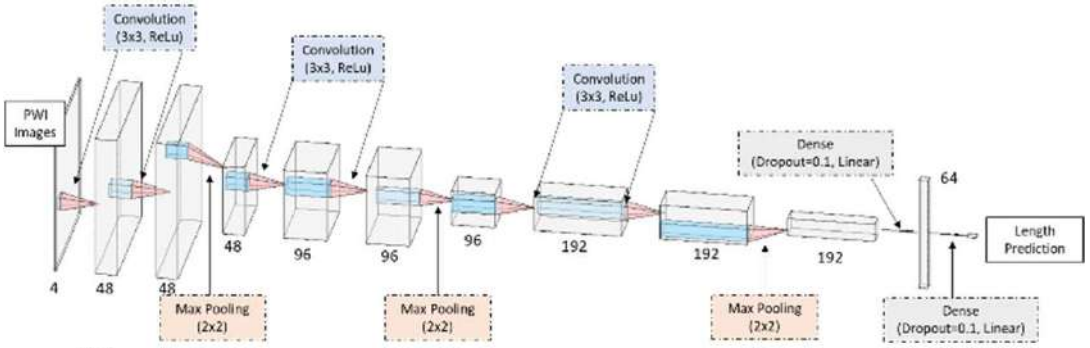


High-fidelity simulation at scale enables ML for NDE

Pyle, Bevan, Hughes, Rachev, Ali, Wilcox, "Deep Learning for Ultrasonic Crack Characterization in NDE", *IEEE UFFC*, 2021

Detection and characterisation

- Machine learning approach
  - Two multi-layer 2D CNNs (one for crack length, one for crack angle)
  - Example CNN for crack length

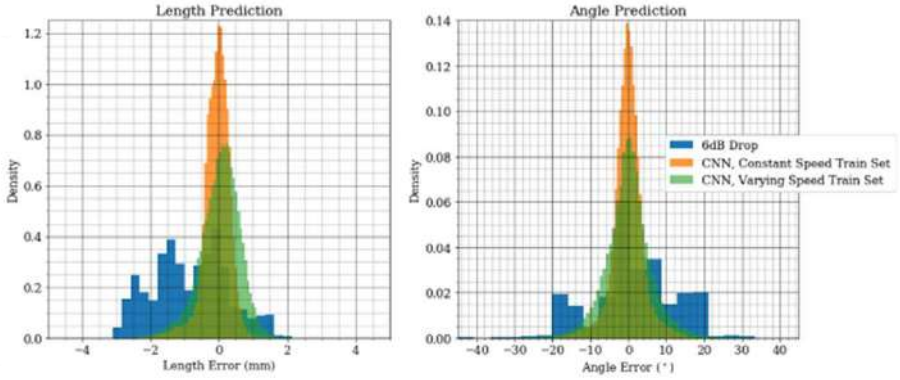


Pyle, Bevan, Hughes, Rachev, Ali, Wilcox, "Deep Learning for Ultrasonic Crack Characterization in NDE", *IEEE UFFC*, 2021

Detection and characterisation

- Results on experimental test data

Method	RMS error	
	Length (mm)	Angle (°)
-6 dB	**1.1**	**12**
CNN (trained fixed vel.)	**0.4**	**4**
CNN (trained var. vel.)	0.6	4

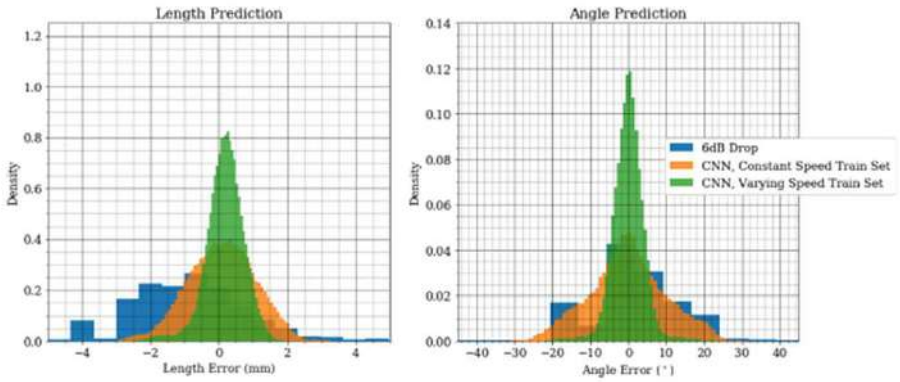


Pyle, Bevan, Hughes, Rachev, Ali, Wilcox, "Deep Learning for Ultrasonic Crack Characterization in NDE", *IEEE UFFC*, 2021

Detection and characterisation

- Results on experimental test data with perturbed imaging velocities*

Method	RMS error	
	Length (mm)	Angle (°)
-6 dB	**1.8**	**20**
CNN (trained fixed vel.)	1.0	10
CNN (trained var. vel.)	**0.6**	**4**

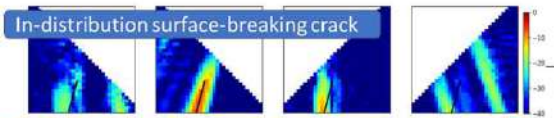


*Proxy for imprecisely-known material velocities

Pyle, Bevan, Hughes, Rachev, Ali, Wilcox, "Deep Learning for Ultrasonic Crack Characterization in NDE", *IEEE UFFC*, 2021

Detection and characterisation

- Key is uncertainty quantification
  - Train an ensemble of models
  - Learn out of bounds knowledge

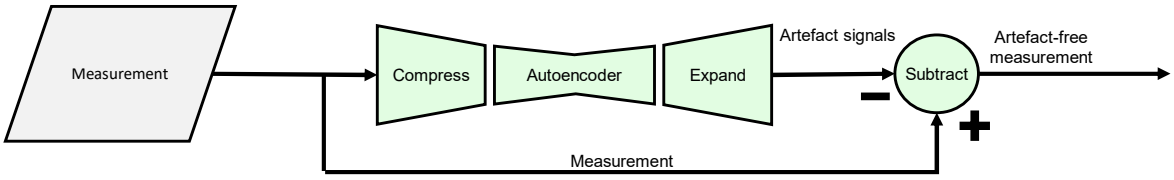


True defect extent (mm)	CNN predicted defect extent (mm)	Predicted uncertainty (mm) *(using deep ensembles)*
2.7	2.9	0.15

Pyle, Hughes, Ali, Wilcox, "Uncertainty Quantification for Deep Learning in Ultrasonic Crack Characterization", *IEEE UFFC*, 2022

Artefact suppression in Ultrasonic images

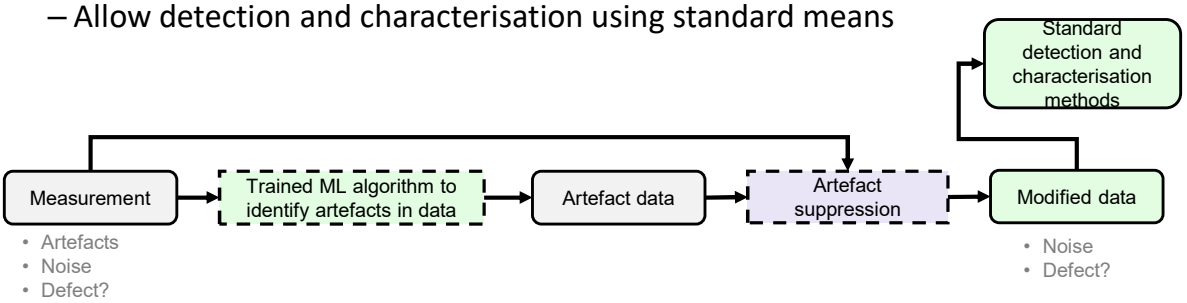
- General problem is artefacts inhibit ability to detect and quantify defects



  - Artefacts are predicted and then subtracted from measured data (rather than just being masked)
  - Based on principal component analysis and autoencoder
  - Potential to generalise to other NDE modalities

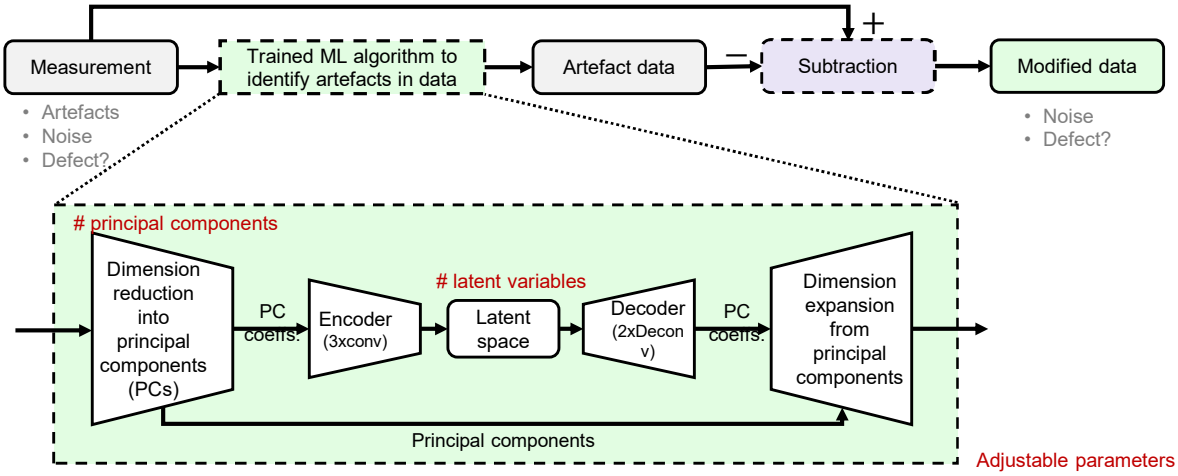
Artefact suppression in Ultrasonic images

- General requirements
  - Avoid forward model – train from defect-free experimental data
  - Less crude artefact suppression – subtract rather than mask
  - Allow detection and characterisation using standard means



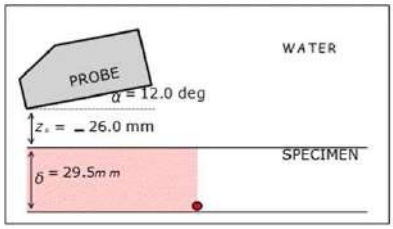
Artefact suppression in Ultrasonic images

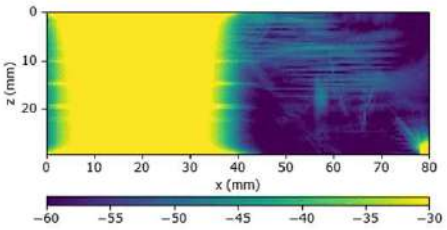
- Architecture



Artefact suppression in Ultrasonic images

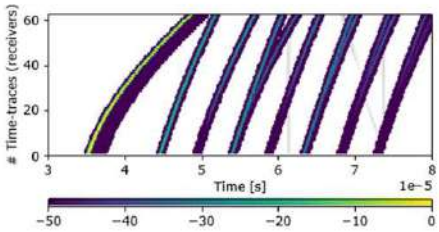
Inspection geometry

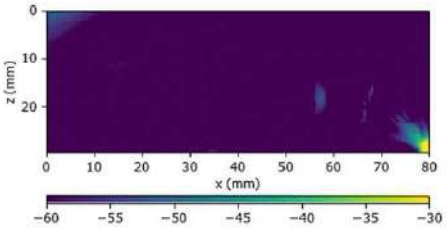




Fused image using extracted probe position <u>without</u> artefact suppression

Artefact masks on raw data





Fused image using extracted probe position <u>with</u> artefact suppression

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Cantero-Chinchilla, Wilcox, Croxford, "A deep learning based methodology for artefact identification and suppression with application to ultrasonic images", *NDT & E Int.*, 2022

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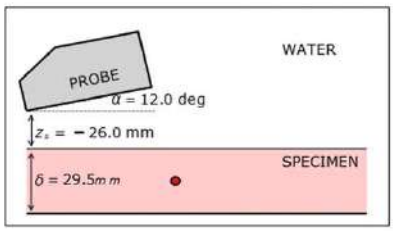
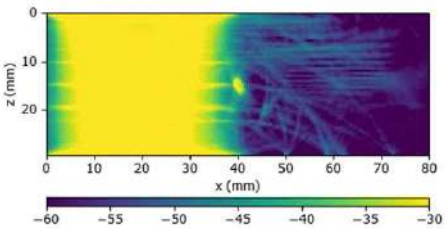
Artefact suppression in Ultrasonic images

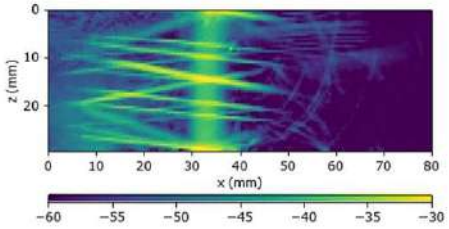
Inspection geometry

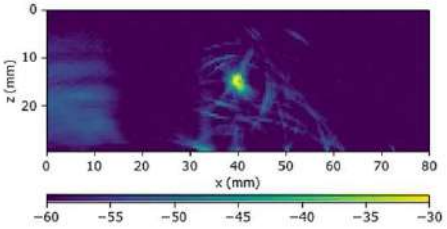




Fused image using extracted probe position <u>without</u> artefact suppression

Fused image assuming <u>fixed</u> probe position <u>without</u> artefact suppression





Fused image using extracted probe position <u>with</u> artefact suppression

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Cantero-Chinchilla, Wilcox, Croxford, "A deep learning based methodology for artefact identification and suppression with application to ultrasonic images", *NDT & E Int.*, 2022

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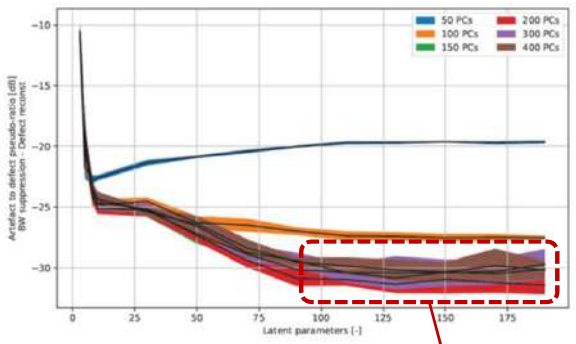
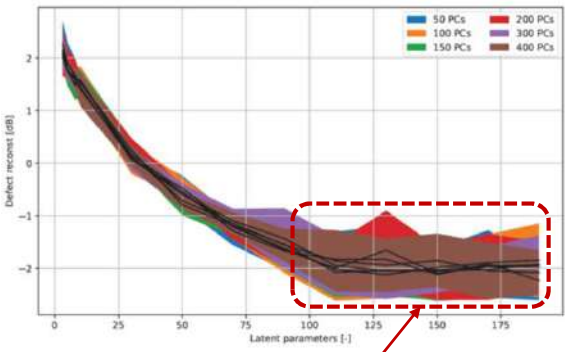
Artefact suppression in Ultrasonic images:
Effect of adjustable parameters

Artefact to defect ratio(dB)
(ideally reduced as much as possible)



Defect response (dB)
(ideally reduced as little as possible)



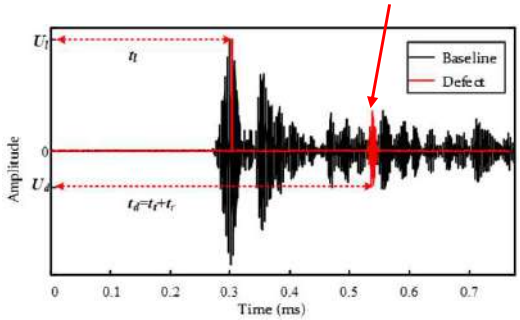
Maximum ratio –30 dB once # PCs > 150 & # latent params > 100

Comes with a reduction in defect response of –2 dB

Artefact suppression in guided wave signals

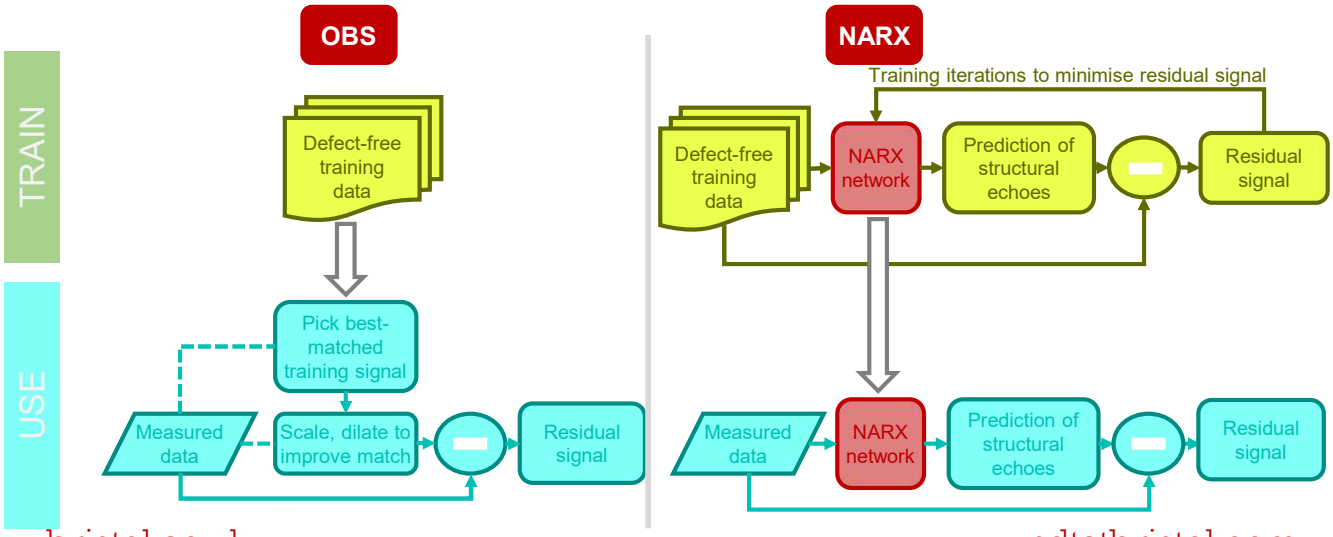
- Motivation
  - Guided wave monitoring data from sparse arrays of sensors
  - Signals dominated by reflections from structural features - artefacts
  - Challenge is identifying changes in signals due to damage

What would be seen if structural signals could be perfectly subtracted



K. Wang, J. Zhang, Y. Shen, B. Karkera, A. J. Croxford, P. D. Wilcox, "Defect Detection in Guided Wave Signals Using Nonlinear Autoregressive Exogenous Method", 21(3), 1012-1030., *Structural Health Monitoring*, 2022.

Artefact suppression in guided wave signals

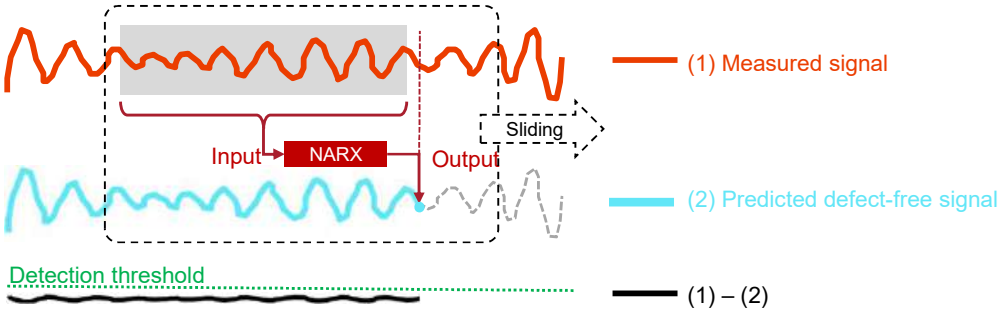


Artefact suppression in guided wave signals

- Machine learning principle
  - NARX network learns a representation of system from baseline A-scans
  - If fed a new A-scan it will try to recreate it using this representation
    - If no damage, the recreated A-scan should match the input A-scan
    - If damage has occurred, extra signals due to damage will not be fully recreated in A-scan
- Machine learning used here as novelty detector
  - Does not require synthetic data for training (defect-free baseline datasets only)
  - Only requires synthetic data at testing stage

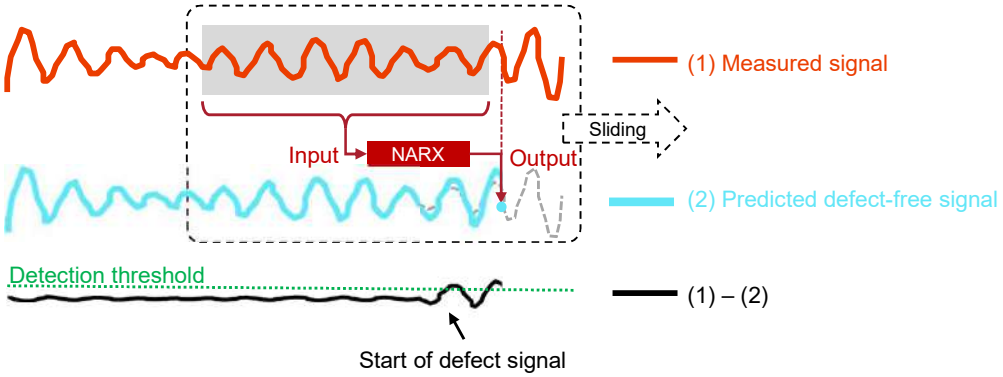
Methods

- Nonlinear Autoregressive Exogeneous (NARX) method



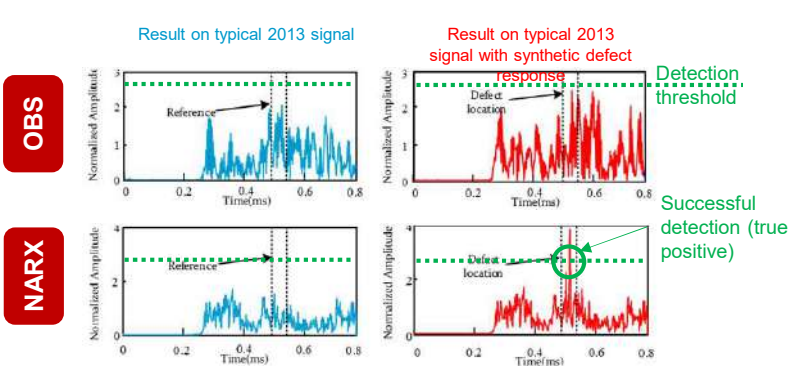
Methods

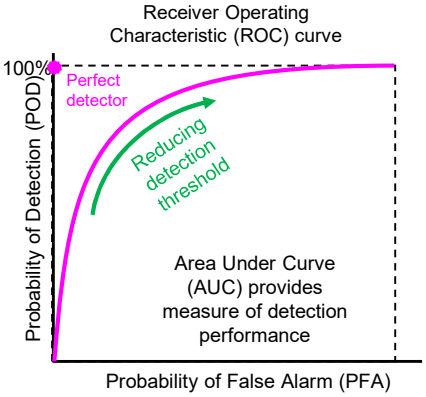
- Nonlinear Autoregressive Exogeneous (NARX) method
- Time series approach



Results

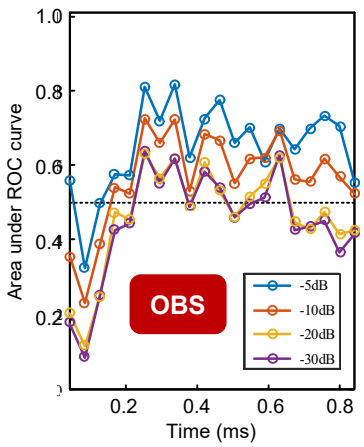
- Detection performance comparison with synthetic defect data

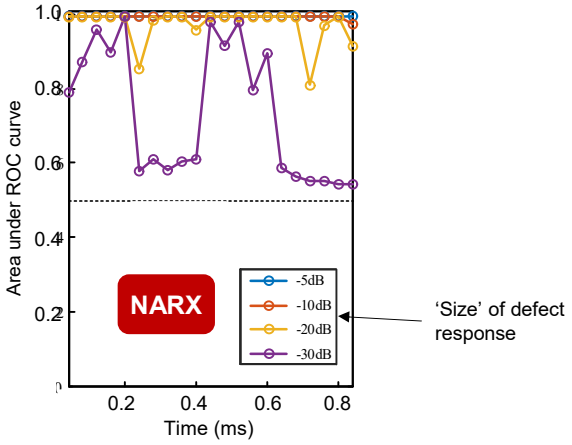




Results

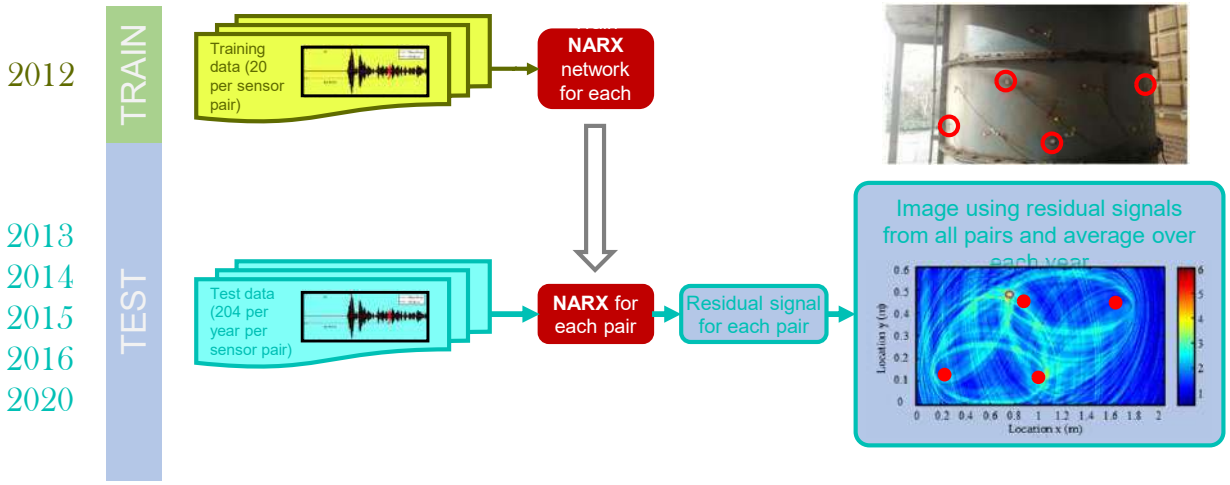
- Detection performance comparison with synthetic defect data





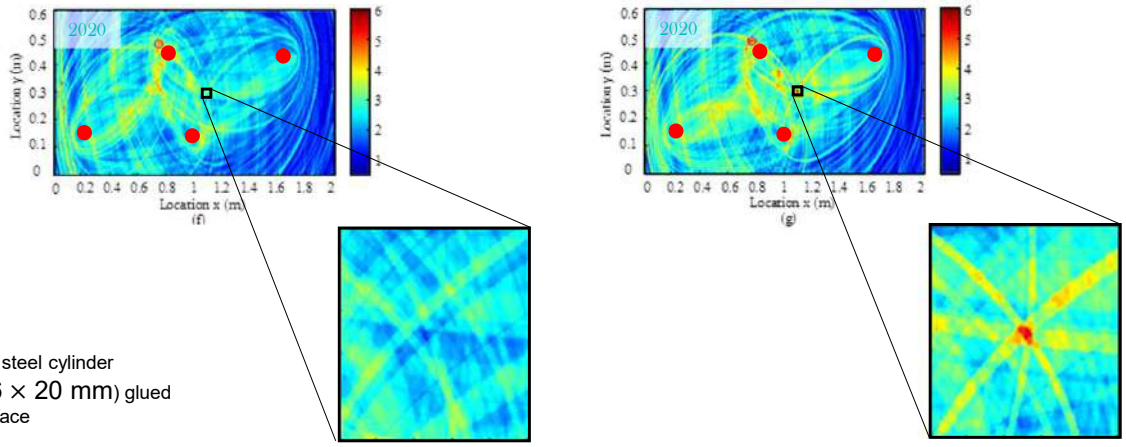
Results

- Application to experimental data from 4-sensor array (2013-20)



Results

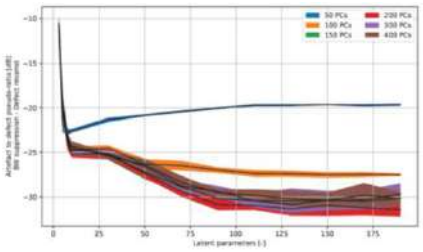
- Detection of physical anomaly* 8 years after training



*Solid steel cylinder (∅16 × 20 mm) glued to surface

Axioms

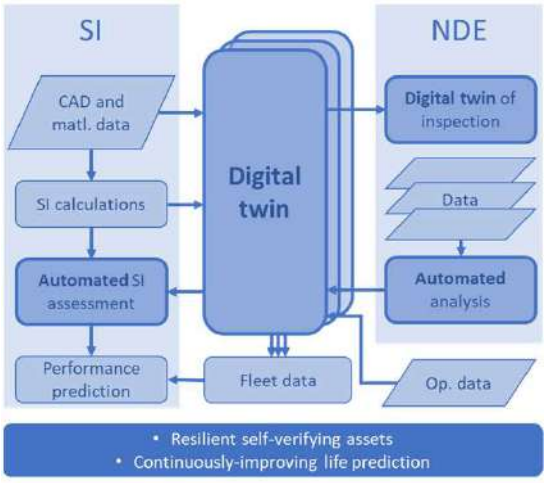
- Axiom 1 – Define domain of operation
  - Know the limits, and make sure users know them too
- Axiom 2 – Quantify performance
  - Use standard metrics to enable comparison
- Axiom 3 – Quantify uncertainty
  - Output should include suitable measure of confidence
- Axiom 4 – Identify adjustable parameters
  - Procedures for setting; sensitivity to values
- Axiom 5 – Self-awareness of limits
  - Network should "know" when limits are being exceeded
- Axiom 6 – Traceability
  - Training logs; metadata; informative APIs



Cantero-Chinchilla, Wilcox, Croxford, "Deep learning in automated ultrasonic NDE –developments, axioms and opportunities", *NDT & E Int.*, 2022

Future perspectives

- Automating NDE data analysis is essential for Industry 4.0
  - Direct digital link between NDE output and probabilistic structural integrity assessment
- Need robust automation pipelines with well-defined steps
  - Statistically consistent and robust physics-based approaches where possible
  - Machine learning applied where appropriate to clearly-bounded problems

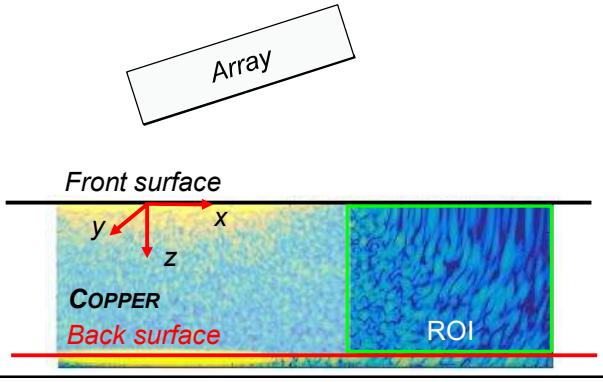


Cantero-Chinchilla, Wilcox, Croxford, "Deep learning in automated ultrasonic NDE –developments, axioms and opportunities", *NDT & E Int.*, 2022

Questions?

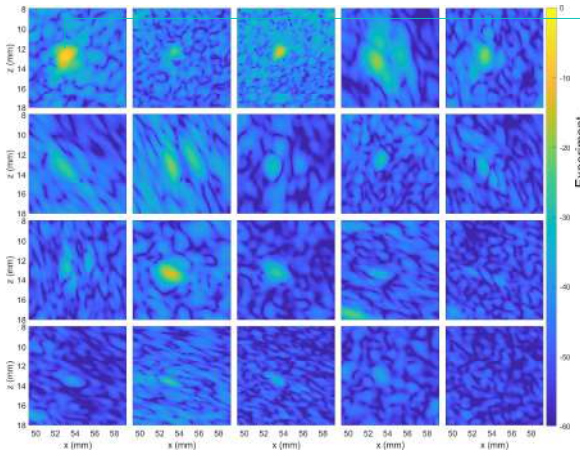
Example 2
Detection and characterisation from images

- Multi-view ultrasonic imaging
  - Same region of interest (ROI) within a specimen
  - Imaging algorithm: Total focusing method (TFM)
  - Linear delay-and-sum beamforming
  - Focusing on both transmission and reception, at all pixels

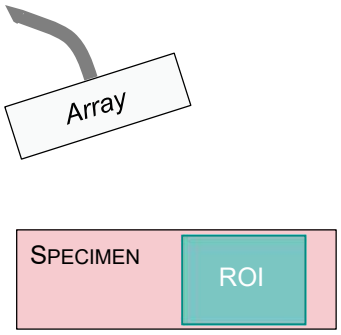


Example 2
Detection and characterisation from images

- Multi-view ultrasonic imaging
  - Maximises the viewing angle range from single location
  - Increases detection likelihood and provides multiple data points for characterisation



Single location
Multi-view TFM of
SDH = 21 data points

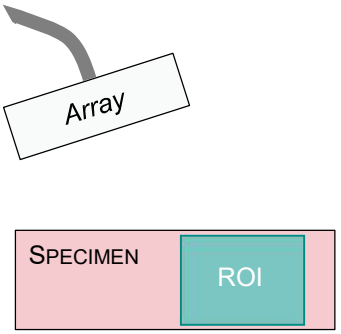


Example 2
Detection and characterisation from images

- Automated methods of detection and characterisation can
  - Increase data throughput
  - Provide consistent outcomes compared to human operator decision making

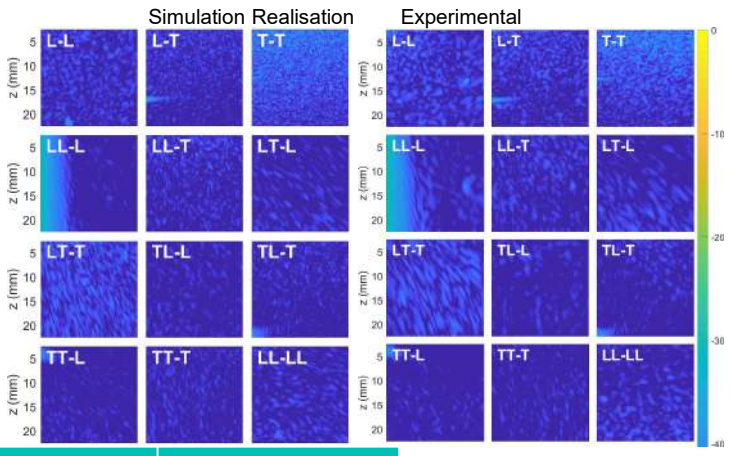
- Off-the-shelf ML models used to demonstrate ease of applying to new inspection scenario

- Data requirements
  - Simulated data used for training and validation
  - Experimental data for testing



Datasets

- Simulated datasets
  - Defect/Pristine ratio adjustable for detection and characterisation
  - Misalignment during imaging is optional
  - Setup parameters based on pristine experimental dataset



Classification	MxNxNxV	Variation	Use
Dataset A	30000x100x100x21	Setup & Misalignment	Training & Validation
Dataset B	4000x100x100x21	Setup & Misalignment	Test
Dataset C	61x100x100x21	Experimental	Test

Machine Learning

- Two stage process
  - Detection
  - Characterisation
- Detection
  - Deep learning: Can use Multi-view TFM images directly as input
  - Shallow learning: Metrics derived from the images
- Characterisation
  - Deep learning
- Baseline: Matched filter data fusion
  - IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 67, no 11, 2387-2401, 2020

Machine Learning

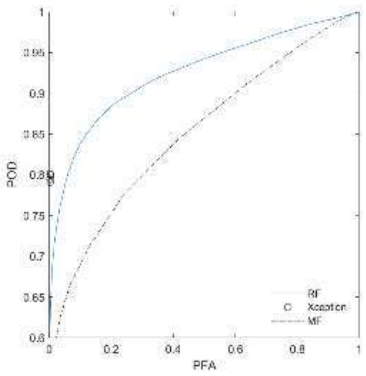
- Off-the-shelf approaches considered
  - Convolutional Neural Networks
    - MobileNet V1 (28 layers)
      - α = 0.25, 220k variables
      - α = 1, 3.2M variables
    - Xception (71 layers) 22M variables
  - Ensemble Methods
    - Random Forest
- Random Forest requires metrics

Coverage	Variable	Value	XZ Location
Box	Maximum	✓	✓
Box	RMS	✓	N/A
Whole-Image	Maximum	✗	✓

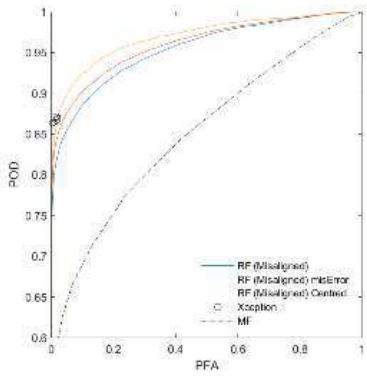
Detection

- Trained on 30000 realisations, 50% pristine, 25% SDH, 25% Cracks
  - Stratified kfold used during training, 80/20 split for training/validation
- Tested on 8000 realisations, 50/25/25 split

Trained on aligned dataset



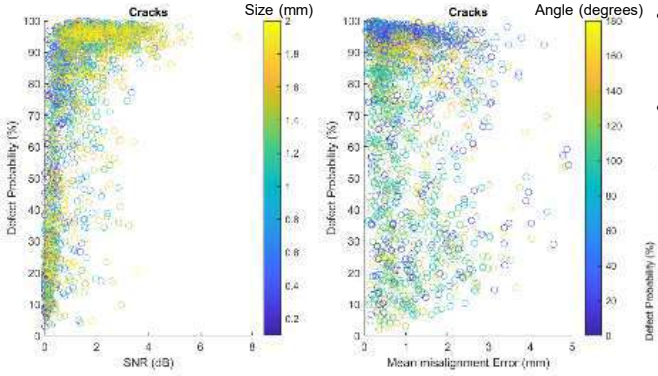
Trained on misaligned dataset



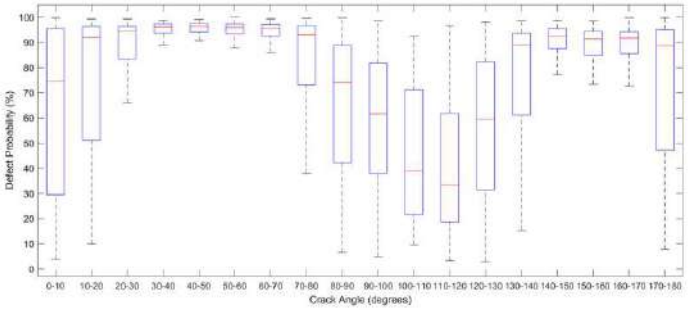
- RF performance is equivalent to Xception when box is centred on specified defect location, minimising chance misalignment moves defect outside tagged box
- Alternatively, can update specified defect location with average misaligned position (over all views)
- Will not affect RF model in practice

Detection

- Trained on 30000 realisations, 50% pristine, 25% SDH, 25% Cracks
  - Stratified kfold used during training, 80/20 split for training/validation
  - Ensembled prediction from all networks



- Crack detection (2000 realisations) performance is limited by small mean SNR and certain orientation angles
- Not by crack size or mean misalignment error



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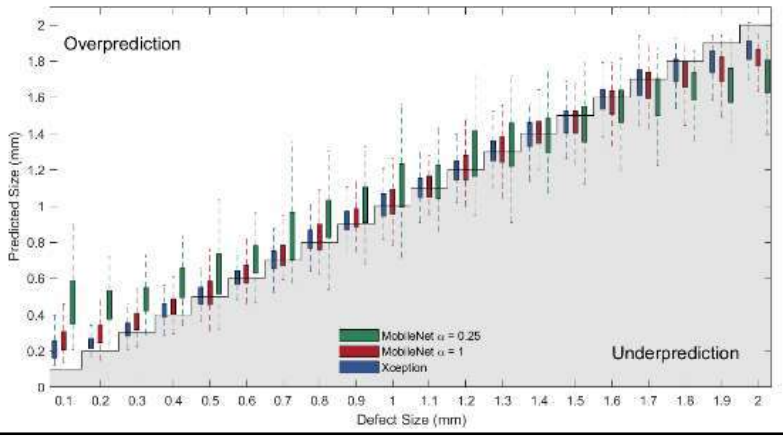
Characterisation

- Neural network complexity investigation
  - Ensemble predictions (10 networks)
  - Variation using shuffled training/validation and randomised weights initialisation
  - Detected only



2000 voids, 100 per size increment

Boxplot showing the true defect size against the predicted size from 3 neural network ensembles, each solid rectangle represents the IQR with 50% of defects

Increasing the model variables improves the prediction, with Xception doing a better job for every defect size

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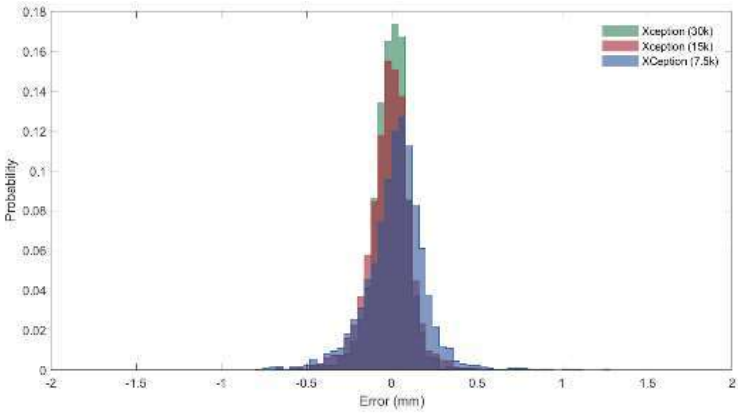
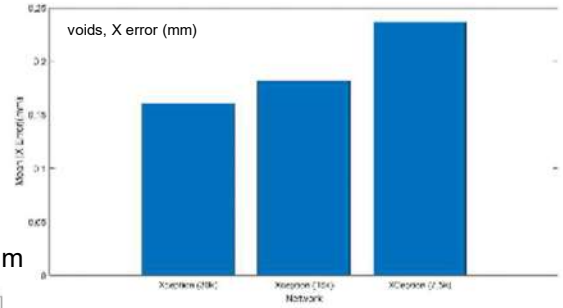
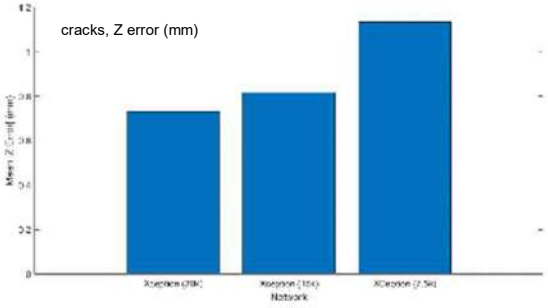
Characterisation

- Training dataset size investigation
  - 7.5k, 15k, 30k investigated
  - Decreasing benefit
  - At 30k, voids located at sub pixel (0.2mm) level
  - At 30k, mean sizing error - cracks: 0.2 mm, voids: 0.1mm





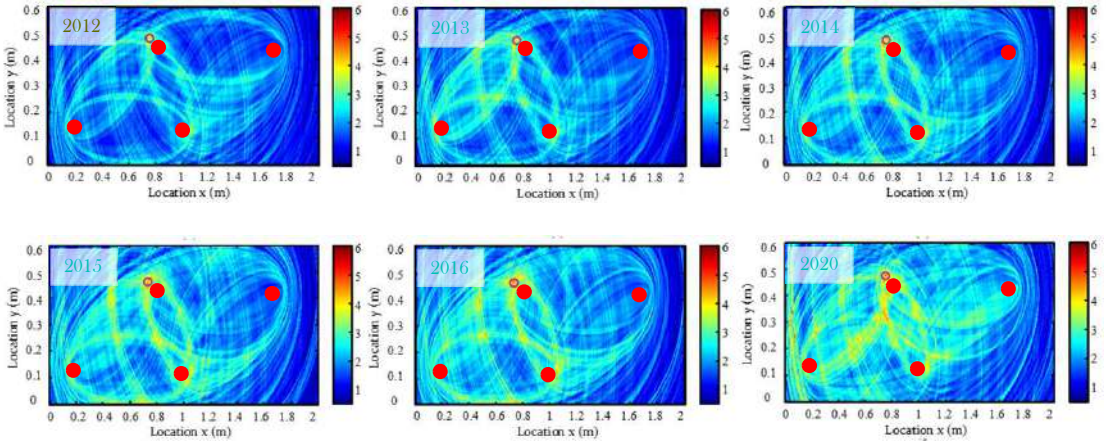


Example 2
Detection and characterisation from images

- Conclusions
  - Well validated models confirm conclusions about data requirements
    - Good simulations key
  - Off the shelf models work well
    - Shallow learning excellent for detection. Produces stochastic results
    - Deep learning offers better performance
    - Can be used to characterise defects

Results

- Application to experimental data acquired over multiple years

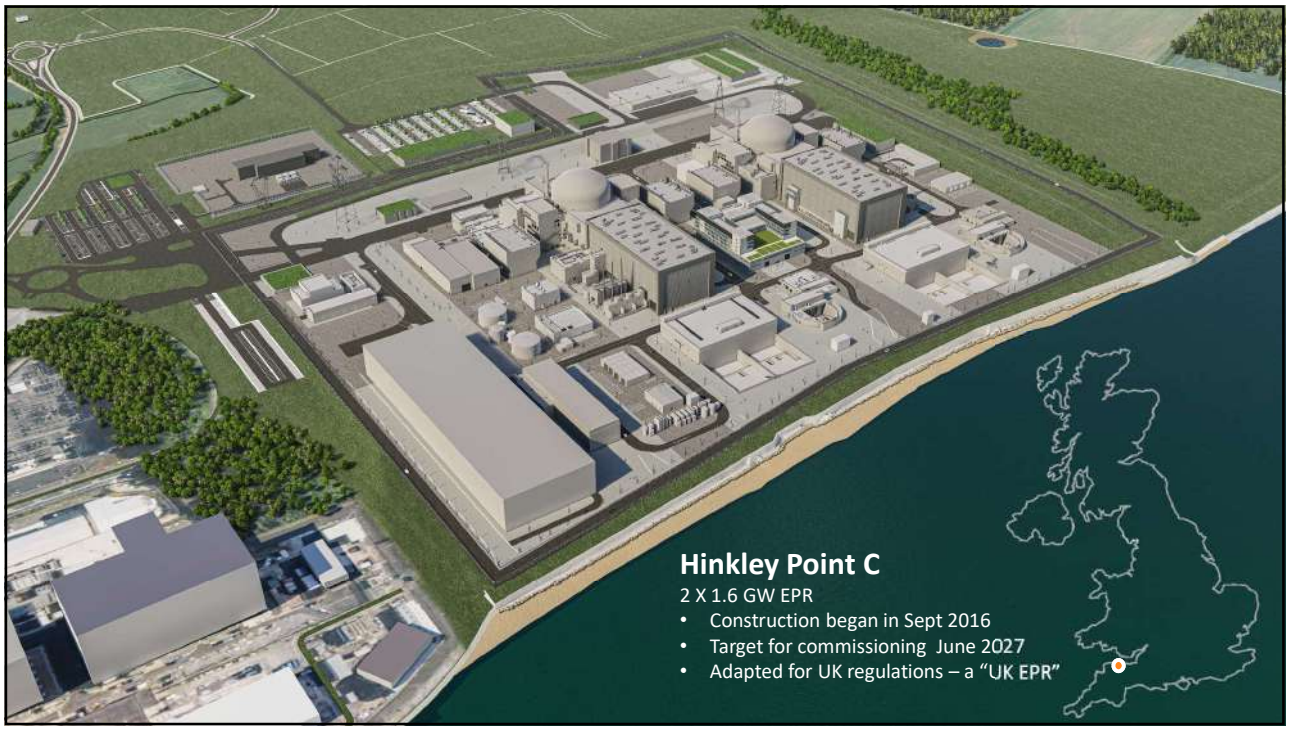


Hinkley Point C

Project Update

Hinkley Point C

- First new nuclear power station **in a generation**
- **Essential in the fight against climate change** and to build a secure, resilient system.
- Will provide **Six million homes with low carbon energy – 7% of UK demand**
- **£18billion investment** in Britain.
- **25,000 job opportunities** – thousands with local people
- Unit 1 **operational in 2027** with unit 2 commissioning in 2028.



The EPR Reactor

- The UK EPR is a **Pressurised Water Reactor**. The most common global design.
- It represents a major development on previous designs, making them amongst the **safest and most efficient civil nuclear power generators ever designed.**
- It has been designed to **use less uranium** and produce almost a third **less long-lived radioactive wastes** compared with water reactors in operation today.
- The UK version of the EPR **meets the most stringent safety and environmental protection standards,** having gone through the UK's Generic Design Assessment Process.

4

EDF Nuclear Power Plant Offers

A comprehensive portfolio of technologies to meet the worldwide demand for carbon-free energy

1650 MWe

- Most powerful reactor in the world
- The leading reference for very high energy demand
- Load following capability

1200 MWe

- EPR adaptation to 1200 MWe
- Adapted to various site and grid conditions
- Load following capability

Designs sharing the Core EPR Technology

340 MWe

- Meeting the 300-400 MWe SMR target
- Adaptable to various environments
- Other low-carbon uses: hydrogen, heat & electricity cogeneration, district heating, water desalinisation
- Load following capability

Fully integrated LWR-SMR design

Shaping our net-zero future with state-of-the-art nuclear technologies and services

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Hinkley Point C – The Physical Scale

176 hectares	**400 km** pipe work	**9000 km** electrical cabling	**6 MILLION** m^3 of earth moved
3 Million tonnes of concrete	**50,000 tonnes** structural steel	**25,000** Employment Opportunities	

6

Project Progress

Journey to construction

- **2006** Government Energy Review states nuclear can make significant contribution
- **2008** EDF acquires British Energy's nuclear sites
- **2010** Government include Hinkley Point in list of suitable sites
- **2011** HPC Development Consent Order application lodged
- **2012** EPR approved for use in UK; HPC nuclear site licence granted and site clearance begins
- **2013** Contract for Difference agreed with Government; Development Consent Order granted
- **2016** Final Investment Decision
- **2018** Start of main construction marked by completion of first concrete pour

Reactor Unit 1

9

Reactor Pressure Vessel Complete

- The first nuclear reactor built for a British power station in more than 30-years is complete and has been safely delivered to site.
- The “reactor pressure vessel” is the high strength cylinder that contains the nuclear fuel and the chain reaction needed to make heat.
- At just 13m long and weighing in at 500 tonnes, each of the two reactors at Hinkley Point C will help power around 3 million British homes.
- The reactor has been built in France by Framatome; the same nuclear engineering company which built Britain’s last nuclear reactor, at Sizewell B in 1991.
- Teams have spent 80,000 engineering hours on its construction.

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First Nuclear Island Pump

- The first of a series of pumps that will be used across the Nuclear Island was successfully installed in one of the Unit 1 Safeguard Buildings.
- The pump will deliver cooling water for the sprinkler safety system located on the underside of the Dome, which would activate in the unlikely event of a fire or accident in the Reactor Building.
- Once delivery from Avonmouth was complete it was picked up by crane, manoeuvred through one of the Safeguard Building's equipment hatches, lowered down to the -9.6m level, slid into position on skates and finally raised onto its installation plinth.

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Conventional Island – Turbine Hall

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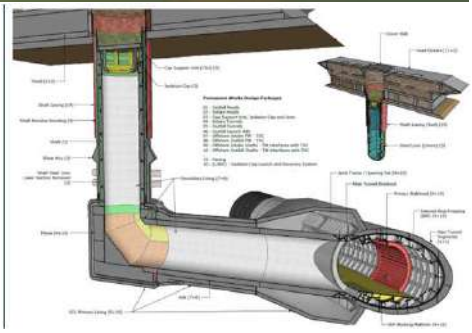
Conventional Island – Cooling Water and Pump House

Marine Works



Replication reduces cost and schedule risk

Hinkley Point C sees major productivity gains in work repeated on Unit 2 from Unit 1
Similar evidence seen in nuclear construction across the world

Turbine Hall base slab concrete pour

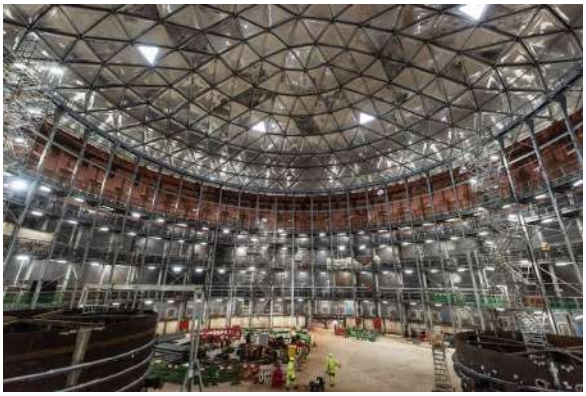
Unit 1	Unit 2	
12 pours	10 pours	30% Quicker in Unit 2
10 months	7 months	

Liner cup floor

Unit 1	Unit 2	
57 days to build	39 days to build	30% Quicker in Unit 2

Modularisation – factory built on site

Reactor Cavity Pool lift 700 tonnes



Bunker factory – for liner rings and domes

Progress throughout 2023

- The project **will reach the peak of construction** with both main-civil works and mechanical and electrical installations in progress.
- This will be **the year we place the Dome onto Unit 1** and receive the Reactor Pressure Vessel on-site.
- In the Bristol Channel, more great work will occur as we **drill the shafts to connect the heads** to the cooling water tunnels.
- **The main control room** that has been pre-fabricated will also be transferred into Unit 1 for its fit-out.
- In addition, the suppliers of our **Nuclear Steam Supply System** (Framatome) and Turbine (GE) will increase their presence on Site and start installing equipment.
- The MEH teams will also be **accelerating the installation of 1,000 km's of pipework and cabling** as rooms are transferred from the main-civils work.

Building a copy – Sizewell C

Advanced Nuclear Reactors

Steve Chengelis
Director – Future Fleet

NDE in Nuclear Meeting
6/27/2023

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EPRI's collaborative platform is unrivaled. Our R&D:

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- Positions you as a leader in addressing industrywide challenges

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- A proven track record
- Scientifically based research you can trust

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- Reduce expenses and increase productivity
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- Benchmark, learn and share best practices
- Increase your awareness of challenges that others are facing and alternate solutions to challenges you might be facing
- Save time and money troubleshooting problems EPRI and its stakeholders have seen before

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Our Members

EPRI members represent 90% of the electricity generated and delivered in the United States, with international participation extending to 45 countries.

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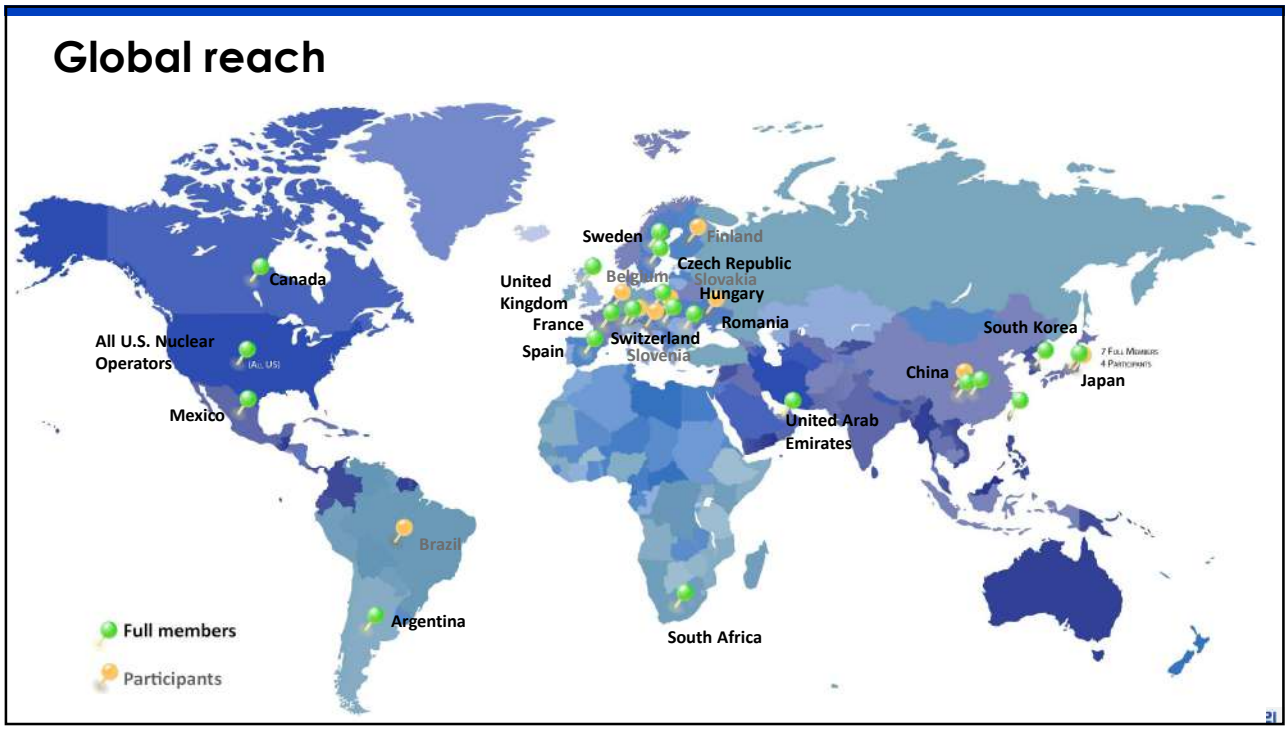
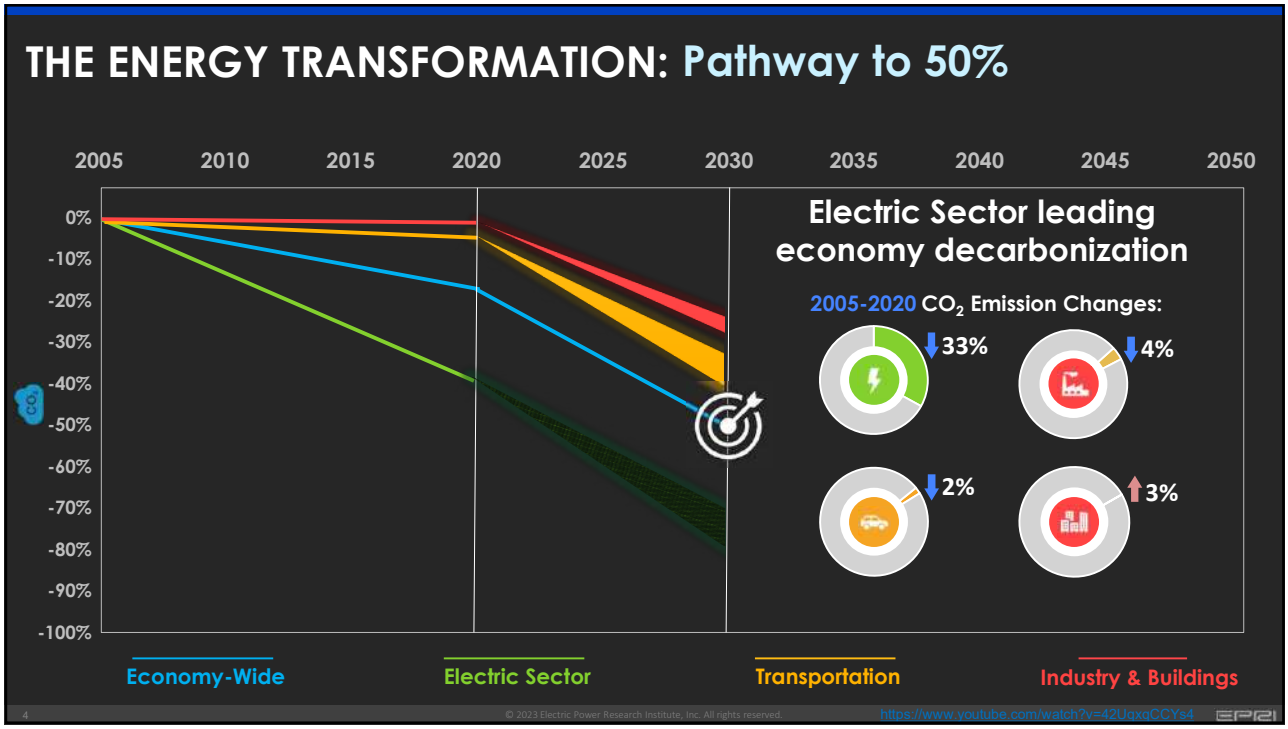

Global reach
Canada
All U.S. Nuclear Operators
Mexico
Brazil
Argentina
Sweden
Finland
Czech Republic
Slovakia
United Kingdom
Belgium
Hungary
France
Romania
Switzerland
Slovenia
Spain
South Korea
China
Japan
United Arab Emirates
South Africa
Full members
Participants


THE ENERGY TRANSFORMATION: Pathway to 50%
2005
2010
2015
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-10%
-20%
-30%
-40%
-50%
-60%
-70%
-80%
-90%
-100%
Electric Sector leading economy decarbonization
2005-2020 CO2 Emission Changes:
33%
4%
2%
3%
Economy-Wide
Electric Sector
Transportation
Industry & Buildings

Decarbonization Pathways Enabled by Innovation

~10-15 years

~15-30 years

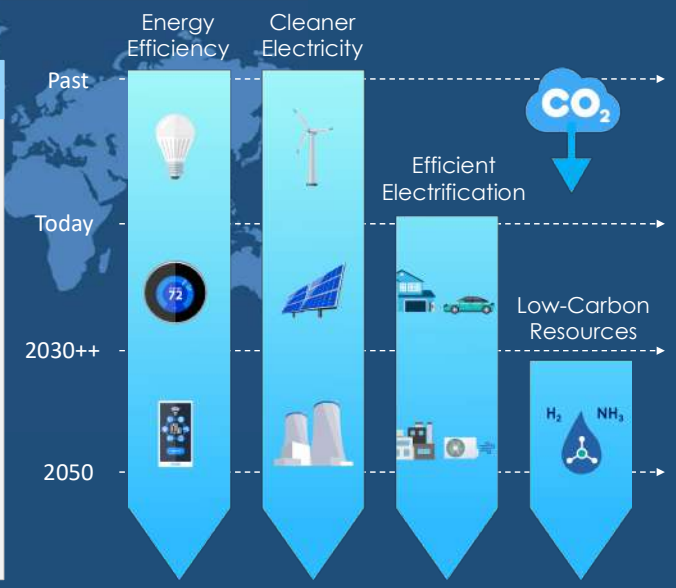
Decarbonization

Accelerate economy-wide, low-carbon solutions

- Electric sector decarbonization
- Transmission and grid flexibility: storage, demand, EVs
- Efficient electrification

Achieve a net-zero clean energy system

- Ubiquitous clean electricity: renewables, advanced nuclear, CCUS
- Negative-emission technologies
- Low-carbon resources: hydrogen and related, low-carbon fuels, biofuels, and biogas



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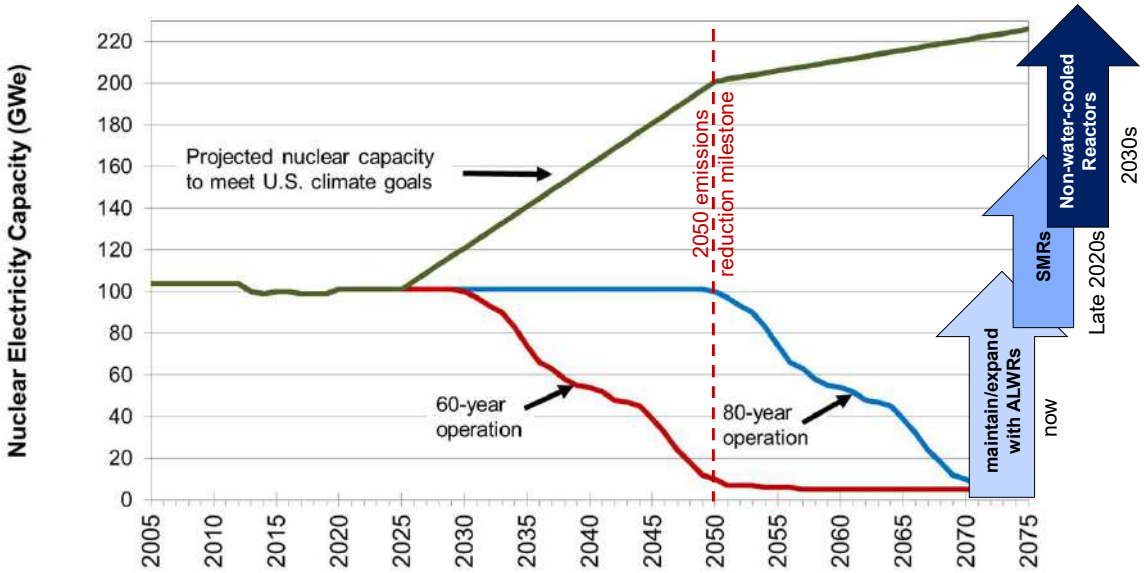
Opportunity and Role for Nuclear in 21st Century



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Adapted from Figure produced by US DOE

Nuclear Beyond Electricity (NBE)

Enable **existing** and **future** nuclear plants to participate in energy markets beyond the practice of generating baseload electricity.

- Flexible Electric Grid
- Low Carbon Fuels
- Process Manufacturing
- District Energy
- Data Centers
- Water & Wastewater

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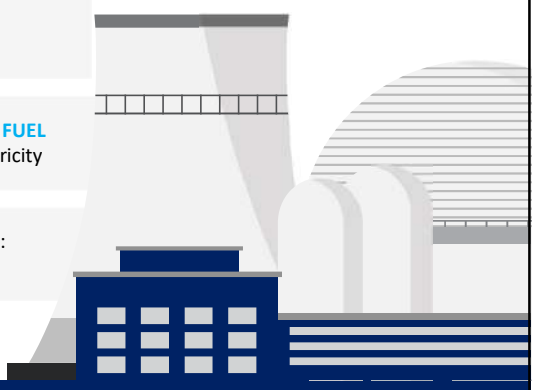
Benefits of Advanced Reactors

Advanced reactors integrate better with renewable energy and improve the utilization of secure energy resources

- Increased **FLEXIBILITY**
- **NEW DESIGNS** can load-follow closer, faster, and more flexibly
- More conducive to **DECARBONIZATION** goals
- Ability to reach **UNIQUE** communities
- Ability to convert more **FUEL ENERGY** to usable electricity
- Many designs are small: **≤300 MWe**



(Source: Resources for the Future, Advanced Nuclear Reactors 101, March 2021)

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How do we get there?

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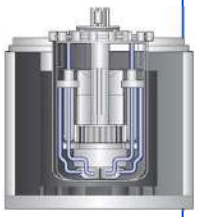
Reactor Types

01 Water-Cooled Reactors

Mature technology with deployment options and wide power range

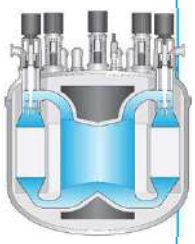
02 Fast Reactors

Highly resource efficient with near-ambient pressure of operation



03 Molten Salt Reactors

Wide diversity of coolant and fuel options for various missions



04 High-Temperature Gas-Cooled Reactors

Test scale experience in Japan for advanced hydrogen production

05 Microreactors

Rapidly deployable, opportunity for industrial heat production

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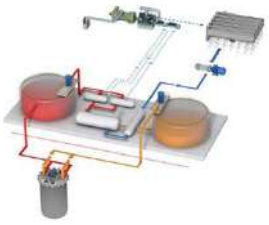
Advanced Reactor Demonstration Project (ARDP) Tier 1

TerraPower

- Awarded $80M USD in initial funding
- Demonstrate integrated thermal storage SFR plant at INL by 2028
- Thermal storage enables nearly 150% peak power output



Natrium SFR
- Intermediate molten salt thermal storage
- Sodium cooled
- 345 MWe Plant

X energy

- Awarded $80M USD in initial funding
- Demonstrate four-unit Xe-100 plant at INL by 2027
- Includes commercial scale TRISO fabrication facility demonstration

TRISO-X Pebble

Xe-100 HTGR
- TRISO-X Pebble-bed fueled
- Helium cooled
- 4x 76 MWe SMR Plant

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Fundamental Design Choices

Coolant
- Temperature
- Pressure
- Corrosivity, Reactivity
- Gas
- Salt
- Liquid Metal
- Water

Fuel
- Fuel Cycle
- Solid vs. Liquid
- Circulating vs. Fixed
- Enrichment
- Dissolved
- Metal
- Oxide
- Carbide
- Nitride, Silicide,…
- F Salt
- Cl Salt
- TRISO-based
  - Prismatic
  - Pebble

n^0 Energy
- Fast
- Thermal
- n^0 Moderation
  - C
  - ZrH
  - BeO
  - H_2O
  - D_2O

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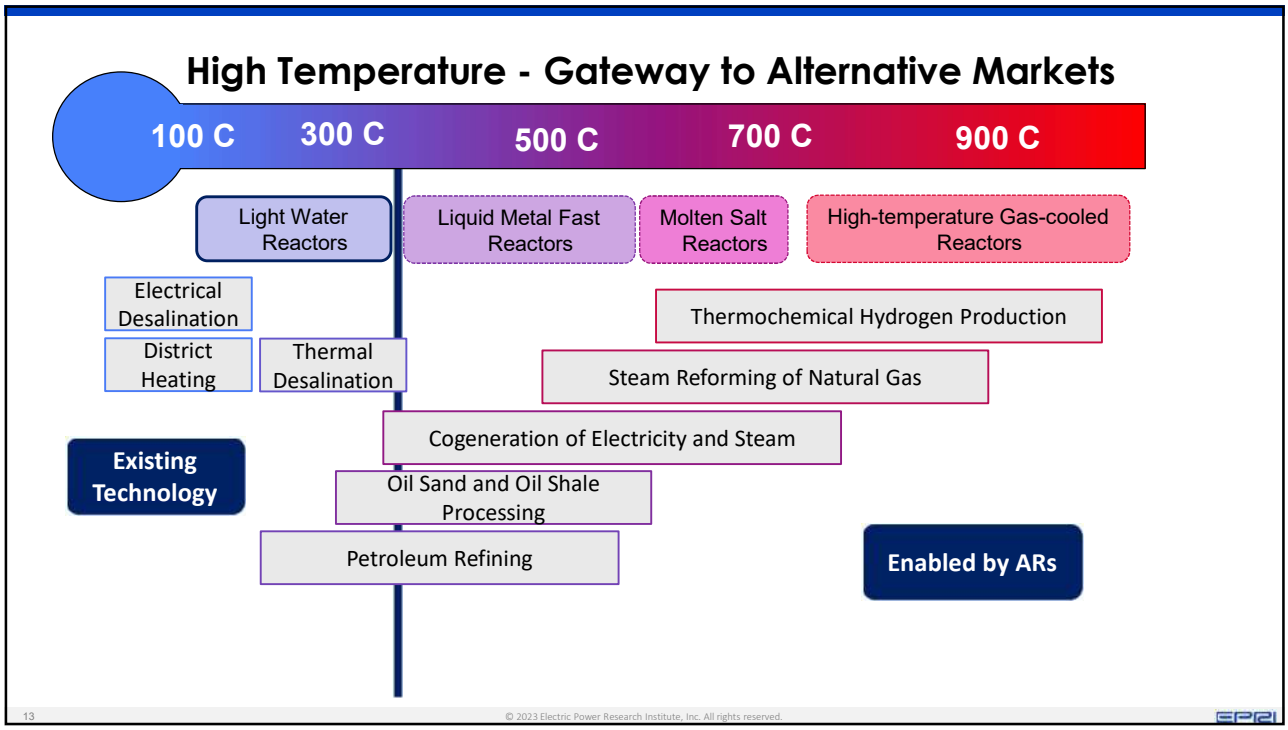

Small and Modular

- Small – electricity output below 300 MWe according to US NRC
  - Rolls Royce and UK SMR has 440 MWe output
- Modular – factory construction, testing, inspection
- Trade economies of scale for economies of:
  - numbers (mass production)
  - manufacture (cheaper assembly in factory than construction on site or “in hole”)
  - flexibility (e.g., right-sizing for replacement for smaller coal units)
  - reduced financial risk (lower capital cost for unit deployment)
- Economic case for SMRs remains to be demonstrated
  - overcoming economy of scale with other economies…
  - increasing generation asset flexibility
  - simplified design and enhanced safety

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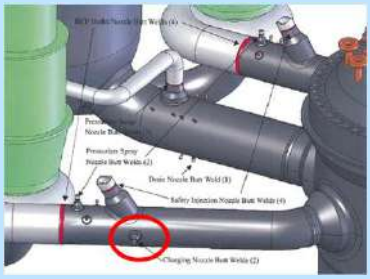
High-Temperature NDE Applications

Up to 200°C
Available with current technology

Up to 350°C – LWRS
Monitor Existing cracks:
Do I need to repair now?



~650°C and up to 1000°C – advanced reactors
Continuous operations

https://natriumpower.com/

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Conventional NDE for LWR Applications

- NDE starting point:
  - Pre-service inspection of fabricated components & installation
  - Periodic inspections of critical components with basic tooling
- Operational experience:
  - HAZ cracks, IGSCC, wall thinning, thermal fatigue, heat exchangers
  - Material/chemical issues—CISCC, molecular transport, DM welds
  - Overridden safety features (e.g. CP)
  - Power uprates, plant life extensions
- Developed basic tooling types:
  - VT, UT, ET, RT, PT, MT, and more
    - Tooling and access can far exceed the cost of the examination
- EPRI has world-class expertise in NDE for LWR fleet—domestically and internationally

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Technology Transition for LWR Monitoring Applications

- Conventional LWR inspections are tailored toward personnel deployment during outages
- Recent efforts have been conducted to demonstrate high-temperature sensors for monitoring cracks in between outages
  - 370 C thermal envelope for all applications
  - Technology is commercially available but not hardened enough
- Non-LWR reactors bring very high temperatures and preclude personnel-deployed NDE
  - Sensor thermal and radiation lifetimes could necessitate substantial technology development

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Considerations relevant to NDE for non-LWR NPP Designs

Non-LWR designs reduce the need for some inspections	Non-LWR designs may however necessitate new types of inspections	Potential inspection needs
• Lower operation pressure • Fewer welds • Fewer or eliminated dissimilar metal welds	• Elevated Temperatures • Robotic delivery of NDE; robotic maintenance of monitoring sensors and cabling • New material/design combinations • Non-water coolant • Asset protection • Lack of operational experience	• Cracking • Wall thinning / thickening • Creep • Corrosion (Non Rx, salt side) • Swelling • Embrittlement • Heat exchangers

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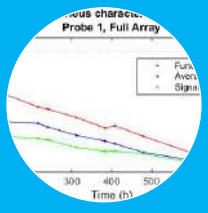
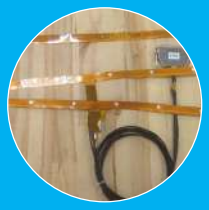
EPRI R&D for High-Temperature Sensors



Explore sensor prototypes

- Thermal limit testing
- Thermal cycling
- Long-term thermal endurance



Accelerate development of advanced sensors

- Directly installed UT for 600 C
- UT phased array for 350 C
- Ultrasonic thermometer/viscosity sensor

Adhesive mounting and coupling

- Many adhesives tested
- Challenging objective
- Recent promise
- Limited irradiation testing

Networking with parallel R&D communities

- National Labs
- Sensor technology developers
- Adjacent industries

- Leverage synergy, avoid redundancy, roadmap forward direction

Conducting yearly workshops since 2021

- 2023 ANS NPIC&HMIT conference: co-sponsoring a sensors panel
- October 2023 sensors workshop at MIT campus

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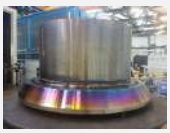
Advanced Manufacturing and Materials

GOAL & VALUE

Identify, develop, qualify, & implement more economical manufacturing, inspection & new materials that enable:

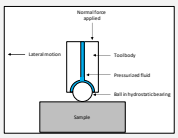
Higher Quality Components | Reduced Lead Times | Alternative Supply Chains | Cost Competitiveness | Enable Deployment



- Evaluate, Qualify, and Demonstrate Advanced Manufacturing Methods
- Additive Manufacturing
- PM-HIP
- Advanced Welding
- Mechanical Connections
- Advanced Cladding

Advanced Manufacturing

- Mitigation Techniques
- Risk-Informed Strategies
- Advanced Sensors
- Enhanced Specifications



Material Performance and Inspection

- AR Materials Development
- Materials Qualification
- Degradation Mechanism (MMM/MDM)

New Materials Development

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How Can EPRI Help

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Advanced Nuclear Technology (ANT) Program Focus

MISSION

Accelerating the deployment of nuclear power around the world

- Informing Resource Planning
- Technology Development
- Reducing Deployment Costs
- Supporting Plant Startup

More than 80 companies make up the broadest advanced nuclear collaborative

From project initiation through initial operation
ANT is an extension of your team

Extensive Portfolio
40+ Ongoing Projects
200+ Past Products

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Advanced Reactor Roadmap

A shared strategy to ensure success at scale

Serving government, academic, industrial, and public **stakeholders**

Almost 100 GWe of **new nuclear** will be needed by 2050. This means around **300 ARs** in the next **30 years**

7 Enablers and **46 key actions** chart our path towards a **net-zero future**

Convening the industry for **strategic action**

Industry's roadmap to the future fleet

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Purpose and Audiences

01 For potential customers of advanced reactors

02 For policy-makers and regulators

03 For financial institutions

04 For public stakeholders, including local communities and Tribal Nations

05 For industry stakeholders

Provides an achievable path forward to support the successful commercialization of advanced reactors

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Strategic Elements

Regulatory Efficiency

- **Licensing** — 7 Actions
- **Environmental** — 7 Actions
- **Oversight** — 2 Actions

Technology Readiness

- **Fuel Cycle** — 3 Actions
- **Plant/SSC Design** — 3 Actions
- **Supply Chain** — 7 Actions
- **Nuclear Beyond Electricity** — 3 Actions
- **Codes & Standards** — 2 Actions

Project Execution

- **Project Management** — 4 Actions
- **Engineering & Procurement** — 2 Actions
- **Construction & Commissioning** — 3 Actions
- **Initial Operations & Maintenance** — 1 Actions
- **Workforce Development** — 4 Actions

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3. NDE 4.0 (I)

The presentations in this session are listed in the table below.

NDE 4.0 (I)	**Chair:** Leif Esp (EPRI)
NDE 4.0 for the Electric Power Industry Low Carbon Energy Future	Terrill Massey (EPRI)
Metallic Materials Fatigue Data Determined through NDE Principles as a Basis for Structural Assessment in Nuclear Engineering	Christian Boller (Saarland Univ.) et al.
New Challenges in Nuclear Power Plant ISI in Czech Republic	Ladislav Horáček (UJV) et al.
Evaluation of Techniques for Compression of Ultrasonic Data	Terrill Massey (EPRI)

NDE 4.0 for the Electric Power Industry Low Carbon Energy Future

Terrill Massey[1], John Lindberg[1], Mark Dennis[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): tmassey@epri.com

The energy and electric power industry is decarbonizing; progressing through a transformative change called the Low Carbon Energy Future (LCEF). Globally, electric power production is evolving; increasing power generation with low to no carbon energy resources, i.e., wind, solar, hydropower and advanced nuclear. Hydrogen, carbon capture utilization and storage (CCUS), advanced nuclear, and novel power cycles will be the catalysts to extend beyond 50% reduction by 2030 to achieving net-zero carbon energy by 2050. NDE 4.0 will redefine how non-destructive examination (NDE) technology and processes will transition to meet the changing demands for the LCEF electric power industry.

Increased power production from low to no-carbon energy resources offers new and diverse asset management challenges. Utilization of different materials, i.e., composites for wind power, piping, and concrete repairs; higher thermal operating ranges for advanced power sources; and operating generation sources in more flexible operating schemes pose unique challenges for implementation of NDE. Integrating structural health monitoring and advanced NDE 4.0 technology must become an essential part of the power system design and asset management plan for these low carbon energy assets. Additionally, performance of NDE needs to factor the future workforce; taking the human out of harms way; harmonizing their skills and expertise in symbiosis with machines as automation and artificial intelligence becomes the norm.

Within this research, the Electric Power Research Institute (EPRI) is developing a strategic research plan to assimilate NDE 4.0 to meet the asset management challenges for the LCEF. The NDE 4.0 plan will address the integration of the diverse technological and digital transforms needed to design, implement, and process diverse NDE data streams for solving future LCEF inspection and asset management challenges. This research will provide an overview and update of EPRI's methodology to transition and execute a NDE 4.0 program for a decarbonized electric power industry.

Keywords: Human Factors, Artificial Intelligence, NDE 4.0, Low Carbon Energy Future, Process Improvement.

NDE 4.0 for the Electric Power Industry Low Carbon Energy Future

Terrill Massey, EPRI
Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

www.epri.com

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Topics for Discussion

- Energy Transformation, Industry 4.0, and NDE 4.0.
- NDE 4.0 for the Inspection Process.
- EPRI NDE 4.0 Plan and Roadmap Approach.
- Summary.

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Energy Transformation, Industry 4.0, and NDE 4.0

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Energy Transformation - What does it mean for the energy industry?

- **Globally, the energy industry is decarbonizing;** progressing through a transformative change into the Low Carbon Energy Future – Energy Transformation.
- **Electric power generation is evolving towards more low-to-no carbon energy resources**, e.g., wind, solar, biomass (renewable fuels), hydropower, nuclear and chemical energy carriers.
- **Hydrogen, carbon capture utilization and storage, advanced nuclear, and novel power cycles will be the catalysts to extend beyond 50% reduction by 2030** target to achieving net-zero carbon energy by 2050.

Reference - EPRI Report 3002020700, February 2021, "Powering Decarbonization, Strategies for Net-Zero CO2 Emissions"

Energy Transformation is Industry 4.0 for Electric Power Industry

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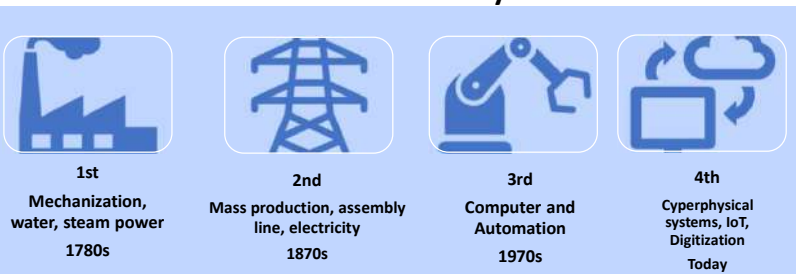
NDE 4.0 and Industry 4.0 – What is it?

- **NDE 4.0** - To improve and refine NDE systems (hardware and software) to enhance inspection performance, reliability, safety, quality, speed, and cost.
  - **NDE 4.0 will leverage the technology developed and implemented in Industry 4.0. Some of these technologies include Cyber-physical systems, Artificial Intelligence approaches, and Cyperphysical digital twins.**

NDE 4.0 supports Industry 4.0

Being Implemented by Many Industries

Evolution of Industry 4.0



NDE 4.0 – Improves NDE Inspection Processes for the Low Carbon Future

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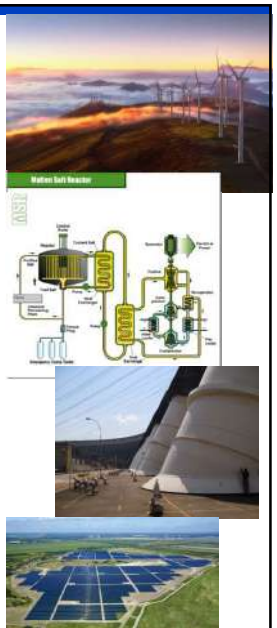
NDE 4.0 for the Energy Transformation

- **NDE supports many industries to inspect, monitor, and ensure the safety of societies' infrastructure.**
- **Power production from low to no-carbon energy resources offers new challenges:**
  - Higher thermal operating ranges, Utilization of different materials.
  - Operating power generation sources in more flexible operating schemes.



Value - NDE 4.0 for the Energy Transformation

The NDE 4.0 will redefine NDE technology and processes to meet the changing infrastructure demands for the low/no carbon energy industry.

Think Automation, AI, Digital Worker

NDE 4.0 Establishes the Future of NDE for the Energy Transformation

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NDE 4.0 for the Inspection Process

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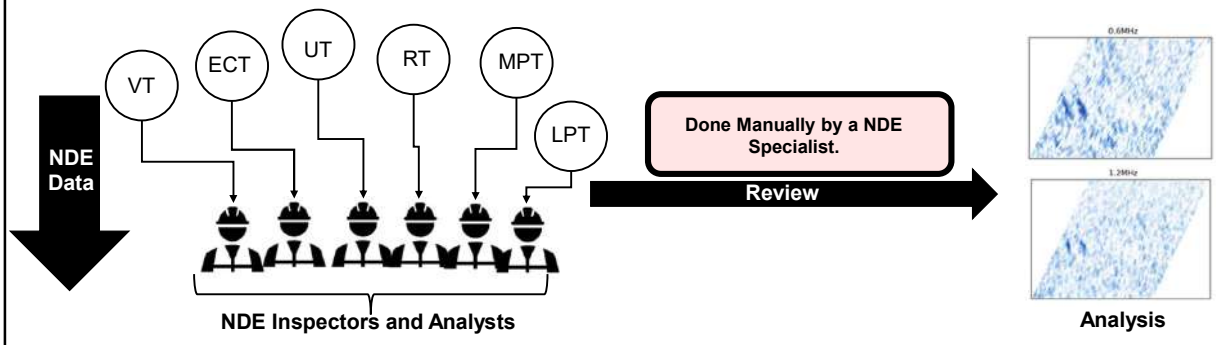
What does the NDE Inspection Process Look Like Today?



A lot of the Inspection Process is Manual, and a Binary Decision is Made

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Example of a NDE 4.0 "Enhanced" Examination

NDE Technician ask NDE AI Assistant on their tablet to display a digital twin of the component.

The AI assistant provides a slightly detailed view of the potential flaw locations.

The AI model could highlight more details of a specific flaw when asked.

NDE 4.0 allows the inspector to make more efficient and reliable NDE decisions, address NDE workforce concerns, and help manage inspection costs

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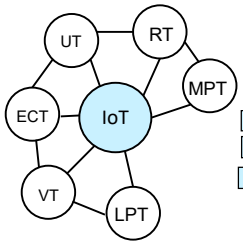
What will a NDE 4.0 "Enhanced" Inspection Look Like?



NDE Data
Operational Data
Component Data

NDE Information

Digital Twin

Information Management

Data Processing

Data Visualization

Artificial Intelligence Assisted Analysis

Operational Experience

Data used to train health monitoring system

Minimized human error
Fewer Man Hours

Knowledge

Execution

Complex and informed decision making
Health monitoring and reporting
Prescriptive Maintenance

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EPRI NDE 4.0 Plan and Roadmap Approach

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EPRI NDE 4.0 Plan and Roadmap Approach

- EPRI initiated a 2- year project to develop a strategic NDE 4.0 research plan and roadmap that will support electric industries' energy transformation.

- This NDE 4.0 roadmap includes a prioritized listing of research projects/ideas to address NDE 4.0 pursuit for stakeholders and technology gaps.
- The NDE research plan includes technology focus areas and value statements for NDE 4.0.
- To familiarize EPRI with NDE 4.0, a technical workshop was held in Q1 2023.
  - This workshop provided EPRI with a background of NDE 4.0 and the ability to begin ideation of a plan for NDE 4.0 pursuit.

Target focus areas where integration of NDE 4.0 result in increased inspection value

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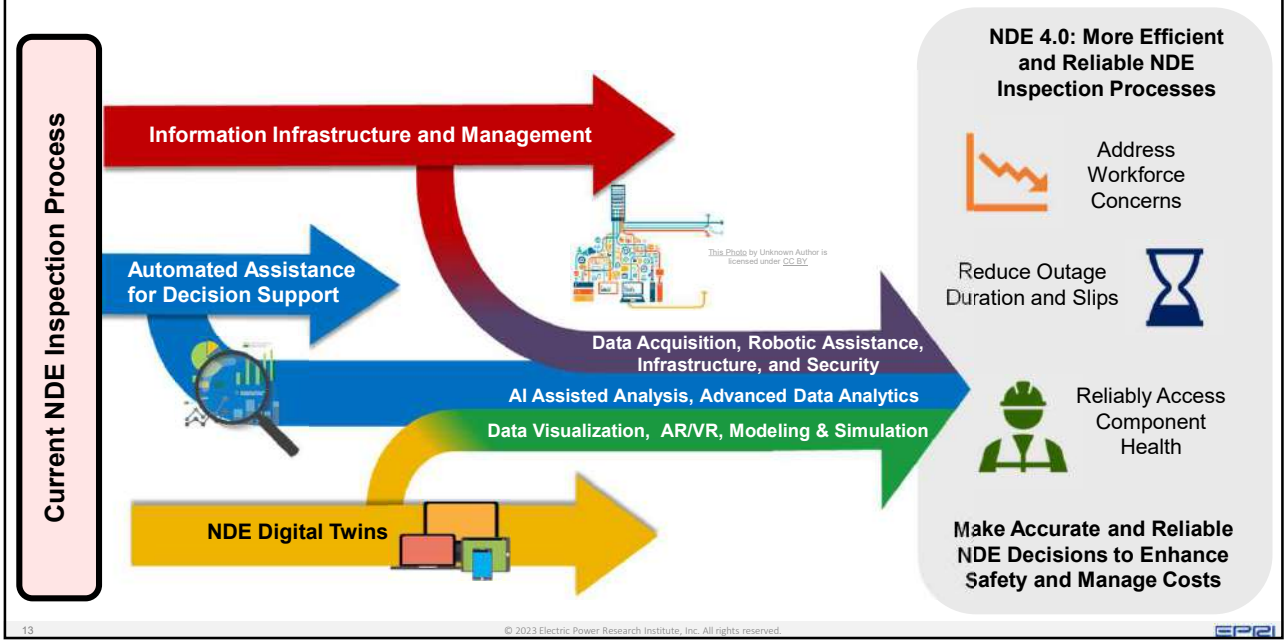
EPRI Technology Focus Areas for NDE 4.0 Roadmap



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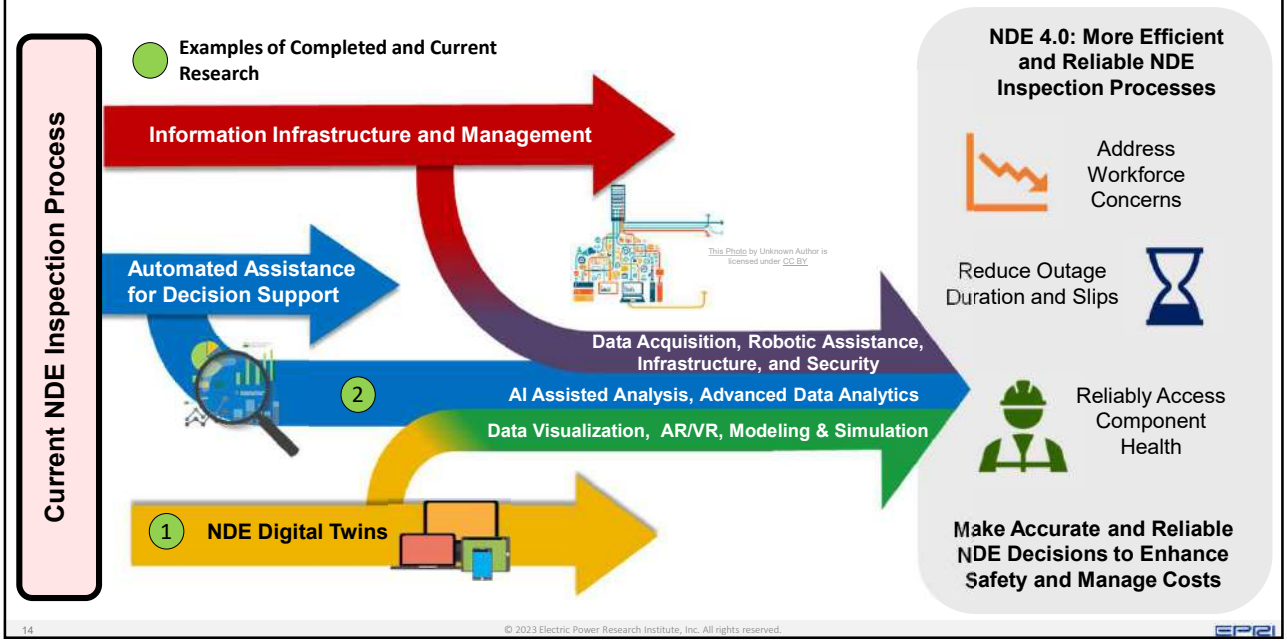
Example Value Cases in Technology Focus Areas



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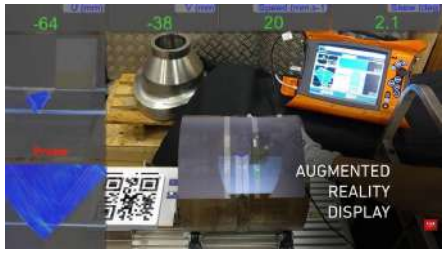
1 Real-Time Augmented Reality(AR) for Ultrasonic Testing

- This project develops and demonstrates a system that:
- **Digitizes the part** to be examined.
- **Locates the part** positionally in a 3D space.
- **Tracks and records the position** of a UT probe in a 3D-space in real time.
- **Generates an augmented reality display** of the digitized part, flaws in the part, the part's internal geometry, heads-up display data, and user interactive touch controls *overlaid on the real-world part.*

- ***EPRI PRODUCT ID: 3002020830***



Value for NDE : Increases examination reliability by allowing examiner to visualize more information

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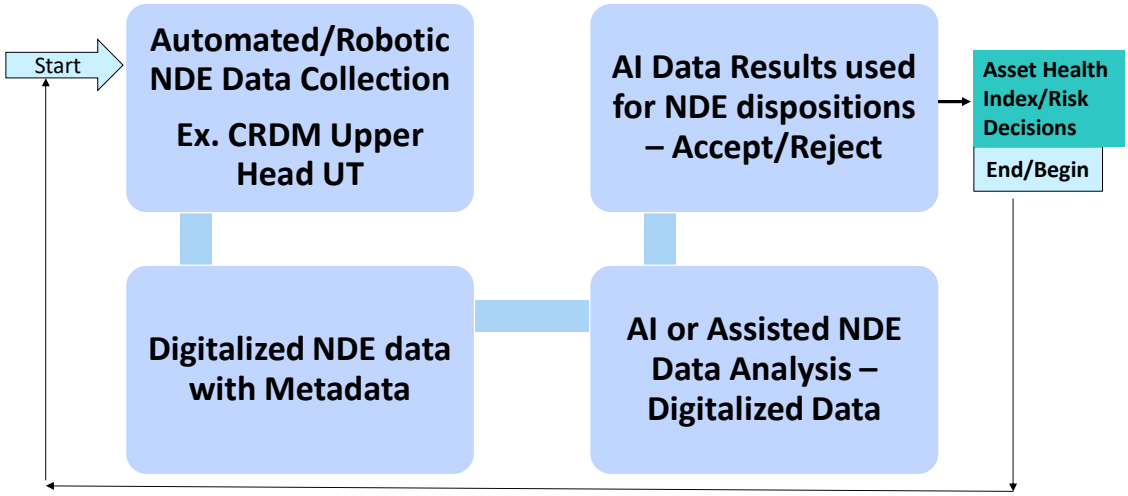
2 Automating Analysis of Ultrasonic Examination (CRDM UH)



Once AI Component is Qualified, this Technology could free-up the schedule for the UT Level III Analyst.
Estimated Labor Time Savings - 24 hrs/day - 5 days) (per outage / examination).
Applicable Product ID : 3002025510

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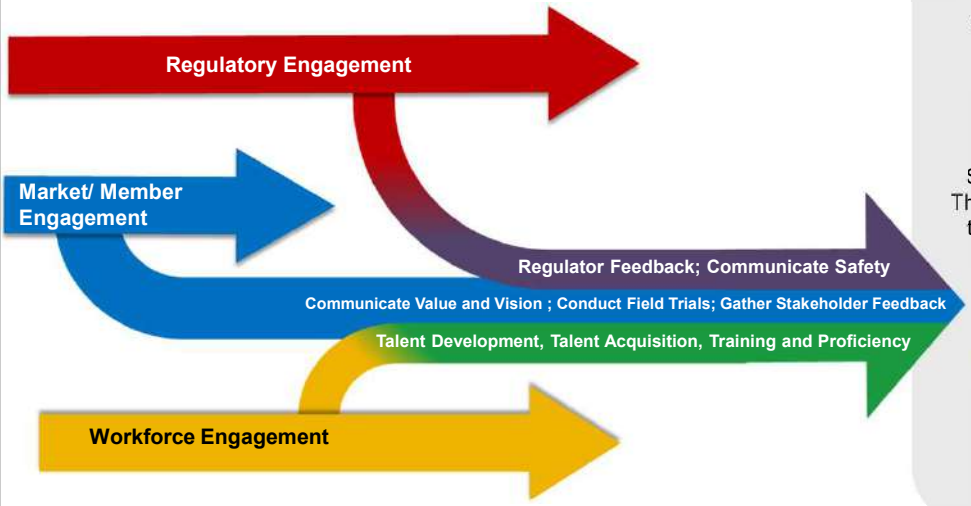
EPRI Engagement With Industry in NDE 4.0 Plan



Engagement for NDE 4.0 Progression

Engage Regulator Early to Design towards Compliance

Showcase Value Through Milestones to Our Members

Attract Talent for expertise in NDE 4.0

Setting a Foundation for Digital Transformation

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NDE 4.0 Roadmap Timeline

Begin Mission Acceleration and Identify Current State of NDE 4.0

- Engage membership and regulator for input.
- Begin projects that survey current NDE 4.0 technology in industry.
- Identify Technology Focus Areas and gaps.
- Align projects(previous and new) to Technology Focus Areas in Roadmap.

Continue R&D for NDE 4.0 Tech.

- Review Current Standards for NDE 4.0 Consideration with Regulator.
- Explore human considerations in Technology Focus Areas.
- Define Guidelines for pursuing NDE 4.0 Tech.
- Continue Research in Technology Focus Areas.

Refine NDE 4.0 Research and Roadmap

- Refine research in Tech. Focus Areas areas based on stakeholder and regulator feedback.
- Explore Technology Transfer Method for NDE 4.0 stakeholders.
- Explore roadmap progress through membership feedback.

Apply NDE 4.0 to Pilot Test Benches

- Begin engagement with stakeholders for piloting prototypes of NDE 4.0 tech. and processes.
- Conduct test benches of NDE 4.0 applied to NDE processes.

Refine NDE 4.0 Roadmap Based on Test Bench Feedback

- Continue roadmap refinement with the results of pilot tests and stakeholder feedback.

Summary

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Summary

EPRI initiated a 2- year project to develop a strategic NDE 4.0 research plan and roadmap that will support electric industries' energy transformation

NDE and monitoring research projects are being evaluated and prioritized for their relevance as NDE 4.0 use-cases

An NDE 4.0 plan and roadmap for the energy transformation will be developed, using information from use-cases and tech. areas;

- Includes a prioritized listing of research projects/ideas to address needs and gaps

Establish and communicate the benefit and value of the future NDE 4.0 research is an integral part of the plan

- NDE 4.0 inspection processes will result in:
  - Addressing the reduction of NDE workforce in industry.
  - Potentially reducing NDE inspection time and slippage.
  - More Accurate and Reliable NDE Decisions.
  - Enhancing safety and manage costs.

NDE 4.0 Establishes the Future of NDE for the Energy Transformation

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21
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EPRI

Metallic Materials Fatigue Data Determined through NDE Principles as a Basis for Structural Assessment in Nuclear Engineering

Christian Boller[1], Bharath Yerrapa[1], Ruth Acosta[1], Tobias Bill[2], Peter Starke[2], Kai Donnerbauer[3], Marina Macias Barrientos[3], Frank Walther[3], Tim Schopf [4], Jens Arndt[5], Klaus Heckmann[5], Jürgen Sievers[5]

[1]Saarland University, LZfPQ, Saarbrücken, Germany
[2]Univ. of Applied Sciences, WWHK, Kaiserslautern, Germany
[3]TU Dortmund University, WPT, Dortmund, Germany
[4]University of Stuttgart, MPA, Stuttgart, Germany
[5]GRS, Cologne, Germany

E-mail address (corresponding author): c.boller@mx.uni-saarland.de

Since the 60ies of the last century nuclear engineering has been a driver on how to use metallic materials data for the operational fatigue life assessment of engineering structures. This has been mainly related to the use of stresses and strains including their non-linearities as parameters to determine a material's damage – or better degradation – including fatigue by the application of damage accumulation hypotheses. However, damage (or degradation) per se is not very well defined from a mechanistic point of view and as such only partially likely to be quantified. The clearest definition of damage so far is possibly cracking including a quantification provided through linear elastic fracture mechanics. This quantification becomes more complex when it comes to non-linear elastic-plastic fracture mechanics and even further complicated when moving into the behaviour of short cracks within a fully plasticly deformed environment. However, even before the incubation of short cracks a structure may have a portion of its life, for which a quantification of degradation based on stresses and strains may be rather limited. Here degradation is driven by physically based mechanisms other than cracking, would it be dislocation movements, martensitic transformation, plasticity or even others.

Non-destructive testing (NDT) is a means on how to apply physics-based principles (i.e. electromagnetism or vibrational mechanics) to assess physical mechanisms (dislocations, plasticity, martensitic transformations, cracks) to occur in a material and structure such as the different degradation mechanisms referenced before. In a larger joint research project the metastable austenitic steel AISI 347 (X6CrNiNb18-10) has been initially analyzed with respect to the material's fatigue behavior under ambient and elevated temperatures as well as aqueous conditions, using different NDT techniques based on electromagnetism including electrical resistance, eddy current, stray flow and thermography, and also mechanical vibrations with ultrasound as an example. The paper and presentation will show how well the different mechanisms of the material's fatigue degradation can be identified and quantified with the different NDT techniques considered. In a second step an AISI 347 pipe under boiling water reactor conditions to be exposed to cold water injections has been tested, which serves to experimentally simulate a condition under which structures are exposed to in nuclear engineering. The material's data retrieved along the initial part of the project will be used to assess the degradation of the pipe in view of demonstrating what improvement might have been achieved with the measures having been taken.

Keywords: Austenitic steel, fatigue, non-destructive testing, structural assessment.

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NDE in Nuclear 2023

NDE in Nuclear 2023

Cutlers' Hall in Sheffield, United Kingdom

27-29 June 2023

[1] Chair of Nondestructive Testing & Quality Assurance (LZfPQ), Saarland Univ., Saarbrücken.
[2] Department of Materials Science and Materials Testing (WWHK), Univ. of Applied Sciences, Kaiserslautern.
[3] Chair of Materials Test Engineering (WPT), TU Dortmund University, Dortmund
[4] Materials Testing Institute (MPA), Univ. of Stuttgart, Stuttgart
[5] Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS), Cologne.

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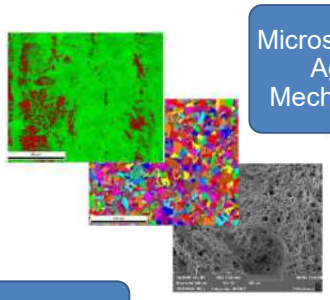
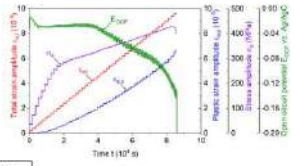
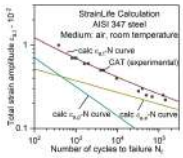
The MibaLeb-Project at a Glance



Microstructural Aging Mechanisms

Materials Data

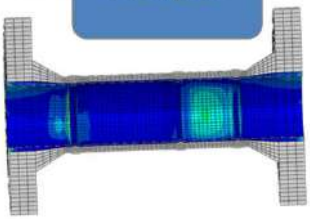




Non-destructive Testing

Residual fatigue life assessment of materials and components in nuclear engineering

Mechanical Analysis



Motivation

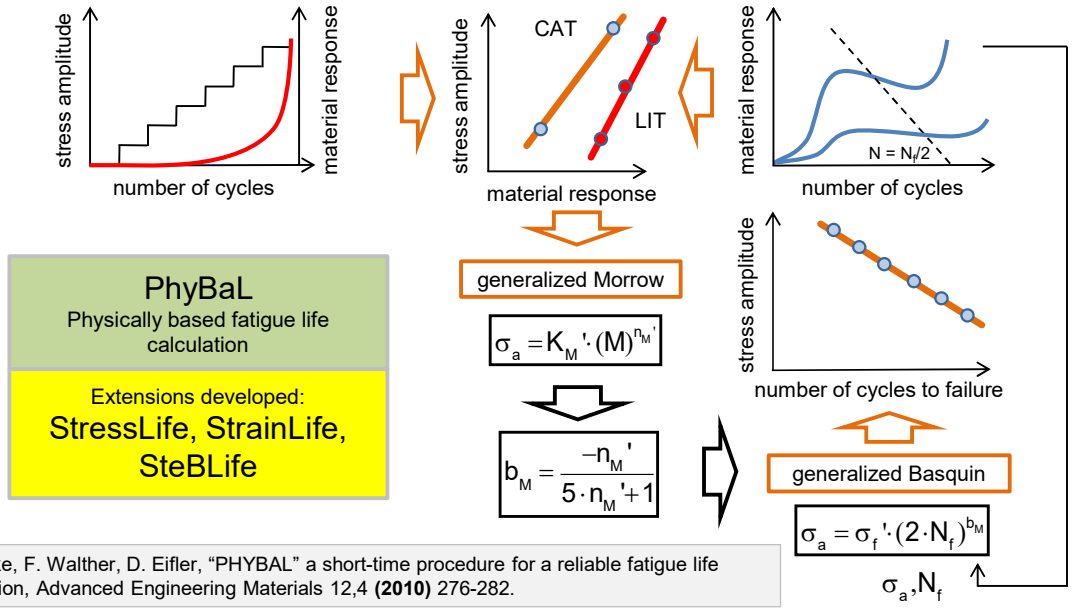
Parameters and mechanisms relevant in structural assessment:

- Stress and strain
- Hardening and softening
- Plasticity
- Fracture
- Degradation

What do the following NDT techniques provide in that regard?

- Eddy current
- Electrical resistance
- Thermography

Short Term Materials‘ Fatigue Evaluation



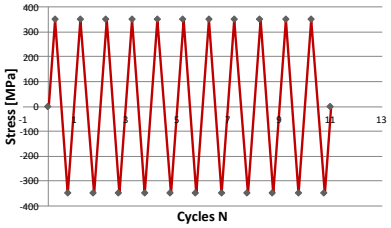
PhyBaL
Physically based fatigue life calculation

Extensions developed:
StressLife, StrainLife, SteBLife

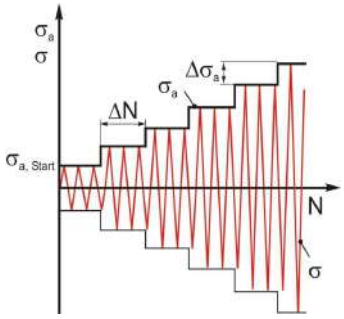
P. Starke, F. Walther, D. Eifler, “PHYBAL” a short-time procedure for a reliable fatigue life calculation, Advanced Engineering Materials 12,4 **(2010)** 276-282.

Two Types of Fatigue Tests

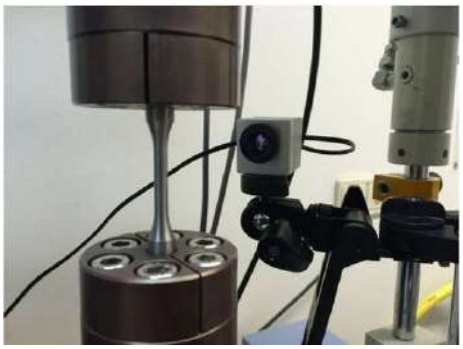
Stress (or strain) controlled constant amplitude fatigue test (CAT):



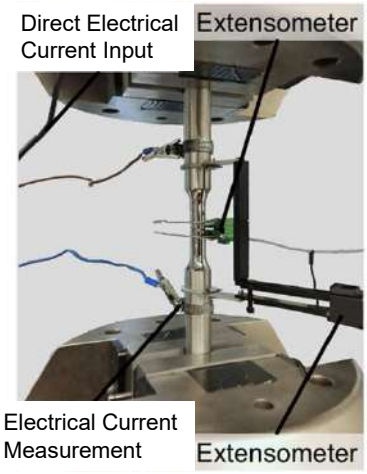
Stress (or strain) increase test (SIT):



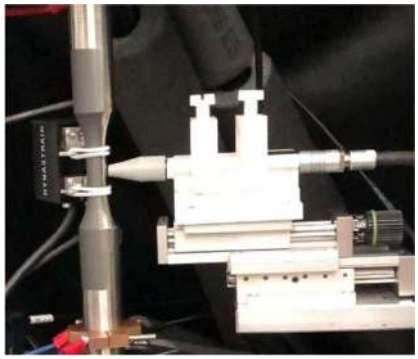
NDT Assisted Fatigue Testing



Thermography



Electrical Resistance

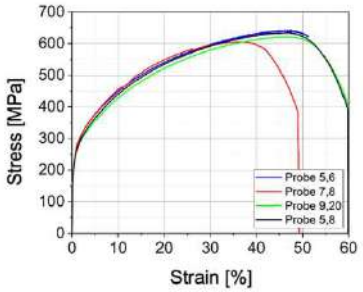


Eddy Current

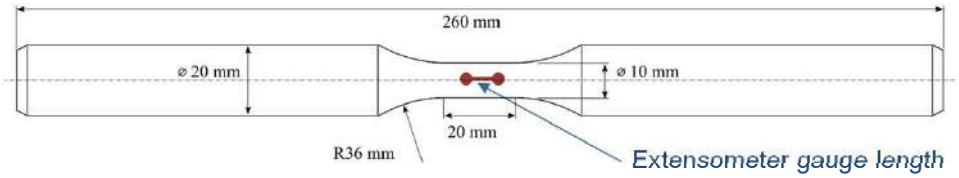
Material: AISI 347 (X 6 CrNiNb 18 10)

Chemical composition %

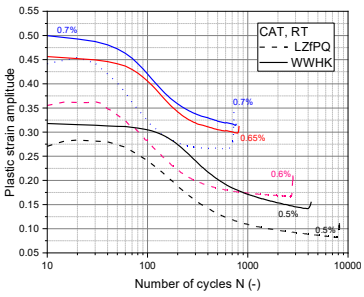
C	Si	Mn	Ni	P	S	Cr	Nb
max. 0.08	max. 1	max. 2	9 - 12	max. 0.045	max. 0.015	17 - 19	max. 1

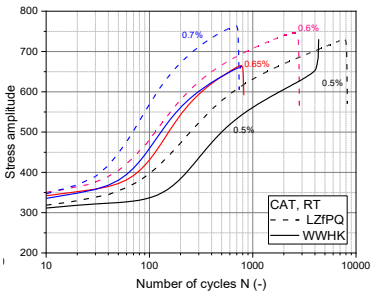


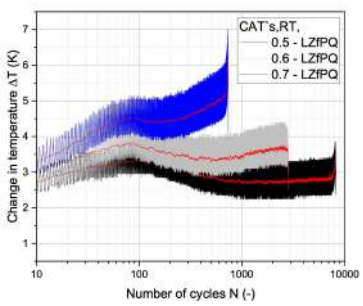
Unnotched specimens: strain controlled

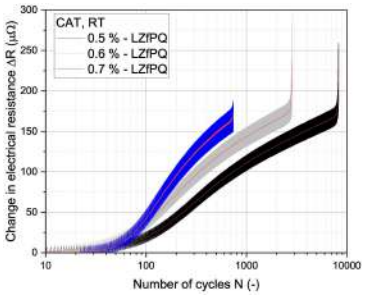


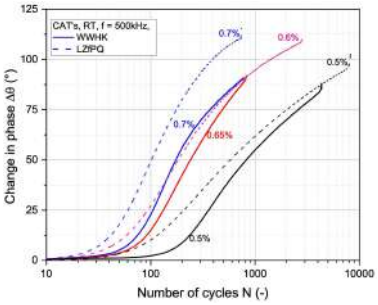
Material Response from CAT



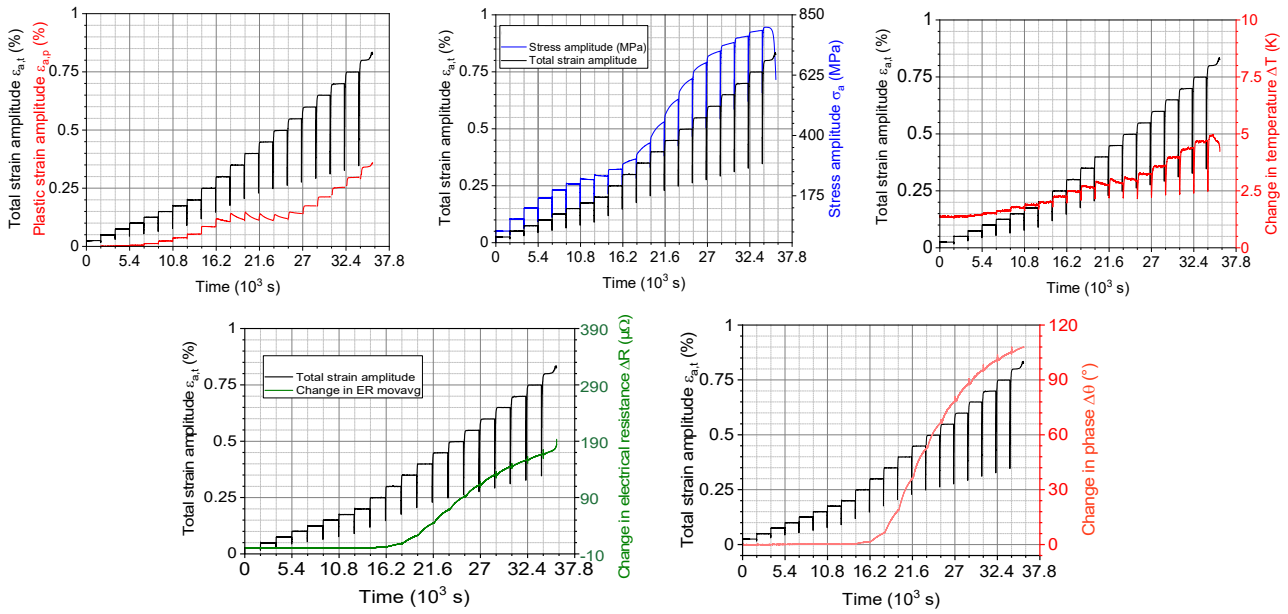




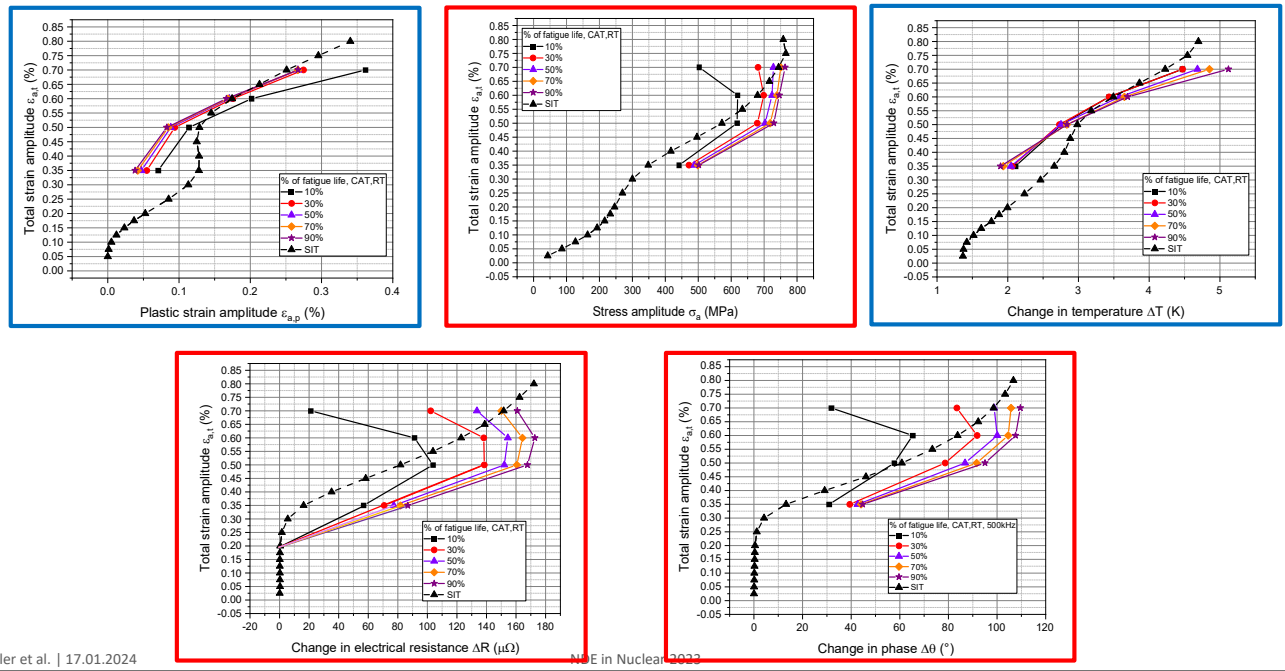




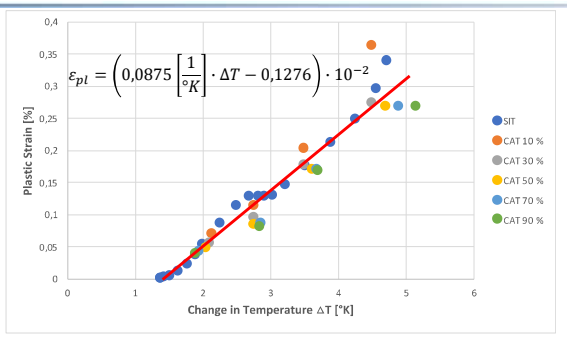
Material Response from SIT

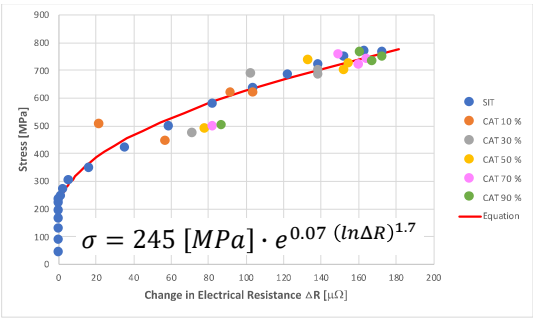


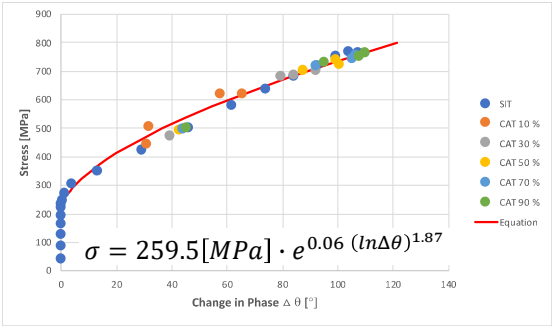
Material Response CAT versus SIT



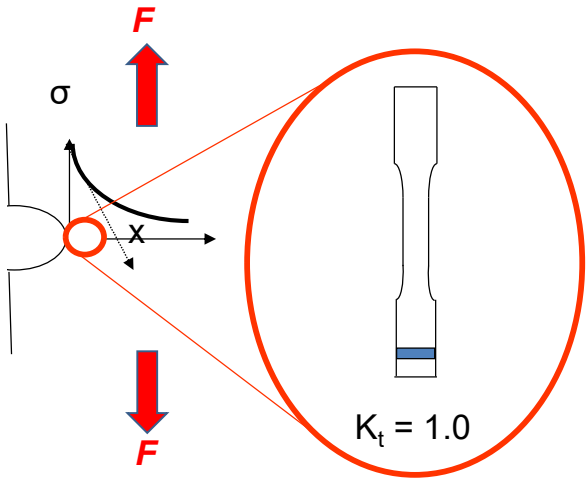
Correlating NDT to Strain & Stress







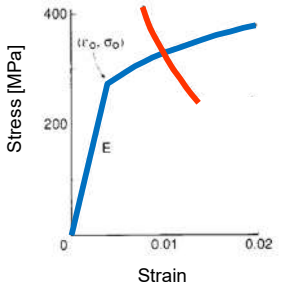
Transfering Material's Response into Notch



How to transfer the material behaviour in a notch root onto an unnotched specimen and vice versa?

Inputs required:

Material stress-strain-relationship

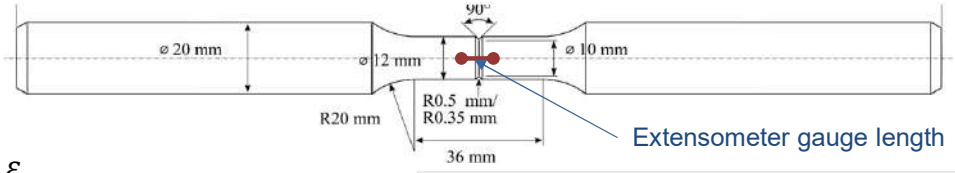


Load-notch strain relationship (e.g. Neuber's rule):

$$\sigma\cdot\varepsilon = K_t^2\cdot S\cdot e = \frac{(K_t\cdot S)^2}{E}$$

Analysis of AISI 347 Notched Specimen

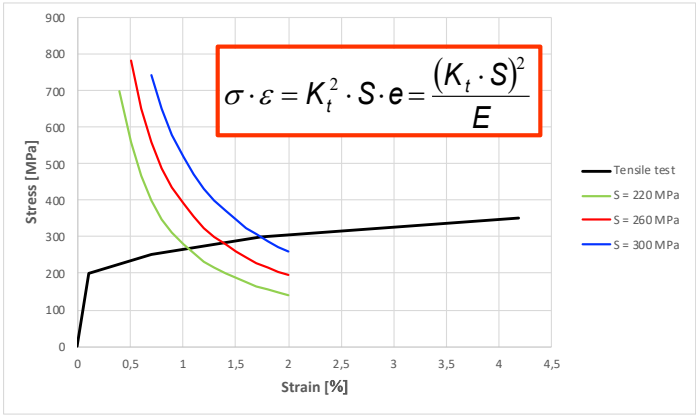
Notched specimens: load controlled



For R = 0.35 mm
$K_t = 3.4$

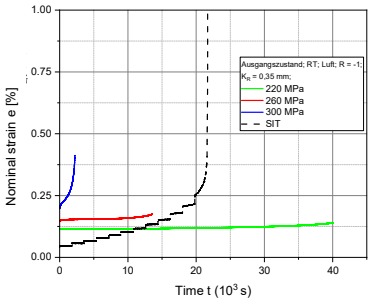
$$\frac{\sigma}{S} \cdot \frac{\varepsilon}{e} = K_\sigma \cdot K_\varepsilon = K_t^2$$

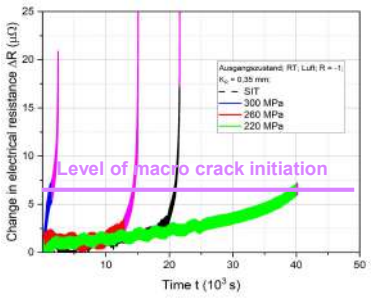
S [MPa]	220	260	300
σ [MPa]	254	280	300
$K_\sigma = \sigma/S$	1,15	1.08	1.0
e [%]	0.125	0.14	0.2
ε [%]	1.1	1.4	1.8
$K_\varepsilon = \varepsilon/e$	8.8	10	9
$K_t = \sqrt{K_\sigma \cdot K_\varepsilon}$	3.2	3.3	3.0

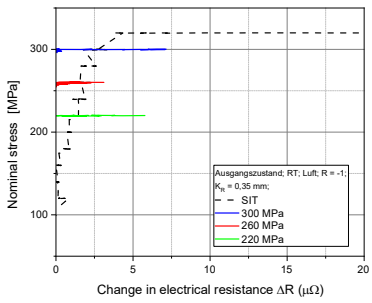


ΔR as a Means for Material's Evaluation

Notched







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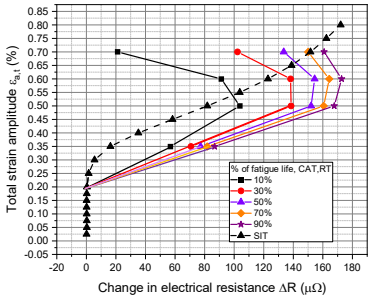
ε [%]	1.1	1.4	1.8
$K_\varepsilon = \varepsilon/e$	8.8	10	9
$K_t = \sqrt{K_\sigma \cdot K_\varepsilon}$	3.2	3.3	3.0

Unnotched



Conclusions

- Stress, strain and material hardening (softening) in a metallic material can be correlated to NDT parameters such as temperature, electrical resistance or eddy current impedance phase
- NDT methods allow for stress and strain distributions to be measured even in or around notches as well as zones of material hardening
- Stress and strain concentration factors can be experimentally determined by NDT
- NDT methods possess a further potential in terms measuring a material‘s degree of fatigue degradation
- A lot of further hidden information in the NDT signals worth to be explored.

New challenges in nuclear power plant ISI in Czech Republic

Ladislav Horáček[1], Petr Vlček[2], Martin Švejda[3], Daniel Dopjera[4]

[1]ÚJV Řež, a. s.,Husinec,Czech Republic
[2]ÚJV Řež, a. s.,Husinec,Czech Republic
[3]University of West Bohemia,Plzeň,Czech Republic
[4] ÚJV Řež, a. s.,Husinec,Czech Republic

E-mail address (corresponding author): ladislav.horacek@ujv.cz

Abstract

The ever-increasing demands on NPP competitiveness and the aging of experienced NDT staff have, among other things, led to growing demands for the development and application of new robotic innovative technologies and an ever wider use of machine learning, artificial intelligence, virtual defect and ISI simulation applications. This contribution summarizes challenges review of several research projects covering new innovative robot development, virtual defect application for PAUT qualification of VVER-440 and WWER-1000 inspection areas, CIVA simulation achievements for site in-service inspection and NDT qualification and other NDT applications within mainly VVER type NPP outages. The prototype of the innovative robot brings the first proof-of-concept of this robotic technology which is suitable for dealing with complex-shaped trajectories of NDT probe with ability to operate in the high-restricted areas with a difficult accessibility. The site complex-shaped trajectories can be solved without calculated position coordinates by intuitive probe guidance with a high level repeatability using several IoT sensors. The new robot has been developed based on previous hyper-redundant robot with conventional part of hyper-redundant module (with 7 DoF for circumferential carriage and conventional part) and alternative part of hyper-redundant module (with 6 DoF). Each part of the innovative robot has been developed according to the latest inspection demands and known restrictions with design innovative modifications taking into account requirements on compact design, reduced size with the same parameters, all cabling routed inside the joint, smooth surface, elimination of sharp edges important for protective packaging and design for minimum protection IP56. The control system of the innovative robot has been developed to meet the new requirements on machine learning module for evaluating in-service inspections and efficient positioning of NDT probes, including the possibility of intuitive programming. These project activities have been supported by the Technology Agency of the Czech Republic (TACR) under the grant TK02020142. Development, testing, validation and implementation of the innovative robotic technology for automated evaluation of flaws during in-service PAUT inspections for selected inspection areas by machine learning methods, including preparation of draft implementation of NDT qualification of inspection procedures using machine learning methods to identify segments of inspection areas with potential flaw indications for further evaluation by a qualified inspector are the objectives of a new TACR 3-years project TM04000031 (2023-2025) also supported by the TACR grant.

Keywords: innovative robot, virtual defect, PAUT in-service inspection, defect simulation, machine learning

ÚJV Řež, a. s.

NEW CHALLENGES IN NUCLEAR POWER PLANT ISI IN CZECH REPUBLIC

June 27 2023, NDE in Nuclear 2023, Sheffield, U.K.

Ladislav Horáček

Skupina ÚJV
LIDÉ | INOVACE | TECHNOLOGIE

CONTENT

- Introduction
- New innovative ISI robot development
- Virtual defect applications
- CIVA simulation achievements
- Recent and ongoing research projects
- Conclusions

INTRODUCTION

- The ever-increasing demands on NPP competitiveness and the aging of experienced NDT staff have, among other things, led to growing demands for the development and application of new robotic innovative technologies and an even wider use of machine learning, artificial intelligence, virtual defect and ISI simulation applications.
- This contribution summarizes challenges review of several research projects covering:
  - new innovative robot development,
  - virtual defect application for PAUT qualification of VVER type inspection areas,
  - CIVA simulation achievements for site in-service inspection, NDT qualification and other NDT applications within mainly VVER type NPP outages.

3

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

- The new robot has been developed and based on previous hyper-redundant robot with conventional part of hyper-redundant module (with 7 DoF for circumferential carriage and conventional part) and alternative part of hyper-redundant module (with 6 DoF)
- The prototype of the innovative robot brings the first proof-of-concept of this robotic technology which is suitable for dealing with complex-shaped trajectories of NDT probe with ability to operate in the high-restricted areas with a difficult accessibility.
- The site complex-shaped trajectories can be solved without calculated position coordinates by intuitive probe guidance with a high repeatability using several IoT sensors.

4

PREVIOUS HYPER-REDUNDANT ISI ROBOT DESCRIPTION

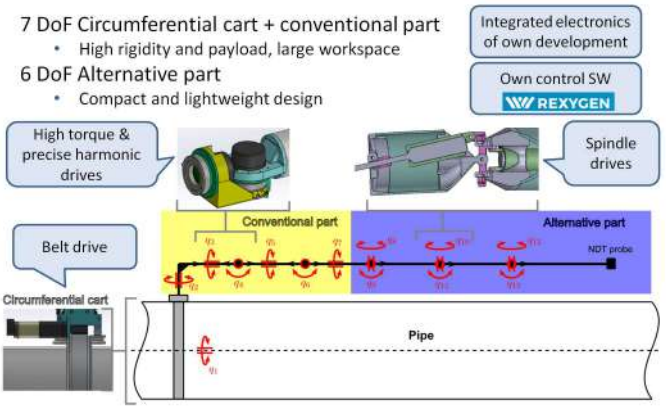
- The ROBIN robot was developed as a hyper-redundant robot, divided into three main parts, namely:
  - The Circumferential carriage module,
  - the Conventional part
  - and the Alternative part
- Each part of the manipulator was developed keeping in mind the inspection demands and restrictions. ROBIN robot was intended to be used in many configurations according to the application in question

5

PREVIOUS HYPER-REDUNDANT ISI ROBOT DESCRIPTION

The electrical part consists of:

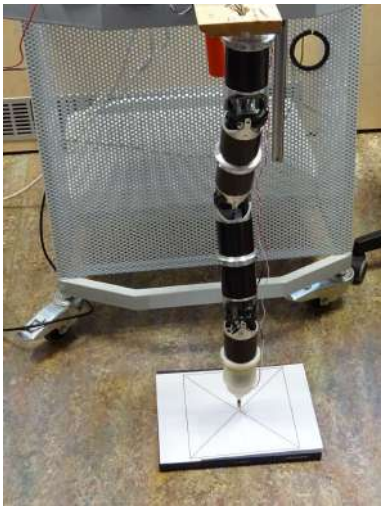
- Controlling electronics of AMC2 (Advanced Motion Controller the 2nd generation) developed by UWB
- Control electronics of Faulhaber Motion Controller MCDC 3002 P + CAN / EtherCAT developed by UWB
- *With the MEGATRON SpaceMouse® Handheld Handheld Module*
- Robot controller in the form of a separate switchboard with control computer, safe stop subsystem and other instrumentation
- Control panel with user interface in the form of industrial tablet



6

ROBIN ROBOT INTUITIVE PROBE GUIDANCE

- ROBIN was equipped by algorithms to simplify an actuator (usually probe or sensor) trajectory determination
- Either for the complete robot covering both
  - the Conventional part
  - and the Alternative part
- or using only the the Alternative part of the robot the site complex-shaped trajectories can be solved without calculated position coordinates by intuitive probe guidance with a high level repeatability.
- Actuator trajectory could be defined also by specific coordinates data or by 2D or 3D drawings where the component surface shape and given obstacles are precisely defined



7

ROBIN ROBOT CONTROL SYSTEM

The control system consists of the following parts:

- Virtual simulation model Matlab / Simulink / SimMechanics, which performs calculations necessary for robot control - required movement of individual elements (up to 13 degrees of freedom including perimeter travel of robotic hand base). This model is designed to move the base around the circumference of the cylinder with the ability to avoid obstacles also formed by a cylindrical surface (sockets of connected pipes). At the same time, it serves as a virtual simulation model to plan the robot's trajectory without the need to use a real robot
- Robot control software designed in REXYGEN real-time control system (including advanced motion control algorithms)
- WEB HMI (Human Machine Interface) using Inkscape Free SW (natively integrated into REXYGEN HMI Designer)
- As stated, an important part of robot control was the virtual simulation model developed within the project designed for a specific situation.

8

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

- The control system of the innovative robot has been developed to meet the new requirements on:
  - efficient positioning of NDT probes
  - the possibility of intuitive programming
  - machine learning module for evaluating in-service inspections

9

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

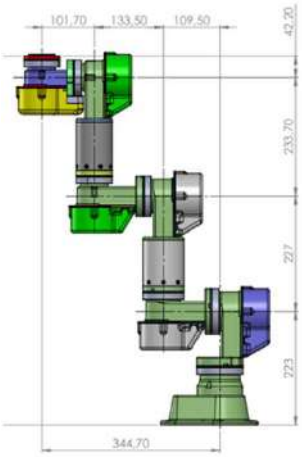
Each part of the innovative robot has been developed according to:

- the latest inspection demands
- known restrictions with design innovative modifications
- taking into account requirements on:
  - compact design,
  - reduced size with the same parameters,
  - all cabling routed inside the joint,
  - smooth surface,
  - elimination of sharp edges important for protective packaging and design for minimum protection IP56.

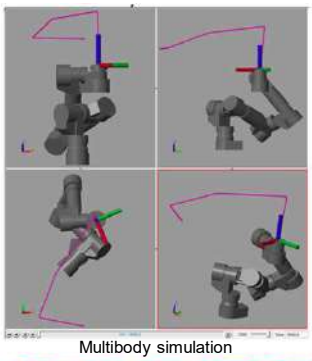
10

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

- Robot design features:
- Robot CAD model applied
- Virtual simulation model developed in:
  - MATLAB/SimScape
  - To real time control system connected
  - HMI developed as NDE user - friendly



Robot CAD design



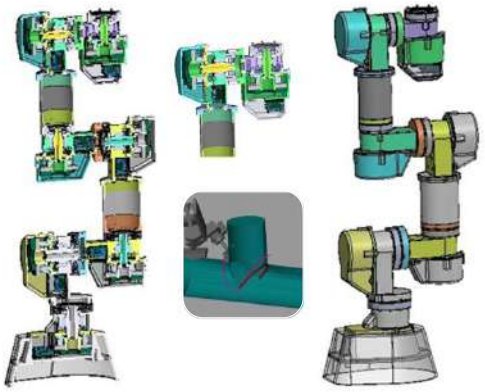
Multibody simulation

New HMI design

11

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

- Robot design features:
- Digital twin - Virtual simulation model
- To real time control system connected
- HMI developed as NDE user - friendly
- A new robot instrumentation
  - two HandGuidance sensors were added
  - (3D mouse 6DoF sensor)
  - Ongoing testing the robot – ready for use
- Sound signalization was added directly at the robot last joint
  - (integrated in AMC2 servocontroller)
  - to improve of the robot programming ergonomy
  - some states/functions of the robot can be signalized
  - acoustically
- The NDT probe holder is under reconstruction
  - the CAD model is comming soon
  - the main purpose is increasing dexterity leading to bigger robot workspace



Digital Twin – Virtual simulation model

12

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

- A new robot instrumentation
  - two Hand-Guidance sensors added
  - (3D mouse 6DoF sensor
  - Ongoing testing – ready for use
- Sound signalization added directly to the robot last joint:
  - integrated in AMC2 servocontroller
  - to improve of the robot ergonomy programming
  - some states/functions of the robot can be signalized acoustically
- The NDT probe holder reconstructed
  - Using the CAD model
  - With the purpose to increase dexterity leading to more robust robot workspace

Single joints & Completed robot manufacture

13

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

Current status activities in the robot packaging

- Centrifugal casting production technology finally chosen for the preselected material,
- Guaranteed the production capability and the quality of the manufactured part.

In detail the technology applied:

- centrifugal silicone casting

Summarized **disadvantages** of this production technology:

- Limited product **shape** options
- Not possible to guarantee the same material thickness in all "folds" of the product

Summarized significant **advantages**:

- Possibility to make **thin walls** also from silicon material
- The current state of production technology: successful cast **basic shape**

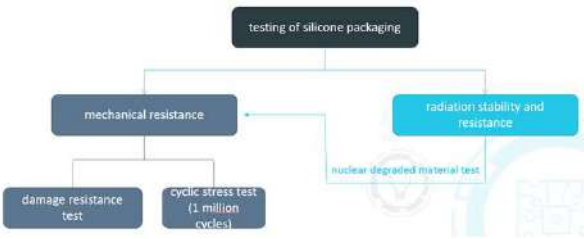
Tester & packaging design & fabrication

14

NEW INNOVATIVE ISI ROBOT DEVELOPMENT

Activities in the robot packaging in the project extension:

- ❑ design of final molds for packaging casting
- ❑ production of molds for centrifugal casting
- ❑ casting of final prototypes
- ❑ basic functionality test
- ❑to assemble the robot arm packaging
- ❑**Final testing** of silicone mold packaging technology for robot validated design



Robot packaging testing procedures

Robot packaging samples for radiation stability testing

15

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

Objectives:

- ❑ To generate virtual flaws for NDE qualification purposes
- ❑ NDE specialist training
- ❑ Virtual flaws for AI/ML training for automated NDE data assessment
- ❑ Virtual test assemblies with virtual flaws or shortly virtual flaws have been modified for three typical large scale 1:1 test assembly with intended artificial and realistic flaws.
- ❑ These three test assemblies are as follows:
  - ➢ VVER-1000 steam pipeline with homogenous ferritic weld
  - ➢ VVER-1000 ECCS validation mock-up with dissimilar metal weld
  - ➢ VVER-440 steam generator collector test assembly with dissimilar metal weld

16

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

- In the VVER-1000 steam pipeline with homogenous ferritic weld have been modified BA3 and BA8 flaws
  - as examples:
  - BA3 flaw
  - 3-PBF type crack with the measured height of 3,7 mm and twice increased defect height,
  - see Fig.1 - Fig.3

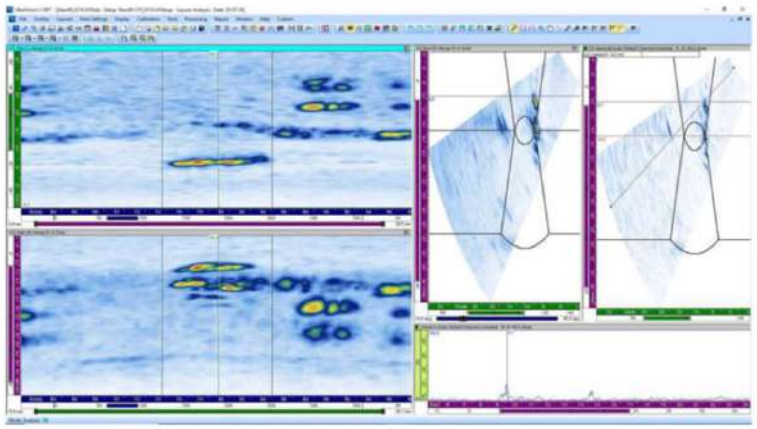


Fig.1 - The original BA3 flaw with the measured height of 3,7 mm

17

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

- In the VVER-1000 steam pipeline with homogenous ferritic weld have been modified BA3 and BA8 flaws
  - as examples:
  - BA3 flaw
  - 3-PBF type crack with the measured height of 3,7 mm and twice increased defect height,
  - see Fig.1 - Fig.3

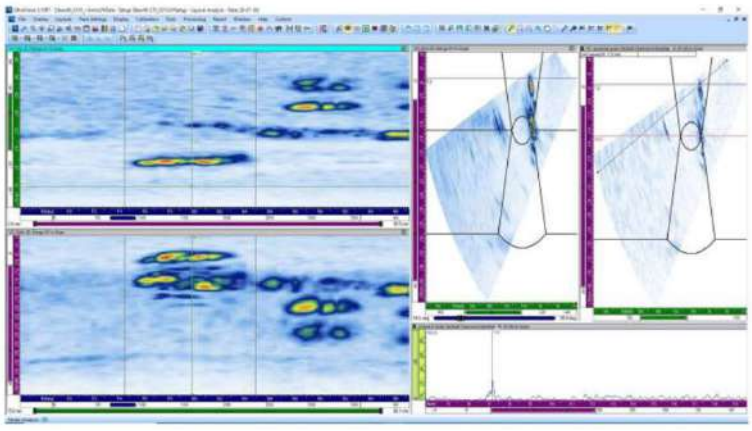


Fig. 2 – The modified virtual BA3 flaw with the measured increased height 3,7+2,5 mm

18

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

- In the VVER-1000 steam pipeline with homogenous ferritic weld have been modified BA3 and BA8 flaws
- as examples:
- BA3 flaw
- 3-PBF type crack with the measured height of 3,7 mm and twice increased defect height,
- see Fig.1 - Fig.3

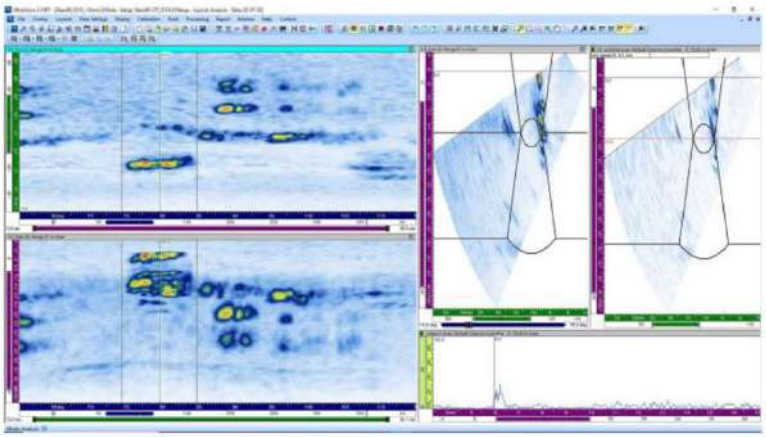


Fig. 3 – The modified virtual BA3 flaw with the measured increased height 3,7+3,4 mm

19

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

- In the VVER-1000 steam pipeline with homogenous ferritic weld have been modified BA3 and BA8 flaws
- as examples:
- BA8 flaw (lack of fusion type defect with the measured height of 4,1 mm and increased height, see Fig.4 - Fig.5)

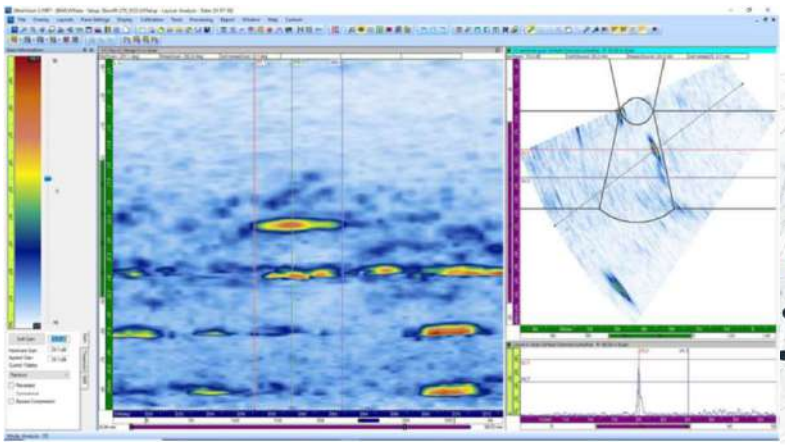


Fig. 4 – The original BA8 flaw with the measured height of 4,1 mm (+18dB)

20

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

- In the VVER-1000 steam pipeline with homogenous ferritic weld have been modified BA3 and BA8 flaws
- as examples:
- BA8 flaw (lack of fusion type defect with the measured height and decreased height of 3,9mm, see Fig.4 - Fig.5)

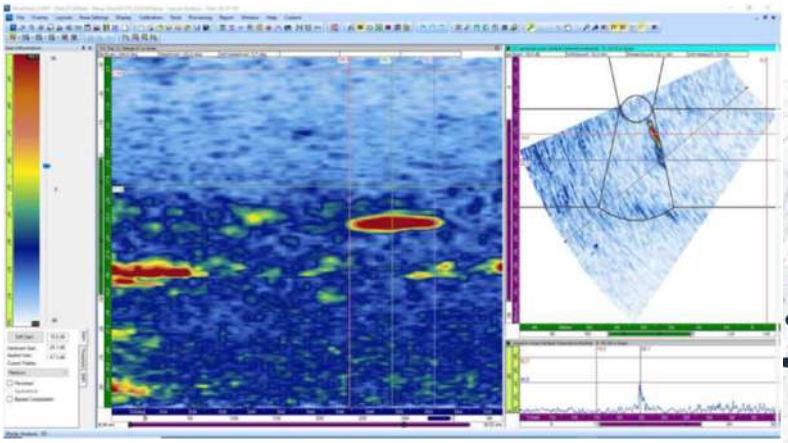


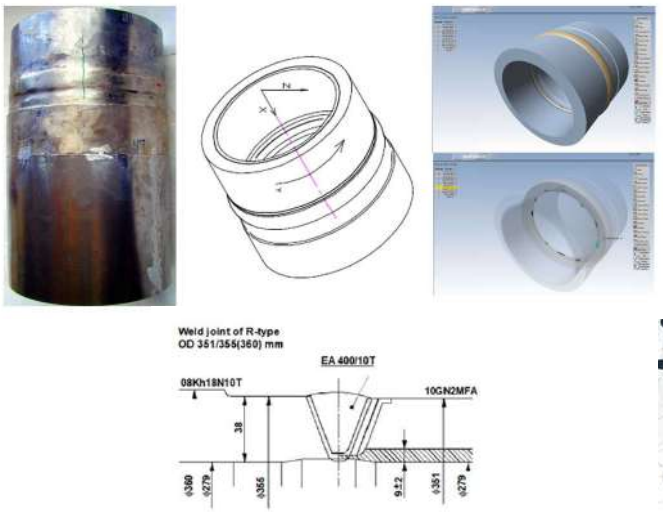
Fig. 6 – The modified virtual BA8 flaw with the measured decreased height 4,1-0,2 mm (+18dB)

21

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- PISC type A defects:
  - specific EDM type defect simulating a service induced crack under compression
  - number of defects: 8
  - defect tip diameter range: 40 – 80 microns
  - defect opening angle: 12°
  - defect length extent: 15 – 33 mm
  - defect height extent: 3-12 mm
  - defect tilt angle extent: 0 to 20°
  - defect orientation: circumferential
  - middle of the defect peripheral location extent: 0° - 310°,

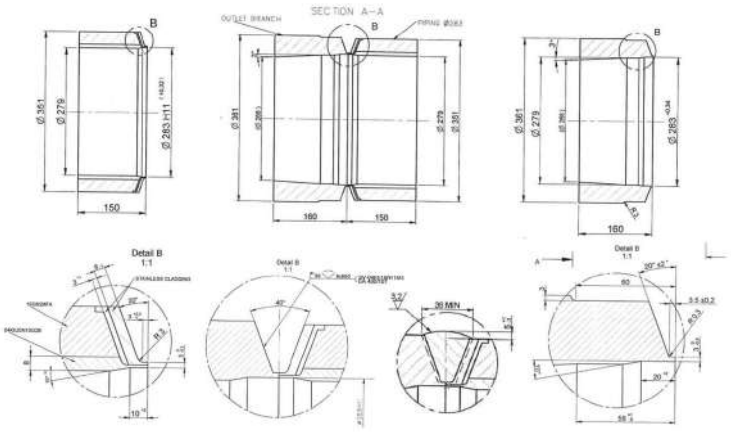


22

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- Realistic fatigue cracks
  - realistic 3-PBF defect simulating a service induced crack
  - number of defects: 2
  - defect length extent: 16 – 20 mm
  - defect height extent: 4 - 6 mm
  - defect tilt angle: 0°
  - defect orientation: circumferential
- middle of the defect peripheral location extent: 180° - 124°



23

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- In the VVER-1000 ECCS validation mock-up with dissimilar metal weld have been modified R6 and R10 flaws
- R6 flaw (3-PBF type crack with the measured defect height of 3,7 mm, see Fig.7 - Fig. 8

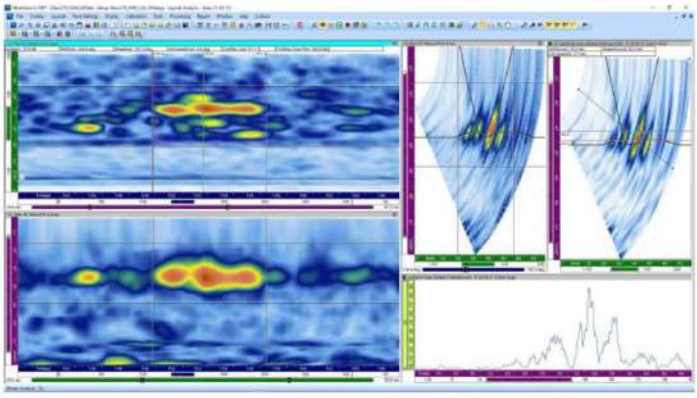


Fig. 8 – The modified virtual R6 flaw with the measured increased height 3,7+2,6 mm (+12dB)

24

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- In the VVER-1000 ECCS validation mock-up with dissimilar metal weld have been modified R6 and R10 flaws
- R6 flaw (3-PBF type crack with the measured defect height of 3,7 mm, see Fig.7 - Fig. 8

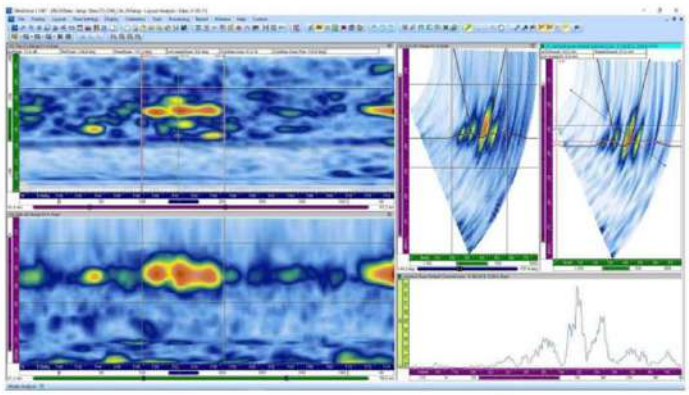


Fig. 8 – The modified virtual R6 flaw with the measured increased height 3,7+2,6 mm (+12dB)

25

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- In the VVER-1000 ECCS validation mock-up with dissimilar metal weld have been modified R6 and R10 flaws
- R10 flaw (3-PBF type crack with the measured defect height of 6,4 mm, see Fig.9 - Fig.10)

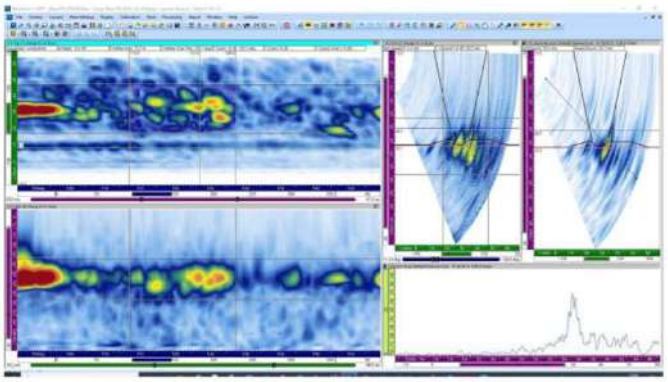


Fig. 9 – The original R10 flaw with the measured height of 6,4 mm (+12dB)

26

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- In the VVER-1000 ECCS validation mock-up with dissimilar metal weld have been modified R6 and R10 flaws
- R10 flaw (3-PBF type crack with the increased defect height of 9,9 mm, see Fig.9 - Fig.10)

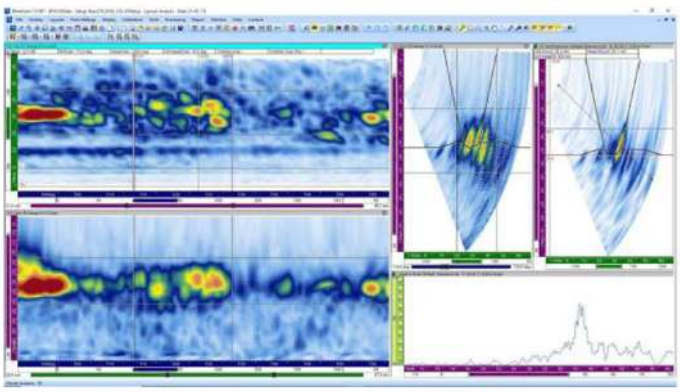


Fig. 10 – The modified virtual R10 flaw with the measured increased height 6,4+3,5 mm (+12dB)

27

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-440 steam generator collector test assembly with dissimilar metal weld

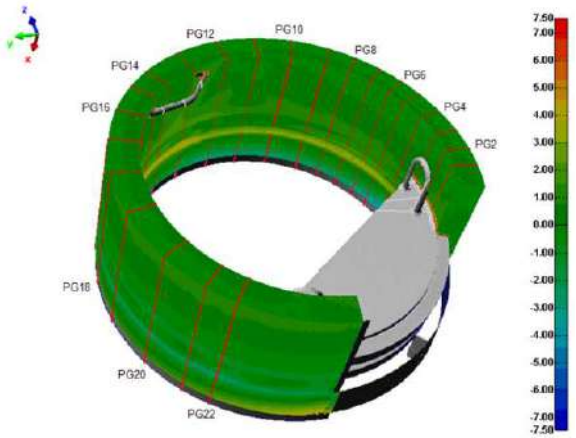
- 1:1 test assembly with intended artificial and realistic flaws
- The VVER-440 SG collector DMW validation mock-up contains the distribution of 20 defects/reflectors of three different types (see Figure 19) as follows:
  - Number of defects / reflectors: 20
  - Artificial EDM SE defects: 11
  - Fatigue cracks: 7
  - LOF lack of fusion EDM simulations: 2

28

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-440 steam generator collector test assembly with dissimilar metal weld

- EDM SE type defects:
  - EDM semi-elliptical defects simulating service induced cracks
  - number of defects: 11
  - defect tip diameter range: given by the EDM electrode thickness
  - defect opening: given by the EDM electrode thickness
  - defect length extent: 10 – 45 mm
  - defect height extent: 3 - 15 mm
  - defect tilt angle extent: 0 - 15°
  - defect orientation: circumferential
  - middle of the defect peripheral location extent: 9° - 209°

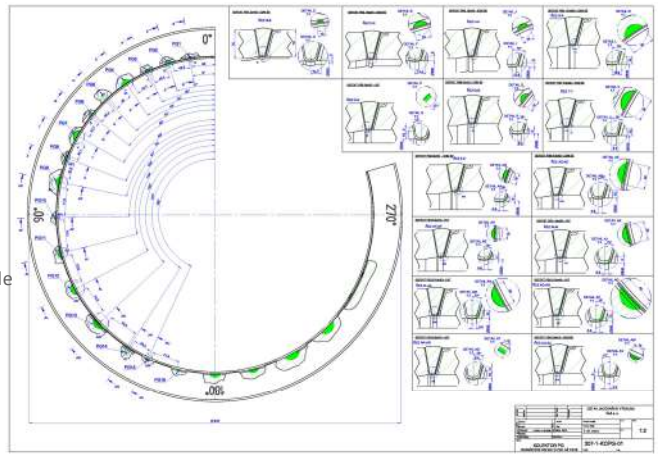


29

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-440 steam generator collector test assembly with dissimilar metal weld

- LOF type defects:
  - EDM rectangular defects simulating manufacturing lack of fusion type defects
  - number of defects: 2
  - defect tip diameter: given by the EDM electrode thickness
  - defect opening: given by the EDM electrode thickness
  - defect length: 10 mm
  - defect height: 5 mm
  - defect tilt angle extent: 10 - 15°
  - defect orientation: circumferential
  - middle of the defect peripheral location extent: 43° - 147°

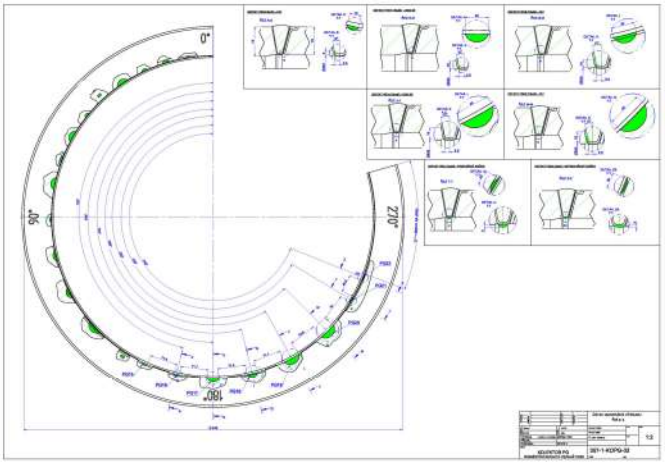


30

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-440 steam generator collector test assembly with dissimilar metal weld

- Realistic fatigue cracks:
  - realistic fatigue defects simulating service induced cracks
  - number of defects: 7
  - defect length extent: 15 – 45 mm
  - defect height extent: 5 - 15 mm
  - defect tilt angle: 10 - 15°
  - defect orientation: circumferential
  - middle of the defect peripheral location extent: 91° - 225°.



31

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- In the VVER-1000 ECCS validation mock-up with dissimilar metal weld has been modified as an example PG13 flaw (3-PBF type fatigue crack with the measured defect height of 11,9 mm, see Fig.11 - Fig. 12).

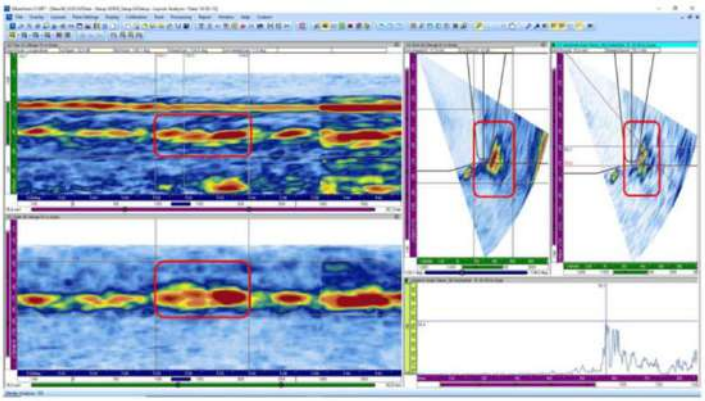


Fig. 11 – The original PG13 flaw with the measured height of 11,9 mm

32

VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

VVER-1000 ECCS validation mock-up with dissimilar metal weld

- In the VVER-1000 ECCS validation mock-up with dissimilar metal weld has been modified as an example PG13 flaw (3-PBF type fatigue crack with the measured defect height of 11,9 mm, see Fig.11 - Fig. 12).

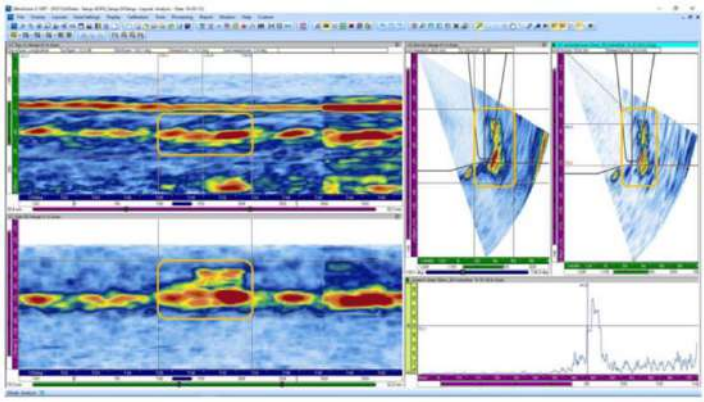


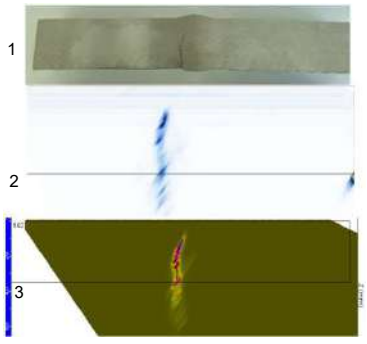
Fig. 12 – The modified virtual PG13 flaw with the measured increased height 11,9+14,1 mm

33

REAL AND REALISTIC FLAW SHAPE VERIFICATON SIMULATIONS

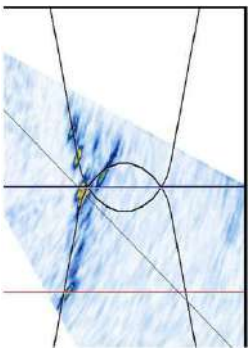
Objectives:

- ❑ NDE simulation (within the CIVA platform) to justify the flaw parameters
- ❑ Verification process

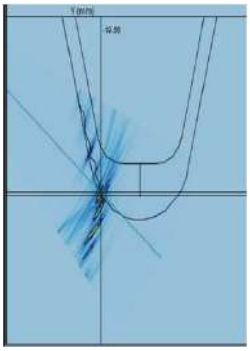


Up/down: manufactured electro-charging flaw
1 - visual check of flaw shape, 2- PAUT exam
3 – CIVA simulation final attempt

PAUT testing and CIVA confirmation



PAUT exam of BA7 flaw
(three point bending cycled)



CIVA simulation of BA7 flaw
(three point bending cycled)

34

CONCLUSIONS - VIRTUAL TEST ASSEMBLIES WITH VIRTUAL FLAWS

Objectives:

- To generate virtual flaws for NDE qualification purposes
- NDE specialist training
- Virtual flaws for AI/ML training for automated NDE data assessment
- Virtual test assemblies with virtual flaws or shortly virtual flaws have been modified for three typical large scale 1:1 test assembly with intended artificial and realistic flaws.
- These three test assemblies are as follows:
  - VVER-1000 steam pipeline with homogenous ferritic weld
  - VVER-1000 ECCS validation mock-up with dissimilar metal weld
  - VVER-440 steam generator collector test assembly with dissimilar metal weld

35

ACKNOWLEDGEMENTS

- The advantages and disadvantages of the innovative specific robot have been compared with the previous robot for in-service inspections of VVER-type components developed with the support of the Technology Agency of the Czech Republic under the grant TF02000041
- The innovative robot has been developed with the support provided by the KDT JU and Czech Ministry of Industry and Trade under the grant „CHARM“ No. 876362
- Virtual flaws generation devoted to VVER type homogenous and dissimilar metal welds has been supported by the Technology Agency of the Czech Republic under the grant TK02020142
- The methodology for evaluating operational flaws with the CIVA simulations has been supported by the Technology Agency of the Czech Republic under the grant TK02020142

36

CONCLUSIONS

This contribution summarizes:

- ❑ experience with the design, fabrication and testing new innovative ISI robot
  - ➢ suitable for inspection areas with difficult access in harsh environment
  - ➢ slim down the robot mechanical construction
  - ➢ increased robot dexterity (e.g. obstacle overcoming in confined spaces)
  - ➢ enabling site complex-shaped trajectories
  - ➢ providing intuitive probe guidance
  - ➢ high inspection repeatability using IoT sensors
  - ➢ with robot control system equipped with machine learning ISI assessment module
  - ➢ with robot joints developer and tested permanent packaging

37

CONCLUSIONS

- ❑ Virtual test assemblies with virtual flaws generation suitable for:
  - ➢ NDE specialists training
  - ➢ NDE qualification defect distribution generation providing additional virtual flaws
  - ➢ Replacing required missing flaws by virtual flaws
  - ➢ Providing additional virtual flaws of different flaw types, locations, heights and lengths
  - ➢ Machine learning ISI assisted assessment module training
  - ➢ Machine learning ISI assisted assessment performance
  - ➢ Several examples provided for VVER type homogenous and dissimilar metal weld PAUT examinations

38

CONCLUSIONS

- Operational or growing manufacturing flaws can be verified and tested to be confirmed their detection, characterization and sizing parameters during site ISI examination using offline NDE simulations (CIVA platform and others) to
  - to test and justify/confirm NDE signals
  - shape of operational flaws (mechanical cycling fatigue, thermal fatigue, stress-corrosion, etc.)
  - as a part of NDE specialists training

  - Several examples provided for realistic 3PBF flaws in the VVER type weld examined by PAUT, verified by CIVA simulations

39

Evaluation of Techniques for Compression of Ultrasonic Data

Terrill Massey[1], George Connolly[1], Mark Dennis[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): tmassey@epri.com

NDE has experienced rapid technological improvements in the past few decades leading to the creation of larger NDE datasets. Larger datasets translate into slow data transfer speeds and under sampling for instruments to keep pace which can negatively impact NDE results which are necessary for asset management.

This research explores ultrasonic data compression with minimal loss to ultrasonic signals. Minimal loss means minimal change to the ultrasonic testing (UT) signal. In this research, quantitative analysis has been performed to characterize the loss due to compression. The main objective of this research was to perform a feasibility study on the compression and decompression (that is compressed sensing) for Non-Destructive Evaluation (NDE) Data, specifically UT, to support efficiency and reliability for the industry.

Benefits of UT data compression include increased data transfer speeds between UT transducers and the storage device and reduced data file storage. These benefits could lead to lower cost UT instruments that require less sophisticated hardware for data transfer and allow for faster scan speeds for UT data collection. These benefits could also lead to less power requirements needed for data transfer in wireless UT applications that may be battery powered.

Keywords: Artificial Intelligence, Non-Destructive Evaluation, Ultrasonic Testing, Data Compression, Data Processing.

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Evaluation of Techniques for Compression of Ultrasonic Data

Terrill Massey, EPRI
Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

www.epri.com

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Outline

- Project Overview
- Signal Compression
- Testing Approach
- Compression Tradeoff
- Results
- Summary

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Project Overview

- Background:
  - Significant data infrastructure costs can be incurred while using Nondestructive evaluation (NDE), including the storage of the data and transmission over internal or external networks. Thus, minimizing these costs can lead to significant downstream savings and increase market potential.
- Scope:
  - Using a dataset of over 1.2 million ultrasonic waveforms (A-scans), EPRI worked with an R/D contractor to build and validate several compression techniques, including both classical and modern learning-based approaches to balance signal loss, compression, and computation time. The dataset was made up of a variety of A-scans from probe frequencies between 0.75 and 5.0 MHz. The A-scans were acquired during ultrasonic testing of carbon steel reference blocks/mockups, stainless steel reference blocks/mockups, and dissimilar metal weld mockups (stainless steel – alloy 600 – carbon steel).
- Objectives:
  - Compression Assessment:
    - Assess the ability to compress and decompress A-Scan files.
  - Compression & Decompression Speed:
    - Evaluation speed in compressing and decompressing files.
  - Signal Loss Evaluation:
    - Evaluate the signal loss from compression and decompression transformation.

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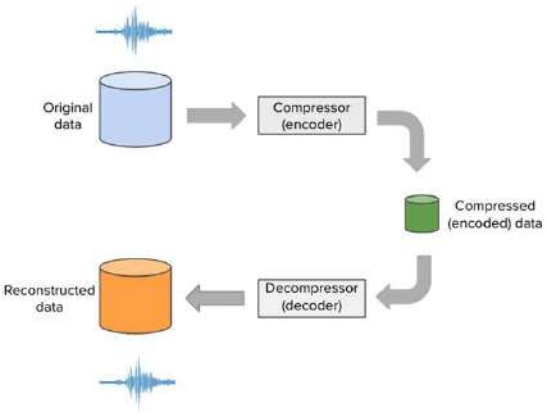
Signal Compression



- Process:
  - Compression:
    - Compression takes an original signal, and encodes it to decrease the size of the signal.
  - Transmission:
    - The signal can then be stored or transmitted at a lower cost.
  - Decoding:
    - The end user decodes the signal for use in NDE.

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Testing Approach - Algorithms

- Discrete Wavelet Transform (DWT) Compression
  - Discrete wavelet transform provides a multi-level time-frequency representation of a signal that allows for efficient compression of data.
- DWT & Huffman Encoding
  - Huffman encoding is a classic lossless data compression algorithm that represents the signal in as few bits as possible. Combining this with DWT compression provides additional compression at no cost in reconstruction error.
- LFZip
  - LFZip combines a traditional predict-quantize-encode compression framework with a neural network predictor to accurately reconstruct the signal at a higher compression ratio.

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Testing Approach - Metrics

- Root Mean Squared Error (RMSE)
  - RMSE is calculated across time between a reconstructed signal and the original signal.
- Relative Difference (RD)
  - Relative difference scales the error at each time by the original signal value.
- Full-Screen Height (FSH) Error
  - Full-Screen Height is defined as the difference of the scaled values at each time step.

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Compression Tradeoff

Data Compression

The amount that the data can be compressed is measured by the **compression ratio,** defined as the relative percentage difference between the uncompressed and compressed file.

Reconstruction Error

Reconstruction error measures the deviation of the reconstructed signal from the original signal, measured in terms of **root mean squared error (RMSE)** or **full screen height (FSH).**

Computation Time

Computation time is the amount of time it takes to compress or decompress a signal, and is crucial for performant data pipelines.

Modern compression methods provide a tradeoff between compression rate, error, and compute time.

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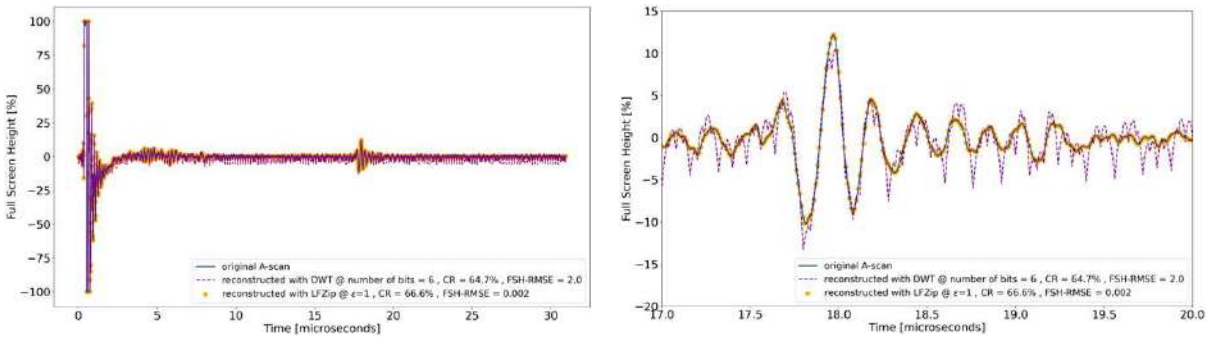
Results - Example



Example of a compressed-reconstructed A-scan for DWT using 6 bits for quantizing the coefficients, and LFZip using 1 as Maximum Absolute Error allowed to reconstruct the data. The left panel is the full A-scan, while the right panel is a zoomed-in view to give a qualitative understanding of the reconstruction error.

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Results

Model Name	Model Parameter	Compression Ratio [%]	Reconstruction Loss (Max-FSH) [%]	GPU time[s]	CPU time [s]
LFZip	0.1	59.01	3.1E-04	8.217	N/A
	1	70.61	0.003	8.136	N/A
	10	83.95	0.03	8.925	N/A
	50	90.54	0.15	6.933	N/A
	100	92.57	0.31	6.996	N/A
	500	96.30	1.52	6.959	N/A
	1000	97.16	3.05	7.067	N/A
DWT	3	80.61	25.44	N/A	0.014
	5	68.01	6.72	N/A	0.017
	7	55.40	1.76	N/A	0.023
DWT- Huffman	4	79.35	11.89	N/A	0.427
	6	68.50	3.46	N/A	0.401
	9	58.60	0.47	N/A	0.441

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Results - Overview

- LFZip was the best at reconstruction error, resulting in 1000x better reconstruction than the closest competitor.
- The tradeoff is that LFZip is very slow, averaging 20x slower than DWT-Huffman.
- Multiprocessing and batch estimation techniques should be investigated to speed up LFZip to a comparable speed as DWT-Huffman.

Model Name	Compression Ratio [%]	Reconstruction Loss (Max-FSH) [%]	Average Computation Time [s]
LFZip-50	**90.54**	**0.15**	6.933
DWT-7	55.40	1.76	**0.023**
DWT-Huffman-9	58.60	0.47	0.441

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Summary

- Compression ratios of between 58%–97% are possible with 0.0002-16.5% information loss.
- Not only are direct data storage and transfer costs reduced, but data compression will allow edge-based compute to be used for situations where connectivity may be limited.
- Investigating reducing the overall compression time to allow time-efficient, performant, and deployable algorithms is the recommended next step.
- More testing and validation of compression techniques will be required before an optimal compression method can be selected.
- These results are preliminary however the project deliverable, *Ultrasonic Data Compression (Product ID: 3002026403)*, will be available at www.epri.com in November 2023.

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EPRI

4. Electromagnetic Methods

The presentations in this session are listed in the table below.

Electromagnetic Methods	**Chair:** Ulf Ronneteg (SKB)
Investigation of Eddy Current Arrays and Ultrasonic Techniques to Inspect Spent Fuel Pool and Transfer Canal Liners	Nathan Muthu, Byungsik Yoon (EPRI)
Modelling the Influence of the Tube Support Plate on the Eddy Current Testing of the Steam Generator: Numerical Tools and Experimental Validation	Audrey Vigneron (CEA) et al.
Use of NEWS and MMM technologies for diagnostics of NPP components	Jaroslav Brom, Petr Vlček (CVR)
Dry Storage Canister Inspection with Eddy Current Arrays	Nathan Muthu (EPRI)

Investigation of Eddy Current Arrays and Ultrasonic Techniques to Inspect Spent Fuel Pool and Transfer Canal Liners

Nathan Muthu[1], Byungsik Yoon[2],

[1]Electric Power Research Institute, Charlotte, NC, USA
[2]Electric Power Research Institute, Charlotte, NC, USA

E-mail address: nmuthu@epri.com; byoon@epri.com

Abstract

Spent fuel pools are typically lined with Type 304 stainless steel plates and are constructed with seam welds, plug welds and/or studs. Leaks are suspected to occur at these welded locations. Viable underwater NDE methods that can operate in high radiation and hard-to-reach areas (below fuel racks) are required to be inspected. Minimum flaw detection thresholds must be understood under this harsh environment as no operating experience is available. This EPRI project has high visibility from CNO's of operating nuclear power plants and is well engaged by other EPRI nuclear sector programs including Chemistry, High Level Waste, WRTC, Groundwater Protection and Decommissioning.

This presentation will discuss the research and results investigated with the eddy current arr ay technology and ultrasonic test methods in a laboratory environment on multiple types of damage mechanism such as cracks, mechanical gouges (caused during welding and repair), u ndercut, and pits to determine NDE capabilities and limitations, and importantly identify min imum flaw detection thresholds.

Keywords:

Spent Fuel Pool Liners
Transfer Canal Liners
Eddy Current Arrays
Ultrasonics
Underwater Inspection

Investigation of Eddy Current Arrays and Ultrasonic Techniques to Inspect Spent Fuel Pool and Transfer Canal Liners

Nathan Muthu, EPRI
Technical Executive, Plant Support / NDE Program

Byungsik Yoon, EPRI
Principal Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Presentation Objectives

- Project Overview
- Spent Fuel Pool & Transfer Canal Liner Welds
- Surface Eddy Current Array Technology
- Phased Array Ultrasonic Technique
- Conceptual ROV Studies by University of North Carolina - Charlotte *Senior Design Engineering Program*
  - Remotely Operated Vehicle
  - Track System
  - Vacuum Box

Spent Fuel Pool

Section of a Transfer Canal

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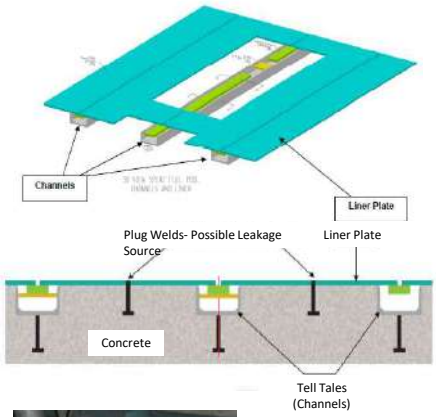
Project Overview

- **Why Was This Project Needed**
  - Some spent fuel pools (SFP) are leaking since early plant life
  - Transfer canals (TC) also leaks during fuel transfer when flooded (same design as SFP)
  - No operating experience (OE) about types of damage mechanism in fuel pool and transfer canal liners
  - When tell tales or channels get clogged, leaks will find its way through construction joints and gaps
  - Fear of groundwater & environment contamination
    - Tritium release beyond regulation is unacceptable
      - The EPA's dose-based drinking water standard of 4 mrem per year is based on maximum contaminant level of 20,000 picocuries per liter for tritium.
      - https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/tritium-radiation-fs.html#water
  - Prepare now for decommissioning



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Project Overview, *cont'd*

- **Key Research Question**
  - What rapid NDE methods are available to inspect SFPL underwater and TCL in dry environments?
    - SFP- High Radiation Levels ~ 10K Rad/Hr close to the fuel and below the fuel rack
    - Temperature ~ 50 to 60℃ (120 to 140°F)
- **Objective**
  - To ensure spent fuel pools and transfer canals are leak tight as utilities continue to store spent fuel on-site before moving them into dry storage. Advanced and rapid NDE inspection methods are needed.

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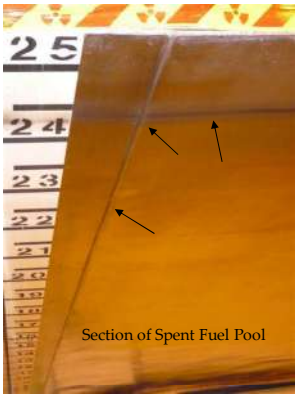
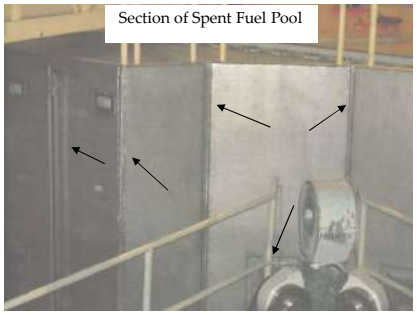
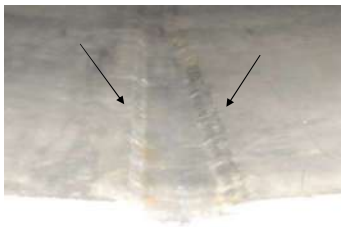
Hundreds of Meters of Seam Weld – Different Weld Configurations with Attachments







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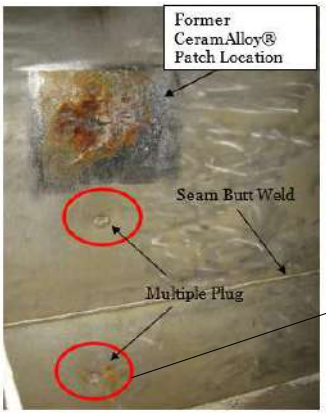
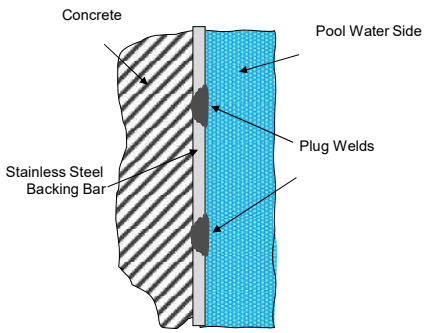
Thousands of Plug Welds



CeramAlloy® is a liquid polymer composite used for repairing, resurfacing and coating components to provide outstanding fluid flow erosion and corrosion resistance. When mixed with metal-based agents, they can cure to a hard, ceramic light material with an extremely smooth surface finish

Schematic View of Plug Welds



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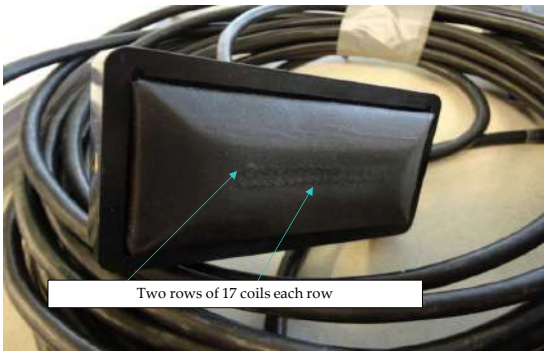
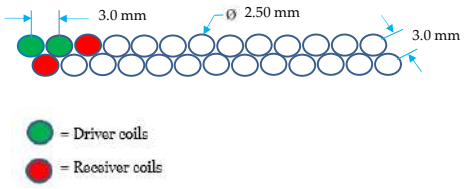
PESD5002 Surface Eddy Current Array Probe

Specially Configured for This Application





Model # / Name	PESD 5002
Serial #	1010901
Manufacturer	EddyFi Technologies
Center Frequency	300 kHz
Frequency Range	100 to 400 kHz
Number of coils	34
Coil Configuration	2 rows of 17 pancake coils each row
Cable Length	12.2 m
Coil Diameter	2.50 mm
Coil-to-coil center distance	3.0 mm
Probe Driving Topology	Single Driver Axial and Single Driver Transverse
Scan Footprint Coverage	47 mm
Scanning Mode	Manual and with ROV
Application Environment	Dry and underwater. Probe cabling can be radiation hardened

Probe Feature

- Coils are triggered in the transmit-receive mode for minimal probe lift-off interference and reduction in material permeability noise signals
- Coils are operated in the Dual Driver Mode; SHORT DRIVER **AXIAL** or SHORT DRIVER **TRANSVERSE** *(good for surface breaking and detecting smaller flaws)*

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EPRI Owned Tester and Analysis Software Used in this Research

- EPRI Owned EddyFi Ectane

Specification	Ectane
Channels	64, 128 or 256
Number of Frequencies	Up to 160
Frequency Range	5 Hz to 10 MHz
Generator output / coil drive	Up to 20 Vpp
Receiver gain	18 to 59 dB (64 and 128 channel) 41 dB (256 channel)

- Data Analysis Software

Tester	Data Acquisition	Data Analysis	Computer Operating Platform
Ectane	Magnifi 4.5R5	Magnifi 4.5R5	Windows 10

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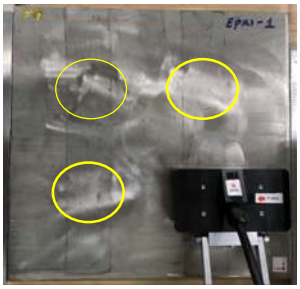
EPRI Built Type 304 Mockup Specimens Used in the Research – Plug Welds

Plug Weld Specimen with Fabricated EDM Notches

Baseline Plate- No Defects



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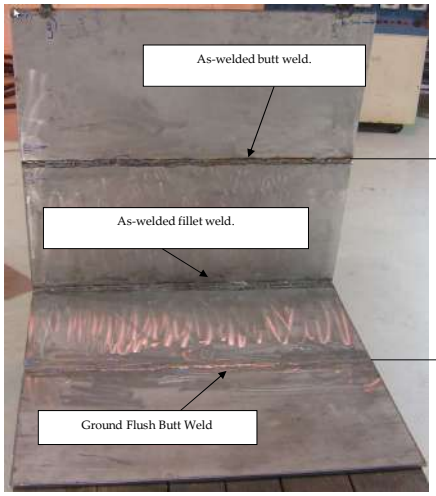
EPRI Built Mockup Specimens Used in the Research, *cont'd*

Butt and Fillet Welds



Unground Weld

Ground Flush Weld

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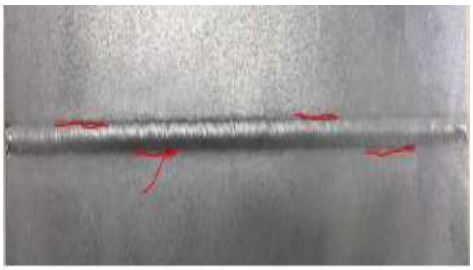
EPRI Built Mockup Specimens Used in the Research, *cont'd*

- Stress Corrosion Cracks – EPRI Fabricated

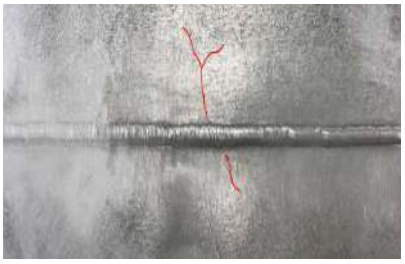
FPSCC-01

Red lines are superimposed crack lines



FPSCC-03

FPSCC-02



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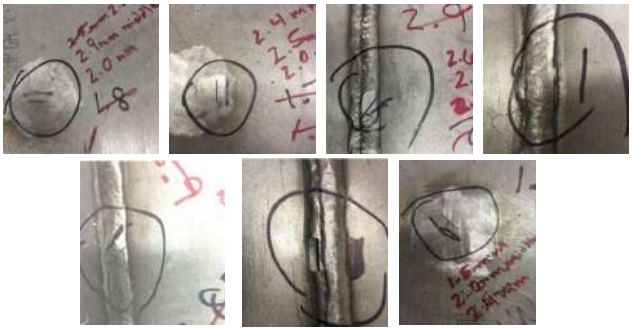
EPRI Built Mockup Specimens Used in the Research, *cont'd*

Type 304 SS Plate with several seam and plug welds



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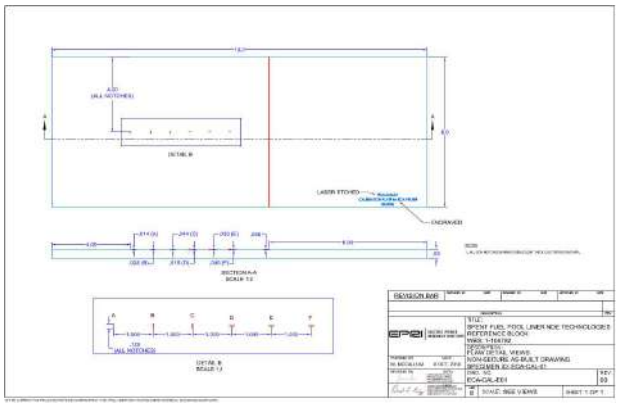
Eddy Current Testing and Data Evaluation Approach

- EPRI ECA-CAL-01 was the primary calibration standard used. It was equipped with three axial and three transverse notches
- Data was acquired from each probe discussed previously with at least two frequencies
  - Typically, the center frequency of each probe is supposed to provide the optimal results



Defect ID	Notch Orientation	Length (mm)	Depth (mm)
A	Transverse	3.2	0.36
B	Transverse	3.2	0.71
C	Transverse	3.2	1.12
D	Axial	3.2	0.38
E	Axial	3.2	0.84
F	Axial	3.2	1.14

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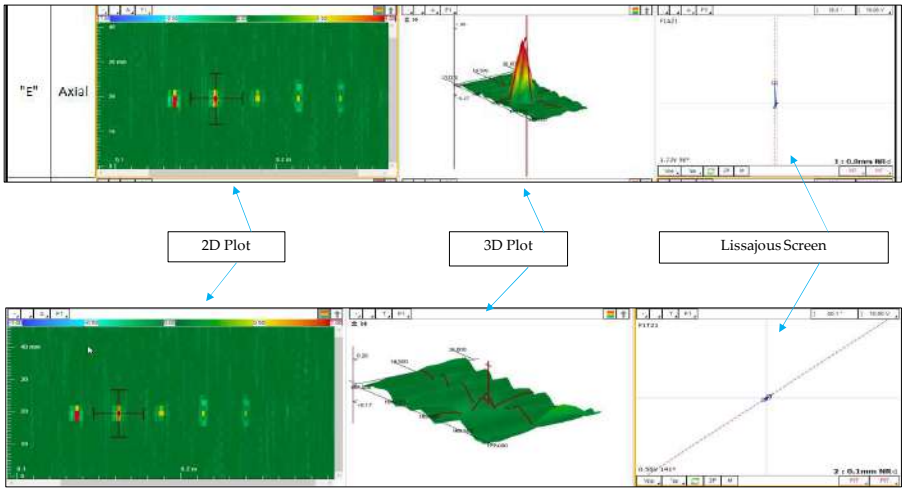
Calibration Notch Signal Response from the PESD5002 Specially Built Probe

Axial Notch Signal Seen in the Axial Channel *(top)* and Not in the Transverse Channel *(bottom)*



PESD5002 ECA Probe

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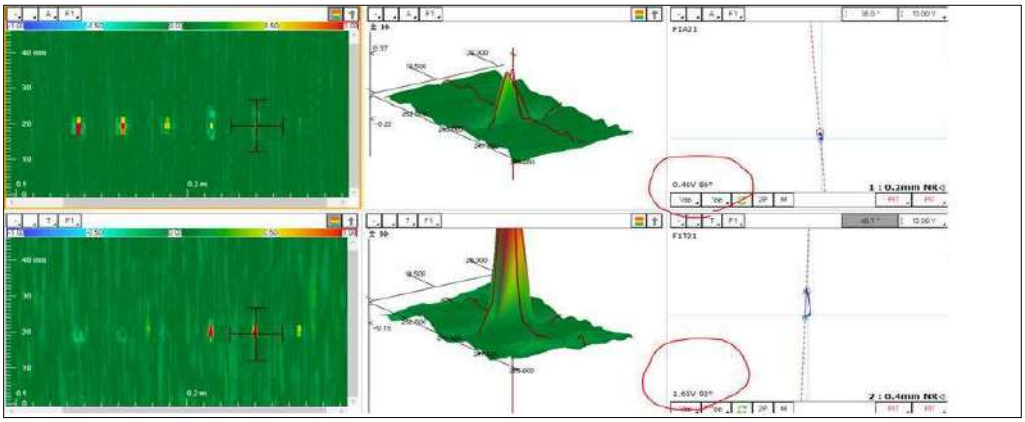
Calibration Notch Signal Response, *cont'd*

Sometimes transverse notch signals can be seen in the Axial Channel *(top)* but with low amplitude (residual signal). In this situation, since the transverse channel amplitude is higher than the axial channel, the measurement will be made from the transverse channel



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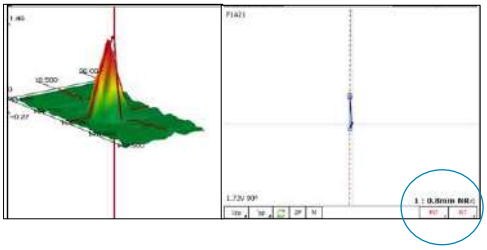
Defect Depth Measurement and Calibration Curves

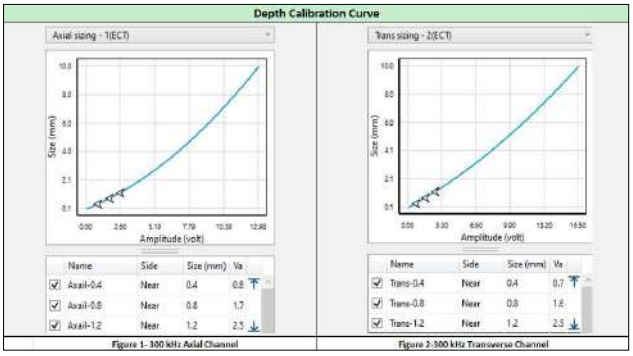
3-D Plot is used to find the signal peak. Built-in measurement tool will measure the peak amplitude and corelate to defect depth



Three points needed to plot cal curve

Axial Channel Curve

Transverse Channel Curve



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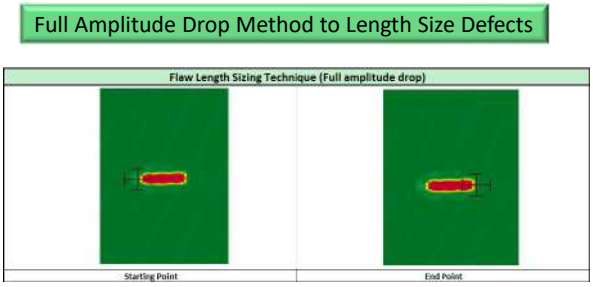
Defect Length Sizing with Full Amplitude Drop Method

- The crosshair at the starting point of the defect is at full amplitude drop.
- From here, the crosshair is moved along the defect length until the full amplitude drop is once again seen at the endpoint of the defect.
- Distance of the cross hair traversed between two full amplitude drops is the defect length.



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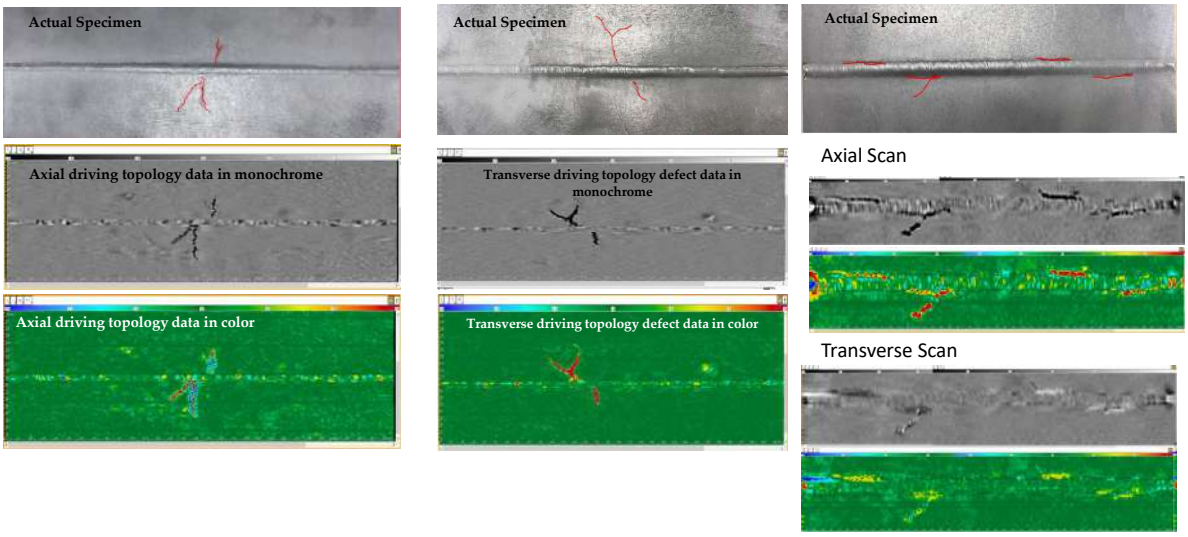
SCC Specimen 2D Plot in Monochrome and Color



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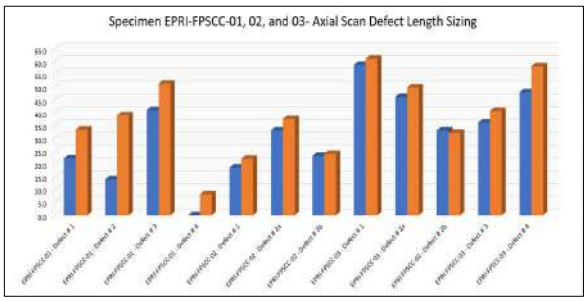
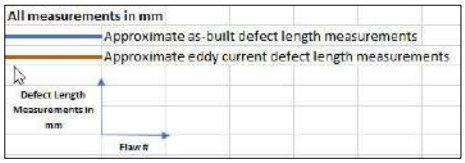
PESD5002 ECA Probe Length Sizing from SCC Specimens

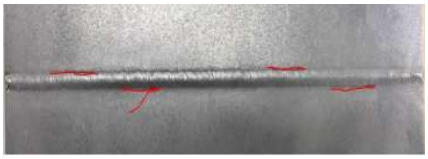




Axial Scan Length Sizing Deviation

- 300 kHz = -0.9 mm to 25.0 mm

Note, these specimens were not destructively analyzed to obtain ground truth information as samples such as these are difficult to obtain and defect morphologies, such as shape and depth cannot be duplicated.



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Eddy Current Array Study Conclusion

- Not all surface eddy current array probes can be used to inspect spent fuel pool and transfer canal liners
- As demonstrated in this research, **SPECIALLY** configured array coils must be used for SPECIFIC component and application
- Inspection requirements must be determined and used
  - Minimum flaw type and flaw detection thresholds must be determined and included in test plan
  - Specific calibration specimens need to be fabricated and provided to the sensor manufacturer so that:
    - The array coils, driving modes, and coil topologies can be configured optimally
    - Optimized examination techniques and analysis guidelines may be generated and used in the inspection
- Eddy Current Arrays are an excellent defect detection and defect length sizing method but not optimal for defect depth sizing as demonstrated in this study. Therefore, an alternate NDE method is required.

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Phased Array Ultrasonics (PAUT)

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Phased Array Ultrasonic Testing Studies Conducted by EPRI

Equipment Used

Zetec Dynaray Lite UT instrument (left), a Zetec motion control drive unit (MCDU), right

Atco LPS1000 pipe scanner

Sensor Networks 00-010275 transducer and 00-010293 Wedge Combination

Transducer		Wedge	
Manufacturer	Sensor Networks, Inc	Manufacturer	Sensor Networks, Inc.
Part #	00-010275	Part #	00-010293
Frequency	4.0 MHz	Material	Rexolite
Number of Elements	16	Velocity	0.0921 in/sec
Pitch	0.0197" (0.50mm)	Wedge Angle	38°
Elevation	0.354" (9.0mm)	Contour	Flat
Beam Angles Used	35° to 70°		

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Data

- The ultrasonic results were evaluated using a quantitative analysis approach,
  - Where the defects length and depth were compared against the information from the drawings.
  - The full amplitude drop technique was used to determine the length of the defects. This criterion provided information about the accuracies of the ultrasonic technique to determine defect lengths.
  - The defect depth sizing technique used in the study relied on obtaining a direct signal response from the tip of the defect.
    - If the tip response could not be obtained, a conservative measurement was made using the upper extent of the defect image.
  - Signal-to-noise ratio (SNR) measurements were also taken for all detected defects.
    - SNR is the measurement of peak amplitude of a defect signal divided by the average noise adjacent to the defect.
    - SNR provides information on how well the ultrasonic technique resolved a defect from background noise.

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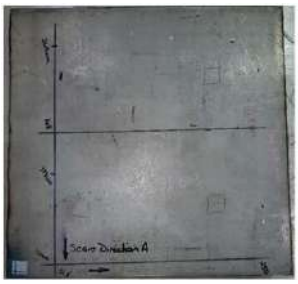
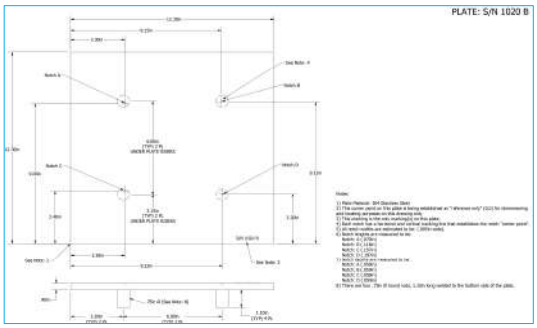
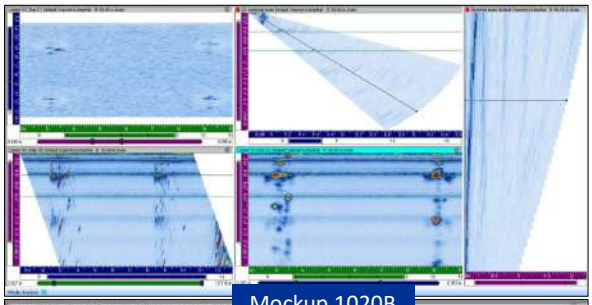
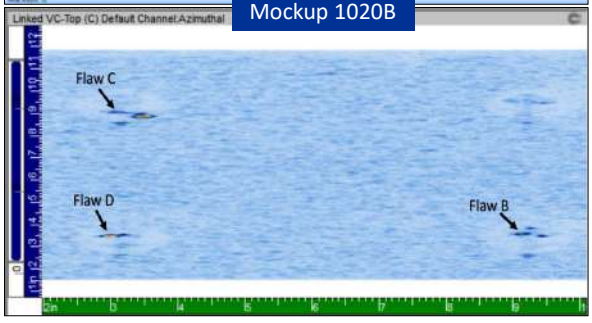
Results from the Plug Mockups







Mockup 1020B



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Results from the Plug Weld Mockups

Length Sizing

Mockup Specimen Serial #	Defect	As-Built Measurement (mm)	Ultrasonic Measurement (mm)	Deviation (mm)
1020 B	A	2.0	Not Detected	Not Detected
	B	3.0	4.0	1.0
	C	4.0	5.0	1.0
	D	5.0	5.0	0.0
SS304-1/4-1	A	2.0	9.0	7.0
	B	3.0	10.0	7.0
	C	4.0	7.0	3.0
	D	5.0	9.0	4.0
	E	12.7	5.0	-7.7
1030 B	A	12.7	4.0	-8.7
	B	12.7	4.0	-8.7
	C	12.7	6.0	-6.7
	D	25.4	24.0	-1.4
SS304-3/8-2	A	No Defect	-	-
	B	6.35	8.0	1.7
	C	6.35	6.0	-0.3
	D	7.0	8.0	1.7
	E*	50.8	52.0	1.2

Depth Sizing & SNR

Mockup Specimen Serial #	Defect	As-Built Measurement (mm)	Ultrasonic Measurement (mm)	Deviation (mm)	SNR (dB)
1020 B	A	2.0	Not Detected	Not Detected	Not Detected
	B	1.5	1.7	-0.2	22.6
	C	1.5	0.7	0.8	13.7
	D	1.5	3.8	-2.3	27.6
SS304-1/4-1	A	1.5	3.0	-1.5	16.2
	B	1.5	2.2	-0.7	13.2
	C	1.5	2.8	-1.3	19.4
	D	1.5	2.9	-1.4	15.7
	E	1.6	2.5	-0.9	25.5
1030 B	A	3.2	3.7	-0.5	28.3
	B	4.8	3.5	1.3	34.3
	C	6.4	6.2	0.2	43.8
	D	3.2	3.4	-0.3	50.2
SS304-3/8-2	A	No Defect	-	-	
	B	2.4	3.7	-1.3	25.1
	C	4.8	3.3	1.5	26.5
	D	7.1	4.7	2.4	25.3
	E*	4.8	4.8	0.0	50.1

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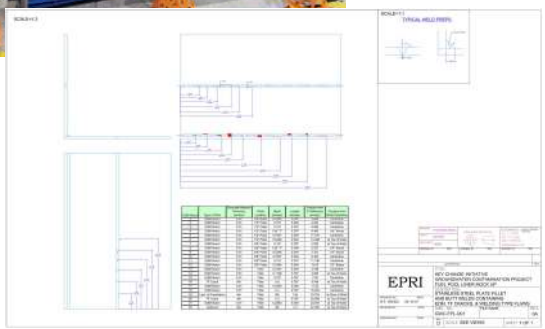
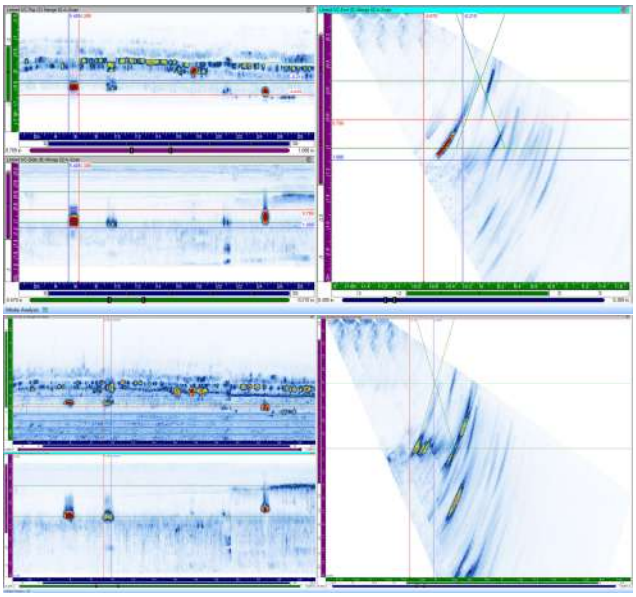
Results from the GWC-FPL-D01





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Results from the GWC-FPL-D01

No.	Flaw Type	Drawing Information (mm)	Data Measurement (mm)	Deviation (mm)
1	EDM Notch	20.0	20.02	0.03
2	EDM Notch	10.0	11.00	0.99
3	EDM Notch	20.0	21.01	1.02
4	EDM Notch	20.0	22.99	3.00
5	EDM Notch	10.0	16.51	6.50
6	EDM Notch	10.0	14.00	3.99
7	EDM Notch	20.0	22.99	3.00
8	EDM Notch	10.0	11.99	1.98
9	EDM Notch	10.0	10.01	0.00
10	EDM Notch	10.0	13.00	3.00
11	EDM Notch	20.0	20.02	0.03
12	EDM Notch	10.0	11.91	1.91
13	EDM Notch	10.0	12.45	2.44
14	EDM Notch	20.0	24.99	5.00
15	EDM Notch	20.0	18.01	-1.98
16	TF Crack	20.0	20.02	0.03
17	EDM Notch	10.0		
18	EDM Notch	20.0	19.99	0.00
19	Lack of Penetration	39.1	41.00	1.88
20	TF Crack	20.0	12.01	-7.98
21	EDM Notch	10.0	21.01	11.00
22	Undercut	48.3	38.00	-10.26

No.	Flaw Type	Drawing Information (mm)	Data Measurement (mm)	Deviation (mm)	SNR (dB)
1	EDM Notch	2.0	3.2	1.23	20.8
2	EDM Notch	4.0	5.3	1.35	23.8
3	EDM Notch	4.0	6.5	2.46	19.7
4	EDM Notch	12.7	12.7	0.00	47.5
5	EDM Notch	2.0	5.8	3.84	28.7
6	EDM Notch	1.0	2.3	1.34	31
7	EDM Notch	4.0	3.5	-0.48	48.2
8	EDM Notch	9.5	5.9	-3.98	51.6
9	EDM Notch	1.0	5.8	4.84	47.2
10	EDM Notch	2.0	2.5	0.52	32.4
11	EDM Notch	4.0	3.8	-0.18	35.9
12	EDM Notch	1.0	1.4	0.40	44.9
13	EDM Notch	2.0	7.6	5.60	32.2
14	EDM Notch	3.0	3.9	0.92	47.6
15	EDM Notch	4.0	6.3	2.31	29.7
16	TF Crack	15.2	3.4	-11.89	38.3
17	EDM Notch	1.0	0.0	-1.00	
18	EDM Notch	7.6	4.3	-3.35	25.4
19	Lack of Penetration	NA	NA	NA	39.4
20	TF Crack	7.6	4.1	-3.56	26.1
21	EDM Notch	7.3	4.6	-2.75	46.9
22	Undercut	NA	NA	NA	37.5

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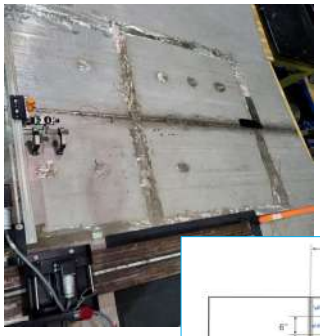
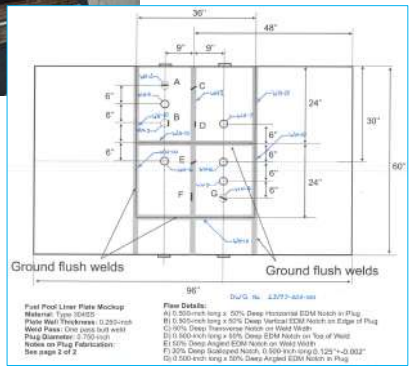
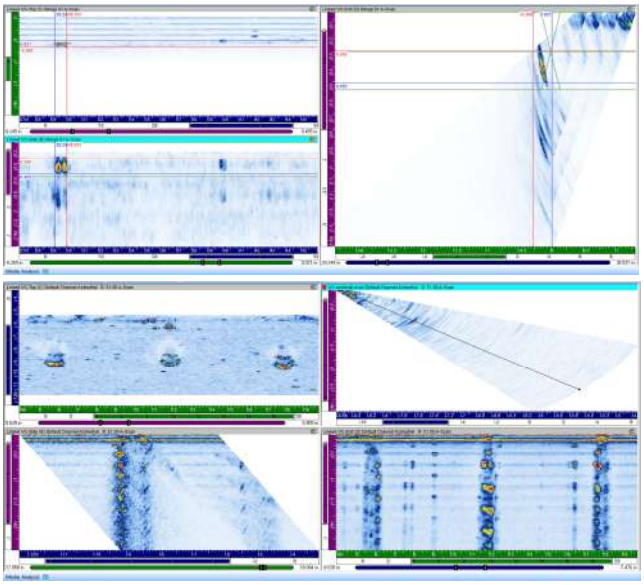
Results from the Fuel Pool Liner Plate 00-23197







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Results from the Fuel Pool Liner Plate 00-23197

No.	Flaw Type	Drawing Information (mm)	Data Measurement (mm)	Deviation (mm)
A	Not Detected			
B	Not Detected			
C	EDM	12.7	14.22	1.52
D	EDM	12.7	20.07	7.37
E	EDM	12.7	20.07	7.37
F	EDM	12.7	11.18	-1.52
G	Not Detected			

No.	Flaw Type	As-Built Measurement (mm)	Data Measurement (mm)	Deviation (mm)	SNR (dB)
A	Not Detected				
B	Not Detected				
C	EDM	3.175	3.0226	-0.2	29.9
D	EDM	3.175	3.2004	0.0	40.1
E	EDM	3.175	3.175	0.0	44.6
F	EDM	1.905	3.2256	1.3	44
G	Not Detected				

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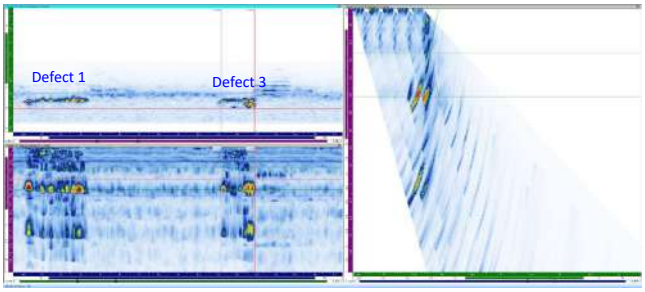
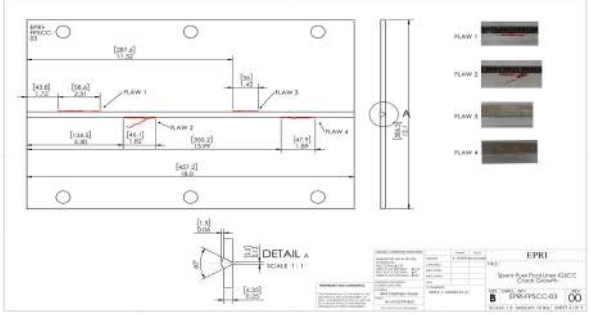
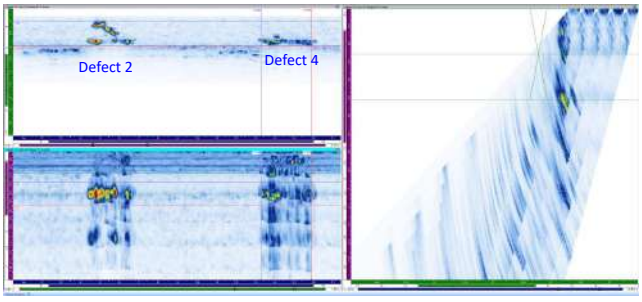
Results from the SCC Mockups







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Results from the SCC Mockups

Mockup Specimen #	Defect #	As-Built Measurement (mm)	Ultrasonic Defect Length Measurement (mm)	Ultrasonic Length Measurement Deviation (mm)	Ultrasonic Defect Depth Measurement (mm)	SNR (dB)
FPSCC-01	1	Length sizing not performed on axial flaws			5.46	34.1
	2				4.98	41.4
FPSCC-02	1	Length sizing not performed on axial flaws			4.88	33.8
	2				5.38	33.4
FPSCC-03	1	58.6	78	19.4	5.57	36.7
	2	46.1	55.02	8.92	5.82	45.9
	3	36	43.99	7.99	6.05	34.5
	4	47.9	66.038	18.138	4.72	38.2

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PAUT Conclusion

Mockups	# of Defects Detected	Average Absolute Error	Average Signal to Noise Ratio (SNR)
Plug Mockups	16 of 17 defects detected (94%)	4.1 mm (Length) 1.2 mm (Depth)	24.1 dB
L-Plate Mockup	21 of 22 defects detected (95%)	3.1 mm (Length) 1.6 mm (Depth)	35.9 dB
Flat Plate & Plug Mockup	4 of 7 defects detected. 4 defects detected were in the seam weld joint. 3 defects not detected were in the plug welds	4.4 mm (Length) 0.4 mm (Depth)	39.6 dB
Stress Corrosion Mockups	All 8 defects were detected	Ground Truth Unavailable to Compare	37.2 dB

- Overall, the results from this study were positive and showed that phased array ultrasound testing (PAUT) technique can be used to successfully inspect some spent fuel pool liner configurations.
- Defects found in or along weld joints were detected and sized as expected. The detection and sizing of defects in plug weld configurations posed a greater challenge for the ultrasonic technique.

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University of North Carolina-Charlotte
Senior Design Engineering Program

Three Conceptual Studies were Conducted:

1) ROV for ECA Probe
2) Manual and Automated Track System for ECA Probe
3) Vacuum Boxes

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Modelling the Influence of the Tube Support Plate on the Eddy Current Testing of the Steam Generator Tubes: Numerical Tools and Experimental Validation

A. Vigneron[1], E. Demaldent[1], C. Reboud[1], J.-M. Decitre[2], T. Sollier[2]

[1]Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France
[2]IRSN, Fontenay-aux-Roses, 92160, France

E-mail address (corresponding author): audrey.vigneron@cea.fr

Eddy current testing (ECT) of Steam Generator (SG) tubes is part of the maintenance program of Nuclear Power Plants. Tube Support Plates (TSP) are usually only considered as extraneous signals for tube inspection. However, for long-term operation of SGs, there is a safety concern related to the build-up of deposits in the TSPs flow holes. The clogging-up of the TSPs flow holes affect the safe thermal-hydraulic operation of SGs. The deposits come from the feedwater train and are mostly iron oxides (magnetite) with a weak electrical conductivity and magnetite permeability.
The ability of ECT probes to detect and characterize TSPs deposits is therefore of great interest and is investigated by CEA and IRSN. The most common and industrial ECT technique, the bobbin coil, averages the surrounding electromagnetic field over 360°, whereas the geometry of tri-foiled and quadri-foiled TSPs, and thus of clogging, is rather complex and non-axisymmetric, hence motivating the evaluation of the performance of conventional ECT rotating probes used for SGs tubes inspection. Although simulation is a powerful tool to support such a study, it requires dedicated models to be made available to NDT experts, and CEA develops ECT physical models in CIVA for this purpose. In addition to standard fast CIVA modules based on 3D semi-analytical or 2D numerical calculations restricted to canonical or axisymmetric parts, respectively, CEA develops a module dedicated to the simulation of SG tube inspection based on a 3D numerical simulation. This module allows tube deformation such as ovalization, bending or tube expansion. It also allows the addition of external objects such as anti-vibration bars, different geometries of tube support plates and now their clogging by deposits. This model is used to study various influent parameters and to perform benchmarks in the framework of a scientific collaboration between the CEA and the IRSN, related for example to the inspection of the U-bend tubes or of a friction wear under the anti-vibration bars. Here, the specificity of the TSPs and their clogging justifies further investigations between CEA and IRSN to qualify the simulation model before evaluating the influence of material and geometry properties of the deposit as well as the performance of the inspection techniques. We will present the main characteristics of the simulation module in CIVA and we will detail the associated experimental validation device: taking into account the TSP, a representative clogging and the extension of the module to rotating ECT probes.

Keywords: ECT simulation, Steam generator tube inspection, tube support plate modelling, clogging

INSTITUT DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Modelling the Influence of the Tube Support Plate on the Eddy Current Testing of the Steam Generator: Numerical Tools and Experimental Validation

Audrey Vigneron[1], Edouard Demaldent[1], Thierry Sollier[2], Jean-Marc Decitre[2]

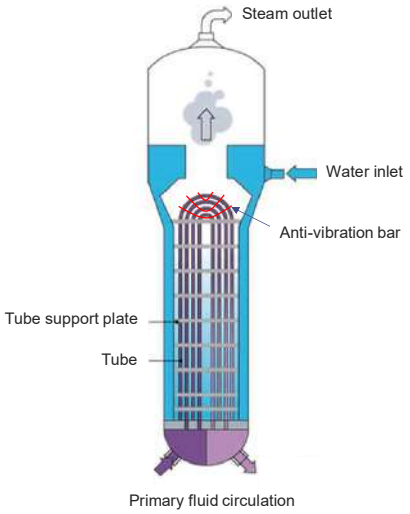
[1] Université Paris-Saclay, CEA LIST

[2] IRSN

NDE in Nuclear 2023, Sheffield

Context and motivation

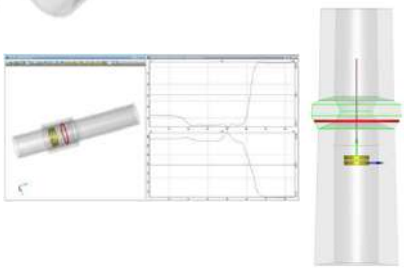
- Tube support plates (TSP) are positioned at regular intervals to secured the tubes in place
- Anti Vibration Bars (AVBs) limit vibratory phenomena in the top of tubular bundle (U-Bend)
- Steam generator (SG) tubes are regularly inspected as part of eddy current non destructive inspection
  - To assess the tube integrity and prevent tube rupture
- The aim of the study between CEA LIST and IRSN is to validate simulation tools for the eddy current inspection of SG tubes, enabling the implementation of parametric studies



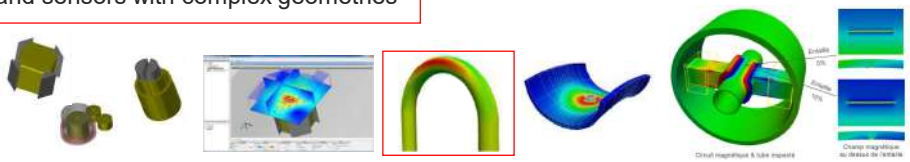
Context and motivation

- Semi-analytical approaches (modal methods)
  - Very fast and accurate
  - Limited to canonical geometries

- 2D solver based on Finite Integration Technique (FIT)
  - 2D numerical approach

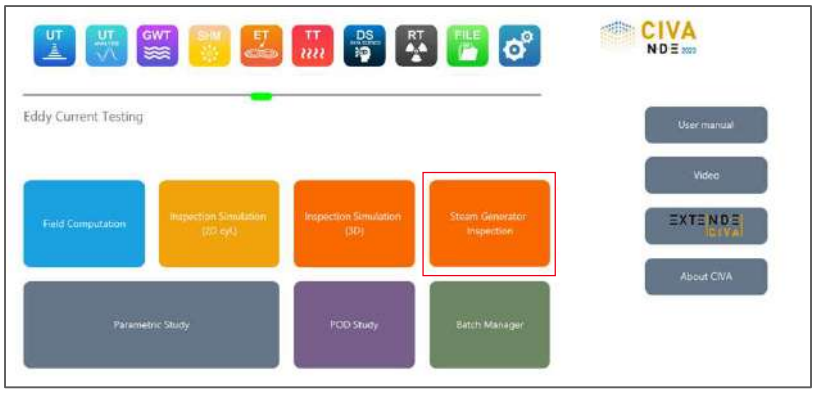


- **3D solver based on Boundary elements**
  - Pieces and sensors with complex geometries



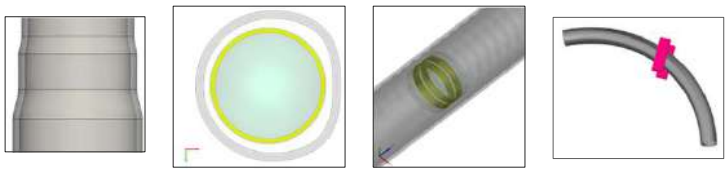
CIVA ET module « Steam Generator Inspection »

- Development and validation of a CIVA NDE module dedicated to the complete eddy current inspection of steam generator tube

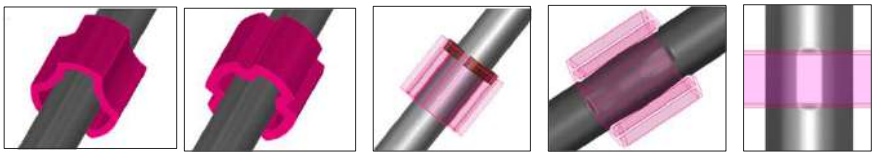


CIVA NDE — ET module « Steam Generator Inspection »

- Tube geometry: U-bend, expanded tube, section distorsion, pilgering distorsion, deposit



- External objects: antivibration bars, trifoiled support plate, quadrifoiled support plate, cylindrical plate,
  - Clogging
  - Wear defect due to the external objects

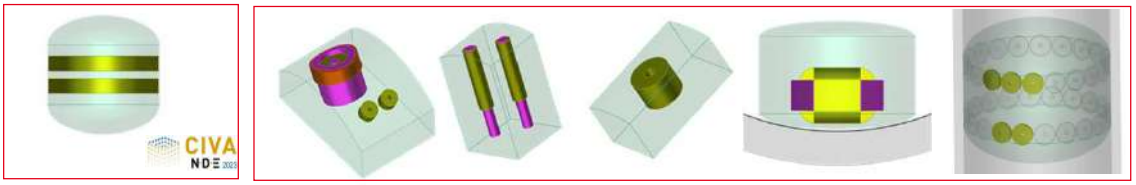


CIVA NDE — ET module « Steam Generator Inspection »

- Defect: Calibration defects, hole, straight wear, bump, groove, progressive groove, notch

- Probes: bobbin coils, rotating probes, +point, multi-element

Version under development

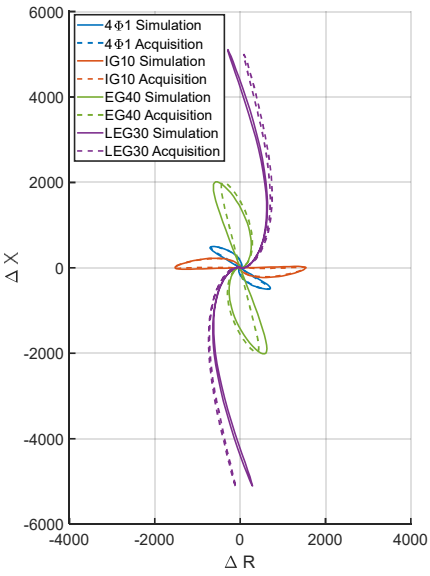


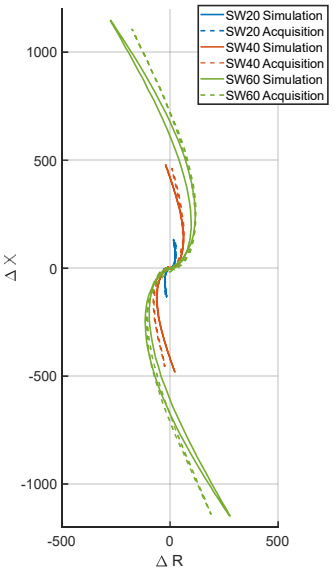
Experimental validations: configuration

- Probe: bobbin coils
- Device: Impedance analyzer
- Frequency: 280 kHz (Differential mode)
- Calibration defect: 4 throught wall Φ1 holes (Amplitude = 1700 mV, Phase = -35°)
- Samples of ¾" OD SG tube made in alloy 690 with calibration defects and straight wears with rectangular bottom flat
- AVB in alloy 600

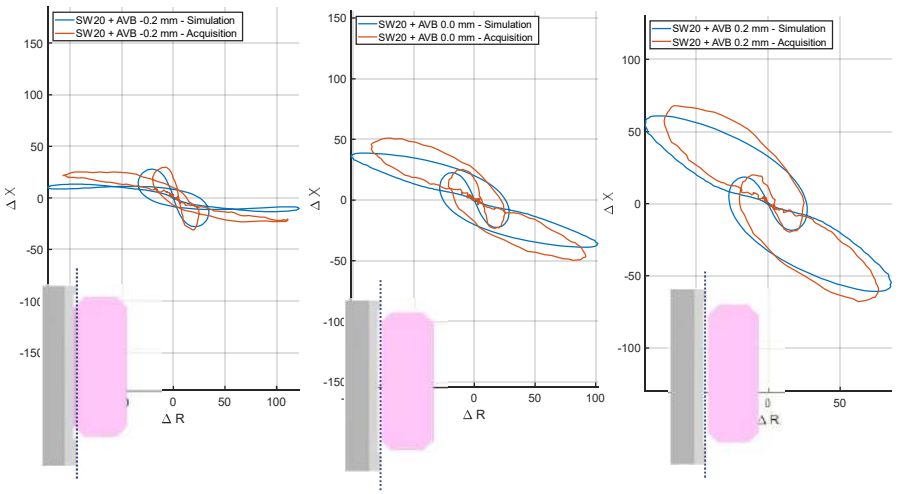
Experimental validation: Calibration defect and straight wear

	Amplitude Difference (%)	Phase Difference (°)
Internal Groove 10%	1,31	0,07
External Groove 40%	3,45	4,57
Large External Groove 30%	0,74	4,33
4Φ1	0	0
Straight Wear 20%	4,80	3,91
Straight Wear 40%	4,54	4,77
Straight Wear 60%	3,69	4,33



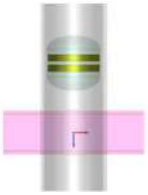


Experimental validation: 20 % straight wear with AVB



	-0.2 mm	0.0 mm	0.2 mm
Amplitude (mV)	245	216	205
Phase (°)	-5	-19	-35

AVB at 90°



Experimental validations: work in progress

- The 3D solver has been experimentally validated for
  - Calibration defects (holes and grooves), straight wears
  - Bobbin coils
  - Anti-vibration bars

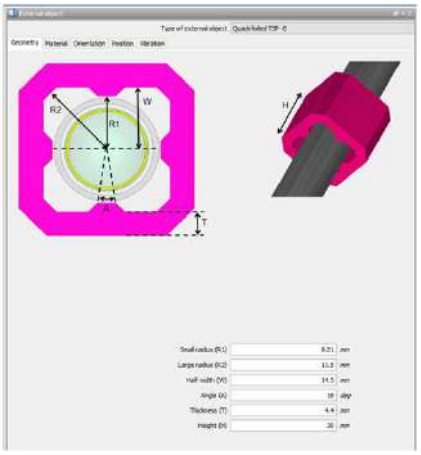
  → Configurations available in commercial version are experimentally validated, the calculation kernels are the same for the different external objects (AVB, TSP)

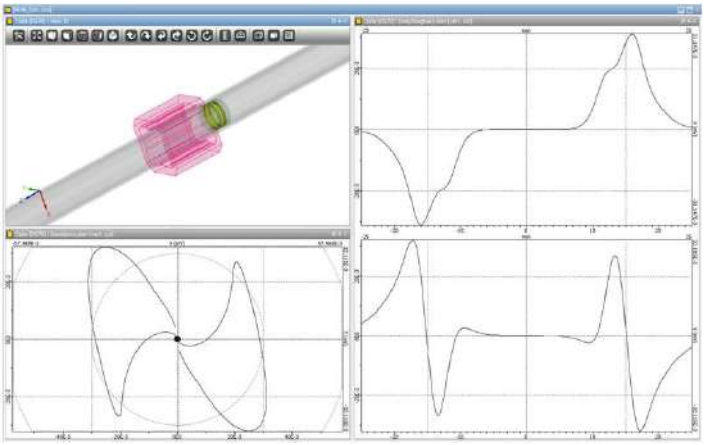
- In progress
  - Tube support plate (cylindrical and quadrifoiled)
  - Clogging
  - Rotating probes

All the simulations presented after are not calibrated and balanced

Simulation of quadrifoiled tube support plate

- EC signal at 280 kHz in differential mode for bobbin coils and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50)

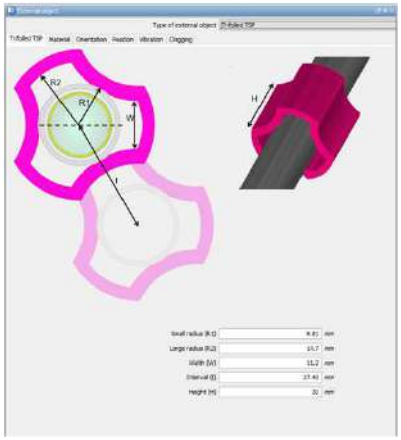


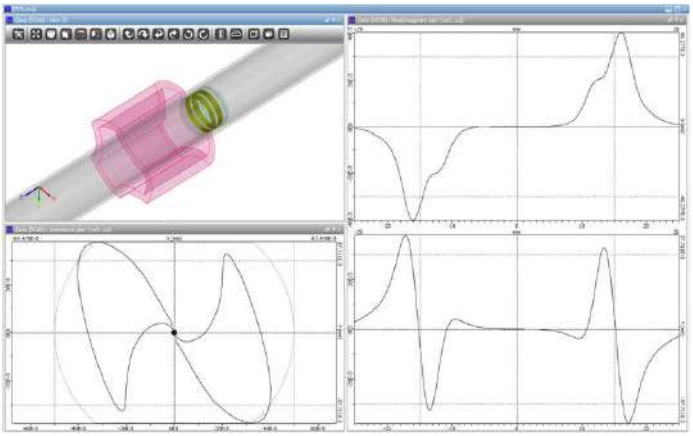


CIVA panel

Simulation of trifoiled tube support plate

- EC signal at 280 kHz in differential mode for bobbin coils and trifoiled plate (σ=1.75 MS/m, μ_r = 50)

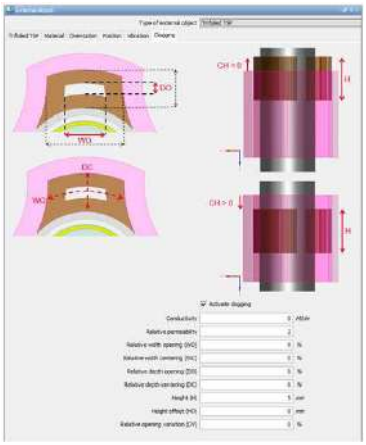


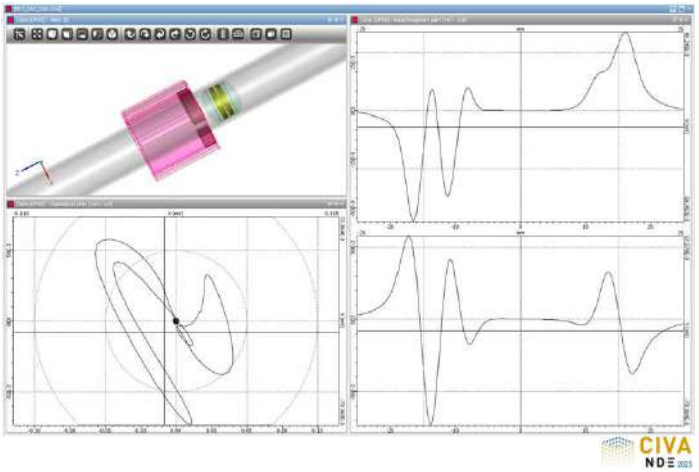


CIVA panel

Simulation of trifoiled TSP with clogging

- EC signal at 280 kHz in differential mode for bobbin coils and trifoiled plate (σ=1.75 MS/m, μ_r = 50) with clogging (μ_r = 2)

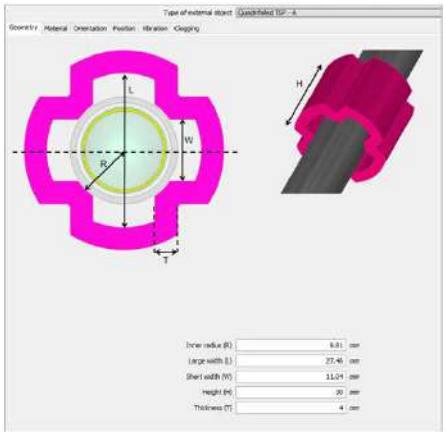


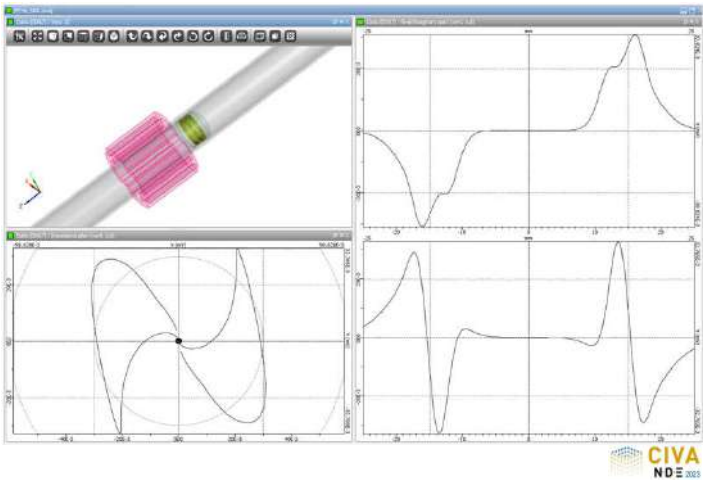


CIVA panel

Simulation of quadrifoiled tube support plate

- EC signal at 280 kHz in differential mode for bobbin coils and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50)

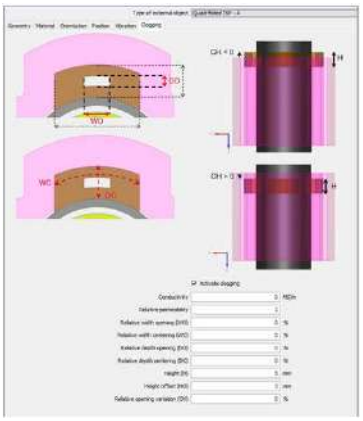




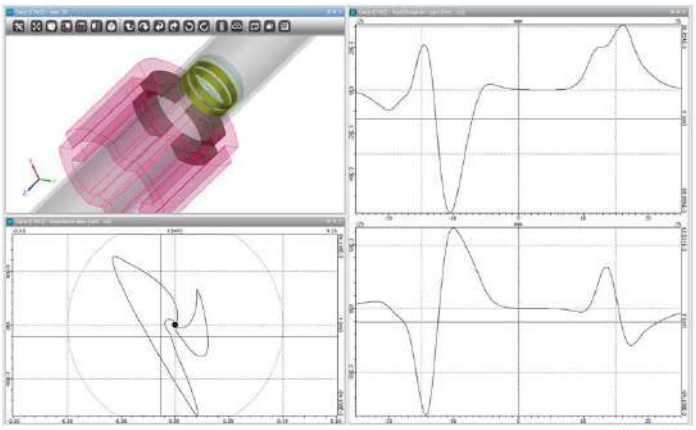
CIVA panel

Simulation of quadrifoiled TSP with clogging

- EC signal at 280 kHz in differential mode for bobbin coils and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50) with clogging (μ_r = 2)

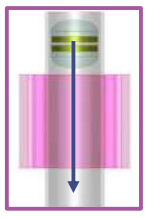


CIVA panel



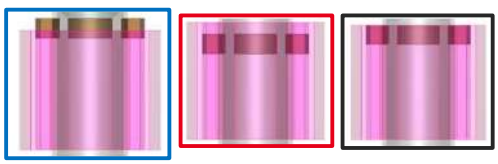
Quadrifoiled TSP with clogging: position effect

- EC signal at 280 kHz in differential mode for bobbin coils and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50) with clogging (μ_r = 2) at different positions

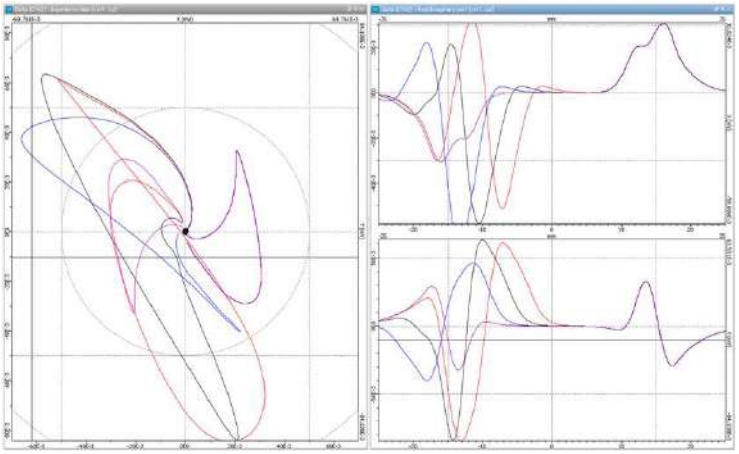


Probe displacement

Clogging geometry



Variation of the clogging position



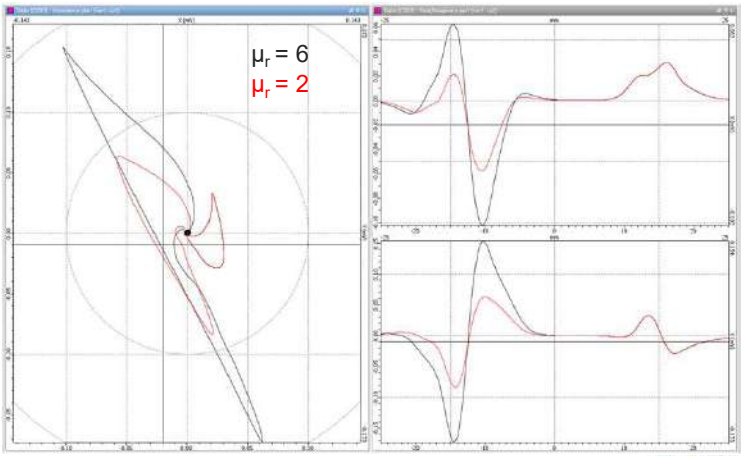
Quadrifoiled TSP with clogging: position effect

- EC signal at 280 kHz in differential mode for bobbin coils and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50) with clogging with different magnetic permeability

Probe displacement

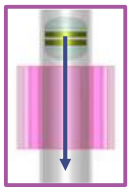
Clogging geometry

Clogging position

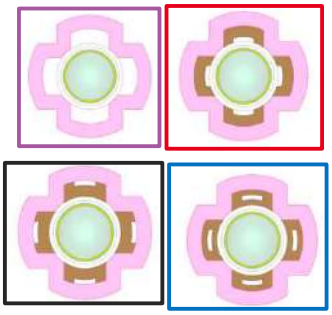


Quadrifoiled TSP with clogging: filling effect

- EC signal at 280 kHz in differential mode for bobbin coils and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50) with clogging (μ_r = 2) with different filling

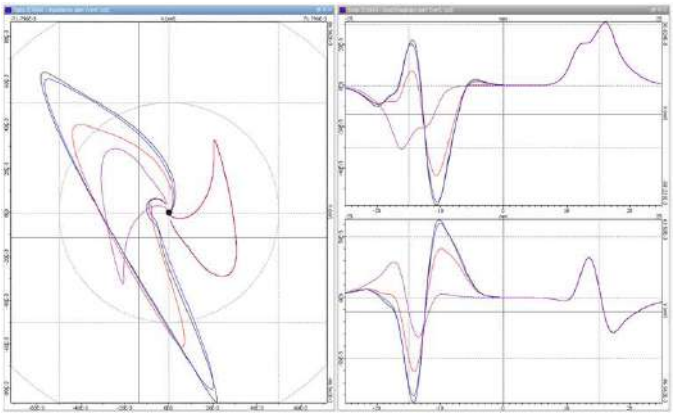


Probe displacement



Variation of the filling

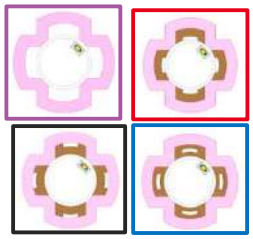
Clogging position



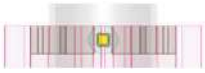
Quadrifoiled TSP with clogging: filling effect

- EC signal at 280 kHz in differential mode for +point and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50) with clogging (μ_r = 2) with different filling

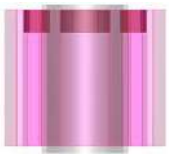
Probe displacement (45°)



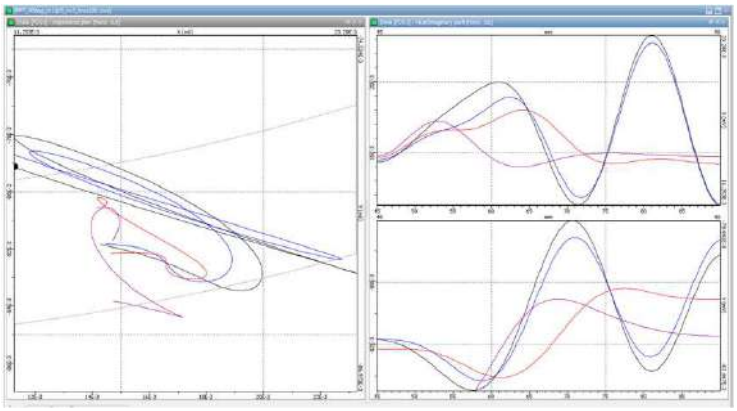
Variation of the filling



Probe position



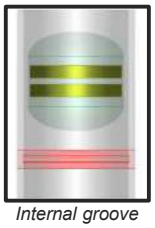
Clogging position



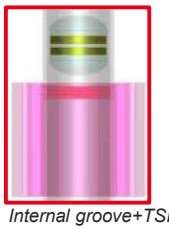
Version under development

Quadrifoiled TSP with clogging: filling effect

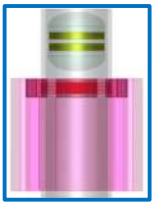
- EC signal at 280 kHz in differential mode for +point and quadrifoiled plate (σ=1.75 MS/m, μ_r = 50) with clogging (μ_r = 2) and internal groove (opening 1mm, depth 10%)



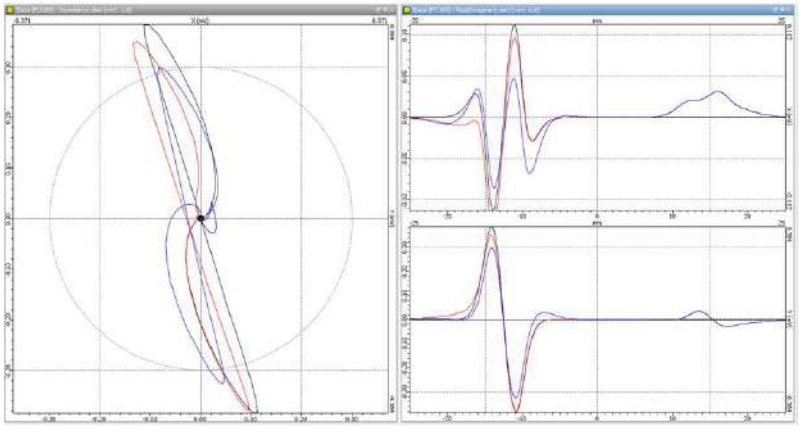
Internal groove



Internal groove+TSP



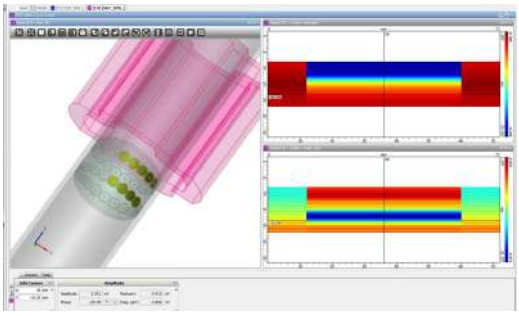
Internal groove+TSP+clogging



Conclusions

- Collaborative study between CEA LIST and IRSN for the simulation of eddy current inspection of steam generator tubes
- Module dedicated to the inspection of SG tubes in CIVA NDE
- Experimental validation for bobbin coils
- Modelling of TSP with different geometries and clogging
- Study in progress on the experimental validation of clogging of tube support plates for various probes
- Numerical tools for sensitivity study of the parameters influencing the EC signal
  - Clogging geometry and position
  - Presence of clogging

  →Civa users can quickly assess the sensitivity of their inspection setup settings



Multi-element probe numerical settings in development

cea IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Thank you for your attention.

Audrey VIGNERON
audrey.vigneron@cea.fr

Use of NEWS and MMM technologies for diagnostics of NPP components

Jaroslav Brom[1], Petr Vlček[1], Jan Patera[1]

[1]Research Centre Rez, Hlavni 130, Husinec - Rez, Czech Republic

E-mail address: jaroslav.brom@cvrez.cz

Abstract

The paper provides information on the results of the R&D projects of the Research Centre Rez carried out between 2019 and 2022 for the Technological Agency of the Czech Republic as part of the "Perspective Diagnostic Methods" projects.
In the first part of this paper, the development of the use of NEWS technology for the detection of cracks in pipelines is described. Results from development on half-pipe and pipe test pieces are presented, as well as results from measurements on the main circulation pipeline and connection pipes up to the first shut-off fitting at NPP Temelín. The method of certification and verification of the methodology is also described.
The second part of this paper describes the development of the use of MMM technology to detect the state of tightening of bolts of flange joints. The development focused on determining the dependence of the tension in the bolt and the values obtained by the MMM method, determining the influence of the measurement location for the MMM method on the assessment of the condition of the flange joint, and determining the sensitivity of the method to unsatisfactory flange conditions such as undertightened bolts, overtightened bolts etc. is described.
At the end, implementation plans are presented, either for specific applications at the NPP or in a subsequent R&D project.

Keywords: NEWS (Non-linear Elastic Wave Spectroscopy), MMM (Metal Magnetic Memory), Diagnosing, Pipeline, Flange joints.

Use of NEWS and MMM technologies for diagnostics of NPP components

Centrum výzkumu Řež s.r.o. (Research Centre Rez)

Jaroslav Brom
Petr Vlček

NDE in Nuclear 2023, Cutlers' Hall, Sheffield, UK
27-29 June 2023

CVŘ Centrum výzkumu Řež | NDE in Nuclear 2023 | Skupina ÚJV TECHNOLOGIE | INOVACE | LIDÉ

Content

1. NEWS (Non-linear Elastic Wave Spectroscopy)
   a) Principles of the NEWS method
   b) Outputs from the R&D project from 2019-2020
      - Development on half - pipe test specimens
   c) Outputs from the R&D project from 2021
      - Development on full - pipe test specimens & a pilot measurement at Temelin NPP
   d) Output from internal R&D project for DMW from 2021-2022
   e) Outputs from the R&D project from 2022
      - Measurement at Unit 2 Temelin NPP & NEWS procedure certification
   f) Conclusions
2. MMM (Metal Magnetic Memory)
   a) Principles of the MMM method
   b) Crack detection in pipeline
   c) Measurements on flange joint stand
   d) Conclusions

NEWS - Outputs from the R&D project from 2019-2020

The principle of the NEWS method using NWMS technique

The principle of the NEWS method using NWMS is to mix two different excitation signals with frequencies f1 and f2 inside the inspected material using two ultrasonic sensors as exciters and monitoring the response in one ultrasonic sensor as receiver. When using this method, the crack is manifested by non-linear behavior, the formation of intermodulation frequencies (especially higher multiples) f12 = a·f1 ± b·f2., where the frequencies f1 and f2 are the excitation frequencies - see the picture.

In the case of application on welded joints, the excitation frequencies f1 = 192 kHz, f2 = 900 kHz proved to be optimal.

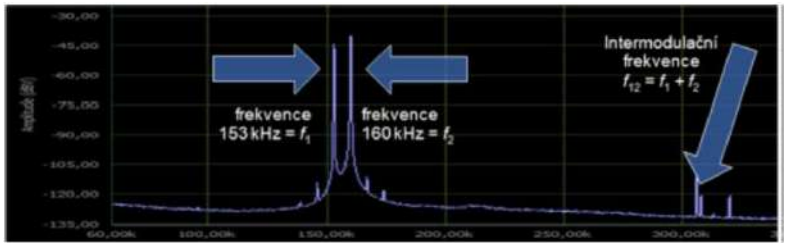


Figure – Demonstration of the principle of the NEWS method using NWMS technique for excitation frequencies f1 = 153 kHz, f2 = 160

NEWS - Outputs from the R&D project from 2019-2020

Information about test specimens used for the project:

3 pcs from ferritic steel with a crack in the weld (12022.1 steel as equivalent for 22K)
- NCKNEWS3
- NCKNEWS4
- NCKNEWS5

3 pcs from stainless steel with a crack in the weld (X6CrNiTi18-10 as equivalent for 08CH18N10T)
- NCKNEWS6
- NCKNEWS7
- NCKNEWS8

ŠKODA JS sensors with waveguides welded to the specimen were used - two exciters side by side, receiver on the other side of the test specimen.

The measurement after making the EDM notch before cycling is compared with the measurement after cycling - the occurrence of intermodulation frequencies (multiples of excitation frequencies). Excitation frequency: f1 = 192 kHz, f2 = 900 kHz.

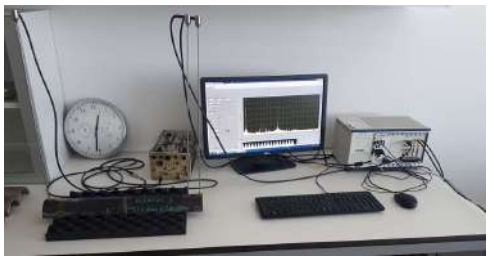


Figure – Measurement arrangement

NEWS - Outputs from the R&D project from 2019-2020

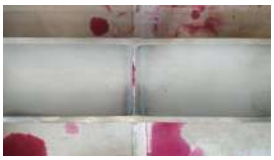
Test specimen manufacturing (approx. 20 pcs. in total)

a) production of the initiation EDM notch

b) 1st measurement by the NEWS before cycling

c) cycling (crack manufacturing)

d) crack verification (PT, UT)



e) 2nd measurements by the NEWS method after cycling

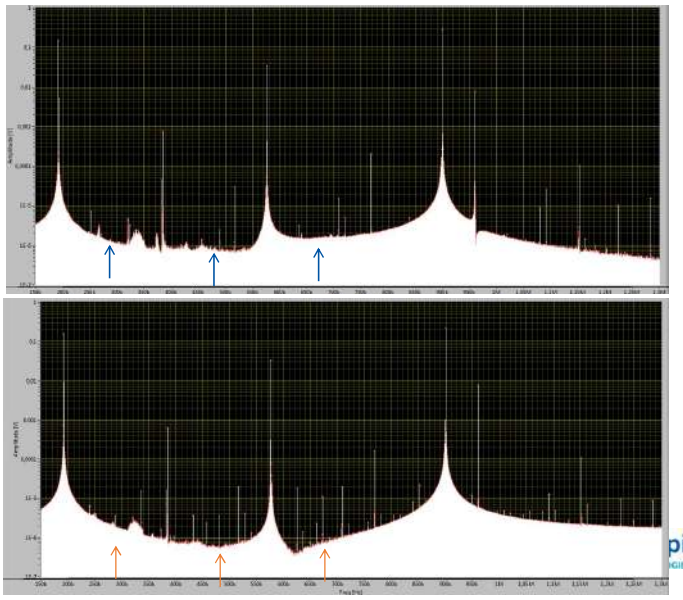
NEWS - Outputs from the R&D project from 2019-2020

NWMS on specimen No. NCK NEWS 3 (12022.1)

Before / after cycling

Excitation: 192+900 kHz

Throw crack



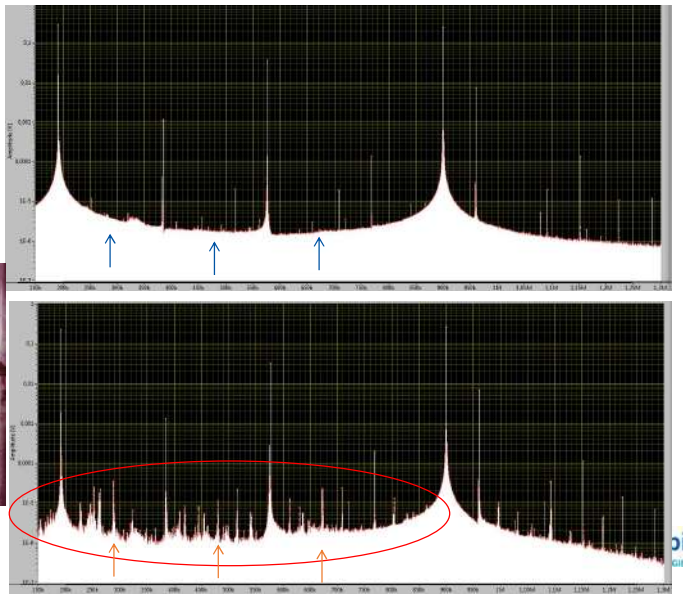
NEWS - Outputs from the R&D project from 2019-2020

NWMS on specimen No. NCK NEWS 6 (X6CrNiTi18-10)

Before / after cycling

Excitation: 192+900 kHz

Double throw crack



NEWS - Outputs from the R&D project from 2019-2020

For the visualization of non-linear phenomena, it turned out to be appropriate to relate the intermodulation frequency f12 to the higher harmonic of the lower excitation frequency f1 = 192 kHz with the inclusion of intermodulation with a higher excitation frequency f2 = 900 kHz.

For example, for a measured peak of 12 kHz = 14 * 192 kHz - 3 * 900 kHz, or for a peak of 24 kHz = 28 * 192 kHz - 6 * 900 kHz, this is the intermodulation frequency f12 related to the 14th or 28. higher harmonic frequency f1 = 192 kHz.

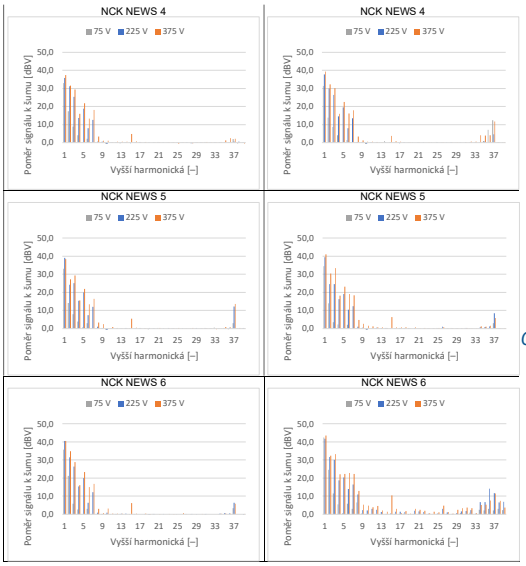


Figure: Spectrograms. On the left – without a crack, on the right – with a crack

NEWS - Outputs from the R&D project from 2021

The following activities were implemented in 2021:

Validation of the NEWS method on full - tube austenitic steel test specimens with a weld crack in the range of:

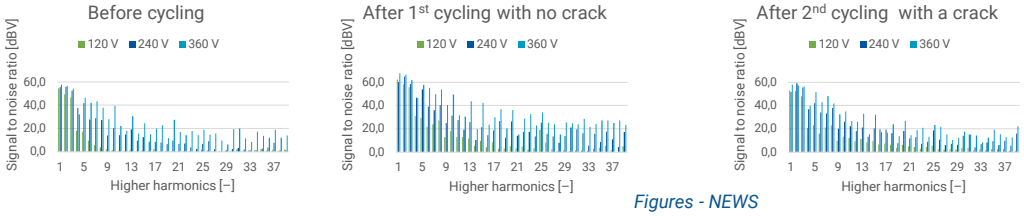
- Verification of the effect of coupling on the results - repeated measurement on the same test specimen after disassembly and rewelding of the sensors - no effect
- Verification of the effect on the outputs from the NEWS method when changing the mutual position of the sensors and the crack - only the effect on the amplitude.
- Verification of excitation of two frequencies with one sensor - proved unsatisfactory results

Pilot measurement at the Temelín NPP using sensors of the ACMS system

- A pair of excitation frequencies f1 = 192 kHz, f2 = 900 kHz was used as the basic one.
- The results from the pilot measurement using sensors of the ACMS system on the Unit 2 Temelin NPP show the applicability of the NEWS method on the main circulation pipeline for crack detection between two exciters and the signal receiver.

NEWS - Outputs from the R&D project from 2021

- Austenitic full - pipe test specimen NCK NEWS16
- Measured before cycling, after 1st cycling without crack and after 2nd cycling with crack
- The results are affected by the nonlinearity of the excitation part of the system (generator, amplifier, exciter)
- There is no difference between individual measurements
- Summary - single sensor excitation is not suitable.



Figures - NEWS spectrograms when excited by a single sensor

NEWS - Outputs from the R&D project from 2021

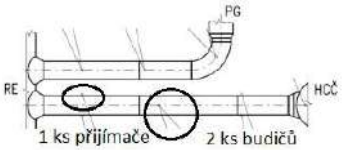


Figure: Location of ultrasonic sensors at the Unit 2 Temelin NPP

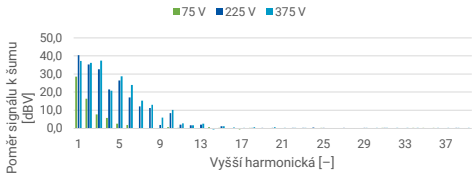


Figure: Spectrum of the ultrasound signal from measurements at the Unit 2 Temelin NPP – without the presence of higher harmonic frequencies. Intermodulation products corresponding to the 35th–38thhigher harmonics were observed in laboratory specimens with a crack.

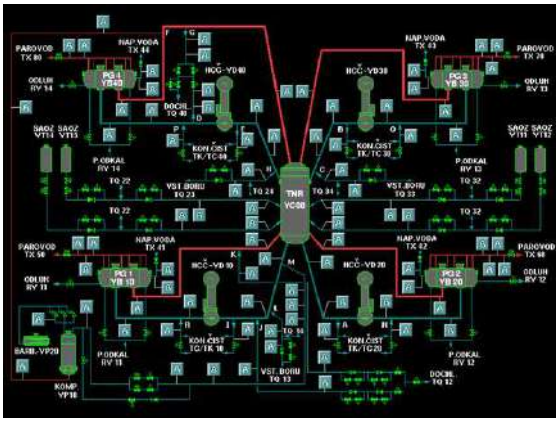


Figure: Schematic representation of the sensors of the LEMOP system at the main coolant pipelines and the connecting pipes to the first shut-off valve at the Temelín NPP

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11

NEWS - Output from internal R&D project for DMW from 2021-2022

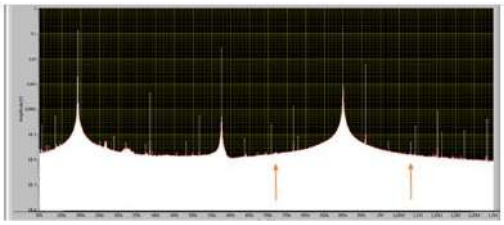

Figure: Before cycling

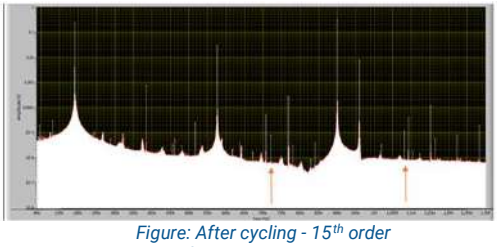

Figure: After cycling - 15th order frequency occurred

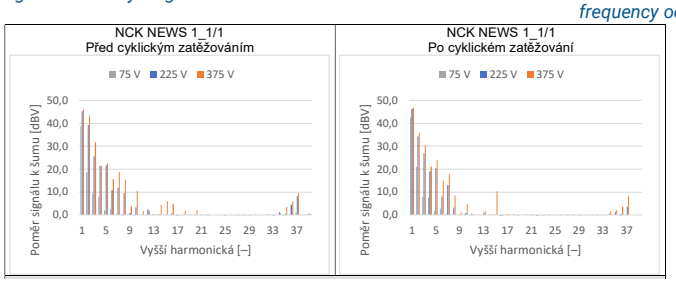

Figure: Spectrograms corresponding to the above spectra

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12

NEWS - Outputs from the R&D project from 2022

Measurements at the Unit 2 Temelin NPP - took place in July 2023.

The results from 2022 confirmed the results from the pilot measurement from 2021. - comparison of measurements from 2021 and 2022. Unit 2 Temelin NPP – 21/07/2021 (left), 8/08/2022 (right).

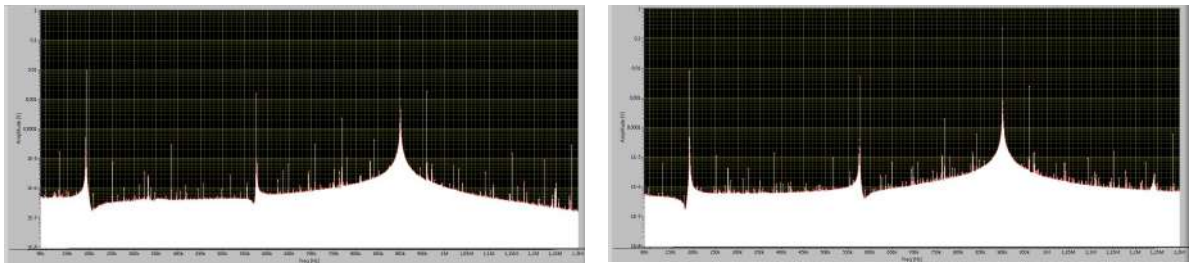


Figure: Comparison of measurements from 2021 and 2022. 21/07/2021 (left), 8/08/2022 (right).

NEWS - Outputs from the R&D project from 2022

Zpracované výsledky ve formě spektrogramů NEWS– v horní části šum na trase, v dolní části při buzení

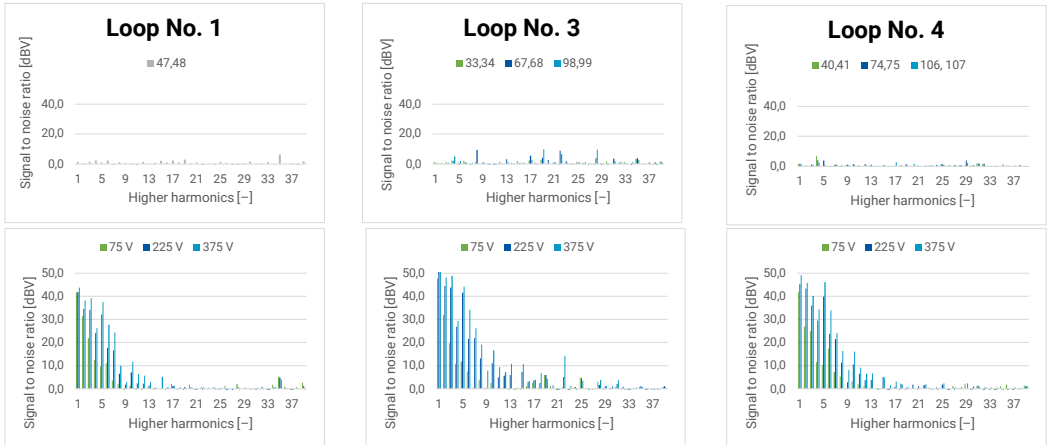


Figure: Examples of NEWS spectrograms of the 1st, 3rd and 4th loops of Unit 2 Temelin NPP

NEWS - Conclusions

1. The NEWS method using NWMS technique was verified for the detection of cracks in pipes with dimensions of 89x6 mm.
2. The NEWS method can be used to detect cracks in the main circulation pipeline of Temelin NPP from the point of view of the sound penetration of individual pipe routes.
3. In order to verify the method for detecting cracks in the main circulation pipeline, it is necessary to further develop the attachable verification test body with a crack and implement verification tests at site using it.
4. A measurement and evaluation methodology was developed and certified for UNIT 2 Temelin NPP. The main principle for evaluation is monitoring changes in spectrograms over time.

MMM – principles of the MMM method

Principles of MMM method -The MMM method is an NDT method based on sensing the intensity of the magnetic field Hp or a gradient dHp/dx depending on the distance travelled Lx using one or more probes, each of which senses the magnetic field in two mutually perpendicular planes.

Residual magnetization of the material is affected by the production process, machining, cutting, welding, bending, heat treatment, cooling, operational stress, etc.

Similar magnetization of the material occurs during the process of material degradation in pipeline operation due to degradation conditions - material fatigue, possible corrosion, etc.

The scanning device on which the probes are located is traversed over the material to be measured and the connected encoder also measures the distance over which the inspection is carried out.

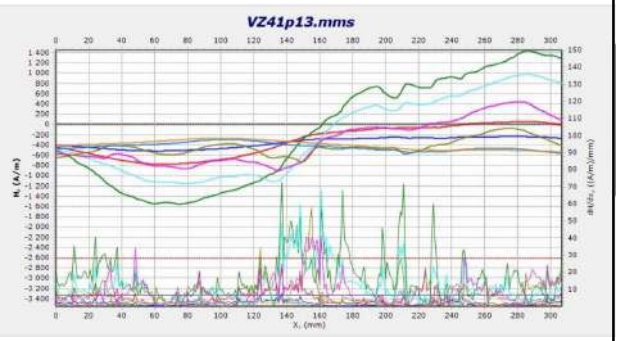
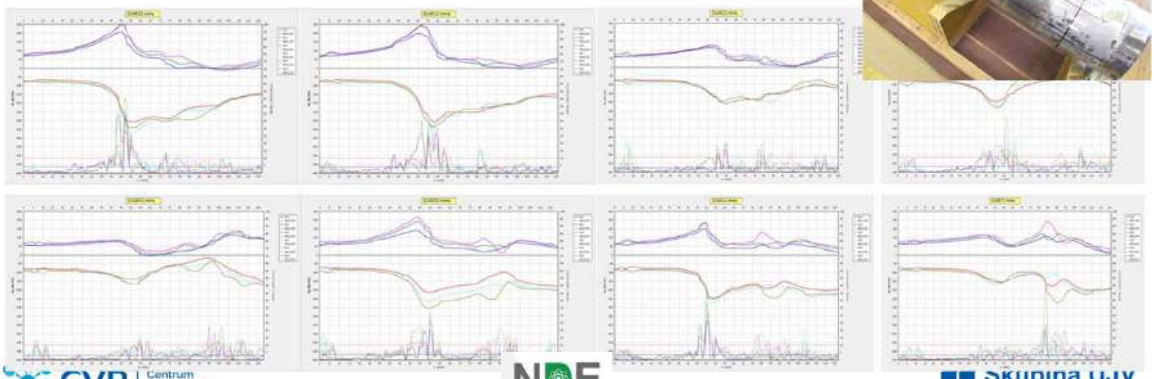


Figure - Example of magnetogram

MMM – Crack detection in pipeline

The R&D program in 2019 - 2020 focused on the use of the MMM method for the detection of crack-type defects in welded joints has shown that the MMM method detects the crack location of the welded joint during longitudinal scanning. The location is identifiable by an increase in magnetic field intensity gradient.



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17

MMM – Measurements on flange joint stand

The aim of the project was to verify the use of the MMM method on flanged joints. The project was divided into the following steps:

Determination of the dependence of the tension in the bolt and the values obtained by the MMM method (simultaneous measurement of the MMM with strain gauges) for the type of bolt chosen in the project.

Determination of the influence of the measurement location for the MMM method on the selected flange joint (see Fig. 6) on the assessment of the condition of the flange joint - assess the most suitable method of measuring the flange - measurement directly on the bolt shaft or by traveling along the flange.

Determination of admissibility criteria on the selected flange connection - defining when it will be necessary for the dispersion of measured values to be permissible for a given case and when not - propose an overview of tests that will verify the sensitivity of the method to individual unsatisfactory conditions of the flanges, e.g.: undertightened bolt, overtightened bolt, bolt tightened through the thread, damaged bolt with a crack, damaged bolt thread, dirt in the parting plane of the flange, etc.

Defining the requirements for the procedure for verifying the condition of bolts and flanges using the MMM method.

Figure: Flange joint stand

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18

MMM – Measurements on flange joint stand

Main R & D project outputs:

Based on the results of experimental measurements on the flange joint stand used in the project, it can be stated that the MMM method can detect the following states of the flange joint:

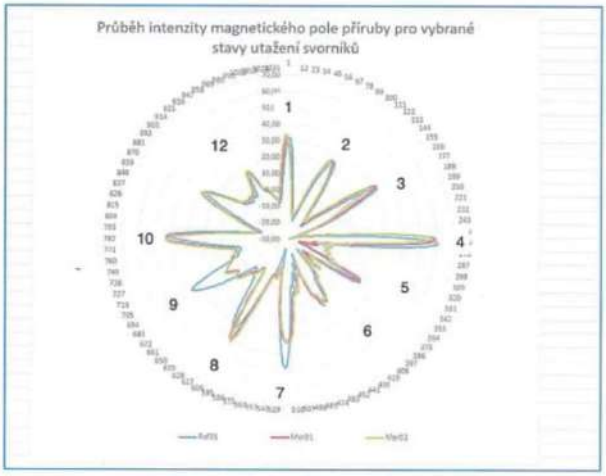
1. Detection of a undertightened bolt of a pressurized flange joint
2. Detection of a undertightened bolt of a non-pressurized flange joint
3. Detection of overtightened bolt of a non-pressurized flange joint

Detection is based on changes in screws adjacent to the screw that is being undertightened or overtightened

Figure: Experimental stand of a flange joint showing the basic measurement method

MMM – Measurements on flange joint stand

Figure – Blind test result of the MMM method verification for an undertightened bolt #8 and then bolt #4 of a pressurized flange joint



MMM – Measurements on flange joint stand

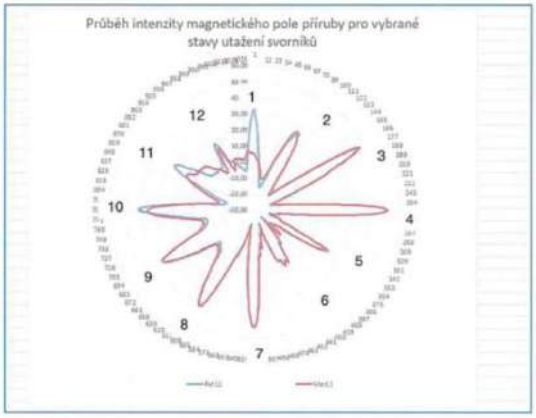


Figure - Blind test result of the MMM method verification for an undertightened #12 bolt of a non-pressurized flange joint

MMM – Measurements on flange joint stand

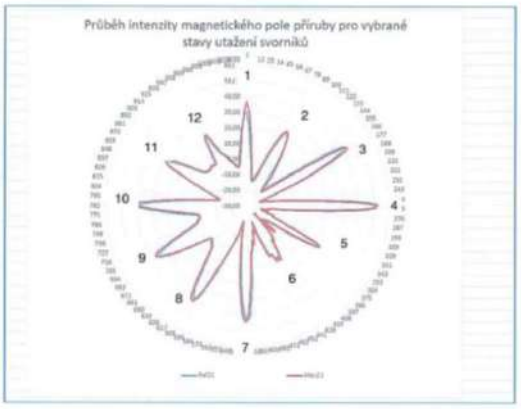


Figure - Blind test result of the MMM method verification for an overtightened #2 bolt of a non-pressurized flange joint

MMM – Conclusions

The achieved results showed that the MMM method can detect the non-standard tightening state of the bolts on the flange joint and thus identify the possible occurrence of damage or leakage.

The value of the magnetic field intensity for the measured bolt/flange material is determined by the material, manufacturing history, operational mechanical stress and load. To assess the condition of an individual flange joint, the assessment is carried out based on the change in the magnetic field intensity values. Therefore, it is necessary to know the reference (baseline) state to which this change will be compared.

A general procedure for measuring flange joints using the MMM method has been developed.

Based on the outputs of this R&D project, it was decided with a partner to continue the development of the use of the MMM method for specific NPP flange joints - for example, for the flange joint of the electric heater of the volume pressurizer and the flange joint of the safety pumps.

Thank you for your attention

jaroslav.brom@cvrez.cz

Dry Storage Canister Inspection with Eddy Current Arrays

Nathan Muthu[1]

[1]Electric Power Research Institute, Charlotte, NC, USA

E-mail address: nmuthu@epri.com

Abstract

Nuclear power plants in the United States are required to store and maintain used nuclear fuel and radiation waste at their own sites for longer than the originally anticipated time. To meet the license renewal commitments of the independent spent fuel storage installations (ISFSI), they are required to develop aging management program for their dry canister storage system (DCSS). Nondestructive evaluation (NDE) will become necessary to support the program as these fully loaded canisters cannot be moved and must be inspected at its permanent location.

EPRI investigated the surface eddy current array nondestructive evaluation (NDE) technology to demonstrate the capability to identify the presence of (or precursors to) stress corrosion cracks and other anomalies to support the aging management program requirements and ISFSI license renewal commitments.

This presentation will discuss the research and results obtained from investigating a large area scan footprint probe that uses the surface eddy current array technology. The final low-profile probe design was configured with 96 total coils arranged in three rows (32 coils/row). This provided an inspection coverage of approximately 7.54 inches (191.5mm) in a single scan sweep. Through industry collaboration, field experiments were also conducted on a large-scale mock-ups

Keywords:

Eddy Current Arrays
Surface Eddy Current Array Probe
Dry Canister Storage System (DCSS)
Spent Nuclear Fuel Permanent Storage System
Nondestructive Evaluation (NDE) for Canister

Dry Storage Canister Inspection with Eddy Current Arrays

Nathan Muthu, EPRI
Technical Executive, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

www.epri.com

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Introduction

Permanent repositories are not available to accept used fuel

- Spent Fuel Pools are approaching capacity at many sites around the world
- Increased need for dry storage systems

>3900 dry storage systems loaded in the US alone

- ~200 systems are added per year
- Dry storage systems will operate for longer than their original licensed period

Aging management is required to extend licenses

- NDE inspections will be required to support aging management

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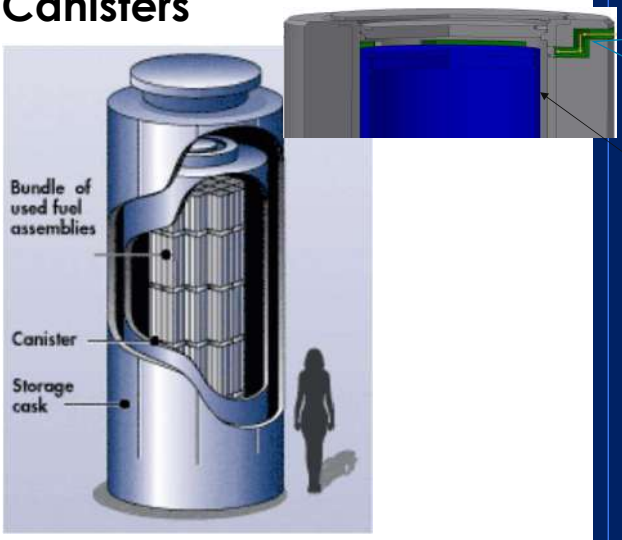
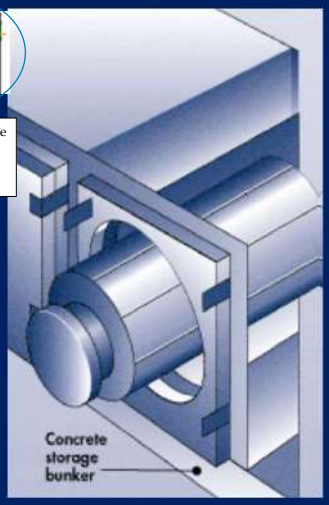
Vertical and Horizontal Canisters



External surface of the canister needs to be evaluated nondestructively



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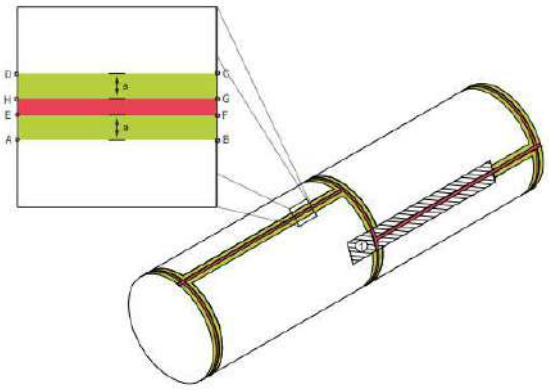
Potential NDE Application Areas with Eddy Currents



LEGEND:

a = 50 mm (2 inch)

A-B-C-D = Extent of the examination surface

E-F-G-H = Visually determined extent of weld

I = Example inaccessible areas; the examination surface does not include inaccessible areas

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Mockup Development

EPRI working to assemble a list of all available mockups across industry

QA Flaw Mockups

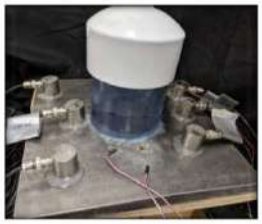
8 flaw mockups with a range of flaw sizes, orientations, etc.

Non-QA Flaw Mockups

6 additional flawed and unflawed mockups are available

Sandia Mockup

SNL donated a full-diameter mockup and PNNL funded flaw implantation



Acoustic Emission Mockups

EPRI is growing SCC in 5 flaw mockups

CISCC Mockups

EPRI has 3 mockups with laboratory-grown CISCC

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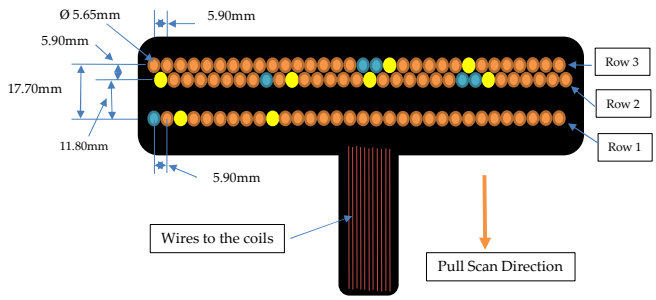
Final Eddy Current Array Probe



Coil Topology	Flaw Detection Capabilities
All coil topologies	Sensitive to volumetric indications
Single driver long axial (SDLA)	Subsurface or deeper, and longer indications in the axial direction (perpendicular to the row of array coils)
Single driver long transverse (SDLT)	Subsurface or deeper, and longer indications in the transverse direction (parallel to the row of array coils)
Double driver short axial (DDSA)	Surface breaking or shallower indications in the axial direction (perpendicular to the row of array coils)
Double driver short transverse (DDST)	Surface breaking or shallower indications in the transverse direction (parallel to the row of array coils)

Single Driver Long Axial and Transverse Topologies	Coil Rows 1 and 2
Double Driver Short Axial and Transverse Topologies	Coil Rows 2 and 3

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Probe Specification

- Probe Specification

Probe body type	Custom to fit curvature of canister
Probe element for testing	Surface of dry Type 304 stainless steel storage canisters
Target flaw size to detect	0.1 inch (2.5 mm)
Surface flaw orientation	Any orientation with respect to the probe
Element topologies	Double driver, short (axial and transverse) Single driver, long (axial and transverse)
Element coverage (scan area)	7.54 inches (191.5 mm)
Connector type	Ectane™ 160-pin
Final probe cable length	39.4 feet (12 m)
Probe pull (scan) speed	4 to 6 inches/sec (101 to 152 mm/sec)
Tester minimum requirement	Ectane E256

- Array Coil Specification

Coil type	Pancake
Each coil diameter	0.222 inch (5.65 mm)
Coil quantity	96
Coil layout	32 coils each row x 3 rows
Coil distance (center to center) (see Figures 2-4 and 2-5)	Short axial: 0.232 inch (5.90 mm) Short transverse: 0.232 inch (5.90 mm) Long axial: 0.465 inch (11.80 mm) Long transverse: 0.232 inch (5.90 mm)
Frequency range	50–300 kHz
Optimum frequency	250 kHz
Scanning frequencies	50 kHz (F1) and 250 kHz (F2)

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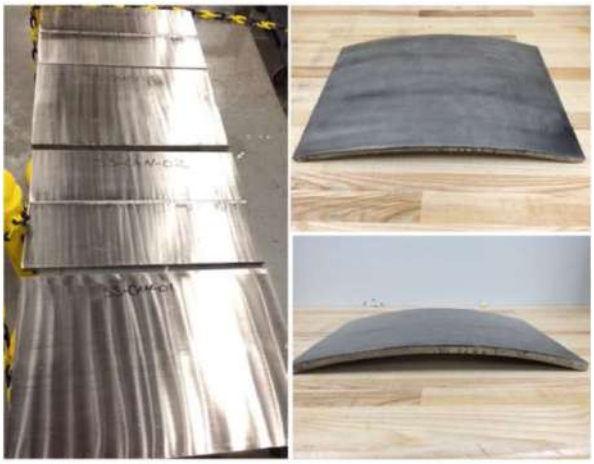
EPRI Mockup Plates

Four Flat and Four Curved Plates



Sandia National Laboratory Mockup

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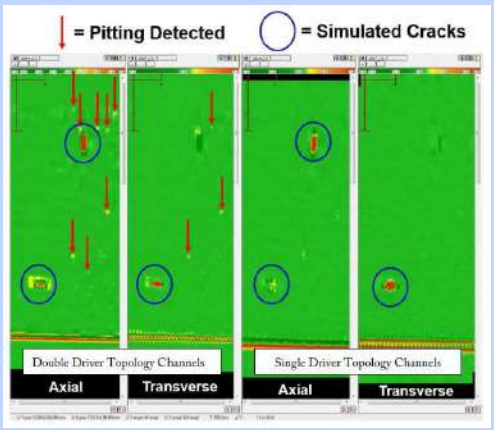
Mockup Specimen with Simulated Cracks and Pitting

Simulated Cracks

Pitting

Eddy Current Scan Results



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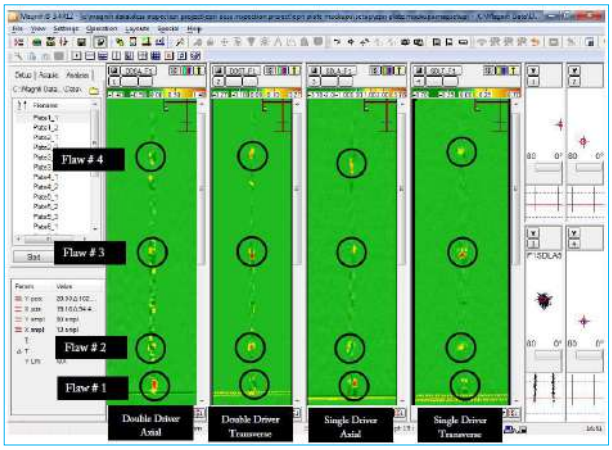
Scan Results from SS-CAN-01 mockup



SS-CAN01 mockup specimen eddy current scanned results

Flaw Orientation and Depth/Coil Topology	Double Driver Short Axial	Double Driver Short Transverse	Single Driver Long Axial	Single Driver Long Transverse	Overall Summary of Flaw Detection
Flaw #1 – Crack parallel to weld approximately 52% deep					
Flaw #2 – Crack transverse to weld approximately 25% deep					
Flaw #3 – Crack transverse to weld approximately 78% deep					
Flaw #4 – Crack parallel to weld 100% through wall					

Note that the double driver coils are suitable for detecting surface-oriented flaws, and the single driver coils are suitable for detecting subsurface and deeper flaws. The axial and transverse configurations of these coils are used to locate flaws that are located accordingly in the respective orientations. The Overall Summary of Flaw Detection column shows the detection capability of all flaws in this mockup specimen.

Good Detection – Easy to Detect

Indications Can be Missed

Low Probability of Detection or No Detection

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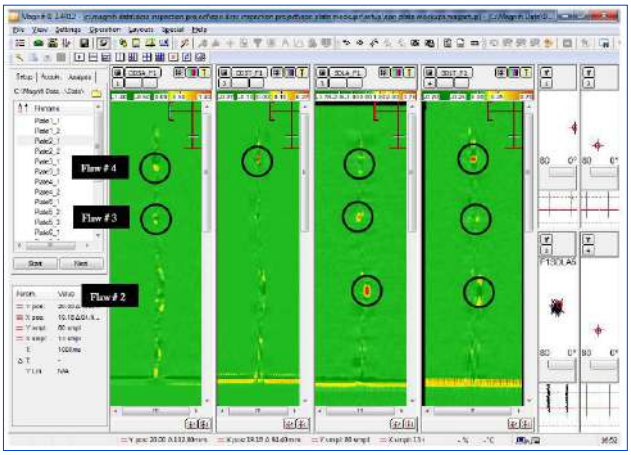
Scan Results from SS-CAN-02 mockup



SS-CAN-02 mockup specimen eddy current scanned results

Flaw Orientation and Depth/Coil Topology	Double Driver Short Axial	Double Driver Short Transverse	Single Driver Long Axial	Single Driver Long Transverse	Overall Summary of Flaw Detection
Flaw #1 – Crack transverse to weld approximately 10% deep					
Flaw #2 – Crack parallel to weld 100% through-wall					
Flaw #3 – Crack parallel to weld approximately 26% deep					
Flaw #4 – Crack transverse to weld approximately 50% deep					

Good Detection – Easy to Detect

Indications Can be Missed

Low Probability of Detection or No Detection

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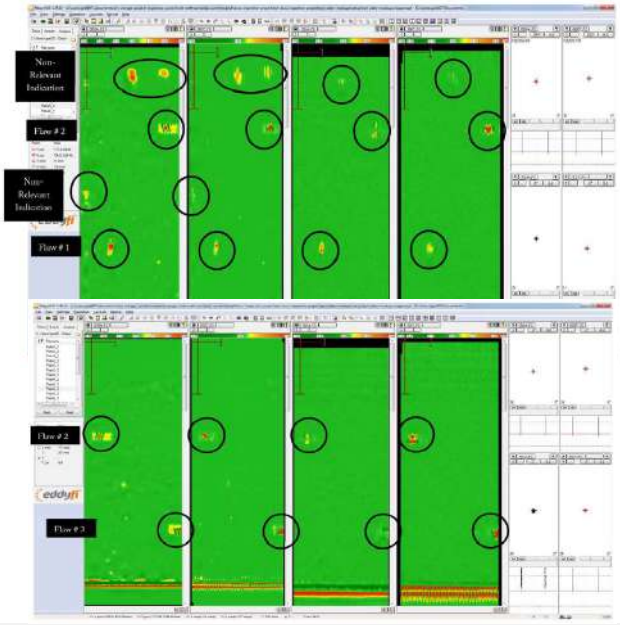
Scan Results from SS-CAN-05 mockup



SS-CAN-05 mockup specimen eddy current scanned results

Flaw Orientation and Depth/Coil Topology	Double Driver Short Axial	Double Driver Short Transverse	Single Driver Long Axial	Single Driver Long Transverse	Overall Summary of Flaw Detection
Flaw #1 – Transverse crack approximately 10% deep					
Flaw #2 – Parallel crack approximately 25% deep					
Flaw #3 – Parallel crack approximately 50% deep					
Flaw #4 – Transverse crack approximately 77% deep					

Good Detection – Easy to Detect

Indications Can be Missed

Low Probability of Detection or No Detection

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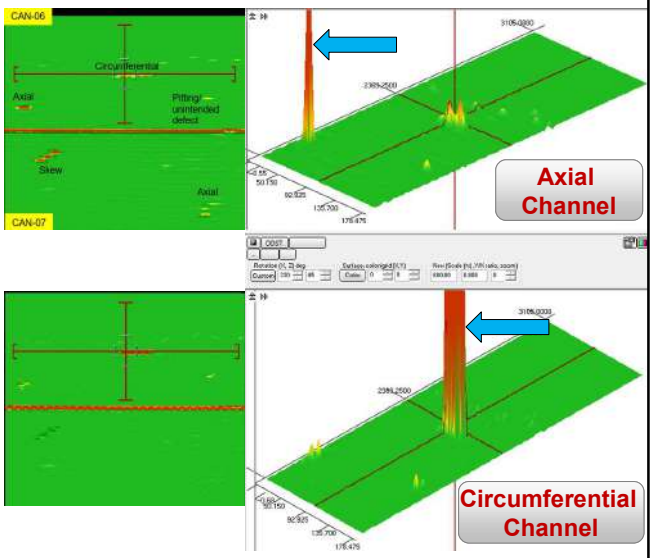
Robotically-Scanned Eddy Current NDE Data

Robotically-scanned data quality comparable to hand-scanned data with high signal-to-noise ratio

- Inspection Improvements
  - Probe Design
    - Foam material & design
    - Probe curvature
    - Flexible array
  - Robotic Design
    - Low-profile connection
    - Deployment arm



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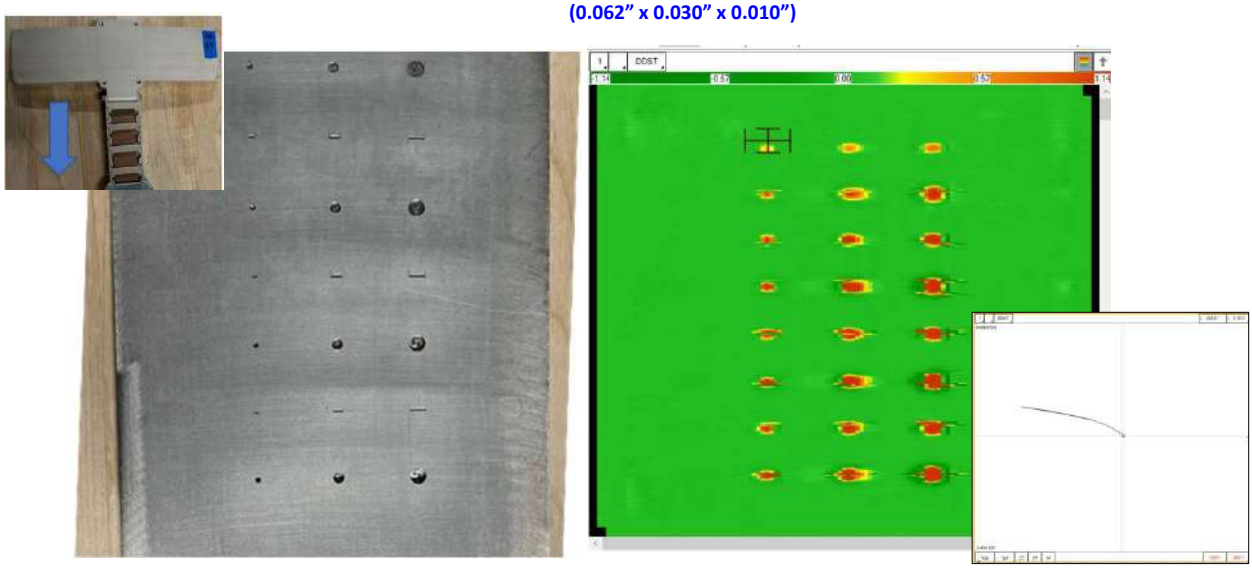
Additional Studies with Eddy Current Arrays

Detection of surface breaking crack with transverse orientation, 1.57 mm long x 0.762 mm deep x 0.254 mm wide (0.062" x 0.030" x 0.010")



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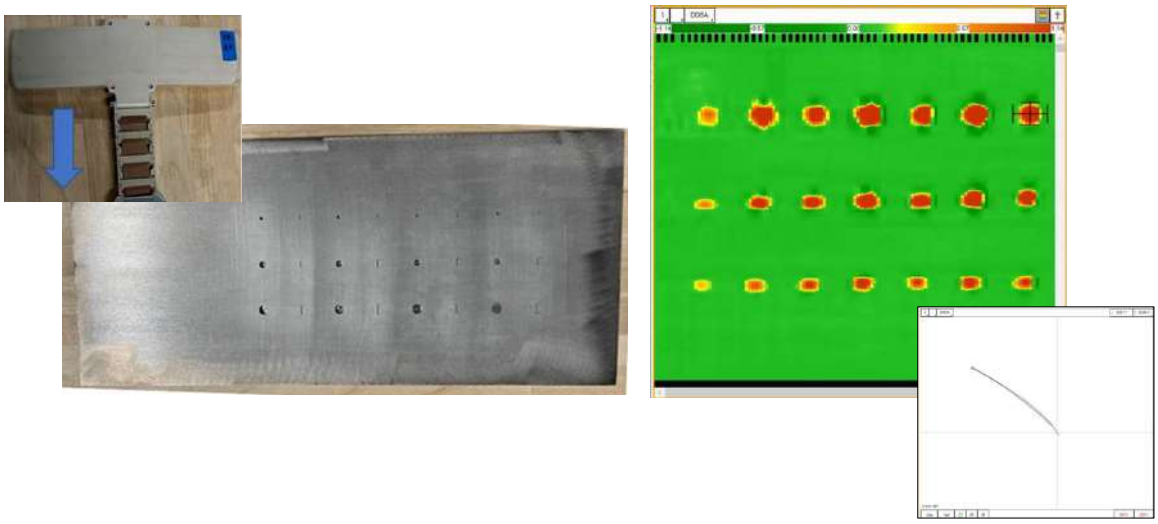
Additional Studies with Eddy Current Arrays

Detection of surface breaking crack with axial orientation, 1.57 mm long x 0.762 mm deep x 0.254 mm wide (0.062” x 0.030” x 0.010”)



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Additional Studies with Eddy Current Arrays with Cold Spray

Detection of real SCC indication with transverse orientation. No strong indications from the cold spray were observed.

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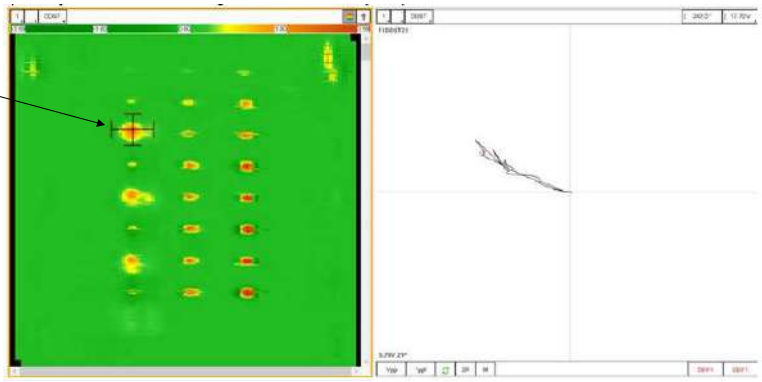
Additional Studies with Eddy Current Arrays- Magnetic Paint

Simulated iron deposit (magnetic paint) directly over the surface breaking transverse crack. Completely masks the defect

Magnetic paint over transverse crack. Completely masked the defect.



Surface cleaning is important for eddy current array testing

17

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Eddy Current Array Study Conclusion

- All flaws were detected with decent sensitivity and resolution by manual scans and by automated scans performed with the probe pay loaded to a remotely operated vehicle (ROV).
- Not ready yet for flaw depth sizing. Need alternate NDE methods for depth sizing
- The array coil arrangement offered short and long driver topologies. These configurations were sensitive to volumetric indications and provided the data analyst with features to discern flaw orientation and depths.
  - The single driver long axial (SDLA—perpendicular to the array coils) and single driver long transverse (SDLT—parallel to the array coils) configurations were sensitive to subsurface or deeper and longer flaws.
  - The double driver short axial and double driver short transverse (DDSA and DDST) were sensitive to both deeper and longer flaws as well as surface-breaking or shallower flaws.
- Flaws in the mockup specimens were fabricated with the electrical discharge machining (EDM) method and using the thermal fatigue process. All flaws were fabricated according to EPRI quality assurance procedures, and some were fabricated according to canister fabricator standard procedure.
- EPRI plate specimens, 30 out of 32 flaws were detected with the specialized eddy current array probe.
- PNNL specimens: Canister weld mockup , 4 embedded flaws generated 7 detectable responses, 3 flat plates with 7 flaws were all detected.
- The revised version of the probe is ready for further field trials and may be used in actual field deployment pending code acceptance from the American Society of Mechanical Engineers (ASME).

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Summary

- Surface eddy currents with the array sensor technology was identified – includes specific probe design and coil configuration.
- Radiation hardened cable to the probe was identified.
- Discussions on-going in ASME space regarding minimum dimensions to be used for flaws in qualification specimens.
  - *Presently in ASME space in Section XI, Appendix IV, Supplement 2; the qualification specimen must meet minimum detection of surface cracks with dimensions of 1.57 mm (0.062”) length x 0.508 mm (0.020”) depth x 0.254 mm (0.010”) width.*
- Calibration specimens with target flaws needed for eddy current inspections.
  - Field demonstration is needed / sought after.

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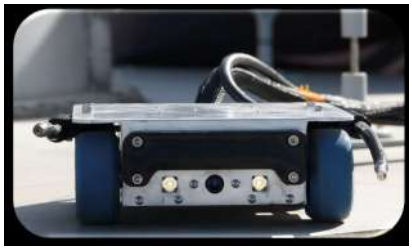
Canister Inspection Technology Development

- Visual – **Completed inspections of loaded canisters** (EPRI 3002016034, 2019)
- Laser Ultrasonic Testing (UT) – Vertical canister mockup demonstration (PNNL-30001 w/EPRI support, 2020)
- Dry Couplant Phased Array UT – Investigated detection capability using laboratory specimens (EPRI Presentation 11/2021)
- Eddy Current – Laboratory specimen testing (EPRI 3002007801, 2016)
- Guided Wave – Feasibility studies (EPRI 3002010447, 2017)
- Acoustic Emission – Feasibility studies with full scale empty mockups (EPRI 3002007816, 2016) and experiments to demonstrate detection capability (EPRI 3002016080, 2019)



STILL NEEDED

- Demonstrate cleaning capability to remove dust and deposits to provide direct visual access to canister shell
- Mockup demonstration of Eddy Current and Guided Wave
- Improved UT equipment and documentation of flaw sizing capability
  - Field trials on additional mockup designs
  - Field trials on loaded canisters
  - Estimate (and improve) flaw sizing uncertainty
  - Estimate (and improve) probability of detection
- Procedure development and inspector qualification guidance

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5. Regulatory & Code Issues and Harmonisation

The presentations in this session are listed in the table below.

Regulatory & Code Issues and Harmonisation	**Chair:** Anders Lejon (Ringhals AB / Vattenfall)
Safety improvements through the use of risk-informed technologies	Patrick O'Regan (EPRI) et al.
Technical Basis for Nondestructive Examination Experience Requirements - ASME Section XI, Appendix VII	Ronnie Swain, Carl Latiolais (EPRI)
Weld Acceptance via Ultrasonic Inspection (in Lieu of Radiography) - Application to Nuclear Components	David Duxbury, Dave Whitehead, Andrew Wood (Rolls Royce)
In-Service Inspection & Repair strategy for newcleo Lead-cooled Fast Reactor	Andrea Barbensi, Jean-Sébastien Genot, Simone Nardi (newcleo), Mariano Tarantino (ENEA)

Safety improvements through the use of risk-informed technology

Patrick O'Regan[1], David Duxbury[2], Robertas Alzbutas[3], Otso Cronvall[4], Carlos Cueto-Felgueroso[5], Anders Lejon[6], Andrey Shipsha[7], Karen Stone[8], Anthony Walker[8], Kaisa Simola[9]

[1]Electric Power Research Institute, Palo Alto, USA
[2]Rolls Royce, Derby, United Kingdom
[3]Lithuanian Energy Institute, Kaunas, Lithuania
[4]VTT Technical Research Centre of Finland, Espoo, Finland
[5]Tecnatom, Madrid, Spain
[6]Ringhals AB, Väröbacka, Sweden
[7]Kiwa Technical Consulting AB, Stockholm, Sweden
[8]Jacobs, Warrington, United Kingdom
[9]European Commission Joint Research Centre, Petten, The Netherlands

E-mail address (corresponding author): PORegan@epri.com

The European Network for Inspection and Qualification (ENIQ) Sub-Area for Inspection Effectiveness (SAE) aims to promote the use of Risk-Informed (RI) methods for In-Service Inspection (ISI) of nuclear power plants (NPPs) and produce associated guidance material and discussion documents.

RI-ISI methodologies have been applied in many countries around the world (e.g. Africa, Asia, Europe, and North America), and have provided improved ISI programmes that both reduce plant risks and radiation exposure to inspection personnel. However, acceptance of RI methods for ISI is still relatively limited in Europe, particularly amongst safety regulators.

This presentation will provide a historical perspective on ISI programmes and give real-life examples of safety improvements achieved via the implementation of risk-informed approaches by NPP operators. Examples of outcomes include physical modifications to the plant, new or updated operating procedures, alterations to deterministic ISI programme scopes, or changes in inspection procedure. Examples of statistics are also presented on the reduction of radiation doses by RI-ISI implementation.

Keywords: ENIQ, RI-ISI, NPP, safety improvements

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Safety improvements through the use of risk-informed technologies

27 June 2023

Acknowledgements

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Robertas Alzbutas	Lithuanian Energy Institute (LEI)	Lithuania
Aranzazu Risquez Bailon	Iberdrola	Spain
Otso Cronvall	Technical Research Centre of Finland (VTT)	Finland
David Duxbury	Rolls Royce	Great Britain
Anders Lejon	Ringhals NPP / Vattenfall	Sweden
Patrick O'Regan	Electric Power Research Institute (EPRI)	United States
Jani Pirinen	Fortum	Finland
Andrey Shipsha	Kiwa Inspecta	Sweden
Karen Stone	Jacobs	Great Britain
Tony Walker	Jacobs	Great Britain
Kaisa Simola	European Commission – Joint Research Centre	European Commission

Premise

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- While deterministic codes and standards provide for an adequate level of plant safety, the nuclear industry goal of continuous improvement requires that existing practices continue to be challenged as to their relevance and effectiveness
- While many aspects of plant design and operation have commonality across the nuclear fleet, all “Risk” is plant –specific and therefore safety improvements opportunities are also plant-specific

What needs to be answered

- How do we currently select locations to be inspected?
- What are we learning from operating experience?
- Is there a more effective way of selecting locations to be inspected?
- What are our current NDE requirements?
- Are there more effective ways of conducting NDE?
- Are there ways to obtain additional safety benefits?
- Are there ways to optimize resources thereby reducing costs and worker exposure?

SUBSECTION IWB
REQUIREMENTS FOR CLASS 1 COMPONENTS OF LIGHT-WATER-COOLED PLANTS

ASME Section XI

Class 1 - also known as reactor coolant pressure boundary

- Reactor coolant pressure boundary means all those pressure-containing components such as pressure vessels, piping, pumps, and valves, which are:
  - (1) Part of the reactor coolant system, or
  - (2) Connected to the reactor coolant system, up to and including any and all of the following:
    - (i) The outermost containment isolation valve in system piping which penetrates primary reactor containment,
    - (ii) The second of two valves normally closed during normal reactor operation in system piping which does not penetrate primary reactor containment,
    - (iii) The reactor coolant system safety and relief valves.

SUBSECTION IWC
REQUIREMENTS FOR CLASS 2 COMPONENTS OF LIGHT-WATER-COOLED PLANTS

ASME Section XI

Class 2 - Systems or portions of systems important to safety that are:

- Designed for:
  - emergency core cooling,
  - post-accident containment heat removal,
  - post- accident fission product removal,
  - reactor shutdown, or
  - residual heat removal.
- Those portions of the steam and feedwater systems of PWRs extending from and including the secondary side of steam generators up to and including the outermost containment isolation valves and connected piping up to and including the first valve (including a safety or relief valve) that is either normally closed or capable of automatic closure during all modes of normal reactor operation.

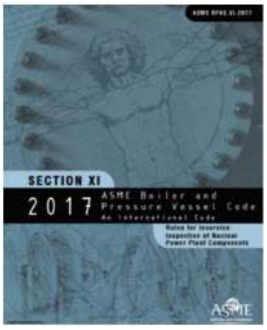
ASME Section XI

SUBSECTION IWD
REQUIREMENTS FOR CLASS 3 COMPONENTS OF LIGHT-WATER-COOLED PLANTS

Class 3 – consists of other pressure vessels, heat exchangers, storage tanks, piping, pumps, and valves that are not Class 1 or 2 and may include:

- Cooling water systems,
- auxiliary feedwater systems
- post- accident containment heat removal,
- post-accident containment atmosphere cleanup,
- residual heat removal from the reactor and from the spent fuel storage pool (including primary and secondary cooling systems).

Determination of Inspection population

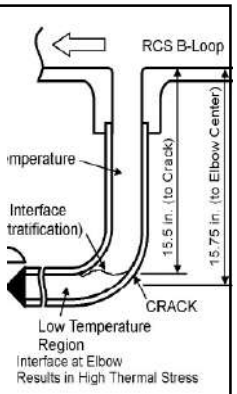


- Examination Category B-F (Class 1)
  - All welds
- Examination Category B-J (Class 1)
  - 25 percent of welds
  - terminal ends and joints where the stress levels exceed either of the following limits:
    - primary plus secondary stress intensity range of 2.4 S_m for ferritic steel and austenitic steel
    - cumulative usage factor U of 0.4
- Examination Category C-F-1 and C-F-2 (Class 2)
  - 7.5 percent of welds
  - terminal ends, dissimilar metal welds, and structural discontinuities

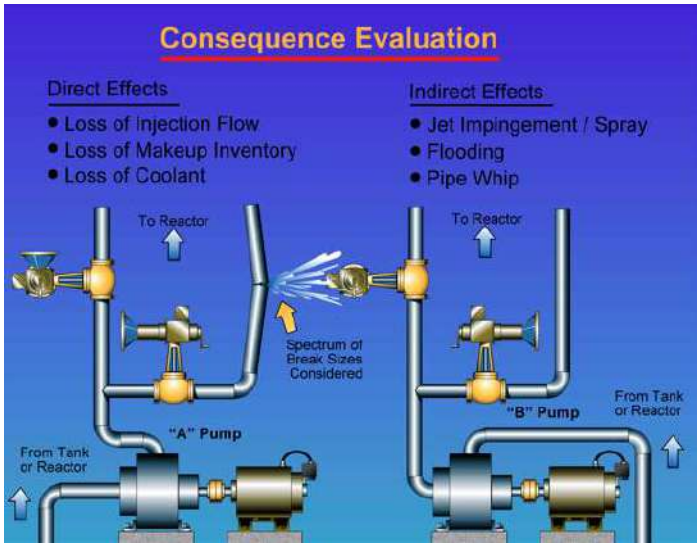
No requirements for inspecting Class 3 or non safety related (balance of plant) piping

Operating Experience is Telling Us

- Inservice failures (cracks, leaks, or breaks) are generally caused by corrosion or fatigue
  - Thermal Fatigue (Thermal Transient & TASCS)
  - Stress Corrosion Cracking (IGSCC, TGSCC, PWSCC, ECSCC)
  - Localized Corrosion (MIC, Pitting, Crevice Corrosion.)
  - Flow Sensitive Attack (FAC, Erosion/Cavitation)
  - High Cycle Mechanical Vibration Fatigue
- Failures do not correlate with stress or fatigue usage factor values contained in Design Stress Reports
- Failures do not always occur in welds



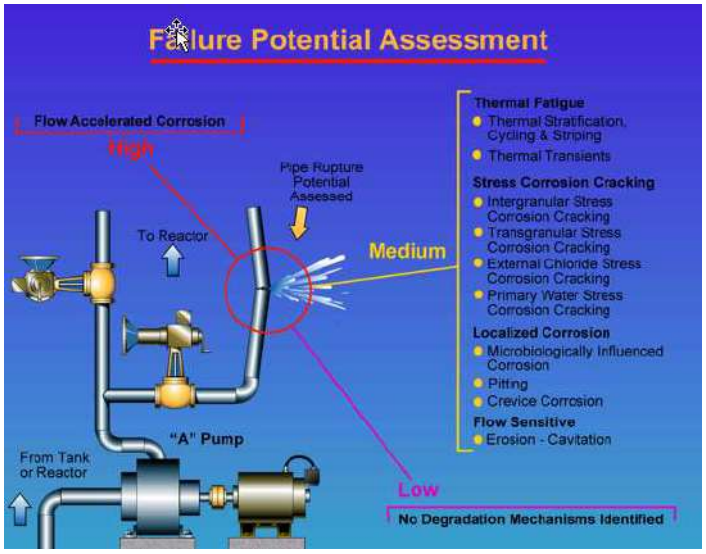
What if we explicitly looked at Consequence of Failure?



System	Class	CCDP	Rank
Reactor Coolant	1	2.90E-03	High
Reactor Coolant	1	3.50E-06	Medium
Reactor Coolant	1	2.50E-07	Low
Steam	2	4.40E-05	Medium
Steam	2	4.40E-07	Low
Component Cooling	3	1.60E-03	High
Component Cooling	3	5.10E-07	Low
Service Water	3	2.70E-03	High
Service Water	3	2.30E-08	Low
Fire Protection	4	7.20E-04	High
Fire Protection	4	9.10E-08	Low

CCDP – conditional core damage probability

What if we explicitly looked at Failure Potential?



System	Class	DMs	Rank
Reactor Coolant	1	TF	Medium
Reactor Coolant	1	SCC	Medium
Reactor Coolant	1	None	Low
Steam	2	None	Low
Steam	2	None	Low
Component Cooling	3	SCC	Medium
Component Cooling	3	None	Low
Service Water	3	LC	Medium
Service Water	3	LC	Medium
Fire Protection	4	LC	Medium
Fire Protection	4	None	Low

Flow accelerated Corrosion – augmented program

Risk Ranking (RI-ISI)

LOW (Cat. 7)	MEDIUM (Cat. 5)	HIGH (Cat. 3)	HIGH (Cat. 1)
LOW (Cat. 7)	LOW (Cat. 6)	MEDIUM (Cat. 5)	HIGH (Cat. 2)
LOW (Cat. 7)	LOW (Cat. 7)	LOW (Cat. 6)	MEDIUM (Cat. 4)

System	Class	RC	Rank
Reactor Coolant	1	2	High
Reactor Coolant	1	5	Medium
Reactor Coolant	1	7	Low
Steam	2	6	Low
Steam	2	7	Low
Component Cooling	3	2	High
Component Cooling	3	7	Low
Service Water	3	2	High
Service Water	3	6	Low
Fire Protection	4	2	High
Fire Protection	4	7	Low

Traditional ISI - Boundaries

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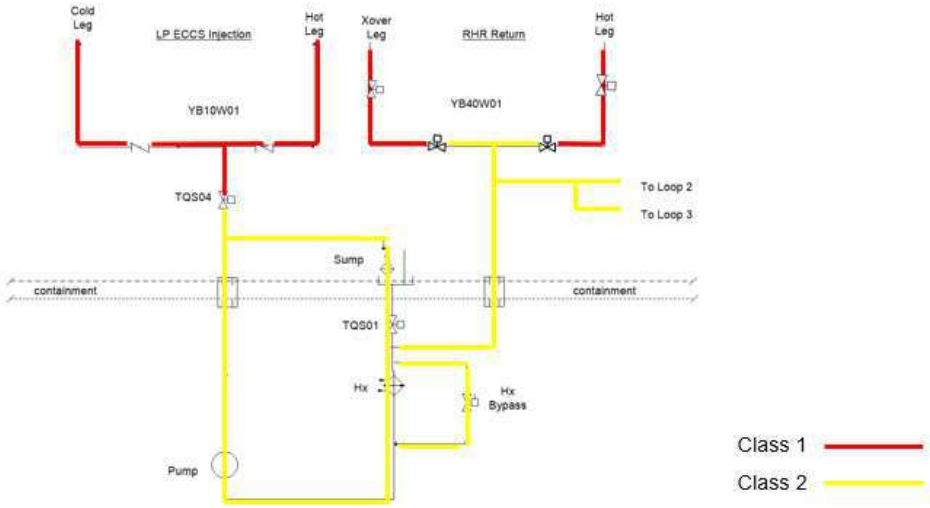

More Effective ISI Boundaries

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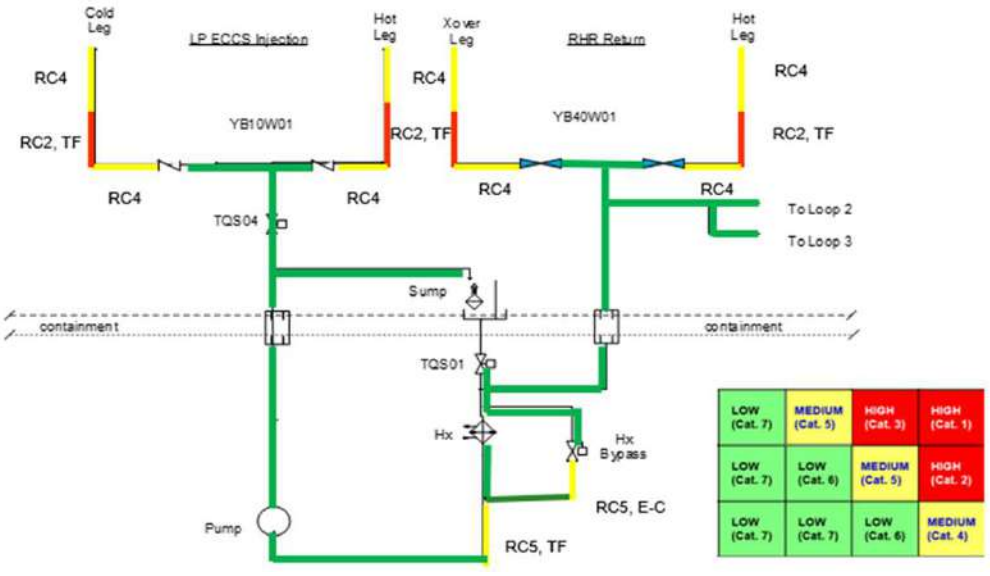
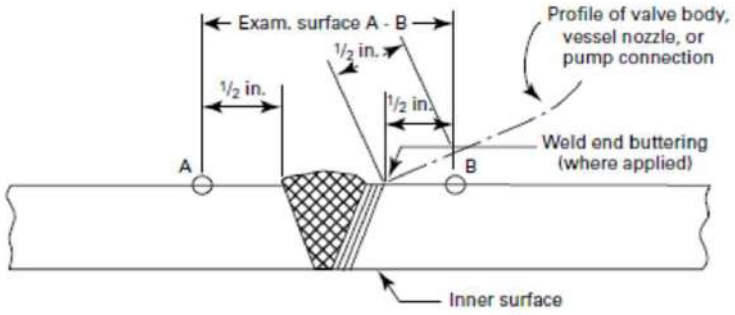


Safety Improvements

- Selecting safety significant locations to inspect (previous slides)
- More informed inspections / techniques / volumes
- Physical changes to the plant
- Worker exposure and radwaste
- Outage management
- Personnel Safety

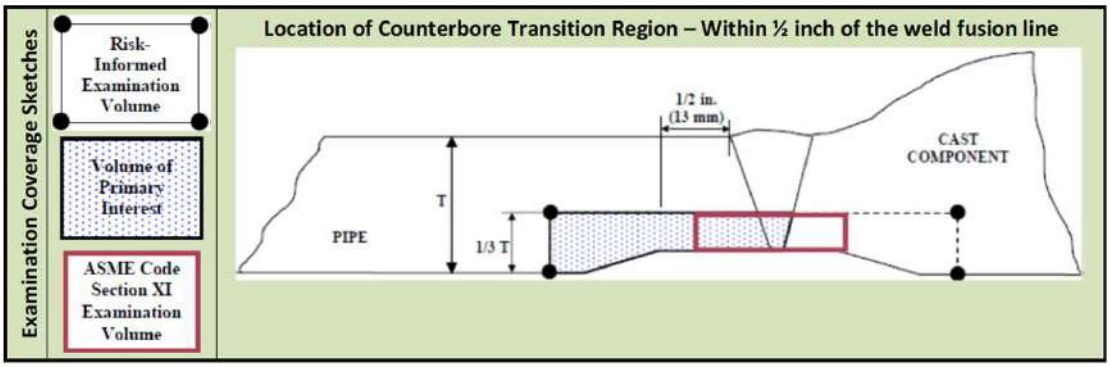
Current NDE Requirements



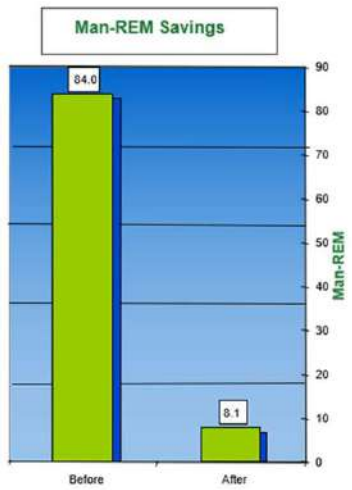
(b) Less Than NPS 4 (DN 100)

Operating experience is telling us that cracking usually occurs at the inside diameter

Inspection for Cause



Reduce Worker exposure



Element Selection Process Considerations

Factors Considered in Element Selection Process	Selection Plus	Selection Negative
Plant Service History	Poor	Good
Severity of Damage Mechanisms	High	Low
Element Configuration / Accessibility	Good	Poor
Radiation Exposure	Low	High
Stress Concentration	High	Low
Physical Access	Readily	Difficult

Voluntary Safety Improvements

Hardware changes - Fire protection piping removed from a plant area with important equipment

Updated operating procedures to better allow flood detection and isolation

New NDE on previously uninspected piping (e.g. non safety-related)

Safety Improvements (1 of 3)

Unit	Issue	Action
1	Interfacing system LOCA exceeded metrics	More refined / realistic analyses
2	Interfacing system LOCA exceeded metrics	More refined / realistic analyses
3	Failure of a fire protection line in the Auxiliary Building which was postulated to flood the Electrical Switchgear Cable Enclosure, Battery Room and Battery Charger	Plant hardware modification (piping removed from area)
	Failures of the circulating water system in the Condenser Pit (CDF contribution of 3.75E-06).	Operating Procedure update to better define human error probabilities (HEPs)
4	Failure of a fire protection line in the Auxiliary Building which was postulated to flood the Electrical Switchgear Cable Enclosure, Battery Room and Battery Charger	Plant hardware modification (piping removed from area)
	Failures of the circulating water system in the Condenser Pit (CDF contribution of 3.75E-06).	Operating Procedure update to better define HEPs
5	Fire protection piping in auxiliary building	Supplementary visual inspection of the associated fire protection piping is required every quarter and 6 UT (thickness) exams per interval.

Safety Improvements (2 of 3)

Unit	Issue	Action
6	Fire protection piping in auxiliary building	Supplementary visual inspection of the associated fire protection piping is required every quarter and 6 UT (thickness) exams per interval.
7	Plant service water exceeded LERF criterion	More refined / realistic analyses
8	Service Water piping in the 480V switchgear room	Five new inspections added looking for wall loss
9	Class 3 nuclear service water in auxiliary feedwater pump room impacting mechanical / electrical equipment	New NDE selected
10	Class 3 nuclear service water in auxiliary feedwater pump room impacting mechanical / electrical equipment	New NDE selected
11	Flooding caused by fire protection piping in the East DC switchgear room	3 of 10 mechanical connections selected for inspection
12	Service Water in Cable Spreading Room – loss of electrical equipment	New NDE selected

Safety Improvements (3 of 3)

Unit	Issue	Action
13	Service Water in Cable Spreading Room – loss of electrical equipment	New NDE selected
14	Service Water in Auxiliary building exceeded metrics	Updated analysis to allow credit for operator action in response to the postulated flood scenario
	Service Water in Control Building exceeded metrics	Updated analysis to allow credit for operator action in response to the postulated flood scenario
15	Failure of fire protection in the control building (3 separate locations) can cause loss of ESWG Rooms and CSR	Hardware (i.e. flow limiting orifice) and procedure modification
16	This remaining scenario involves a flood originating in the turbine building zone designated TGB. The area is located at elevation 46 feet, essentially plant grade.	More refined / realistic analyses
17	High Pressure Firewater in Auxiliary building exceeded metrics	New NDE and/or removal of piping
	Raw Cooling Water in Auxiliary Building exceeded metrics	New NDE and/or removal of piping
18	Failure of expansion bellows can cause loss of ESWG Rooms	Hardware and NDE being investigated

Concluding Thoughts

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- While a number of safety improvements can be generically developed (e.g. inspection for cause), given that "Risk" is plant specific;
  - many safety improvement will also be plant specific
- Given the improvements in workers exposure, inspection effectiveness and efficiencies;
  - what is the safety case for not implementing RI-ISI
  - what is the business case for not implementing RI-ISI

ENIQ REPORT

Safety Benefits of Risk-Informed In-Service Inspection

ENIQ Position Paper

NUGENIA Association
c/o EDF, Avenue des Arts 53, 1000 Bruxelles, BELGIUM
Email: secretariat@nugenia.org
Website: http://www.nugenia.org

Thank you!

SNETP
Sustainable Nuclear Energy Technology Platform

Technical Basis for Nondestructive Examination Experience Requirements for ASME Section XI, Appendix VII

Ronnie Swain[1], Myles Dunlap[2]

[1]EPRI, Charlotte North Carolina, United States of America
[2]EPRI, Charlotte North Carolina, United States of America

E-mail address: rswain@epri.com

Abstract:

Ultrasonic testing (UT) personnel working in commercial nuclear power plants in the United States and other countries that adhere to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code are certified based on the qualification requirements set by ASME Section XI, Appendix VII. In the United States, these requirements are further conditioned by the Nuclear Regulatory Commission through the Code of Federal Regulations (10 CFR 50.55a). The requirements in these codes and regulations specify the minimum number of hours of training and experience, and written examinations, for each level of UT personnel. The objective of this work was to develop and establish the technical basis specifically for the required experience for qualification of nuclear UT personnel. The technical basis in this document can be used to amend the currently prescribed criteria in ASME Section XI, Appendix VII.

Keywords:

ASME
Nondestructive Examination
Experience
Certification
Ultrasonic Testing

Technical Basis for Nondestructive Examination Experience Requirements

ASME Section XI, Appendix VII

Ronnie Swain, EPRI
Sr. Program Manager, Plant Support / NDE Program

Carl Latiolais, EPRI
Sr. Program Manager, Plant Support / NDE Program

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June 26 – 29, 2023

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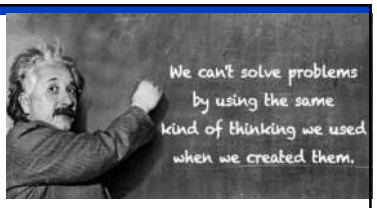
Status Quo and Problem Statement



- Section XI of the ASME Boiler & Pressure Vessel Code governs nuclear inservice inspection in many countries worldwide
  - Appendix VII has experience requirements for Ultrasonic technicians
- Present experience requirements had become onerous
  - Shorter outages and Risk-Informed ISI programs reduced examinations
    - Resulting in experience requirements becoming a hardship
- Experience is defined as “the practice of skill activities”
  - There’s a defined list of skills in the code and its supporting documents
  - Human factor literature and rulemaking support lab time for obtaining experience
- There was an impetus for developing a technical basis on experience hours and exploring how Appendix VII might be modified

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Summary of Approach

- EPRI formed a focus group of industry subject matter experts from five utilities, four ISI vendors, and EPRI
  - 12 Level IIIs; 11 Section XI NDE committee members; Several Principal Level IIIs
- Thoroughly reviewed the current Code requirements and supporting documents
- Identified Section XI UT skills and knowledge that constitute qualification
  - Starting with the ASME ANDE Job Task Analysis for UT and included additional inputs from the focus group
- Developed essays on each skill or knowledge area, describing what is needed to obtain proficiency
  - What goes into each activity, what is important, and what are the variables?
  - How long does one evolution of each activity take to complete?
  - How many performances of each activity can be reasonably expected to establish proficiency for that skillset?
- Summed the experience hours for each skill and knowledge area to establish the hours needed
- Identified environments appropriate for obtaining experience for each item
  - Field (examinations in the plant)
  - Lab exercises (including use of simulators)
  - Vocational (office, conferences, code meetings)

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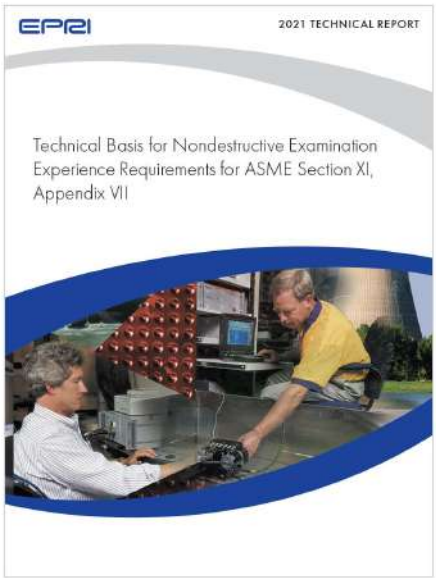
Publicly Available EPRI Report

- Available for free at EPRI.com
- **Title:** *Technical Basis for Nondestructive Examination Experience Requirements for ASME Section XI, Appendix VII*
- **Product ID Number:** 3002018615



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Analysis of Appendix VII and Associated Requirements

- The report contains an assessment of Code rules to determine the requirements based on its current wording
  - IWA-2300 and Appendix VII (2017 Edition)
  - ASNT/ANSI CP-189-2006
  - ACCP-CP-1 Rev. 8
  - Walks the reader through the documents, shows how experience is accredited and what skills and knowledge are specified for UT personnel
  - This analysis enabled the identification of points that might need revision based on findings of this study

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Technical Basis for Experience Hours

- Discusses representative skills and knowledge needed for qualification along with the experience hours needed to attain proficiency in each area
  - The study resulted in a basis for the following experience hour numbers
    - Minimum of 542 hours for initial certification to UT Level II
    - Minimum of 1246 hours for initial certification to UT Level III
  - Values were derived through technical essays provided in Appendix A of the report
- In addition to the technical basis for experience hours, the report provides
  - A comparison of the recommended experience levels with the historical requirements
  - Discussion on exceptions to the selected experience parameters
  - Justification for removing the educational background options for Level III
  - Basis for minimum durations spent at certification levels, to help ensure knowledge retention
  - Discussion on alternative environments and technologies available for obtaining experience
  - Important considerations for the decision to advance an individual's certification level

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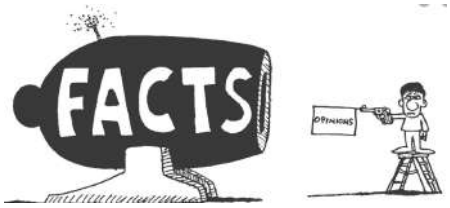
Conclusions

- The Code aims to ensure a sufficiently skillful and knowledgeable UT workforce
- This project reviewed the training requirements, finding no issues
- Explored the skills and knowledge needed and the time to obtain proficiency, calculated a basis for experience hours
- We show that the educational options for Level IIIs does not appear defensible
- We argue that a minimum time-at-position component should be added to the experience hour levels for optimum knowledge retention purposes
- We show that a percentage of experience can and should come from the lab
- We point out that training and experience are not the only important criteria for advancing a technician to the next certification level



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Code Case N-930

- As of December of 2022, Code Case N-930 was approved to:
  1. Remove educational background options for Level III
  2. Modify Level II hours to 600 and Level III hours to 1300
     - 25% reduction for Lv II; 70% - 85% reduction for Lv III
  3. Add a lab option for obtaining a percentage of experience hours
  4. Add minimum time-in-position requirements
     - At least one calendar year at Level I before eligibility for certification to Level II
     - At least two calendar years at Level II before eligible for certification to Level III
- EPRI Report provided the technical basis for the action

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EPRI

Weld Acceptance via Ultrasonic Inspection (in Lieu of Radiography): Application to Nuclear Components

Dr David Duxbury[1], David Whitehead[1], Andrew Wood[1]

[1]Rolls-Royce, United Kingdom

Abstract text (1/2 – 1 A4 page)
This paper reports the development of requirements for the acceptance of welds in nuclear plant via ultrasonic examination. Such inspections are deployed in lieu of the radiographic examination required by the ASME Boiler and Pressure Vessel Code Section III. Requirements are presented which are based on ASME code case N-659 plus additional targeted enhancements for the ultrasonic inspection procedure as well as performance demonstration. Enhancements are informed by positions reported by the United States Nuclear Regulatory Commission and the United Kingdom Health and Safety Executive. An alternative route for the demonstration of ultrasonic inspection effectiveness is also proposed based on a capability statement.

Experiences from pilot application of the requirements discussed are presented for inspections applied to welds in a thick section pressure vessel manufactured from low carbon steel and smallbore pipework welds in austenitic stainless steel.

Keywords: Welds, acceptance criteria, design code, ultrasonic examination, radiographic examination.

Weld Acceptance via Ultrasonic Inspection (in Lieu of Radiography)

Application to Nuclear Components

NDE in Nuclear 2023, Sheffield

David Duxbury, Dave Whitehead, Andrew Wood

Introduction

- The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section III requirements for construction of nuclear facility components requires the use of radiography (RT) to meet the requirement for volumetric inspection
- Code Cases have existed for several years to permit the use of ultrasonic inspection (UT) in lieu of RT, principally code case N-659
- This paper reports Rolls-Royce experience from the application of UT in lieu of RT on pressure boundary welds within a Pressurised Water Reactor (PWR):
  - Low alloy steel pressure vessel shell structural welds
  - NPS 50 mm (2”) pipework welds in austenitic stainless steel

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Agenda

01 Regulator Views

02 Principles & Requirements Adopted

03 Summary of Pilot Study Experiences

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Regulator Views

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Regulator Views

Commissioned Studies on UT vs RT

- Several regulator commissioned and endorsed studies exist, for example see:
  - US NRC instructed trials, NUREG/CR-7204, 2015.
  - UK Health and Safety Executive, Report 301, 2005 (ISBN 0-7176-2947-3)..
- Key findings:
  - In general ultrasonic inspection is better suited for the rejection of structurally significant weld defects.
  - But good UT procedure design is important

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Example

Note:
- RT interpretation was independent and blind, based on X-ray sources
- RT capability likely to degrade for T> 50mm

Example from NUREG/CR-7204
Based on back-to-back trials on test pieces containing 150 flaws in 19-56 mm thick carbon steel welds

Flaw Type	Missed by RT	Missed by UT
Planar	**70 %**	2 %
Volumetric	16 %	**64 %**

Of which only one flaw was rejectable to ASME III criteria

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Regulator Views

Note: N-659 Performance Demonstration Requirements:

- Two planar surface flaws
- One planar embedded flaw

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US & UK Regulator Views

- Code case N-659 requires UT procedure demonstration via practical trials
  - Similar principle to ASME XI Appendix VIII Performance Demonstration
  - Requirements are **far** less onerous
- N-659 requirements are limited and the code case has not be accepted for uncontrolled use by the US Nuclear Regulatory Commission

> *'**Additional performance demonstrations are needed** to address acceptance criteria for procedures, personnel, and the UT equipment'.*

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- Similar conclusions drawn for non-nuclear applications by the UK Health and Safety Executive* Based on ASME Section I & VIII code case 2235 – requirements are almost identical to N-659

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- Similar conclusions drawn for non-nuclear applications by the UK Health and Safety Executive* Based on ASME Section I & VIII code case 2235 – requirements are almost identical to N-659
- Therefore Rolls-Royce concluded that requirements beyond code case N-659 are needed to ensure UT inspections achieve the required levels of capability

*UK Health and Safety Executive, Report 301, 2005 (ISBN 0-7176-2947-3).

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Principles & Requirements Adopted

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Principles & Requirements Adopted

Principles Adopted for UT in Lieu of RT

The requirements invoked for UT (procedure & performance demonstration) should be consistent with the role of radiograph

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Principles & Requirements Adopted

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Quality Control

- Feedback to the welding process – '**ensure process stability**'
- Ensure the weld enters service as defect-free as practicable
- Typically use workmanship-based acceptance criteria

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Rejection of Credible Defects of Structural Significance

- NDE is used as a screening tool to reject defects which could lead to component failure
- High level of reliability required (eg inspection qualification)
- Within the UK, reserved for components with a **high consequence of failure** & applied **in addition quality control**

Increasing cost in resources and times

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Principles & Requirements Adopted

Principles Adopted for UT in Lieu of RT

The requirements invoked for UT (procedure & performance demonstration) should be consistent with the role of radiograph

Alignment of ASME III radiograph requirements

- No demonstration of inspection capability
- Known limitation of inspection capability and reliability for thick sectioned welds

Quality Control

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Principles & Requirements Adopted

Principles Adopted for UT in Lieu of RT

- Volumetric flaws are not typically structurally significant and therefore application of a well designed UT inspection applying workmanship based acceptance criteria is appropriate for the rejection of volumetric weld defects. For example:
  - Procedural requirements - BS EN ISO 17640
  - Acceptance standard - ASME NB-5330 & BS EN ISO 11666
- **Planar weld flaws are of greater engineering concern and therefore warrant a greater focus**

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Principles & Requirements Adopted

Weld Roots

- Code case N-659 contains no requirements for weld roots with restricted access for visual inspection
  - Eg pipework welds, vessel closure welds.
- The capability of UT for the detection of weld root geometry defects requires consideration.
- Confidence is needed that significant weld process failures have not occurred (eg root concavity, excess penetration)
  - Such defects are often readily detectable with RT

Gross examples for manual welds

Excess penetration

Gross concavity due to unfilled root burn-through

Local excessive penetration due to burn-through

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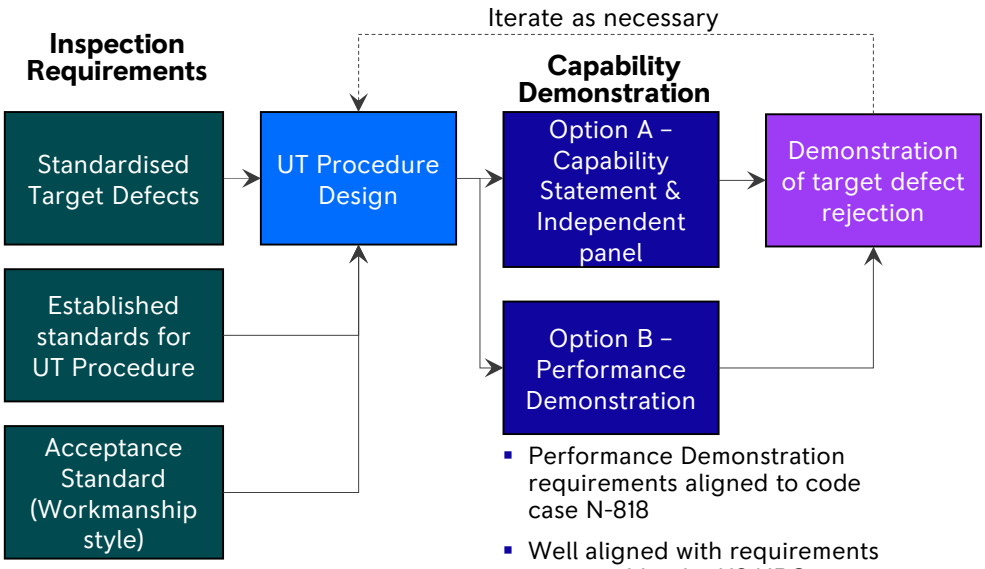
Principles & Requirements Adopted

Overview of Requirements Adopted



Aligned to ASME V & ISO 17640

Based on ASME NB-5330 & enhanced to align with ISO 11666 as far as practical

- Performance Demonstration requirements aligned to code case N-818
- Well aligned with requirements accepted by the US NRC

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Principles & Requirements Adopted

Standardised Target Defects

- A selection of standardised target defects have been selected based on structural significance and likelihood of occurrence.
- Definitions have been developed with welding specialists
- This approach has been adopted to:
  - Avoid the need for expert elicitation for each and every weld - disproportionate for a manufacturing quality inspection?
  - Target UT procedure design at the defects of engineering significance

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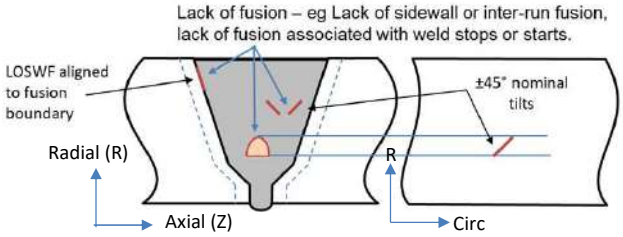
Principles & Requirements Adopted

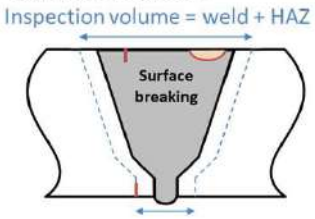
Other examples include:

- **Lack of root fusion**
- **Lack of root penetration etc**

Lack of Fusion Defects

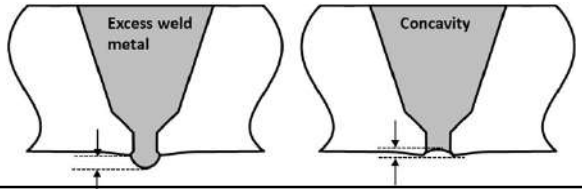


Surface Defects



Root Geometry Defects - if 100% visual can't be achieved

Note: Lack of root penetration also included if relevant



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Pilot Studies

Pilot Studies

Pressure Vessel Pilot Study

- Heavy Pressure Vessel Structural Welds, T = approx. 50-90 mm
- Capability Statement Route

Pipework Pilot Study

- NPS 50 mm pipework, approx. 5-8 mm thick
- Austenitic Stainless Steel
- Performance Demonstration Route

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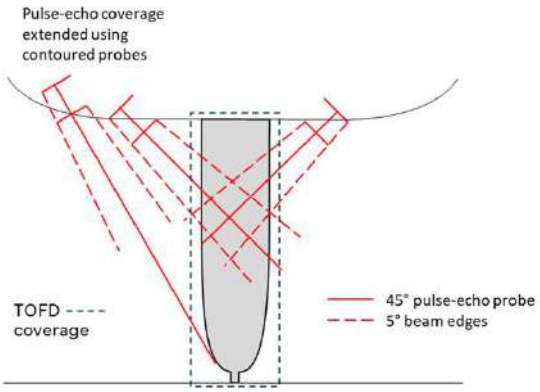
Pilot Study 1

Pressure Vessel Pilot Study

- Low carbon steel narrow gap (<2°) mechanised TIG welds
- 'As-welded' roots included in group
- Minimum Planar Target Defect Size = 2-3 x 19 mm
- Inspection based on automated Time-of-Flight-Diffraction (TOFD) and Pulse-echo Phased Array
  - TOFD used for detection of lack of side-wall fusion defects and to aid indication characterisation
  - Tandem scans applied where possible to aid indication characterisation

Example of pulse-echo coverage limitations



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Pilot Study 1

Pressure Vessel Pilot Study

- Test piece trials and capability statement used to demonstrate capability against target defects
- TOFD show to be highly effective for lack-of-fusion and weld root geometry defects
- Experience has shown that the acceptance standard must clearly define how TOFD and pulse-echo indications are sentenced considering all the data

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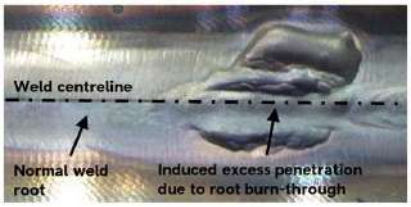
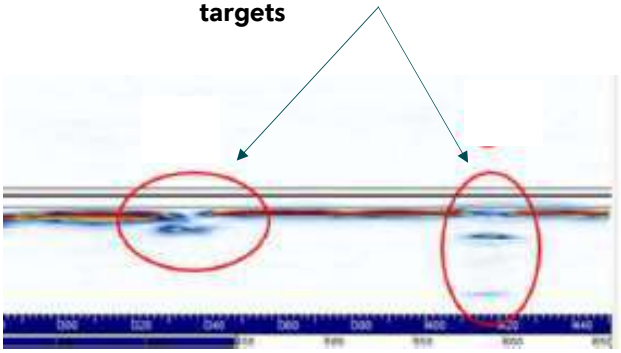
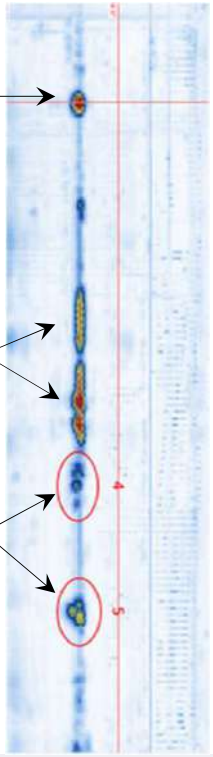


Example phased array response from burn-through/excess pen targets





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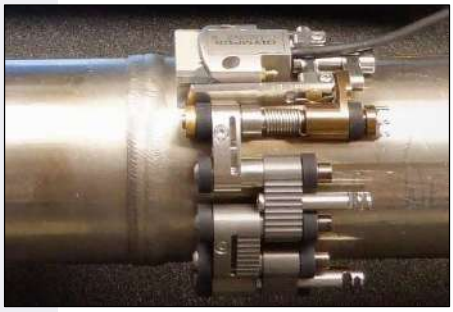
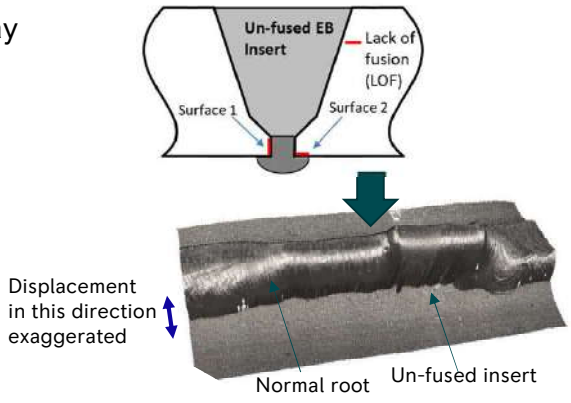
Pilot Study 2

Pipework Pilot Study

- NPS 50 mm pipework, approx. 5-8 mm thick
- Positional Welds
- Austenitic Stainless Steel
- Mechanised J-prep welds with ‘as-welded’ roots with weld root insert
- Dressed weld crown
- Encoded TRL phased array





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Pilot Study 2

Typical variation in weld root geometry in positional welds

Horizontal and inclined fixed pipe (5G and 6G)

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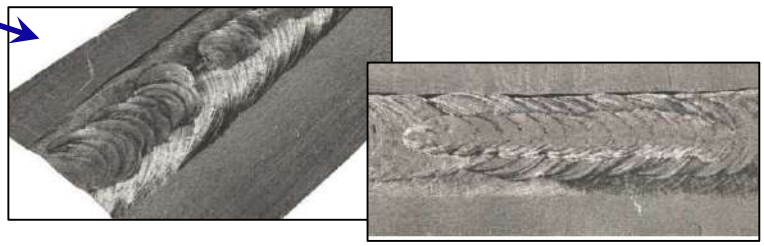
Pipework Pilot Study

- Minimum Planar Target Defect Size = 1.2 x 6 mm
- Performance demonstration test piece set (10-20) produced containing a range of flaws, both inside and outside of the acceptance standard.

Principle findings:

- UT capability found to be very good
- High false call rates on weld root defects
- Differentiation between variations in root geometry (positional welds) and root defects requires reference material (eg handbooks) to aid data interpretation



Summary

- Requirements and a process have been developed for the use of ultrasonic inspection for weld acceptance, in lieu of radiography
- Requirements are aligned to ASME code case N-659 and have been enhanced in several areas
- Requirements have been trialled on heavy pressure vessels and pipework welds
  - Application on pressure vessels has been agreed with the licensee
  - Trials on pipework are still in progress

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Recognition of contributions on pilot studies:

- **Vessels – Jez Hodgkins & Tim Stubbs**
- **Pipework – Andy Bishop, Lee Armstrong, Luke Urquhart**

In-Service Inspection & Repair strategy for *new*cleo Lead-cooled Fast Reactor

Andrea Barbensi[1], Jean-Sébastien Genot[2], Mariano Tarantino[3]

[1]*new*cleo Srl, Turin, Italy
[2]*new*cleo SA, Lyon, France
[3]Enea, Bologna, Italy

E-mail address (Andrea Barbensi): andrea.barbensi@newcleo.com

*new*cleo is designing and building the next generation of nuclear lead-cooled fast reactors (LFRs) fuelled with MOX. They will provide effective, sustainable, safe and competitive energy. A Small Modular Reactor of 30 MWe will be commissioned in 2030 (the Demonstrator) and a First-Of-Kind 200 MWe a few years later. The 30MWe can swiftly meet the commercial demand for small electric generating units. The 200MWe can be a competitive solution for central station power plants. This ambitious project is led by a team of high skilled engineers standing for more than 300 years of experience in design, erection, and operations.
Inclusion of ISI&R (In Service Inspection and Repair) at the earliest stages of designs is a necessity to achieve a sufficient level of maturity and confidence in the technologies, and to increase safety, availability, and preservation of investments of experimental devices and reactors during their whole life.
To this end, *new*cleo develops an incremental strategy, starting first with the consolidation of mature and promising technologies with its own R&D laboratories and collaborations with major nuclear companies as well as universities and international laboratories and institutes with high expertise in inspection and robotics.
This step aims to demonstrate their applicability to a full mockup of the reactor (the Precursor) available in 2026 for experiments. All levels of maintenance will be addressed, from continuous monitoring (N1) to repair (N4). For gaps identified, complementary R&D will be made and eventually deployed on the 30 MWe, and on the 200 MWe later on. Extrapolability from one reactor to another is a cornerstone of the project, and it is delt with from the beginning.
It is no secret ISI&R of LFRs faces big and new challenges, to name a few: high shutdown temperature of 400°C due to the risk of the lead freezing (requiring inspections to be performed at high temperature), opacity of lead that prevents inspection by visual means, high density making inspection instruments hard to insert, conductivity potentially impairing the read-outs of eddy currents techniques, low difference in density between lead and steel, decreasing the sensitivity of ultrasonic inspection methods, oxide layer (necessary to limit the corrosion risk) or coatings, potentially disrupting the contact between the coolant and the system walls and impairing ultrasound transmission quality, low wetting capability of lead on oxidized or coated steels . at above 380°C… All techniques will be employed and adapted to these conditions, in particular ultrasonic and electromagnetic transducers, optical systems (cameras, fibers…), thermocouples, gauges, core specific systems, and electro-mechanical systems supporting these devices.
*new*cleo is putting emphasis on the monitoring of all critical structures, promising advances for steam generators, vessels and in-vessel inspections, robotics, digital twin approaches coupled to measured data for predictions, and easy and safe operations during the whole lifetime of the reactor.

Keywords: In-service inspection, Repair, Inspectability by design, lead-cooled fast reactors

In-Service Inspection & Repair strategy for newcleo Lead-cooled Fast Reactor

27 June 2023, Sheffield, UK

Andrea BARBENSI[1], Jean-Sébastien GENOT[2], Simone NARDI[1], Mariano TARANTINO[3]

1 newcleo srl; Turin, Italy; e-mail: andrea.barbensi@newcleo.com , simone.nardi@newcleo.com

2 newcleo sa; Lyon, France; e-mail: jean-sebastien.genot@newcleo.com

3 ENEA, C.R. Brasimone; Bologna, Italy; E-mail: mariano.tarantino@enea.it

newcleo

A new, disruptive player in nuclear energy!

- *new*cleo is building a **new competitive industrial standard in nuclear energy**, rapidly and efficiently addressing the major current concerns of our industry: **waste, safety and cost**

- *new*cleo's approach is based on existing, accessible technologies and the best choices in terms of **safety and sustainability**:
  - the use of **liquid lead** as a coolant is the key element of *new*cleo's innovation. It is based on long-term international research, resulting in the ownership of a **significant number of relevant patents** in the field
  - *new*cleo **uses as fuel the radioactive waste** produced by the current nuclear industry, **eliminating** the **need to mine uranium** for hundreds of years and significantly reducing the global nuclear waste problem

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A new, disruptive player in nuclear energy!

- *newcleo* in facts
  - *300 employees in 2023, 500 in 2024*
  - *3 offices: Italy, UK, France*
  - *High Expertise of its Management Teams*
  - *Collaborations with major partners and Research Centers*
  - *Fund raising of more than 1 billion Euros*

Stefano Buono
Chief Executive Officer

Luciano Cinotti
Chief Scientific Officer

Elisabeth Rizzotti
Chief Operating Officer / MD Italy

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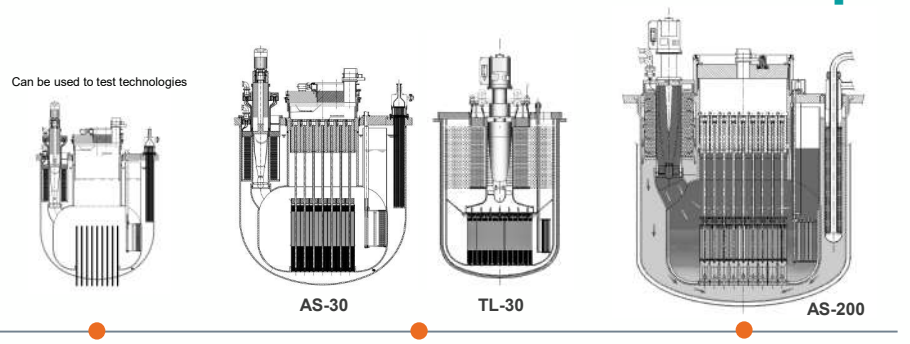
*new*cleo's LFR-SMRs – Reactor development goals



5 years | 7/10 years | 10/12 years

Precursor

Electrically heated facility **10MWth**, with turbogenerator.

It reproduces scaled or full-scale components of the Mini LFR

Mini LFR-SMR (30 MWe)

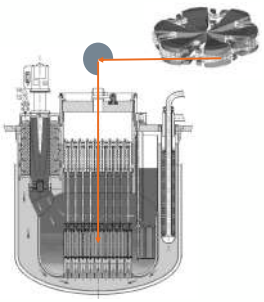
Power: **30 MWe**
Core outlet T: 430/440°, later 530°
Fuel: MOX

***new*cleo's present activity is focused on LFR-AS-30**

Small LFR-SMR (200 MWe)

Power: **200 MWe**
Fuel: MOX + MA

Terrestrial plant to burn existing nuclear waste



Long term

ADS LFR-SMR

Power: TBD
Fuel: MOX + MA, U free fuels, Thorium

The future Accelerator-Driven reactor

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Precursor realised in partnership with ENEA in Italy

- Agreement signed in March 2022, partnership to build the **first non-nuclear prototype of a lead cooled Generation IV reactor in the world**
- ENEA brings unique global know-how in the field of liquid lead
- Team of 30 *new*cleo engineers, working permanently for about 10 years at the Brasimone Centre (between Bologna and Florence)

***new*cleo Brasimone site**

H: main hall, E: electricity buildings, C: chemistry lab, O: offices

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ENEA Partnership – Brasimone activities

The forecasted investment sums up to **EUR50+ millions in a 10-year period**, with **25 to 30 engineers** on site.

Main non-nuclear facilities

Existing equipment	Using **NACIE-UP** in early 2023 for our Lead Heat Transfer (LHT) section reproducing *new*cleo steam generator conditions, soon starting on **HELENA** Using **CIRCE-UP** in early 2024 for our Spiral Tubes Steam Generator (STSG) section reproducing *new*cleo steam generator tube rupture conditions event
COR-E	**Loop-type** facility to develop in 2023, with a forecasted **100 kW** power, dedicated exclusively to corrosion-erosion investigation
OTHELLO	**Loop-type** molten lead test facility to develop in 2024, forecasted power of **1.5 MW**, dedicated to topic like chemistry control and purification, thermohydraulic performance of core and primary system components, etc
Precursor	A **pool-type** integral test facility reproducing the LFR-AS-30 at a reduced scale, powered by electrical heaters up to **10 MW**, to be operational in 2026

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ISI&R

Methodology

- The inspection is the cornerstone of the safe exploitation of the reactor
- Safety Authorities require an adequate strategy from operators
- From Design…

§ 4.2.5.2 The Equipments that are Important for the Protection (of the environment) must be designed in such a way as to allow their maintenance and monitoring in operation (in-service inspection, periodic tests) to ensure:

- *The integrity of their components and their tightness, in particular when they are designed to confine radioactive fluid;*
- *The availability and performance of system components, including, if necessary, when the reactor is in power operation;*
- *Maintaining the required performance of the systems for all the events of the reference design domain and extended design domain.*

Methodology

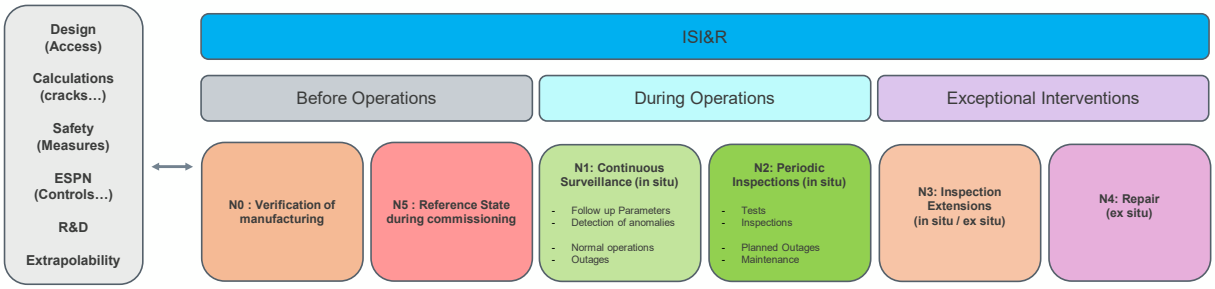
- … to manufacturing and maintenance

5.2.1.2 Arrangements shall be made to ensure, for the duration of operation of the installation, integrity of CPP and CSP equipment. These provisions must cover both:

- *The quality of the design and the associated verification*
- *Manufacturing quality and associated controls*
- *Compliance with the conditions for which the equipment was designed and manufactured*
- *Carrying out maintenance and monitoring operations, periodic inspections and repairs necessary to maintain their level of safety. These provisions aim to prevent the appearance of failure modes of the equipment and, if necessary, detect damage in time.*

Methodology

- *newcleo* identifies 6 *interdependent* levels, with a specific strategy for each
- It interfaces with all reactor activities



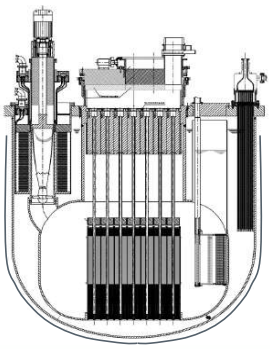
newcleo approach

- Identify for each level of inspection most promising technologies.
- Tests these technologies on the Precursor to reach TRL 6 in 2025.
- For N1 levels (continuous monitoring), give priority to external and indirect ways of inspection.

TRL	Maturity
1	Basic principles are observed *(Observation du principe de base)*
2	The technology concept is formulated *(Formulation du concept technologique)*
3	The experimental proof-of-concept is made *(Preuve expérimentale du concept)*
4	The key-functions of the concept are validated at lab-scale *(Validation des fonctions clés du concept en laboratoire)*
5	The technology is validated in a relevant (not fully representative) environment *(Validation de la technologie en environnement représentatif)*
6	The technology/the component is validated in simulated real-case-like environment *(Démonstration dans un environnement réel simulé)*
7	The technology/the component is validated in an operational environment (mock-up) *(Démonstration dans un environnement opérationnel)*
8	The total system is successfully used in an operational environment (prototype) *(Qualification du système complet dans un environnement opérationnel)*
9	The total system is successfully used in real conditions (project operations) *(Validation du système dans un environnement réel)*

High TRL instrumentation

- Can be implemented in less than 3 years



AS-30

Technology	Application	Interest	How	ISI&R Level	Limits	Challenges
Thermocouples	Core, Lead, many others	Monitor min/max temperatures	Mineral Cables, specific mounting	N1	Up to 1200°C (type K)	Response time (thermowell) Robustness / Corrosion Accesses
RTD (Resistance Temperature Detector)	Lead, many others (pipes…)	Monitor min/max temperatures	Mineral Cables, specific mounting	N1	650°C to 800°C	Robustness / corrosion
Pressure gauge (piezo-resistive)	Steam Generator Gas cover	Confinement	Specific mounting	N1	400°C 150 bar	Temperature Dynamics
Level meters (continuous and discrete)	Vessels	Free level variations and fatigue	Specific mounting	N1	450°C 400 bar	Temperature Robustness / Reliability (discrete) Space
Strain gauges in Lead and Air/Argon	Components and vessels	Yield Vibrations (low freq.)	Mineral Cables, guide thimbles…	N1	Up to 800°C	Corrosion Robustness
Accelerometers (passive)	Components and vessels	Vibrations (pump, SG…)	Specific mounting	N1	Up to 700°C	Temperature Noise/Signal Ratio Lead
Standard Flowmeters	Water systems	Flow rates in water	In pipes… not intrusive	N1	400°C	Space

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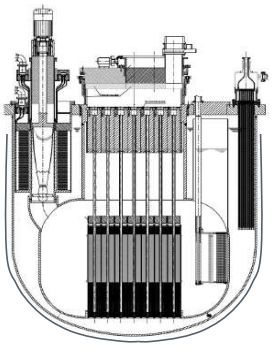
Medium TRL Instrumentation

- Developments are needed to reach TRL 6 in a few years

Technology	Application	Interest	How	ISI&R Level	Current Limits	Challenges
US in Lead	ASIV, reactor vessel	Welds, cracks Geometry	Carriers from roof	N2	Up to 600 °C Impedance	Signal/Noise Ratio, Temperature Wetting, Accesses
US in air with coupling fluid	Reactor Vessel	Welds, cracks Defects	Robot	N2	Up to 400°C 50 mm thickness	Temperature Coupling fluid Accesses
EC with probes in Argon	Steam Generators	Welds, cracks Defects	Carrier / robot	N2	Up to 380°C Max 10 mm	Temperature Speed Size Accesses
EMAT	Vessels	Welds Cracks	Robot	N2	Up to 400°C	Temperature Space Qualification
HT Fission Chambers	Core	Reactivity	Carrier	N1	600°C	Temperature Response Time Location



AS-30

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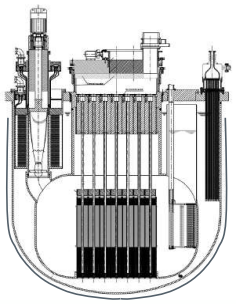
R&D

- TRL of 6 could be achievable in the longer term (before 2030)

Technology	Application	Interest	How	ISI&R Level	Limits	Challenges
EM Flow	Pump, core…	Flow rates in Lead	In pipes, veins… (SPX pump)	N1	600°C	Space Qualification
Spectro	Gas cover	Water traces…	Cables, specific system	N1	Sensitivity (a few PPM) and dynamics (ms)	Noise/Signal Ratio Temperature Space
Electrical detectors	Pipes, coatings…	Leaks, defects	Specific system	N1	Up to 1200°C	Sensitivity
Optical Fibres	Vessels and many other	Visual, Thermal, Strain, Vibrations, Shape sensing, Multiplexing, Time response, Robustness to T°	Robot or specific device	N1, N2	Up to 600°C	Irradiation Corrosion Sticking methods
HT Cameras	Reactor vessel, roof	Visual exam. Thermal	Robot	N2	Up to 200°C	Temperature Vapours Compactness
Active Acoustics (low freq.)	ASIV or SG	Welds in Lead w/o contact	Cables and specific mounting	N1, N2	Up to 200°C	Temperature Loads Sound/Noise
Laser US	Reactor vessel…	Welds, Cracks w/o contact	Robot	N2	Ambient	New



AS-30

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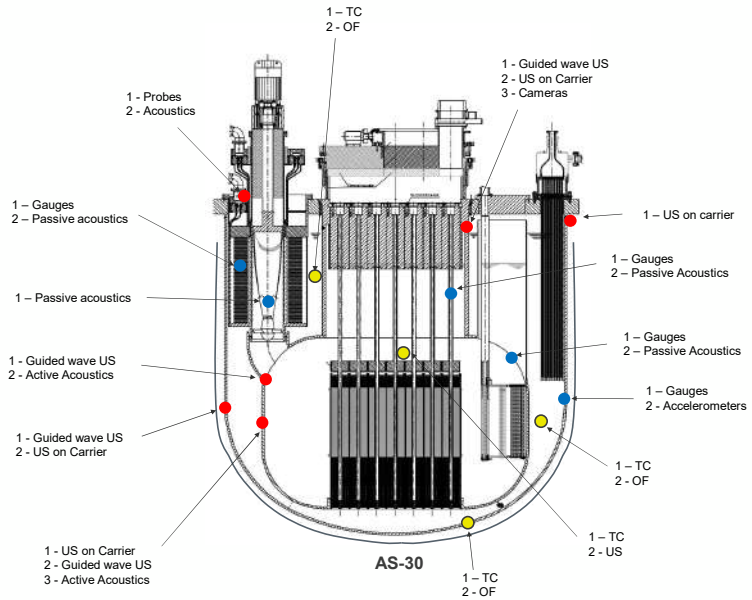
Uses

Potential uses of technologies

- Red: welds
- Blue: vibrations
- Yellow: temperatures



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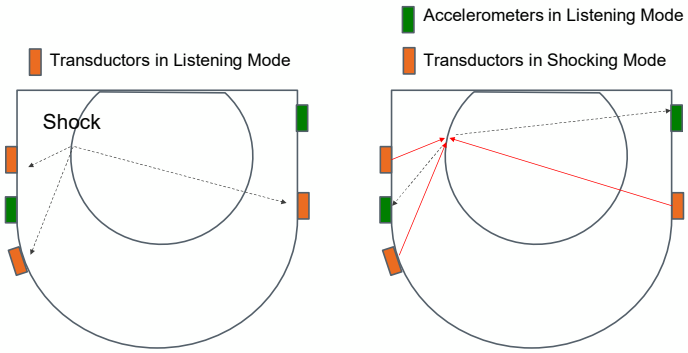
Case Study (time reversal)

Time Reversal

- STEP 1: learn Transfer function from Shock to transducer (*Shock can be virtual, using a digital twin*)
- STEP 2: create located shocks by time reversal
- Make a reference at start of project
- Inspect regularly and compare with reference



6. NDE 4.0 (II) and NDE Optimisation

The presentations in this session are listed in the table below.

NDE 4.0 (II) and NDE Optimisation	**Chair:** Iikka Virkkunen (Trueflaw)
Nuclear NDE research progress and its integration into a data centric engineering approach	Frederic Cegla et al. (Imperial College)
Interactive Database Knowledge Visualization Platform	Mike Mouchet (EPRI)
Ultrasonic array inspection of safety critical components with complex structure	Jie Zhang, Xiaoyu Sun, Paul Wilcox (Univ. Bristol)
Investigation of Wave Propagation Pattern in a Multilayer Planar Structure	Vinooth Rajendran et al. (Robert Gordon University)
Optimization of NDE Examination Requirements - A Modern Approach	Robert F. Grizzi, Do Jun (DJ) Shim (EPRI)

Nuclear NDE research progress and its integration into a data centric engineering approach

Frederic Cegla[1], Laurence Clarkson[1], Georgios Sarris[1], Bo Lan[1], Peter Huthwaite[1], Mike Lowe[1]

[1] NDE Group, Mechanical Engineering Department, Imperial College London, London, United Kingdom

E-mail address (corresponding author): f.cegla@imperial.ac.uk

This presentation will give an overview of the progress of our research on topics that are relevant to the nuclear sector. The Imperial NDE group is actively researching structural health monitoring techniques, sensor technology for robotic inspections, material characterisation and inversion techniques, data acquisition and permanently installed monitoring systems as well as realistic modelling techniques for the qualification of inspection techniques.

In the talk we will give a brief overview of the current state of the art in each of the research themes before presenting a vision of how nuclear NDE, structural integrity assessments and monitoring systems will become interlinked as part of new technological progress that is being enabled by the general adoption of data centric engineering approaches, which are often also contextually combined with the terms of the 4th industrial revolution, NDE4.0 and the IoT. The presented vision will be grounded by referring to the progress that has been made by co-author Clarkson towards monitoring of thermal loads that are driving thermal fatigue damage, progress on the NDE for detecting small changes in material properties that are linked to the onset and progression of fatigue as investigated by co-author Sarris and the general progress in modelling of the damage phenomena and NDE techniques, sensors for robotic data acquisition and monitoring systems that are being researched by the wider group.

Keywords: Thermal fatigue, Ultrasonic assessment of fatigue damage, robotic inspections, NDE4.0, Fusion of SHM and NDE data

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Nuclear NDE research progress and its integration into a data centric engineering approach

Frederic Cegla, Laurence Clarkson, Georgios Sarris, Bo Lan, Peter Huthwaite, Mike Lowe

Contact: f.cegla@imperial.ac.uk

NDE Group, Mechanical Engineering Department, Imperial College London, London, United Kingdom

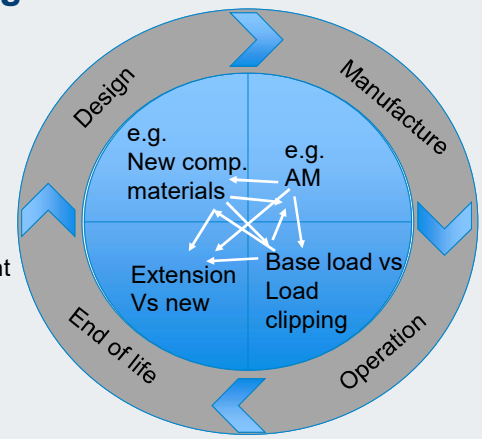
Imperial College London

Contents

- Data centric engineering overview (NDE4.0, etc.)
- Group research activities
  - SHM (DAQ and sensors)
  - Sensors for Robots
  - Material characterization and inversion techniques
  - Modelling techniques for the qualification of inspection techniques
- Spotlight on Inspection and monitoring for HCT fatigue damage
- Conclusion

Data centric engineering overview

- Engineering Product life cycle
  - Design
  - Manufacture
  - Operation
  - End of life/ Recycling
- Optimization of cycle is data driven
- Measurement and Model paramount
- NDE data is measurement



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Nuclear NDE research progress

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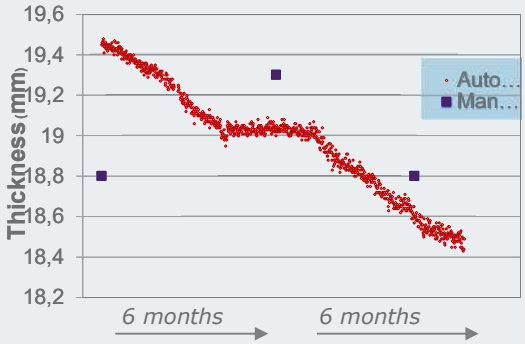
SHM sensors and DAQ

Key drivers

- **Quality and frequency of data**
- Cost of acquisition
- Data to information



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SHM sensors and DAQ

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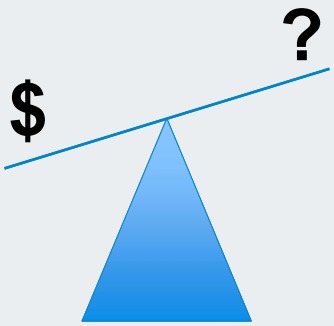

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SHM sensors and DAQ

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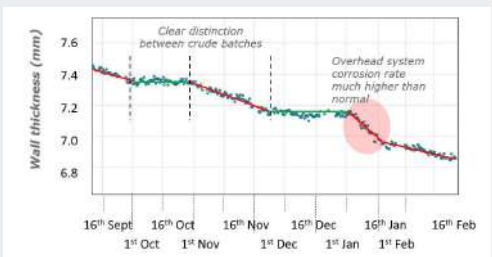

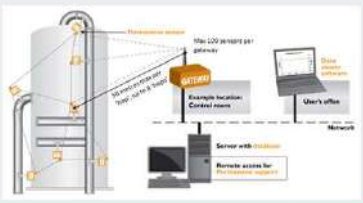

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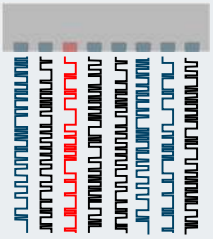
SHM sensors and DAQ

Current research

- Coded excitation for cost effective data acquisition
- EMAT Sensors for temperature monitoring, e.g. see L. Clarkson presentation Thursday 29th, 10:20am



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Sensors for robots

Key drivers

- Access costs account for >75% of inspection costs
- Some environments never designed for human access
- Hazardous environments so human exposure to be limited

Sensors for robots

Current work

- Sonobotics Ltd system
  - Light weight, powerful, no-couplant
- Integration onto drones
- Integration onto crawlers/multi-peds
- Integration on AR human operator

Material characterization and inversion techniques

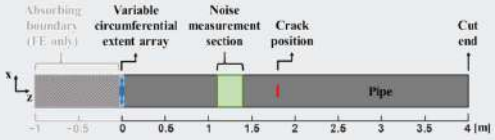
Key drivers

- Identifications of grain structure differences, macro zones
- Understanding scattering and improve detectability
- Remove conservatism from rough defect characterization
- Limited access problems

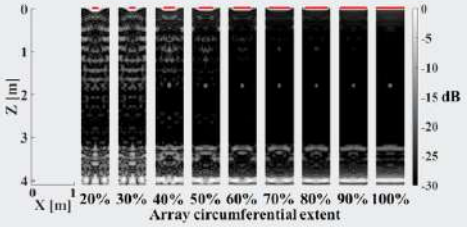
Material characterization and inversion techniques

Current research

- Limited access problems



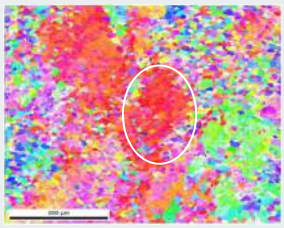
F. Szlaszynski PhD Thesis

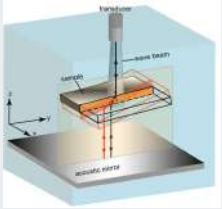


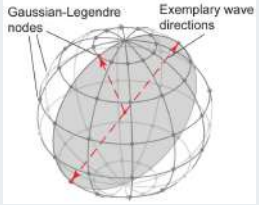
Material characterization and inversion techniques

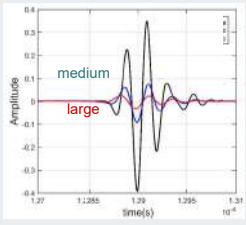
Current research

- Microstructure and grain size determination
- Simulation of complex materials
- Heterogeneity of AM parts









Simulation and modelling

Key drivers

- NDE procedures are often bespoke to particular components
- Reliability studies (i.e. to verify POD) require large N
- This is very cost intensive to do experimentally
- → realistic simulations accelerate the process and are more cost effective

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Nuclear NDE research progress

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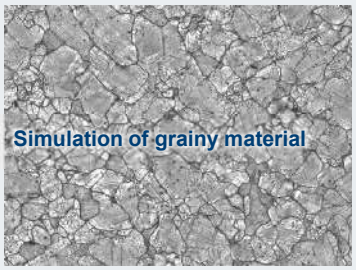
Simulation and modelling

Current research

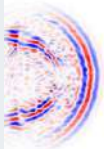
- Realistic simulation of real systems



Simulation of grainy material

pogo.

www.pogo.software



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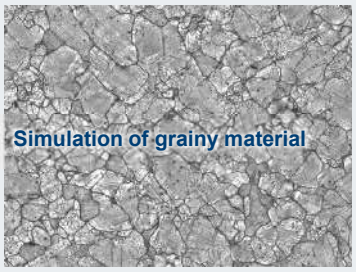
Simulation and modelling

Current research

- Realistic simulation of real systems



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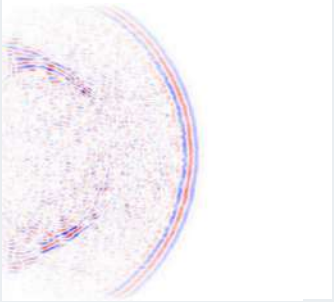

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Nuclear NDE research progress
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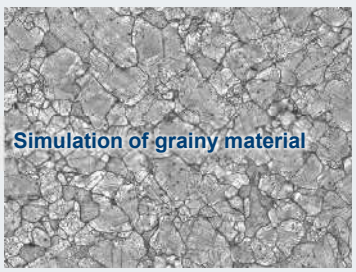
Simulation and modelling

Current research

- Realistic simulation of real systems



Simulation of grainy material

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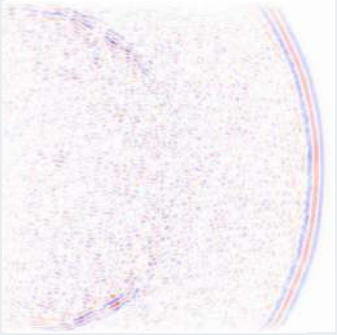
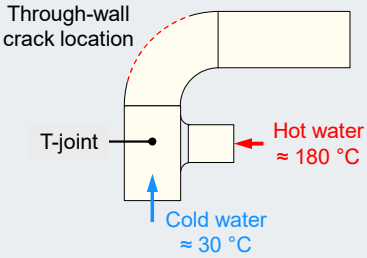


Inspection and monitoring of HCT Fatigue

- Mixing of flows causes fast temperature fluctuations that can lead to thermal fatigue
- Documented failure mechanism
- Standard NDE → crack detection → too late
- Pre-cursor detection? G. Sarris PhD
- Can we monitor for it? L. Clarkson project



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Nuclear NDE research progress

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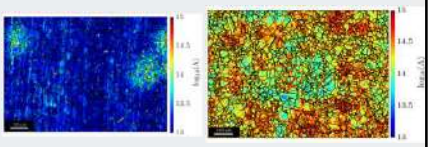
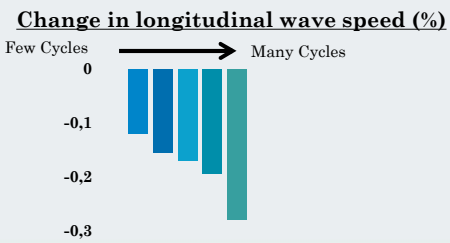
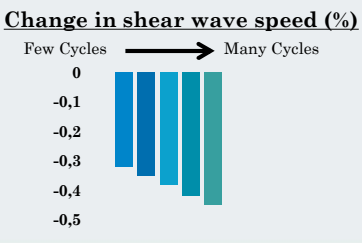
Inspection of HCT Fatigue pre-cursors

- G. Sarris PhD
- Dislocation density increase → UT velocity reduction
- Longitudinal velocity least sensitive
- Shear velocity 2-2.5 x more sensitive







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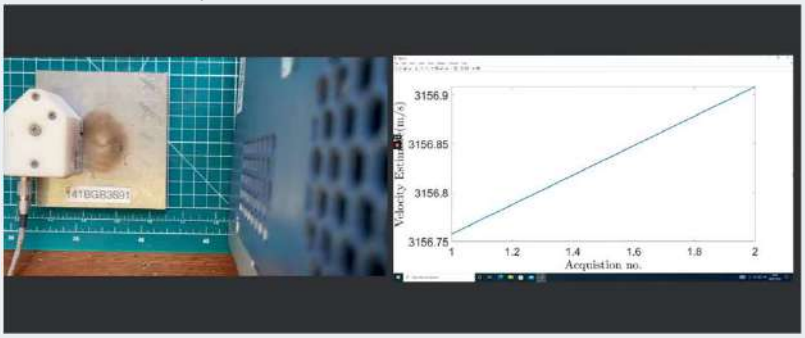
Inspection of HCT Fatigue pre-cursors

- G. Sarris PhD
- Shear wave velocity measurements with EMAT



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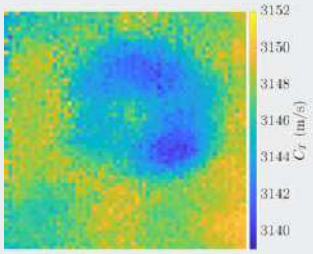
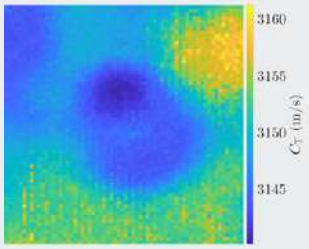
Nuclear NDE research progress
27/06/2023

Inspection of HCT Fatigue pre-cursors

- G. Sarris PhD
- Shear wave velocity measurements with EMAT confirmed



Few Cycles

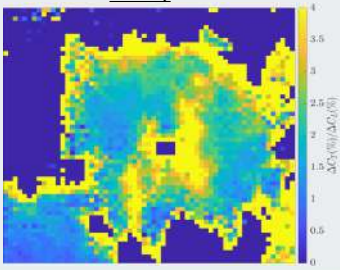


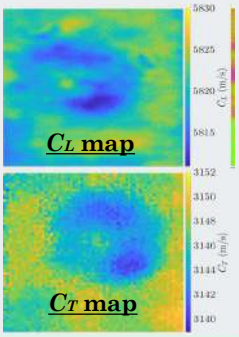
Many Cycles

Inspection of HCT Fatigue pre-cursors

- G. Sarris PhD
- Field inspection complications
- Use relative L and S wave changes

Ratio map(ΔC_T /ΔC_L)





For our specimen:
$\frac{3\gamma^2}{4} \approx 2.51$,
experiments:
$\frac{\Delta C_T/C_T}{\Delta C_L/C_L} \approx 2.20$

This ratio scan can distinguish between fatigue and thickness change

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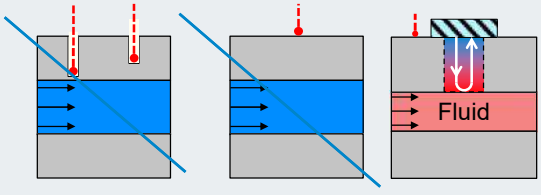
Nuclear NDE research progress

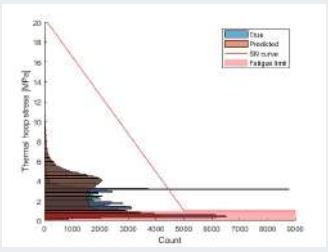
27/06/2023

Inspection of HCT Fatigue pre-cursors

- L. Clarkson PhD project
- Monitor temperature gradients that drive HCT
- Perform Cycle counting and hence state estimation
- Presentation on Thursday 29th at 10:20am

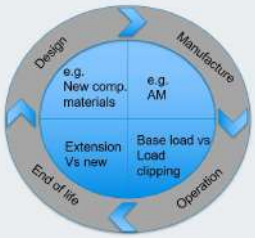
$$D = \sum \frac{n_i}{n_f}$$





Conclusion

- Data centric engineering overview (NDE4.0, etc.)
- NDE data is key enabler
- Knowledge of value of information required
- Sensors, models, acquisition systems all can add value
- We are researching different aspects/ingredients
- HCT fatigue inspection and monitoring projects examples show aspects fusion of NDE-SHM into NDE4.0



Imperial College London

Nuclear NDE research progress

27/06/2023

Questions ?

Acknowledgements

funding from and interactions with:

- EPSRC
- RCNDE
- Jacobs
- RR
- EDF
- And indirectly many more

Interactive Database Knowledge Visualization Platform

R. F. Grizzi, M. M. Mouchet, N. Glunt, D. Galbally
EPRI, Charlotte, USA
EPRI, Charlotte, USA
EPRI, Charlotte, USA
Innomerics, Inc., Spain

E-mail address: rgrizzi@epri.com, mmouchet@epri.com, nglunt@epri.com, dgalbally@innomerics.com

A significant amount of the industry's workforce is aging and facing retirement in the short term. In addition, mobility within the workforce has resulted in utility personnel spending less time in programs before moving on to the next assignment. Experience and knowledge transfer and retention are paramount to sustaining a safe, efficient, and viable industry, as new resources backfill these voids. Many of the tools and resources available to execute this transfer and retention of knowledge are found in antiquated formats that oftentimes require searching several separate knowledge repositories to compile all the relevant information sought after. Existing tools in use no longer lend themselves to the concept of an agile workforce and generally have been left behind for the ways in which current society goes about gaining knowledge. Furthermore, the formats do not facilitate ease of maintenance or updating for an expanding knowledge and experience base. New tools and modernized knowledge transfer and retention methods need to be developed to facilitate counteracting the industry's loss of knowledge base and experience through utility personnel attrition. Industry will benefit from having a resource that provides a means to "visualize" knowledge for the less experienced utility personnel, which saves time and effort for both the experienced person having to convey knowledge and those trying to digest it. This interactive database knowledge visualization platform is meant to accelerate the learning curve for early career or new utility personnel and facilitate the knowledge transfer and retention of experienced utility personnel.

Keywords: Visualization, Interactive, Knowledge Transfer, Experience, Modern Tools

Interactive Database Knowledge Visualization Platform

Mike Mouchet, EPRI
Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Outline

01 Background
02 Interactive Database Knowledge Visualization Platform
03 Development Methodology
04 Development Process
05 Model Development
06 Database Development
07 Tool Demonstration
08 Key Takeaways

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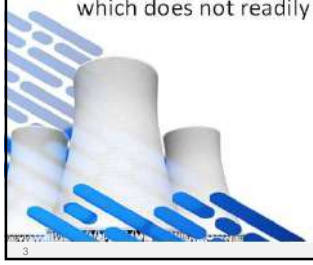
Background

Problem Identification

- A significant amount of the nuclear industry's workforce is aging and facing retirement in the short term. Additionally, utility personnel are spending less time in program roles than in the past before moving on to their next assignments.
- The transfer of the experience and knowledge gained through the years of nuclear plant operation to the new personnel backfilling these roles is of utmost importance to sustaining a safe, efficient, and viable nuclear industry.
- Many of the resources available to execute knowledge transfer are found in antiquated formats and consolidation of information often requires searching several different repositories.
- Furthermore, the formats of most of the existing knowledge transfer methods are not easy to maintain/update, which does not readily support the capturing of an expanding knowledge and experience base.



Solution Approach

Create a modernized knowledge transfer tool that utilizes a 3D model-based visualization platform to connect the user to a database of inspection-related information that will serve and function as a "living" knowledge retention resource to continually build upon in the future.

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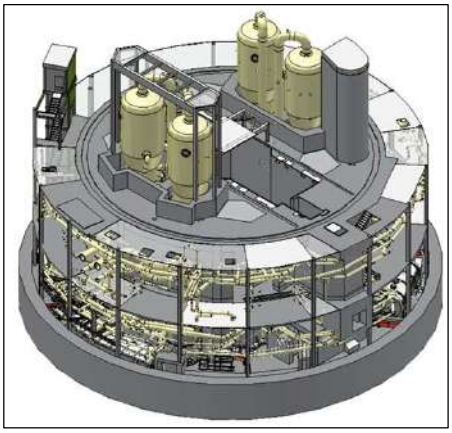
Interactive Database Knowledge Visualization Platform

Integrates and leverages technical and commercial resources including the application of graphic interfaces with embedded databases.

- 3D model-based user interface with the ability to navigate through the plant systems and components.
- Database contains required examinations and inspection information for plant components, piping, and associated welds (e.g., ASME Code requirements).
- EPRI Product 3002024066 (NDE Guide for Compliance of Class 1, 2, 3, IWF, and Common Augmented ISI Requirements) was used as the basis for populating the majority of the database.



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Development Methodology

Proof-of-Concept Applications

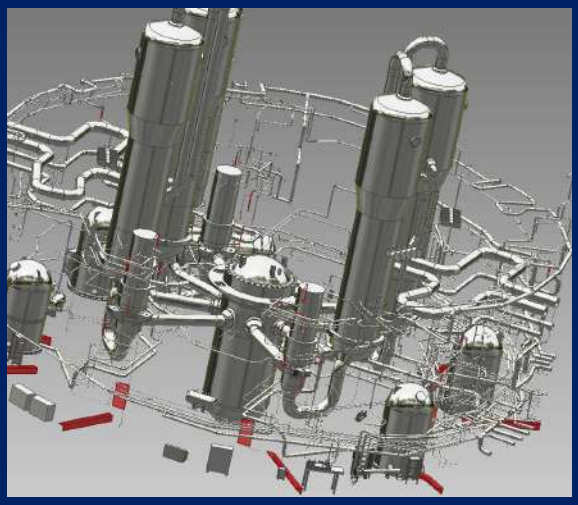
- Develop a generic model of a PWR plant.
- Develop a plant specific model using a pilot plant.

Model Development Input

- LIDAR scans and 3D CAD models to construct the visual platform.
- Desired data sets or database inputs (e.g., governing inspection requirements).

Database Technical Features

- Exam Categories/Item Numbers
- Examination Methods and Requirements
- ISI Program components
- Thermal Fatigue inspection components
- Risk Informed inspection components
- Mitigated components (WOL, MSIP, etc.,)
- Code Case Inspection Requirements



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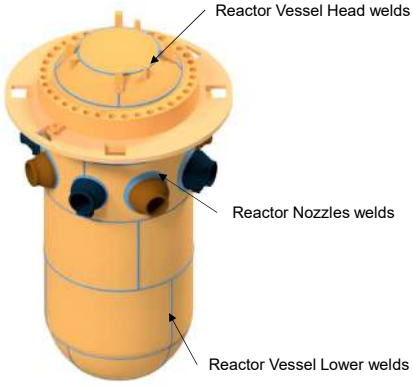
Development Process

Original model (as received)

- Development consisted of starting with 3D CAD models and making modifications and enhancements to improve the level of detail.
- LIDAR scan images were used to fill any gaps from the 3D CAD models and gain additional graphics information when necessary.
- System architecture was built around the model facilitating the interface of the model with the server database.
- The inspection details were input into the tool's database which is accessed through the 3D graphical user interface.



Enhanced elements

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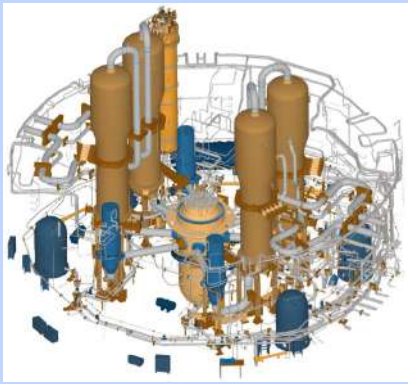
Model Development

Pilot System

Completely develop one plant system to finalize the design and incorporate early feedback to establish a firm design target.



Remaining Systems

Develop remaining systems with the design target that was defined during the pilot system development.

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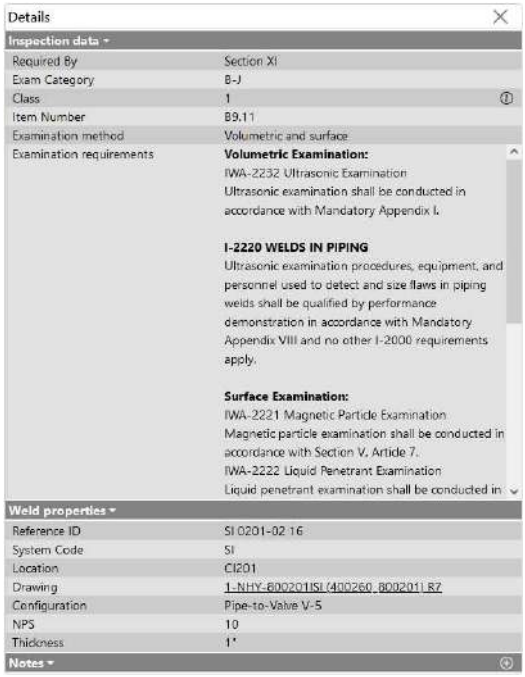
Database Development

Database Inputs:

1. Generic plant inspection requirements
   - EPRI Product 3002024066 (NDE Guide for Compliance of Class 1, 2, 3, IWF, and Common Augmented ISI Requirements) was used as the basis due to familiarity, convenience of access, and applicability for proving concept.
2. Plant specific system and component data
   - Data gathered from pilot plant



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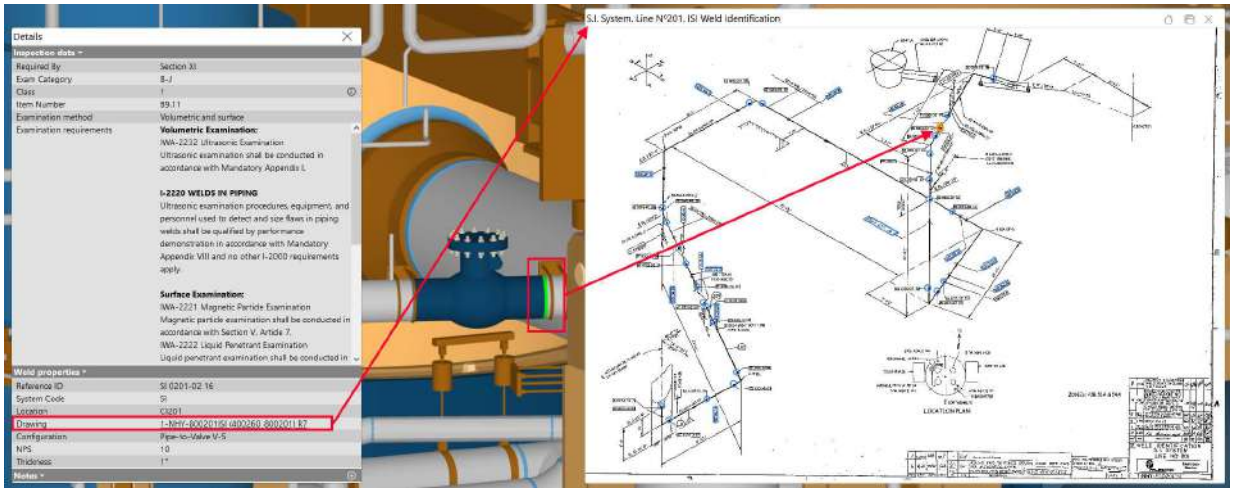
Database Development

Database Inputs:

3. Plant specific isometric drawings



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Tool Demonstration

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Key Takeaways

- This is a modernized knowledge transfer tool that that will serve and function as a "living" knowledge retention resource to continually build upon in the future.
- The database could be easily modified or expanded to include more plant information other than NDE/inspection (e.g., pipe stress information, thermal fatigue monitoring system information, real-time data monitoring and document management, etc.).
- While the proof-of-concept development has been focused on back-fitting to a current operating reactor, there are many potential broader applications for this type of tool:
  - New build applications
  - SMRs
  - Advanced and next generation reactors

Imagine the value this tool would have if used from the first day of plant operation and continually built throughout the life of the plant.

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Optimisation of ultrasonic array inspection configuration for safety critical components with complex structure

Jie Zhang[1], Paul Wilcox[1],

[1]Ultrasonics and NDT group, University of Bristol, Bristol, UK

E-mail address (corresponding author): j.zhang@bristol.ac.uk

Abstract text (1/2 – 1 A4 page)

One barrier for industrial take-up of ultrasonic array techniques is a lack of procedures and standards for specific inspection problems. For a specific inspection problem, the array inspection configuration has to be optimised to achieve best possibility of detection with a reasonably low possibility of false alarm. A simple optimisation procedure could help industry for this. The main aim of this paper is to deliver step-by-step procedures of how the optimal inspection configurations were arrived at and show the detectability of the optimised configurations for three chosen case studies. The proposed procedure includes experimental protocol of measurements of key parameters and inspection configuration optimization.

In the paper, the proposed procedure has been used successfully to find the optimal inspection configurations for: (1) a lack of fusion defect from far side of weld in a 6 mm thick specimen (provided by BAE systems), as shown in Fig. 1(a), (2) possible defects in a 6 mm thick weld specimen (provided by Jacobs), as shown in Fig. 1(b), and (3) a flat bottom hole with a 0.2 mm deep and 0.5 mm diameter in a 2 mm thick aluminium plate (proposed by Hitachi) , as shown in Fig. 1(c).

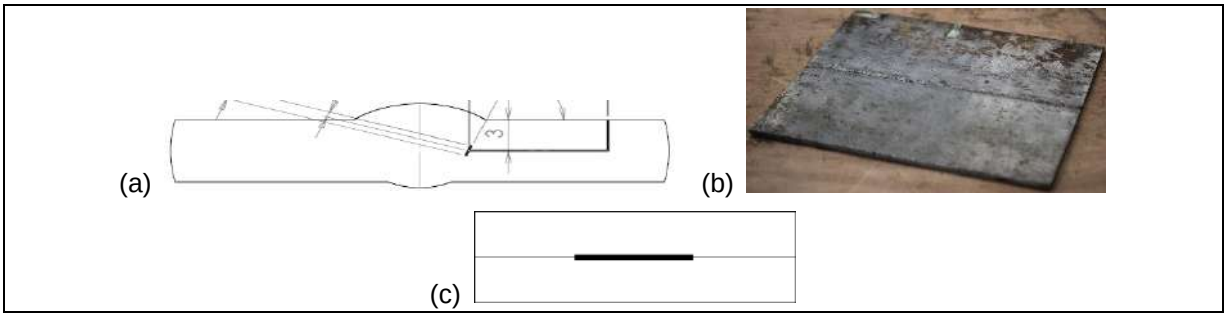


Fig. 1 The specimens provided by: (a) BAE systems, (b) Jacobs and (c) Hitachi. Note that the thickness of the specimens are: (a-b) 6 mm and (c) 4 mm.

Keywords: ultrasonic arrays, total focusing method, defect detection

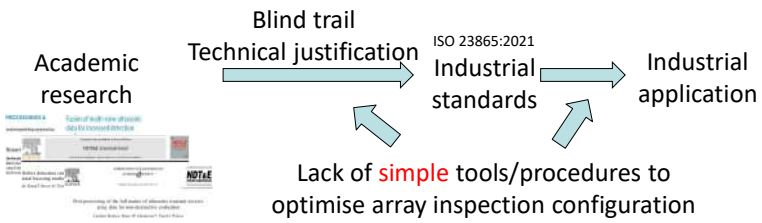
Ultrasonic array inspection of safety critical components with complex structure

Jie Zhang, Xiaoyu Sun, Paul Wilcox
UNDT group, University of Bristol

Proc. R. Soc. A 478: 20210762.

Motivation & Aim

Motivation: inspection of safety critical components using FMC/TFM techniques



Aim:

a simple inspection design procedure.

Procedure

Step 1: define geometry of a structure/sample with material properties and a defect of interest.

Step 2: propose array inspection configuration candidates.

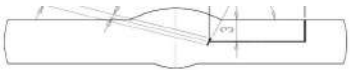
Step 3: experimental measurements of time delay from equipment, wave speeds, material attenuations, and image noise.

Step 4: predict the defect response under the proposed array inspection configuration candidates using any simulation tools.

Step 5: optimise inspection configuration based on best SNR.

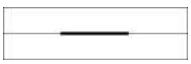
Case studies

BAE systems: pipes in submarines (lack of fusion defect)



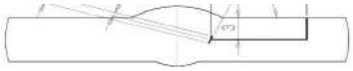
Jacobs: welds in nuclear plants (blind test)

Hitachi: train body-shell in InterCity Express Programme (IEP) fabricated using friction stir welding

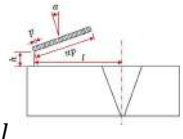


Case study 1 (BAE systems)

- Lack of fusion defect required to be inspected from the far side.

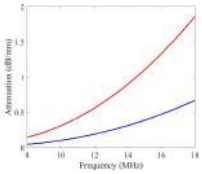


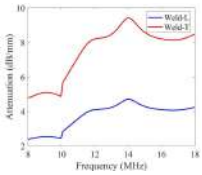
- Procedure
  - Step 1: define geometry of a structure/sample with material properties and a defect of interest.
  - Step 2: propose array inspection configuration candidates.
    - 15 MHz linear 1D array
      - 64 els, 0.21 mm pitch
    - Find optimal probe angle, α, and lateral distance, l.



Case study 1 (BAE systems)

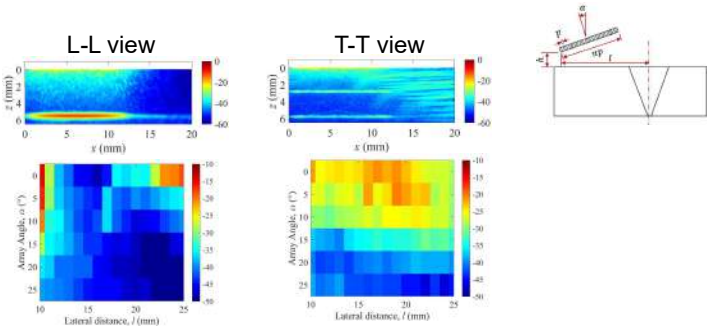
  - Step 3: experimental measurements of time delay from equipment, wave speeds, material attenuations, and image noise.
    - Measured speeds in parent material: v_1 = 1480 m/s, and v_2 = 5050 m/s, v_3 = 2500 m/s; equipment delay: 0.3 μs
    - Attenuation:





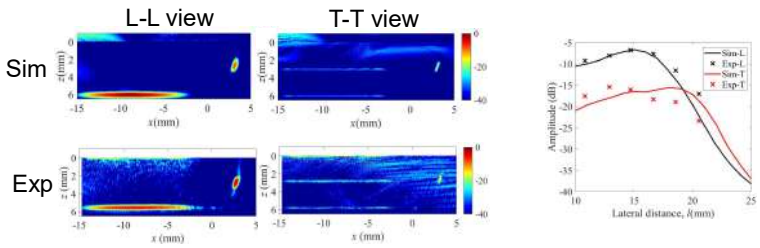
Case study 1 (BAE systems)

– Step 3: Experimental measurement (in parent material): noise
  • At the proposed defect location, as a function of α and l
  • Need to combine with defect response



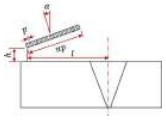
Case study 1 (BAE systems)

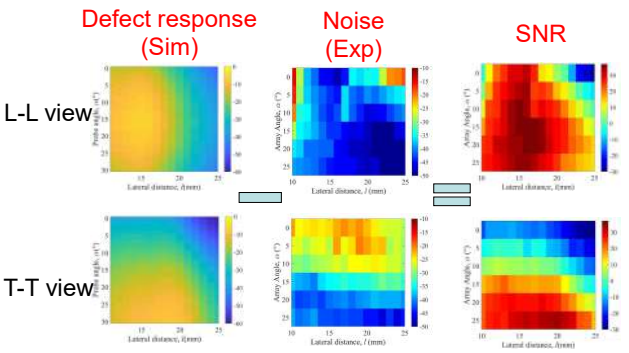
– Step 4: predict the defect response under the proposed array inspection configurations using any simulation tools.
  • Model validation (in parent material)



Case study 1 (BAE systems)

– Step 5: Inspection configuration optimisation (parent material)



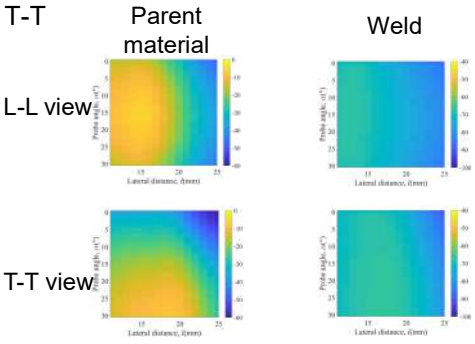


l = 16 mm
α = 15°

l = 19 mm
α = 25°

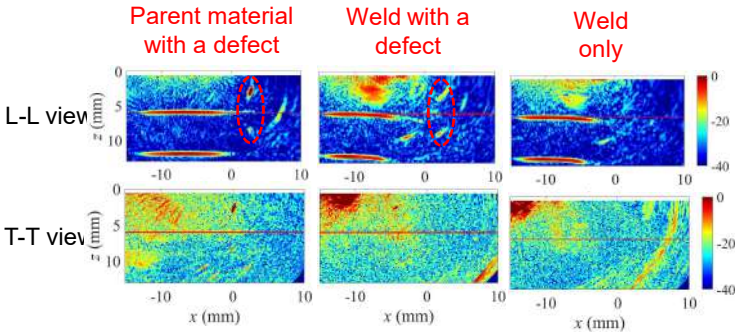
Case study 1 (BAE systems)

– Effect of weld attenuation in defect response (exp + simulation)
  - ~40 dB SNR drop for L-L
  - ~60 dB SNR drop for T-T



Case study 1 (BAE systems)

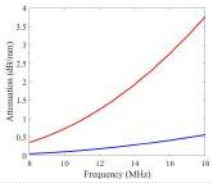
- TFM images from experimental measurements



Case study 2 (Jacobs)

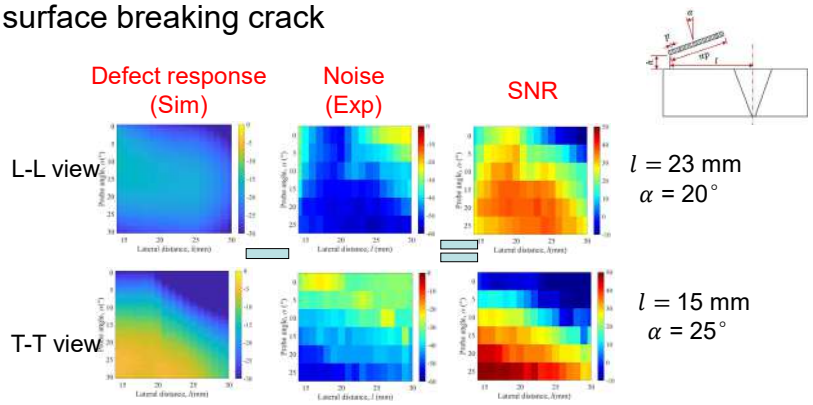
- Blind test

  - Defect of interest: a 2mm long surface breaking crack
  - Measured speeds: v_1 = 1480 m/s, and v_2 = 5960 m/s, v_3 = 2980 m/s
  - Equipment delay: 0.3 μs
  - Attenuation:



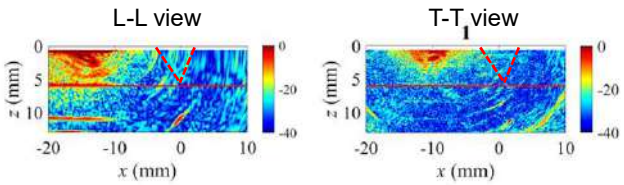
Case study 2 (Jacobs)

– Inspection configuration optimisation for a 2mm long surface breaking crack



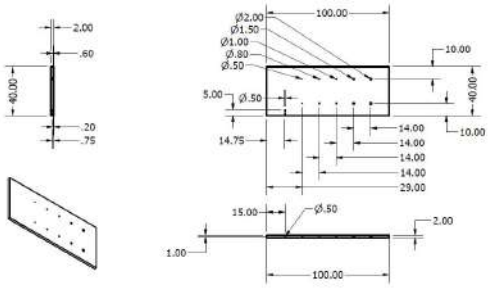
Case study 2 (Jacobs)

- Blind test results (inspections from the right side)
  - L-L view: $l = 23$ mm, $\alpha = 20^\circ$
  - T-T view: $l = 15$ mm, $\alpha = 25^\circ$



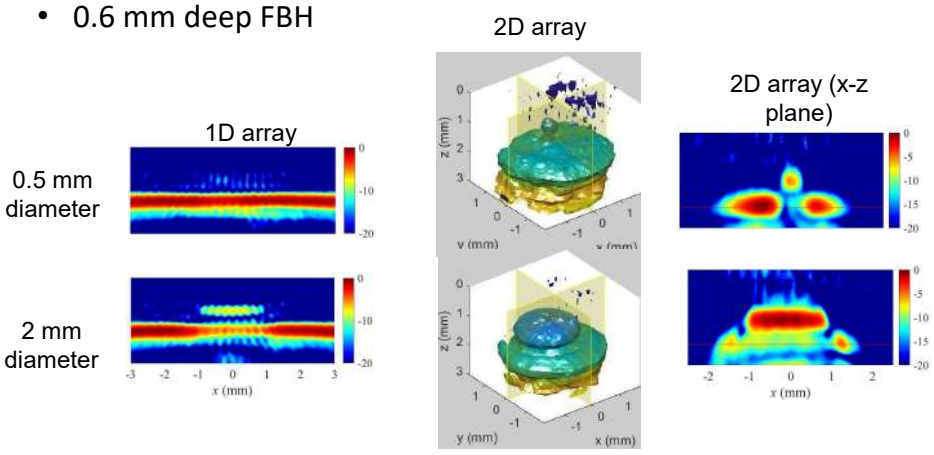
Case study 3 (Hitachi)

- Proposed: train body-shell in InterCity Express Programme (IEP) friction stir welding
- Actual:
  - Most challenging defect: 0.5 mm diameter, 0.2 mm deep, FBH



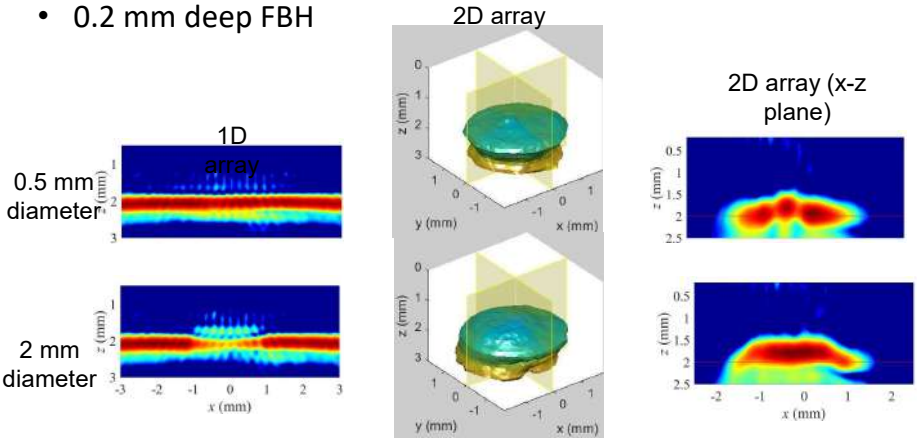
Case study 3 (Hitachi)

- 0.6 mm deep FBH



Case study 3 (Hitachi)

- 0.2 mm deep FBH



Conclusion and possible future works

- Proposed the procedure for array inspection optimisation and used it for 3 case studies.
- Provided a possible solution to overcome a barrier of taking-up the technique in industry.
- Procedure can be used to support technical justification and industry standard.

Investigation of Acoustic Emission Wave Propagation Pattern with Defect Locations in a Multilayer Structure

Vinooth Rajendran[a,1], Anil Prathuru[a], Carlos Fernandez[b], Nadimul Haque Faisal[a]
[a]*School of Engineering, Robert Gordon University, Garthdee Road, Aberdeen, AB10 7GJ, UK*
[b]*School of Pharmacy and Life Sciences, Robert Gordon University, Garthdee Road, Aberdeen, AB10 7GJ, UK*

Abstract
Understanding the transient elastic waves in multi-layered structure have long been of great interest for its wide applications and their non-destructive evaluation. This paper experimentally analyses the acoustic emission (AE) wave propagation pattern changes with defect locations (i.e., surface, cross-section). A set of epoxy phenolic-coated mild steel plates was arranged together (without any adhesion), and the two piezoelectric AE sensors were placed on the coating layer. Used pencil lead break (PLB) test to initiate the AE waves from the surface and cross-section of different layers (**Fig. 1**). From wavelet transforms (WT) analysis, significant energy zone changes are observed up to 450 kHz frequency level with PLB on the surface and cross-section of different layers (**Fig. 2**). Love wave propagation on the coated plate structure resulted in wave pattern changes with PLB locations and layers. Wave duration, energy, energy ratio, and peak amplitude levels were also analysed to characterise the AE wave pattern relationship with defect location in a multilayer plate structure. Approaches through this work could be useful to provide a greater understanding of the defect on a surface (e.g., corrosion) and cross-section (e.g., hydrogen embrittlement) within multilayer structure, potentially offering an alternative way to monitor changes in corrosion under-insulation (CUI) applications.

Keywords: acoustic emission, multilayer, pencil lead break, wave propagation.

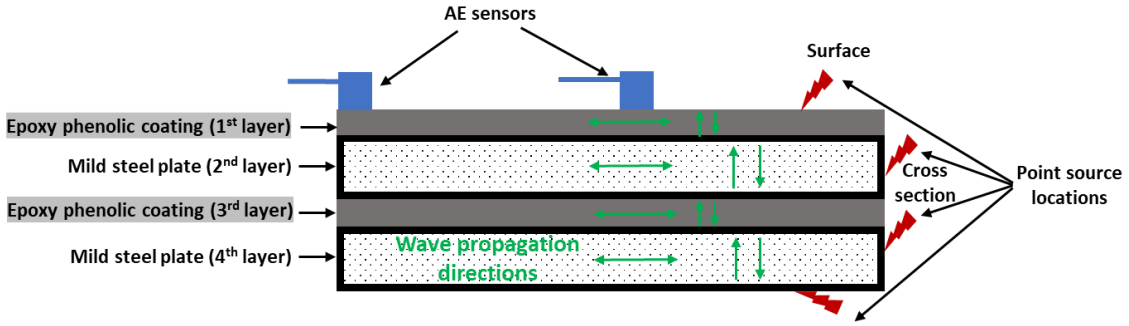


Figure 1. Acoustic emission (AE) elastic wave propagation with defect locations in a multilayer structure.

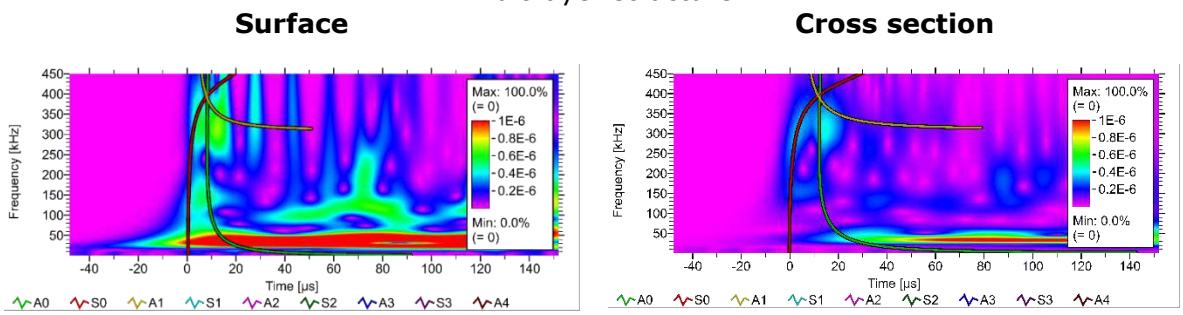


Figure 2. Representation of surface and cross section wavelet transforms.

[1]Corresponding authors. E-mail addresses: v.rajendran1@rgu.ac.uk

NDE in Nuclear 2023

ROBERT GORDON UNIVERSITY ABERDEEN

Investigation of Wave Propagation Pattern in a Multilayer Planar Structure

Vinooth Rajendran

Supervisors: **Prof Nadimul Faisal, Dr Anil Prathuru, Dr Carlos Fernandez**

School of Engineering, Robert Gordon University, Aberdeen, UK

School of Pharmacy and Life Sciences, Robert Gordon University, Aberdeen, UK

27 June 2023

Contents: Problem statement, Introduction, Sensors and Instrumentation, Methodology, Results, Summary

Problem Statement

Industries

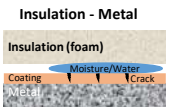
Oil and Gas

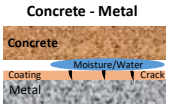
Nuclear

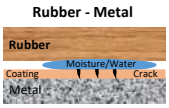
Chemical Storage

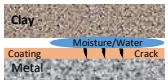
Subsea

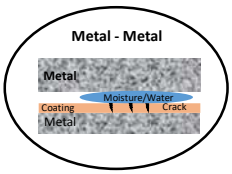
Degradation in multi-layer structures











In this study investigated

Oxidation

$Fe \rightarrow Fe^{2+} + 2e^-$ and $Fe \rightarrow Fe^{3+} + 3e^-$

Reduction

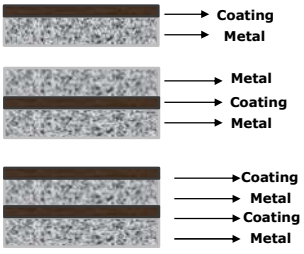
$O_2 + H_2O + 4e^- \rightarrow 4OH^-$

Precipitates

$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$

$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3$

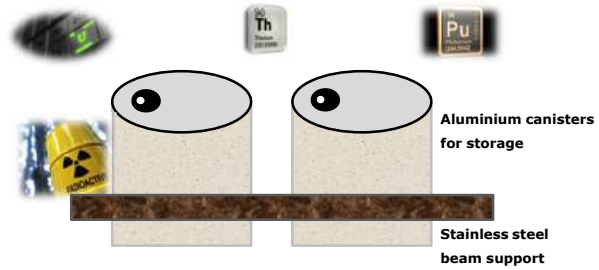
Defect free conditions



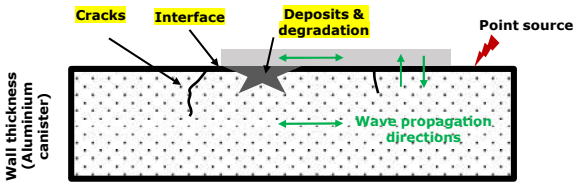
- Various industries use multilayer structures for **wide applications**. Especially, materials and liquid safe storage, vibration control and etc.
- Materials degradation on the multilayers and multilayer interface conditions ends in **accidents** and huge amounts of **economic losses**.

Rajendran, V., Prathuru, A., Fernandez, C. and Faisal, N.H., 2023. Corrosion monitoring at the interface using sensors and advanced sensing materials: methods, challenges and opportunities. *Corrosion Engineering, Science and Technology*, *58*(3), pp.281-321.

Nuclear Applications (Storage Canister)



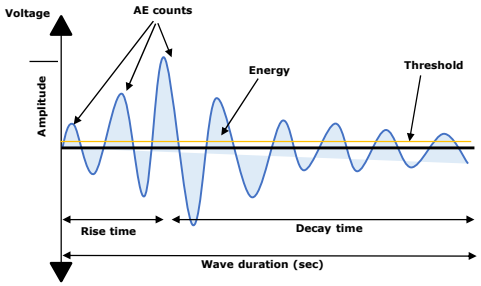
Storage facility of SNM



Structure failure and wave propagation

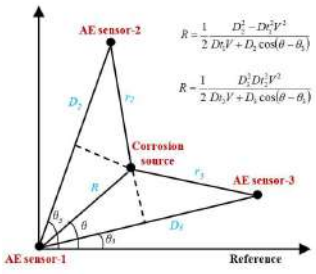
- Special Nuclear Materials (SNM) are packaged into stainless steel containers and aluminium extrusion for **safe and secure storage**.
- Presence of electrolytes (e.g., water, soil) leads to the initiation of an **electrochemical reaction** (i.e., corrosion). Due to materials degradation, the containers could not serve the purpose.
- Especially in the slat environment, aggressive **pitting, intergranular corrosion** and **chloride** formation on the containers.
- Monitoring the **structural health of containers** is required to maintain a safe environment. Particularly, an advanced study needs to carry out effective monitoring in multilayer structures.

Acoustic Emission (Signals & Processing)



AE signal features

- AE waves frequency: 100 kHz to 1 MHz
- Materials crack initiation and growth, degradation are sources which releases the **elastic stress waves**
- Source needs to be **active** for monitoring
- Potential use of multiple sensor could find the source location.



Finding source location

Corrosion type from AE

$$cdd = \frac{24 \times C}{A \times T}$$

Cdd - count per square decimetre per day, **C** – AE counts, **A** – area in square decimetre, **T** – time in hours.

- Type of **corrosion and failure** can be classified based on the AE counts.
- Detailed investigation is required to find the **source location** in the multilayer structures.

$$x = \frac{(t_{s1} - t_{s2})V + L_{s1-s2}}{2}$$

L_{s1-s2} - distance between first and second hit, $t_{s1} - t_{s2}$ -arrival time difference of sensors 1 and 2, **X** – Source location, **V** – Wave velocity.

- ALI, S.M., et al., 2019. Observations of changes in acoustic emission parameters for varying corrosion defect in reciprocating compressor valves. *Ain Shams Engineering Journal*, *10*(2), pp.253-265.
- Dong, Y. and Ansari, F., 2011. Non-destructive testing and evaluation (NDT/NDE) of civil structures rehabilitated using fiber reinforced polymer (FRP) composites. In *Service life estimation and extension of civil engineering structures* (pp. 193-222). Woodhead Publishing. https://doi.org/10.1533/9780857090928.2.193
- Ozevin, D. and Harding, J., 2012. Novel leak localization in pressurized pipeline networks using acoustic emission and geometric connectivity. *International Journal of Pressure Vessels and Piping*, *92*, pp.63-69.

Sensor and Instrumentation

Micro – 80D AE sensor

Physical Acoustics, 1220A

Preamplifier – 2/4/6

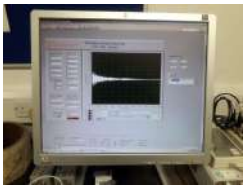
- 60 dB
- 40 dB
- 20 dB

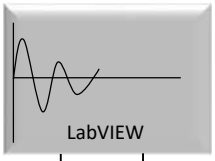
Signal Processing Unit (SCU)

Connector block BNC - 2110

Data Acquisition Card (DAQ)

Data Acquisition Card (NI 6115)
4-Channel, 10 MS/s



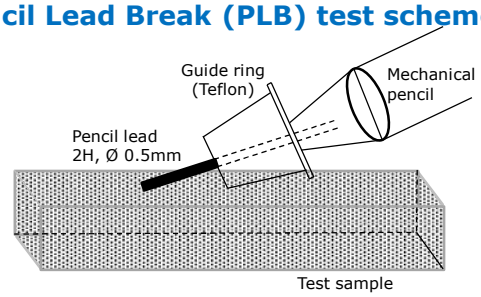


- Number of channels
- Trigger channel
- Sampling rate
- Number of scans
- Trigger level
- Pre trigger scans

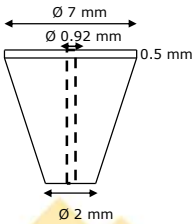
PC

AE instrument block diagram

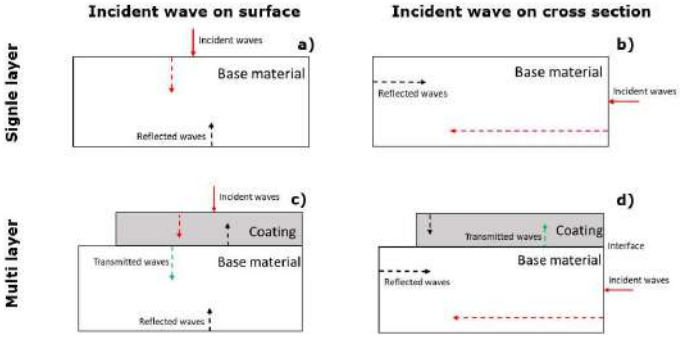
Pencil Lead Break (PLB) test scheme and wave propagation



PLB test illustration (ASTM E 976 – 99)

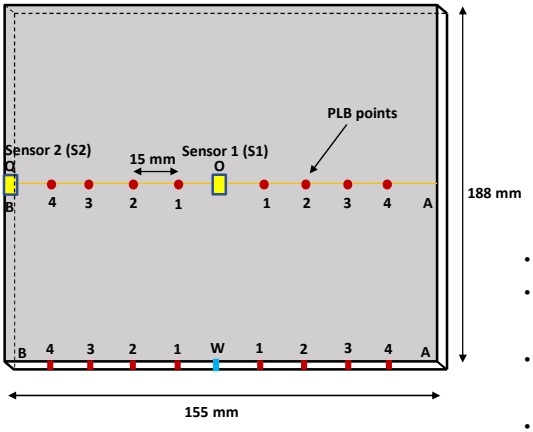


Guide ring dimension

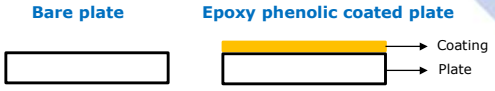


ASTM: E 976–99 Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response. ASTM (1999)

Experimental Conditions – Bare and Coated Plate



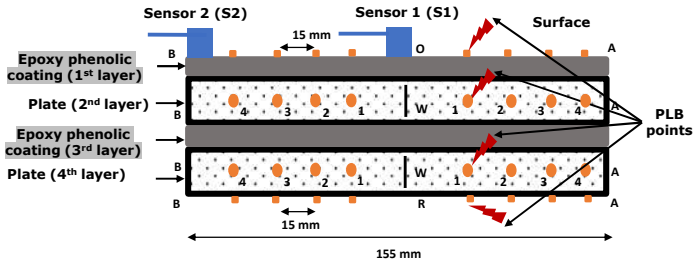
Top view – Plate with coating



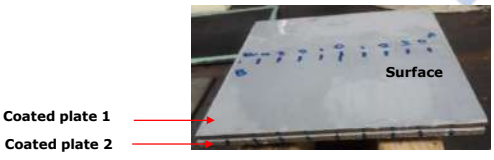
Cross section view

- To understand wave propagation with single layer (i.e., coating).
- Mild steel (ASTM A106) and epoxy phenolic coating are used in industry most for storage purposes.
- PLB test is performed on **surface and cross section** of the bare and coated plate.
- Each point PLB test was performed 5 times repeatedly.

Experimental Conditions – Two Coated Plates



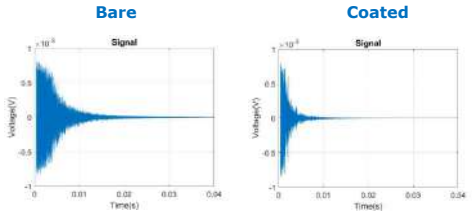
Cross section view of two coated plates



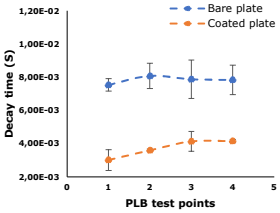
Original experimental plate

- To understand wave propagation with multilayer structures and wave initiation from different layers.
- Plate size is 155 mm (L) * 188 mm (W) * 5 mm (H).
- The coating thickness is 0.272 mm (layer 1) and 0.270 mm (layer 3).
- **No adhesion** between two coated plates (similar to nuclear storage containers condition).
- PLB tests on surface and cross sections of layers 1, 2, 4.

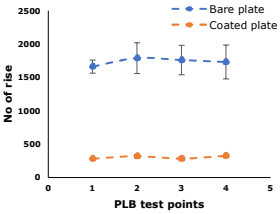
Results – Bare and Coated Plate



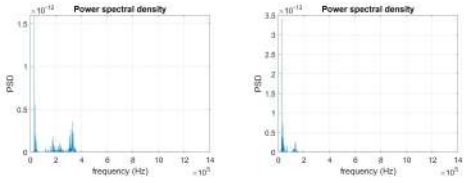
Time domain analysis



Decay time



No of rise

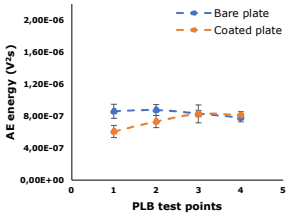


Frequency domain analysis

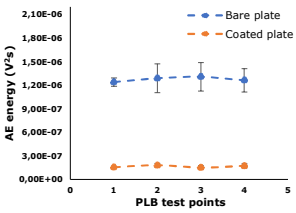
- Time and frequency domains are changed based on the plate conditions (bare, coated).
- Wave propagation pattern depends on the **layer properties of Young's modulus, density and shape** (Mild steel – 190-210 GPa, 7800-8000 kg/m^3, Epoxy coating: 2.7-4.1 GPa, 1200-1400 kg/m^3).
- Coated plate shows minimized peak amplitude, low decay time and number of rises compared to bare plate.
- Coating layer act as a **damping layer** and restricts wave propagation in the form of dispersion.

Ozevin, D. and Harding, J., 2012. Novel leak localization in pressurized pipeline networks using acoustic emission and geometric connectivity. *International Journal of Pressure Vessels and Piping*, *92*, pp.63-69.

Results – Bare and Coated Plate



100 kHz low pass



100 kHz high pass

$$E = \int_0^t V^2(t)dt$$

AE energy calculation

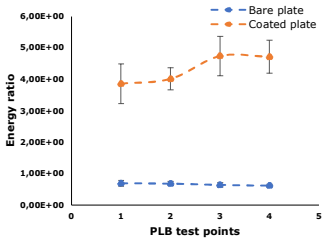
Distance (d) / Time (t)

Wave velocity (v)

100 kHz lowpass/
100 kHz high pass

Energy ratio

- **Digital filter** is applied below and above 100 kHz.
- Mixed response in a low frequency level (below 100 kHz)
- Coated plate has low energy level in high frequency level (above 100 kHz).
- Wave velocity decreased with coating.
- Overall, the wave **propagation parameters and pattern changes with layers** on the primary material.

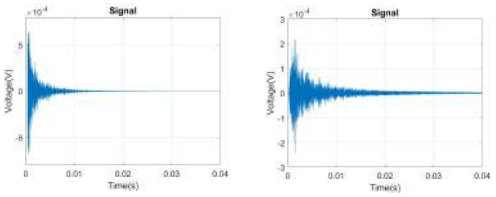


Energy ratio

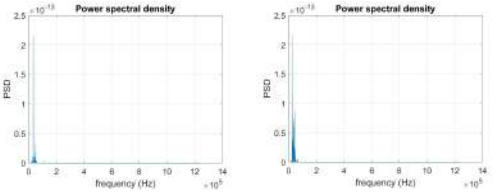
Droubi, M.G., Reuben, R.L. and White, G., 2012. Statistical distribution models for monitoring acoustic emission (AE) energy of abrasive particle impacts on carbon steel. *Mechanical Systems and Signal Processing*, *30*, pp. 356-372.

Results – Cross Section Layers 2 & 4

Layer 2 | Layer 4

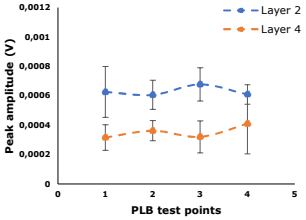


Time domain analysis

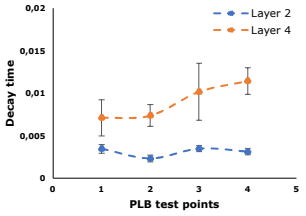


Frequency domain analysis

- Wave propagation pattern and frequency changes with layer of wave initiation.
- Maximum peak amplitude level decreases as PLB test points move away from the sensor location.
- Layer 4 shows a high decay time and number of rises as a result of low frequency wave domination.



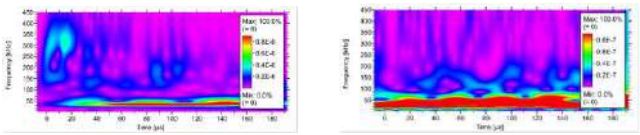
Peak amplitude



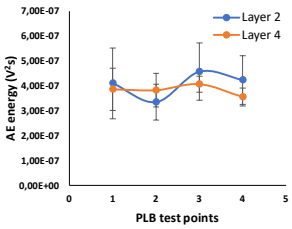
Decay time

Results – Cross Section Layers 2 & 4

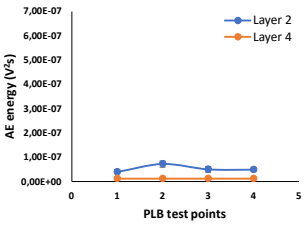
Layer 2 | Layer 4



Wavelet transform



100 kHz low pass

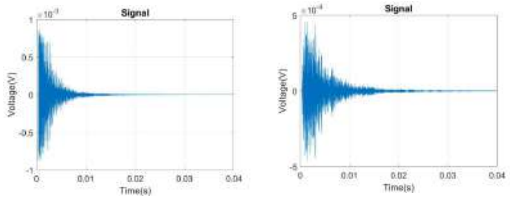


100 kHz high pass

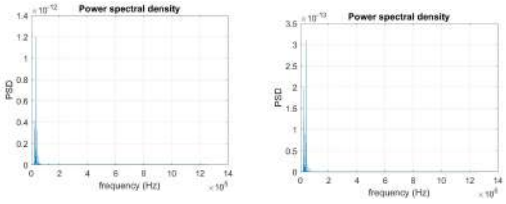
- **Wavelet transform** is a combination of time and frequency domain
- Showed the distributed energy zones across the frequency level, however **low energy** level in layer 4.
- Low frequency waves are not affected by multilayer structures and wave initiation points.
- Minimisation of high frequency waves is dominated in multilayer structures compared to single structure.

Results – Surface Layers 1 & 4

Layer 1 | Layer 4

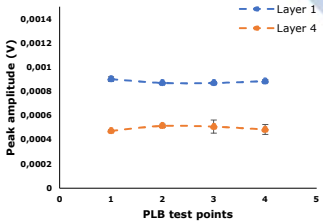


Time domain analysis

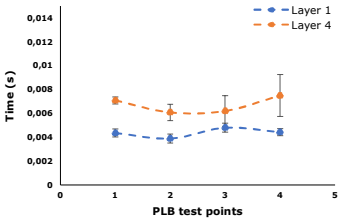


Frequency domain analysis

- Layer 1 and 4 surface points have different wave propagation patterns.
- Significant reduction in the **high frequency** energy level (no peaks).
- Similar to cross section points, the peak amplitude decreases with the addition of layer.



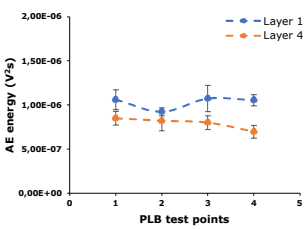
Peak amplitude



Wave duration

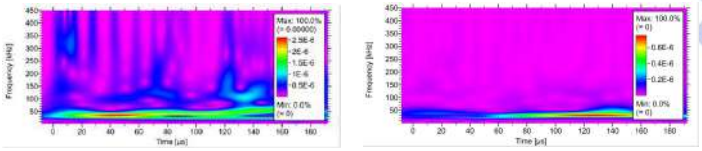
Results – Surface Layers 1 & 4

- High frequency waves are fully absorbed when wave initiation from layer 4 with domination of low frequency waves.
- Overall, AE energy level does not show much change, however, the **AE parameters** are changed based on the source initiation layers and points.
- Sensor placement on the **outer layer of storage container** could help find the degradation in layers.

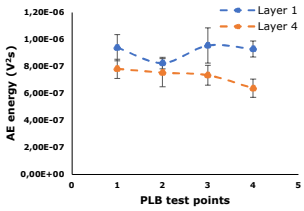


AE energy

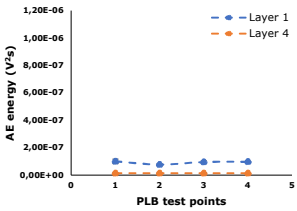
Layer 1 | Layer 4



Wavelet transform



100 kHz low pass

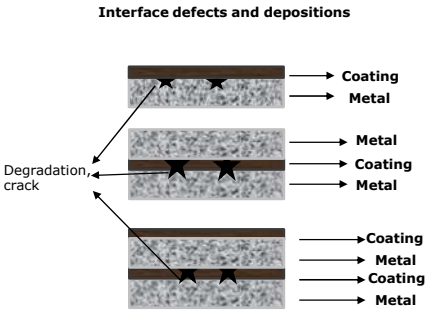


100 kHz high pass

Summary

- Detecting and assessing the effect of coating layers (assumed surrogate of deposits or protective layer) is one of the major challenges in metallic structures or structures with one or more than one interfaces.
- Through this case study, we aimed to address one of the challenges, i.e., non-destructive measurement of the effect of layers.
- The results show that through introducing wave propagation at sub-MHz range at different surface and layers, the proposed method can be effective route to monitor the effect of coating layers.
- Low frequency waves (below 100 kHz) are more appropriate to monitor the multilayer structure. The above results explain that high frequency waves are almost damped in multilayer structures because of different layers and their properties.

Upcoming study



Thank you

v.rajendran1@rgu.ac.uk

Technical Bases for Inspection Optimization of NDE Requirements for Select ASME Code Category Class 1 & Class 2 Components

R. F. Grizzi, D. J. Shim, S. T. Chesworth, N.G. Cofie, D. Dedhia
EPRI, Charlotte, USA
EPRI, Palo Alto, USA
Structural Integrity Associates, Palo Alto, USA
Structural Integrity Associates, Palo Alto, USA
Structural Integrity Associates, Palo Alto, USA

E-mail address: rgrizzi@epri.com, dshim@epri.com, schesworth@structint.com, Ncofie@Structint.com, ddedhia@structint.com

Pressurized water reactor (PWR) and Boiling Water Reactors (BWR) Class 1 and Class 2 welds/components are required to be inspected every ten years by ASME Code, Section XI. A comprehensive survey of over forty years of examination results have shown that no known degradation has occurred in these select components. This leads to the belief that these components are very flaw tolerant and can accommodate a much longer inspection period. A comprehensive study involving stress analyses, probabilistic and deterministic fracture mechanics analyses supported this observation and have shown that the inspection frequency of the components can be decreased without compromising safety. The technical bases cover the following ASME Code Categories and Item Numbers:

- Class 1, Category B-N-1, general area VT-3 of reactor internal surfaces
- Class 1, Category B-G-1, Reactor Pressure Vessel Closure Studs (Item No. B6.20)
- Class 1, Category B-G-1, pressure-retaining bolting >2" dia. (Item No. B6.60, B6.90, B6.120, B6.150, B6.180, and B6.210)
- Class 1, Category B-B, pressure-retaining welds in vessels, other than reactor vessels (Item Nos. B2.11, B2.12, B2.21, B2.22, B2.31, B2.32 and B2,40)
- Class 1, Category B-D, full penetration welded nozzles in vessels, other than reactor vessels (Item No. B3.110, B3.130)
- Class 2, Category C-D, pressure-retaining bolting >2" dia. (Item No. C4.10, C4.20, C4.30, and C4.40)
- Class 2, Category C-A, pressure-retaining welds in pressure vessels, other than reactor vessels (Item Nos. C1.10, C1.20 and C1.30)
- Class 2, Category C-B, pressure-retaining welds in pressure vessels, other than reactor vessels (Item Nos. C1.10, C1.20, C1.30, C2.21, C2.22, and C2.32)

This presentation provides the information on the process and approach for developing the technical bases supporting ASME Code, Section XI code actions to leverage optimizing the associated inspection requirements.

Keywords: NDE, Optimization, Inspection, Technical Bases, Requirements

Optimization of NDE Examination Requirements

A Modern Approach

Robert Grizzi, EPRI
Program Manager, Plant Support / NDE Program

Do Jun (DJ) Shim, Ph.D., EPRI
Technical Executive, Materials Reliability Program (MRP)

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Special Acknowledgements

Structural Integrity Associates, Inc.®

Dominion Engineering, Inc.

Contributing Organizations

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Content

- Background and Overview
- Problem Statement
- Objective
- Generic Process
- Selected Components – Across US Fleet of PWR & BWR Designs
- Technical Basis Overview
- Generalized Conclusions
- Summary of Technical Bases Development
- US Implementation Strategy & Benefits
- In Process “Request for Alternatives” with the US NRC
- Broader Implementation Strategy for International and SMR (LWR)
- Key Take Aways

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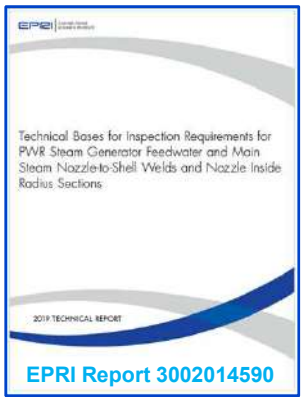
Background and Overview (1/2)

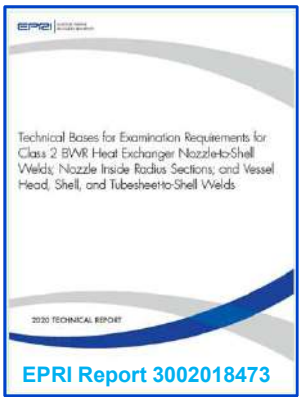
- EPRI developed a **series of technical reports** establishing the technical bases **for optimizing examination intervals** for the components listed in each report title below.
- Following publication of the EPRI technical bases for optimization of NDE examination intervals, several pilot plants submitted “Requests for Alternative” to the US NRC and were granted permission to use the new intervals via Safety Evaluation Reports (SERs)



EPRI Report 3002014590

EPRI Report 3002015906

EPRI Report 3002015905



EPRI Report 3002018473

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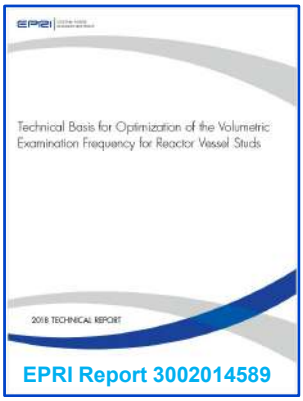
Background and Overview (2/2)

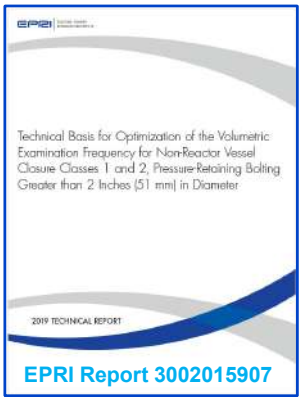
- EPRI developed a **series of technical reports** establishing the technical bases **for optimizing examination intervals** for the components listed in each report title below.
- Following publication of the EPRI technical bases for optimization of NDE examination intervals, several pilot plants submitted "Requests for Alternative" to the US NRC and were granted permission to use the new intervals via Safety Evaluation Reports (SERs)

EPRI Report 3002023713

EPRI Report 3002012966



EPRI Report 3002014589



EPRI Report 3002015907

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Problem Statement (1/2)

There are many examinations being performed that are **perceived** to have **low value** based on a history of **few or no relevant indications** being identified during routine inspections **on prescribed intervals.**

When were these intervals established?

- Generally, 40+ years ago during the construction and early operations eras

Who established these intervals?

- Codes and Standards organizations

How were these intervals established?

- Engineering judgment
- No supporting technical bases were developed

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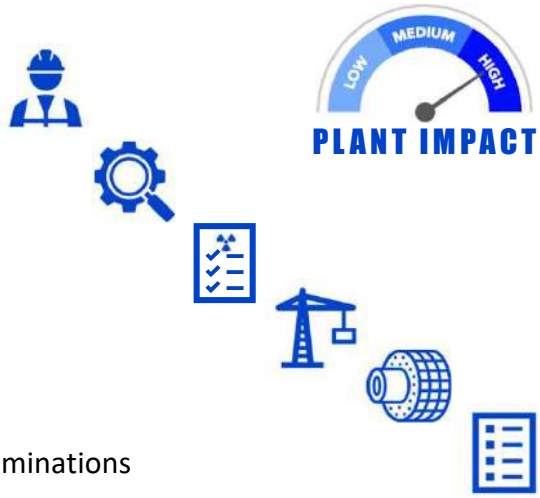
Problem Statement (2/2)

Repetition of low value examinations has significant impact and burden

- **Outage Scope**
  - General health and safety of personnel
  - Radiation exposure (i.e., ALARA)
  - Radiation worker procedures
  - Planning evolutions
  - Pre-job briefs
  - Scaffold building and tear down
  - Insulation removal and reinstallation
  - Contracting vendors to perform the examinations



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Objective

Optimize component examination requirements using:

- Historical operating experience,
- Historical inspection data and results,
- Fundamental engineering methods,
- Modern day analysis tools to develop robust and comprehensive technical bases, and
- All without any adverse impact to the safe and reliable operation of nuclear facilities

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Generic Process

1. Formation of industry/utility focus group (i.e., stakeholders)
2. Survey stakeholders, bounded by common Codes & Standards or Regulation, to create a list of NDE examinations to be evaluated for optimization
3. List and rank survey results collected by the focus group
4. Select examinations categories and items to pursue
5. Survey of utilities for examination and operating experience history
6. Analyze survey results to establish a sub-group of representative reactor designs and/or components
7. Determine component grouping to be analyzed within the same technical basis
8. Collect pertinent component information from established sub-group of utilities or designs
9. Analyze sub-group's components for commonality and applicability range
10. Generate Technical Bases for optimization of examination interval (i.e., final report - next slide)
11. Implement optimized examinations

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Selected Components – Across US Fleet of PWR & BWR Designs

- Accessible Areas of Reactor Vessel Interior (Visual Examination)
- Reactor Vessel Studs
- Non-Reactor Vessel Pressure-Retaining Bolting (< 2" / 51 mm in diameter)
- PWR Steam Generator Feedwater and Main Steam Nozzle-to-Shell Welds and Nozzle Inside Radius Sections
- PWR Steam Generator Auxiliary Feedwater Nozzle-to-Shell Welds and Nozzle Inside Radius Sections
- PWR Steam Generator Primary Nozzle-to-Shell and Pressure Vessel Welds
- PWR Pressurizer Nozzle-to-Shell and Pressure Vessel Welds
- BWR Class 2 Heat Exchanger Nozzle-to-Shell Welds; Nozzle Inside Radius Sections; and Vessel Welds

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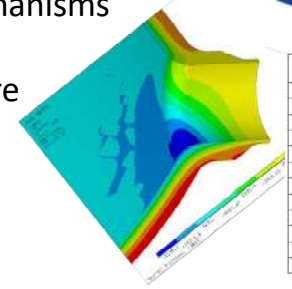
Technical Bases Overview

- Introduction
- Review of Previous Related Work
- Review of Inspection History and Examination Effectiveness
- Survey of Components and Selection of Representative Components for Analysis
- Material Properties, Operating Loads, and Transients
- Evaluation of Potential Degradation Mechanisms
- Component Stress Analysis
- Probabilistic and/or Deterministic Fracture Mechanics Evaluation
- Plant Specific Applicability
- Summary and Conclusions



Sensitivity Study Variable	Importance Factor (%) for Probability of Leakage
Fatigue Crack Growth Rate Coefficient	87.82
Crack Length	9.39
Crack Depth	0.00
Fatigue Crack Growth Rate Threshold	0.01
Fracture Toughness	0.01
Crack Face Pressure	0.04
Pressure	1.82
Residual Stress	0.00
Heat-Up/Cooldown	0.01
Loss of Load	0.04
Load Increase (5%)	0.69
Load Decrease (5%)	0.18

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Generalized Conclusions

- ✓ Results are **consistent with previously implemented strategies**
  - Reduced scope for BWR RPV weld examinations (eliminated circ welds)
  - PWR RPV welds examination frequency extended to 20-years
  - RPV threads in flange
  - PWR Alloy 690 RPV head penetrations nozzles extended to 20-years
  - PWR and BWR inner radius examinations eliminated
- ✓ Analyses **considered 80 years of operation**
- ✓ Results are **acceptable relative to safety margins** (probability of leak or rupture < $1x10^{-6}$ failures per reactor year of operation)
- ✓ Results **support mitigation of personnel health and safety risks**
- ✓ Results **promote ALARA**
- ✓ Results allow **resources and schedule to be focused on higher priority** outage activities

Technical bases support optimizing (deferring) examination intervals

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Summary of Technical Bases Development

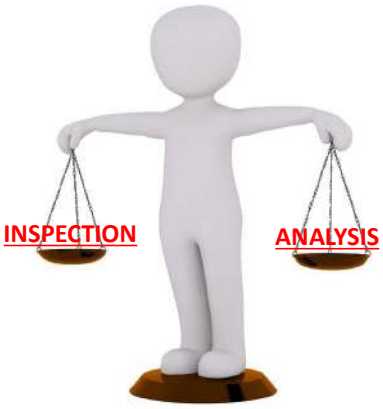
Optimizing NDE Examination Requirements

Establishing The Plan
- Stakeholders
- Bounding Governance
- Target Examinations
- Surveys
- Rank and Prioritize

Operating Experience
- Examination History
- Examination Data & Results
- Industry Guidance Documents
- Supporting Code Actions

Fundamental Engineering
- FEA models
- Evaluation of Operating Conditions
- Evaluation of Transients
- Evaluation of Material Properties
- Evaluation of Degradation Mechanisms

Current Analysis Tools & Software
- Probabilistic Fracture Mechanics
- Deterministic Fracture Mechanics
- Sensitivity Studies



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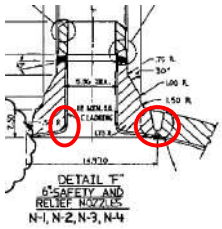
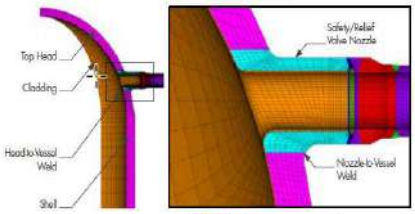
US Implementation Strategy & Benefits (1/3)



Industry leading utilities piloted the implementation of a series of EPRI NDE technical reports establishing the technical bases for optimizing inspection intervals of mandatory ASME component examination requirements, paving the way for other industry members to follow.

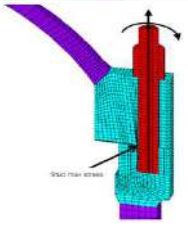
Highlights of Implementation

1. Used the NRC Request for Alternative process
2. First-of-a-Kind applications utilizing PFM as a cornerstone of the analysis
3. SERs received for all pilots allowing for optimized examination intervals up to 30 years
4. Current ASME Code actions leverage Technical Bases and SERs
5. EPRI has compiled a Lessons Learned document and relief request templates to support future submittals



Benefits

1. Maximize overall plant safety by focusing resources where they are needed (higher valued examinations)
2. Minimize health & safety risk profile of plant personnel by reducing low-value work activities
3. Potential cost savings (per unit) is on the order of millions of dollars
4. Potential dose savings (per unit) is on the order of multiple man-rem years



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US Implementation Strategy & Benefits (2/3)

EPRI Technical Basis Report	US NRC Safety Evaluation Report (SER) Issued Utility – Pilot Unit(s)	Combined Estimated Utility Savings
EPRI Report 3002014590, Technical Bases for Inspection Requirements for PWR Steam Generator Feedwater and Main Steam Nozzle-to-Shell Welds and Nozzle Inside Radius Sections	US Nuclear Utility #1 – 2 Units US Nuclear Utility #2 – 1 Unit	**Vogtle** – Granted 30-year examination deferral **Millstone** - Granted examination relief through 60 years (i.e., end of operating licenses, ~14 years) **Savings** - **~$2.4M** across 3 units
EPRI Report 3002015906, Technical Bases for Inspection Requirements of PWR Steam Generator Primary Nozzle-to-Shell and Pressure Vessel Welds	US Nuclear Utility #2 – 1 Unit	Granted examination relief through 60 years (i.e., end of operating license) saving **~$3M** and **~30 man-rem** in dose for 1 unit
EPRI Report 3002015905, Technical Bases for Inspection Requirements of PWR Pressurizer Nozzle-to-Shell and Pressure Vessel Welds	US Nuclear Utility #3 – 2 Units	Granted examination relief through 60 years (i.e., end of operating license) saving **~$400K** and **~6 man-rem** in dose, across 2 units
EPRI Report 3002018473, Technical Bases for Examination Requirements for Class 2 BWR Heat Exchanger Nozzle-to-Shell Welds; Nozzle Inside Radius Sections; and Vessel Head, Shell, and Tubesheet-to-Shell Welds	US Nuclear Utility #4 – 2 Units	Granted examination relief through 60 years (i.e., end of operating license) saving **~$330K** across 2 units. This estimate does not include dose, which also has a significant dollar value associated with it.

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US Implementation Strategy & Benefits (3/3)

EPRI Technical Basis Report	US NRC Safety Evaluation Report (SER) Issued Utility – Pilot Unit(s)	Combined Estimated Utility Savings
EPRI Report 3002012966, Evaluation of Basis for Periodic Visual Examination of Accessible Areas of Reactor Vessel Interior per Examination Category B-N-1 of ASME Section XI, Div. 1 (ASME Code Case N-885)	US Nuclear Utility #4 – 7 Units US Nuclear Utility #2 – 7 Units US Nuclear Utility #5 – 1 Unit US Nuclear Utility #6 – 1 Unit	Granted examination relief on an interval-to-interval basis saving **~$14M** across 16 units, for the remainder of current operating licenses. Dose estimate considerations vary and are less significant on a singular unit basis, but the **cumulative dose savings across the industry** is significant.
EPRI Report 3002014589, Technical Basis for Optimization of the Volumetric Examination Frequency for Reactor Vessel Studs	US Nuclear Utility #5 – 7 Units	Granted examination relief through 60 years (i.e., end of operating license) saving **~$1.5M** and **~2 man-rem** in dose across 7 units
EPRI Report 3002015907, Technical Basis for Optimization of the Volumetric Examination Frequency for Non-Reactor Vessel Closure Classes 1 and 2, Pressure-Retaining Bolting Greater than 2 Inches (51 mm) in Diameter	This report is being implemented directly through the development of an ASME Code Case. Proceedings are currently underway with Code actions being championed by EPRI and Dominion Engineering Inc. staff that participate on the code committees.	

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In Process "Requests for Alternative" with the US NRC

- Steam Generator FW & MS Nozzles, EPRI Report: 3002014590
  - Constellation
  - Southern Nuclear Operating Co.
  - Dominion Energy
  - Duke Energy
- Steam Generator Primary Nozzles & Vessel Welds, EPRI Report: 3002015906
  - Constellation
  - Dominion Energy
  - Duke Energy
- Pressurizer Nozzles and Vessel Welds, EPRI Report: 3002015905
  - Constellation
  - Dominion Energy
  - Duke Energy

Multiple Additional Utilities in Various Stages of Evaluation

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Broader Implementation Strategy for International and SMR (LWR)

- Technical basis must be reviewed by each utility that wishes to apply the results
  - Technical Staff, Licensing, Plant Management
- Applicability of analyses is a plant-specific effort
  - Plant-specific information must be assessed against the technical bases criteria
    - Do your components fall within the bounds of the current analyses?
    - If not, supplemental analyses of plant-specific component parameters can be performed

International Implementation

- Strategy considerations for the technical bases
  - Many international designs are very similar to US designs
  - Should you, or can you, engage with your regulator?
  - Revisions to governing Codes and Standards?
  - ENIQ or other regional licensing processes?

Small Modular Reactors (LWR)

- Strategy considerations for the technical bases
  - Already using qualified materials
  - Should be able to leverage:
    - Established material performance
    - Operating Experience and inspection history from existing LWR fleet
  - Should be factored into inspection intervals

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Key Take Aways

- The earlier this approach can be implemented in a plant's life cycle, the earlier the benefits of personnel health & safety, increased reliability in plant operations, dose savings, and cost savings can be realized
- The combination of plant operating experience and current analytical tools can be, and should be, leveraged
- The process and technical approach utilizes fundamental engineering and analysis principles that can be applied universally
- The existing technical bases may apply directly to international and/or new LWR reactor designs
- The process and analysis can be adjusted to accommodate variability in design or analytical parameters associated with other codes and standards
- There are economies of scale, multiple units or commonality of design across a fleet should be considered

If we knew then what we know now…..would we do it the same?

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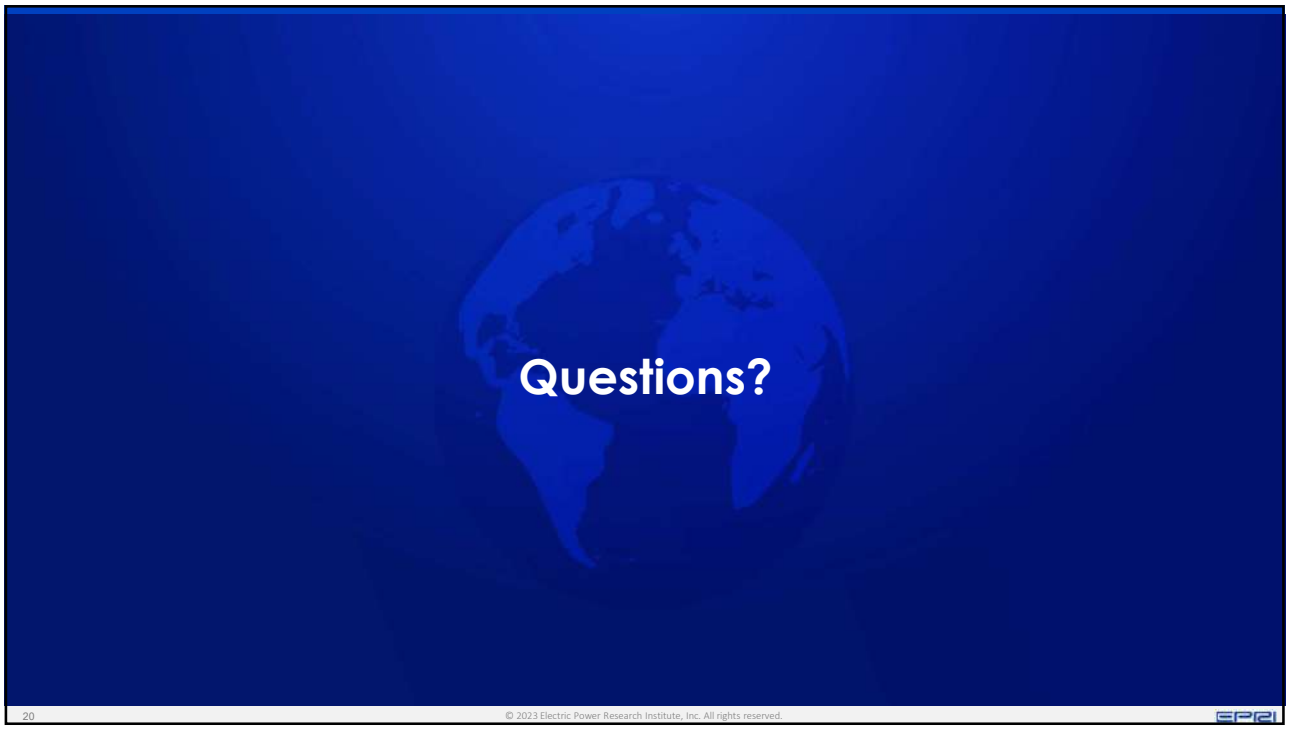

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EPRI

7. Advanced Ultrasonic Inspections

The presentations in this session are listed in the table below.

Advanced Ultrasonic Inspections	**Chair:** David Duxbury (Rolls Royce)
Total Focusing Method Application for Reactor Pressure Vessel Welds: Case Studies	Terrill Massey (EPRI) et al.
Using phase relationships in non-symmetric ToFD configurations	Thomas Bloodworth (Bloodworth Consulting), Mikaël Debroise (Framatome)
Laser-induced ultrasonic phased array imaging for non-contact, non- destructive evaluation of tokamak power plant welds	Matthew Riding (Univ. Strathcycle) et al.
Visualisation of Multi-Frequency Ultrasonic Data	Terrill Massey (EPRI)
LLT-tandem inspection of thick-section welds using phased-arrays	Thomas Bloodworth (Bloodworth Consulting) et al.

Full Matrix Capture / Total Focusing Method Applied to Piping and Reactor Pressure Vessel Welds

Terrill Massey[1], Mark Dennis[1], George Connolly[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): tmassey@epri.com

Full Matrix Capture (FMC) is a data acquisition process in ultrasonics which represents a relatively novel and emerging technology for industrial applications. The Total Focusing Method (TFM) is one data reconstruction method that can be used to process and image FMC data. Based on the potential benefits of FMC/TFM, along with industry interest in the technology there is a need to further investigate its usage as well as to outline a pathway forward for procedure development and regulatory acceptance to support field implementation.

In this research, laboratory case studies were performed on piping and reactor pressure vessel component mockups to compare existing Phased Array Ultrasonic Testing (PAUT) techniques against the emerging FMC/TFM techniques. Also, within this research, a high-level roadmap is presented that can be used to help guide further progression and implementation of this technology in the nuclear Non-Destructive Evaluation (NDE) industry. At the conclusion of this research, a summary and next steps for future research are presented and discussed.

Keywords: Full Matrix Capture (FMC), Non-Destructive Evaluation (NDE), Piping, Total Focusing Method (TFM), Ultrasonic Testing (UT)

.

Total Focusing Method Application for Reactor Pressure Vessels Welds: Case Studies

Tuesday 27 June 2023

Terrill Massey, EPRI, Inc.
Mark Dennis, EPRI, Inc.
George Connolly, EPRI, Inc.
Adam Conti, DCR Workforce
Giovanni Gbemudu, DCR Workforce
James Neale, DCR Workforce

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Outline

- PAUT vs TFM case studies:
  - Reactor Pressure Vessel (RPV) Mockup
  - Dissimilar Metal Weld (DMW) Mockup
  - Discussion of comparative results
  - All data acquired by certified UT Level II examiners and reviewed by certified UT Level III examiners
- Perspectives on Industrial Implementation of matrix capture techniques
- Summary

Report #3002023708 publically available at epri.com

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RPV Mockup

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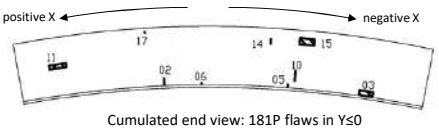
Mockup and Apparatus

RPV Mockup

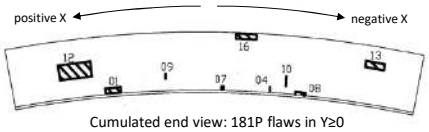
- Mockup 181P Attributes:
  - Ø259.3in. (6.58m) at OD
  - Thickness: 6.63in. (168mm)
  - Material: Carbon steel
    - Stainless steel cladding at ID, 0.33in. (8.4mm)
  - 7 circumferential flaws; 10 axial flaws
- Instrument:
  - Zetec TOPAZ64
  - Acquisition software: UltraVision Touch 3.10R20
  - Analysis software: UltraVision 3.10R20
  - Free scanning; no encoding

SEARCH UNIT ATTRIBUTES

Attribute	First Search Unit	Second Search Unit
Probe	Krautkramer 115-000-018	GEIT 115-000-292
Centre frequency	2.0MHz	2.25MHz
Aperture	64 el	32 el
Pitch	1.0mm	3.1mm
Wedge	Krautkramer 118-340-306	GEIT 360-141-072
Wedge Angle	21.5°	14.7°



Cumulated end view: 181P flaws in Y≤0



Cumulated end view: 181P flaws in Y≥0

First Search Unit on Mockup

Second Search Unit on Mockup

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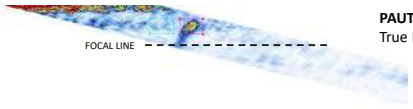
Acquisition Techniques

RPV Mockup

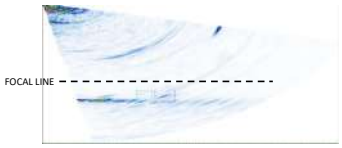
- Four simultaneous acquisitions
- Three PAUT channels based upon a qualified PD technique
  - Evaluation carried out offline after acquisition
  - In practice two manual scans are needed to interrogate zone 1 (initial 2 in.) and zone 2 (remainder after initial 2 in.)
- One Half Matrix Capture (HMC) channel
  - Frame resolution: (1024×1024)pix.
  - Grid resolution: (0.18×0.23)mm
  - Amplitude fidelity: 0.2dB
  - The full volume can be interrogated in a single scan
- Focal attributes determined in real-time by the UT technician separately for each flaw
  - TFM removes this complication

ACQUISITION ATTRIBUTES

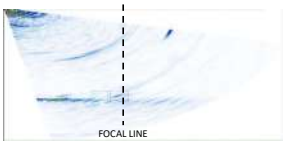
Channel	Scan Type	Scan Angle(s)	Active focus	Area of Interest
PAUT 1	Linear L	65°	True Depth	Initial 2 in. thickness
PAUT 2	Azimuthal L	10° to 70° in 1° increment	True Depth	Remainder after initial 2 in. thickness
PAUT 3	Azimuthal L	10° to 70° in 1° increment	Projection	Remainder after initial 2 in. thickness
HMC 4	L-L	*n/a*	None	Total



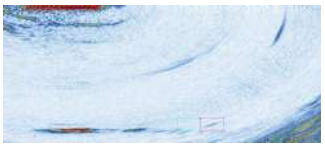
PAUT 1
True Depth Focus in Zone 1



PAUT 2
True Depth Focus in Zone 2



PAUT 3
Projection Focus in Zone 2



HMC 4

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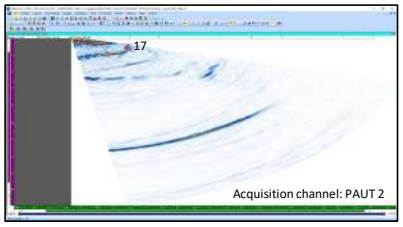
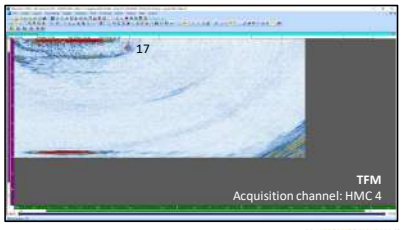
Evaluation Example in Zone 1

RPV Mockup

- First search unit (2.0MHz, 21.5° wedge angle)
- Flaw 17 (embedded)
- Scanning in negative X direction
- Flawed region (magenta) and “clean” region (cyan) for SNR computation

Acquisition	Actual TWS	Measured TWS	Difference	Mean SNR	Max SNR
PAUT 1 (zone 1)	2.5mm	2.6mm	0.1mm	30.8dB	16.5dB
PAUT 2 (zone 2)		2.9mm	0.4mm	29.3dB	19.1dB
PAUT 3 (zone 2)		2.9mm	0.4mm	29.4dB	18.2dB
HMC		2.8mm	0.2mm	30.9dB	18.4dB





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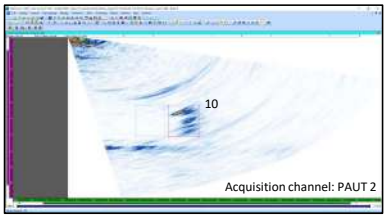
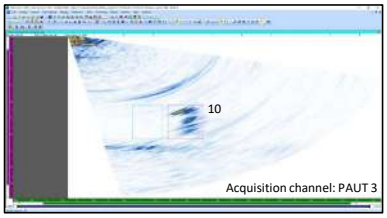
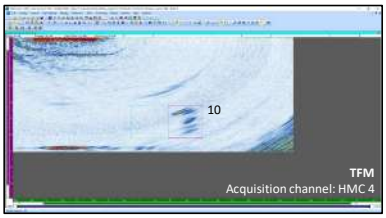
Evaluation Example in Zone 2

RPV Mockup







- First search unit (2.0MHz, 21.5° wedge angle)
- Flaw 10 (embedded)
- Scanning in positive X direction
- Flaw appears in zone 2 so PAUT 1 (zone 1 acquisition) not applied
- Flawed region (magenta) and "clean" region (cyan) for SNR computation

Acquisition	Actual TWS	Measured TWS	Difference	Mean SNR	Max SNR
PAUT 2 (zone 2)	27.4mm	28.6mm	1.2mm	31.1dB	14.3dB
PAUT 3 (zone 2)		28.6mm	1.2mm	33.2dB	19.7dB
HMC		28.5mm	1.1mm	26.4dB	11.2dB

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Discussion

RPV Mockup

- First search unit shows consistently superior TWS capability
- Second search unit often shows superior SNR
- Strengths of the HMC/TFM
  - Only one scan required for entire volume
  - Currently-qualified PAUT technique requires 2-3 scans
  - Potentially greater performance at higher steering angles
- Limitations of the HMC/TFM
  - Comparable but greater TWS error
  - Comparable but lower SNR
  - Instrument capability limited at the time to HMC; future releases capable of TFM and PWI

COLLATED RESULTS AVERAGED ACROSS FLAWS

Search unit	Acquisition	Average TWS Error	TWS RMSE	Average Mean SNR	Average Max SNR
First (2.0MHz, 64-el, 21.5° wedge angle)	PAUT 1 (zone 1)	0.1mm	0.2mm	28.2dB	15.3dB
	PAUT 2 (zone 2)	0.8mm	1.1mm	26.8dB	13.2dB
	PAUT 3 (zone 2)	0.8mm	1.1mm	27.1dB	14.1dB
	HMC	0.8mm	1.1mm	24.3dB	9.5dB
Second (2.25MHz, 32-el, 14.7° wedge angle)	PAUT 1 (zone 1)	1.1mm	1.1mm	38.3dB	16.1dB
	PAUT 2 (zone 2)	1.7mm	2.5mm	25.7dB	14.4dB
	PAUT 3 (zone 2)	1.7mm	2.5mm	25.3dB	13.7dB
	HMC	1.8mm	2.6mm	26.1dB	11.9dB

Comprehensive imaging results for both search units available in Appendix A of #3002023708

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DMW Mockup

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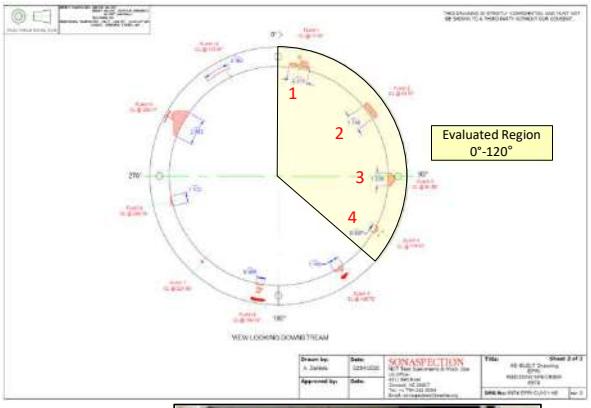
Mockup and Apparatus

DMW Mockup

- Mockup 6974-EPRI-CUI-01-AB Attributes:
  - Ø28in. (711mm) at OD
  - Thickness: 2.1in. (54mm)
  - Material: Carbon steel
    - Stainless steel cladding at ID, 0.33in. (8.4mm)
  - 10 circumferential flaws; some embedded and some surface-connected
- Instrument:
  - Zetec DYNARAY (256/256PR)
  - Software: UltraVision 3.10R20
  - Encoding in three scan line pattern

SEARCH UNIT ATTRIBUTES

Attribute	Value
Probe	Imasonic CL (DMA)
Centre frequency	1.5MHz
Aperture	(32×2) el
Pitch	[2.0,7.5]mm
Wedge	Zetec ADUXE171A
Wedge Angle	22.3°



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Acquisition and Post-Processing

DMW Mockup

- Two simultaneous acquisitions: One PAUT and one FMC
- PAUT channel post-processing
  - Volumetric merge at high resolution similar to PD qualified technique
- FMC channel post-processing
  - Frame resolution: (512×512)pix.
  - Grid resolution: (0.30×0.20)mm
  - Post-processed twice:
    - Delay Multiply and Sum (DMAS)
    - Sectorial Total Focusing (STF) with DMAS and corresponding volumetric merge
- Quantitative data processing to yield SNR and TWS for each flaw

Zetec DYNARAY acquisition instrument

ACQUISITION ATTRIBUTES

Attribute	Value
Scan Resolution	0.25in. (6.35mm)
Index Resolution	0.5° (3.0mm)
Acquisition Rate	0.6Hz
Scan Speed	1.3mms^{-1}

ACQUISITION ATTRIBUTES

Channel	Scan Type	Scan Angle	Active focus
PAUT	Azimuthal L	10° to 70° in 1° increment	2.0in. (50.8mm) half path
FMC	L-L	*n/a**	None

* STF angles in post-processing: 0° to 70° in 1° increment

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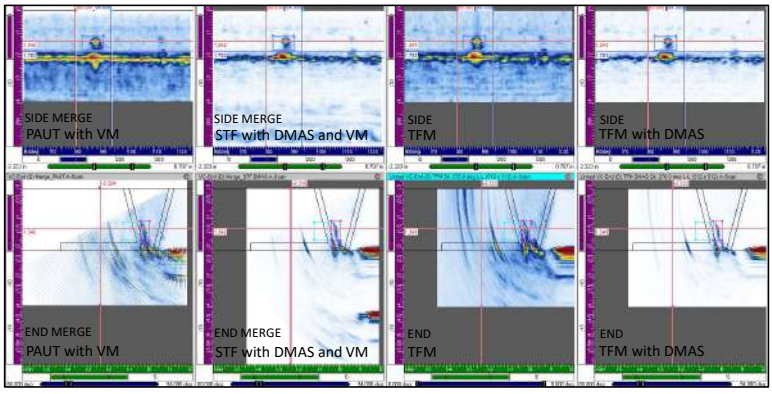
Imaging Example: Surface-connected flaw

DMW Mockup

- Flaw 3 (surface-connected) on DS side
- Flawed region (magenta) and “clean” region (cyan) for SNR computation
- Reference cursor (red) indicates flaw tip
- STF DMAS post processing technique displayed the best continuity between the flaw base and tip



Imaging	Actual RL	Measured RL	RL Error	Mean SNR	Max SNR
PAUT with VM	34.0mm	34.1mm	0.1mm	39.4dB	14.3dB
STF with DMAS and VM		34.1mm	0.1mm	52.4dB	26.8dB
TFM		34.1mm	0.1mm	32.6dB	15.3dB
TFM with DMAS		34.1mm	0.1mm	57.4dB	28.2dB

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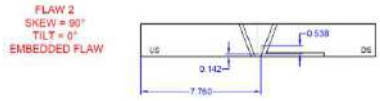
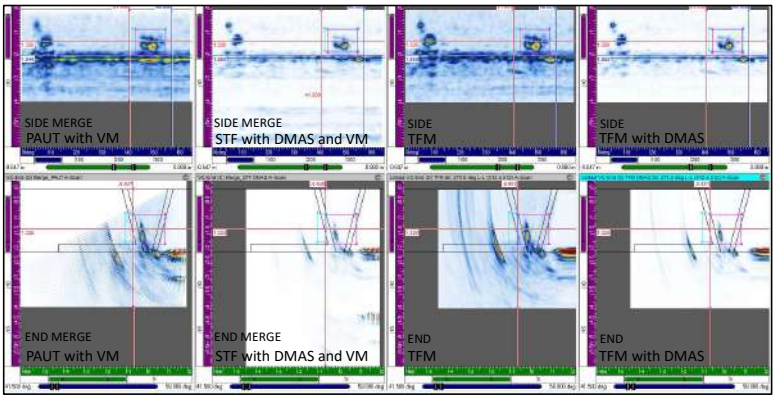
Imaging Example: Embedded flaw

DMW Mockup



- Flaw 2 (embedded) on DS side
- Flawed region (magenta) and “clean” region (cyan) for SNR computation
- Reference cursor (red) indicates flaw tip
- The TFM DMAS post processing technique displays the best resolution for characterizing the flaw as embedded and not surface connected



Imaging	Actual RL	Measured RL	RL Error	Mean SNR	Max SNR
PAUT with VM	33.7mm	33.7mm	0.0mm	40.5dB	19.3dB
STF with DMAS and VM		33.7mm	0.0mm	67.5dB	32.4dB
TFM		33.7mm	0.0mm	34.4dB	17.9dB
TFM with DMAS		33.7mm	0.0mm	63.3dB	32.6dB

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Discussion - DMW Mockup Results

- TWS results similar for all UT techniques
- Images derived from FMC displayed sharper flaw tip responses than the standard PAUT technique due to superior focusing
  - Evaluation of the image post-processing methods to potentially assist examiners in distinguishing between embedded and surface connected defects
- DMAS post-processing techniques yielded the best SNR and image quality
  - Important characteristics when determining whether or not a defect is embedded and surface-connected defects
  - Supportive of our earlier work in 2019-2020 [1,2] demonstrating that FMC/TFM can identify flaws that are embedded very closely to the surface

COLLATED RESULTS AVERAGED ACROSS FLAWS

Acquisition	Imaging	Average TWS Error	TWS RMSE	Average Mean SNR	Average Max SNR
PAUT	VM	0.5mm	0.7mm	34.5dB	12.0dB
FMC	TFM	0.5mm	0.7mm	29.0dB	12.1dB
FMC	TFM with DMAS	0.5mm	0.7mm	52.2dB	22.3dB
FMC	STF with DMAS and VM	0.5mm	0.7mm	50.7dB	21.4dB

[1] Quantitative Evaluation of Advanced Imaging Hardware for Ultrasonic Inspections. EPRI, Palo Alto, CA: **2019**. 3002015973
[2] Full Matrix Capture (FMC)-Based Ultrasonic Testing (UT) in Practical Piping Applications. EPRI, Palo Alto, CA: **2020** 3002016272

Comprehensive imaging results for both search units available in Appendix B of #3002023708

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Perspectives on Industrial Implementation of Matrix Capture Techniques

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High-Level Roadmap

Perspectives on Industrial Implementation of Matrix Capture Techniques

- Conceptual overview of tasks in focus areas to address for industrial implementation of TFM
  - Equipment
  - Workforce
  - Industry Engagement
  - Technology Deployment
- The advanced ultrasonic MC techniques roadmap includes the following major activities:
  - Leveraging Resources and Collaboration
  - Technology Development
  - Technology Transfer

High-level Tasks	Phase 1	Phase 2	Phase 3	Phase 4
Equipment				
Survey of Matrix Capture Instruments				
Survey of Image Reconstruction Algorithms				
Development of Time Efficient Matrix Capture and Image Reconstruction Hardware and Software				
Workforce				
Integration into Ultrasonics Computer Based Training and Distance Learning Programs				
Data Generation for Artificial Intelligence Algorithms				
Availability of User-friendly Data Acquisition and Processing Tools				
Industry Engagement				
Utility Engagement to Identify & Prioritize Applications				
Collaboration with Advanced Manufacturing Researchers and Vendors				
Collaboration with Robotics Manufacturers for Autonomous Examinations				
Technology Deployment				
Laboratory Testing with Realistic Mockups				
Field Trials				
Adaptation of Existing Codes to Address Matrix Capture and Image Reconstruction as Needed				
Examination Procedure Development & Demonstration as Needed				

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Roadmap Tasks Summary

Perspectives on Industrial Implementation of Matrix Capture Techniques

- Leveraging Resources and Collaboration
  - Survey of other industries implementing similar technologies
  - Collaboration with vendors for more flexibility and support of FMC
- Technology Development
  - Identification of key parameters for technology guidance in codes and standards
  - Procedure development involving sensor selection, ultrasonic settings, and reconstruction inputs
  - Exploration of AI and autonomous robotics for NDE personnel safety
- Technology Transfer
  - Develop best practices for the use of FMC and TFM for vendors and utilities for incorporation into ultrasonic examination procedures
  - Training opportunities for the NDE practitioner workforce
  - Regulatory acceptance and support for later technology guidance

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Summary

- Two case studies from weld mockups
- General observations:
  - Similar TWS performance for both case studies
  - PAUT provides slightly better SNR with active focusing than HMC
  - DMAS post-processing improved SNR and flaw characterisation ability
  - Report #3002023708 also provides information on a third case study: Weld Overlay Repair on a EPRI mockup
- Equipment used during this study is the same as that used by EPRI utility members and/or their inspection vendors as part of industry-qualified procedures for RPV, DMW and WOR applications
  - All data acquired by certified UT Level II examiners and reviewed by certified UT Level III examiners
- A high-level roadmap has been developed to guide stakeholders in industrial implementation of FMC-based techniques

Report #3002023708 publically available at epri.com

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Using phase relationships in non-symmetric ToFD configurations

Thomas Booodworth[1], Mikaël Debroise[2]

[1]Bloodworth Consulting Limited, Wigan, UK
[2]Framatome, 71380 St Marcel, France

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E-mail address (corresponding author): tbloodworth@btinternet.com

In conventional ToFD, operators are taught that diffracted echoes from the top and bottom of a planar defect have opposite phase and such defects can thus be discriminated from a pair of slag lines. This phase-inversion test is therefore used as a tool for characterizing an indication. When using non-symmetric probe arrangements and less-conventional beam angles, the situation becomes less clear-cut.

Early in the development of the ToFD technique in the 1980s and 1990s, theoretical models enabled the amplitude and phase of diffracted signals from a crack edge for any incident and diffracted angle. Experimental studies at the time gave results that supported the theoretical predictions in idealized situations, but showed that for finite pulses and finite probe dimensions, it was more difficult to confirm the predictions for phase.

In an inspection of a weld in a high-integrity component for the Hinkley Point C power station an asymmetric ToFD design was adopted as a solution to an access restriction. Comparison of top/bottom phase of indications was used as part of the procedure for characterization of indications.

An analysis is made of the reasons why certain asymmetric configurations could not be used to identify planar defects using top-bottom phase inversion. The resulting re-design of the ToFD inspection configurations for a non-symmetrical inspection surface is presented, in which phase inversion remains a robust tool for defect characterization.

Keywords: Ultrasonic testing, time-of-flight diffraction, defect characterization, phase inversion.

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Using phase relationships in non-symmetric ToFD configurations

Tom Bloodworth

NDE in Nuclear 2023
Sheffield, June 2023

Phase relationships in ToFD

- How the phase of echoes is usually used in ToFD
- What about when the ToFD configuration is not symmetric?
- The conditions for phase inversion – general case
- Loci of phase inversion
- Design of non-symmetric ToFD configurations that show top/bottom phase inversion

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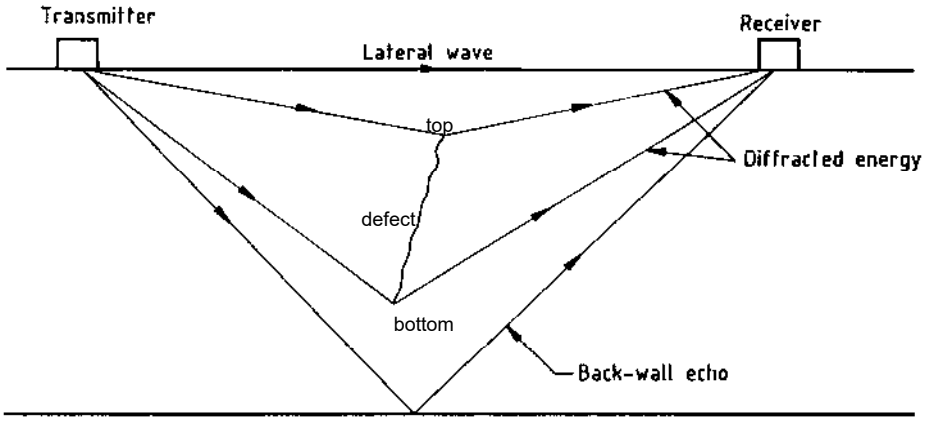
Conventional ToFD configuration



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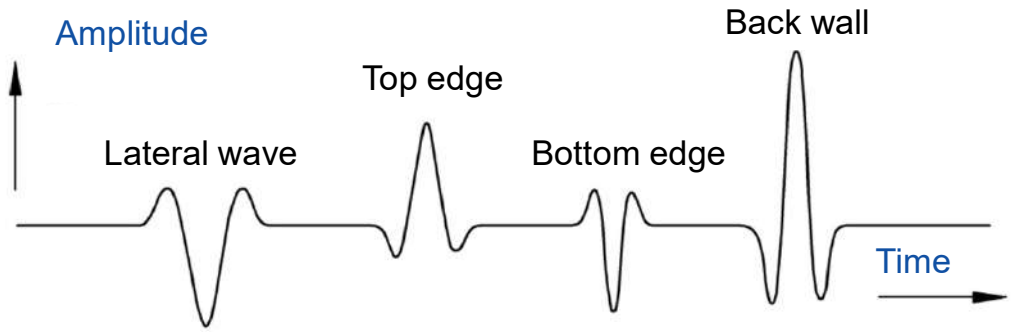
Conventional ToFD phase relationships



- LW and BW have opposite phase
- Top and bottom have opposite phase
- Discrimination between separate indications and top/bottom edges

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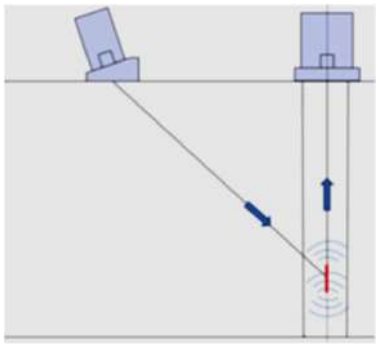
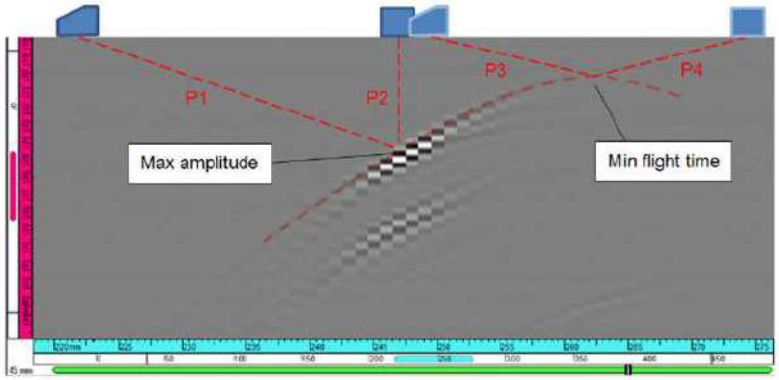
Asymmetric “ToFD”





- Used because of restricted access on one side
- Max amplitude used rather than minimum flight time
- Can we rely on top and bottom edges having opposite phase?

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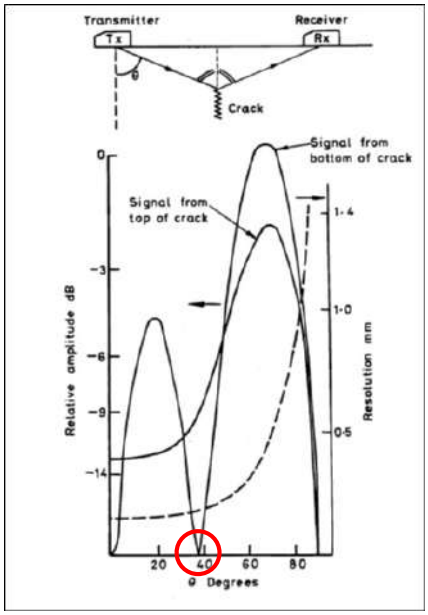
Top- and bottom-edge diffraction amplitudes



Classic (and often reproduced) image from Ogilvy and Temple 1983 paper for symmetrical configuration and defect without tilt

Amplitude from bottom edge crosses zero at about 38°

This is where echo amplitude changes sign; i.e. echo changes phase.

Bottom-edge phase on second peak is opposite to top-edge phase.

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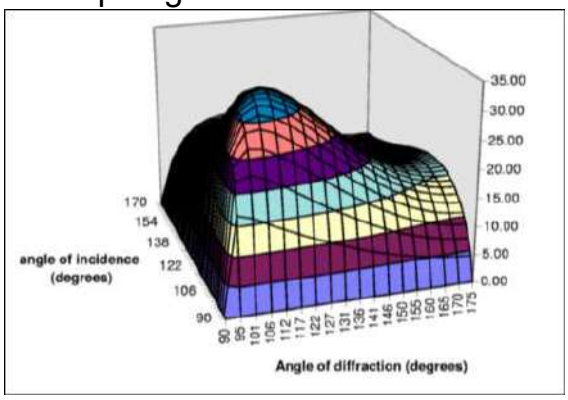
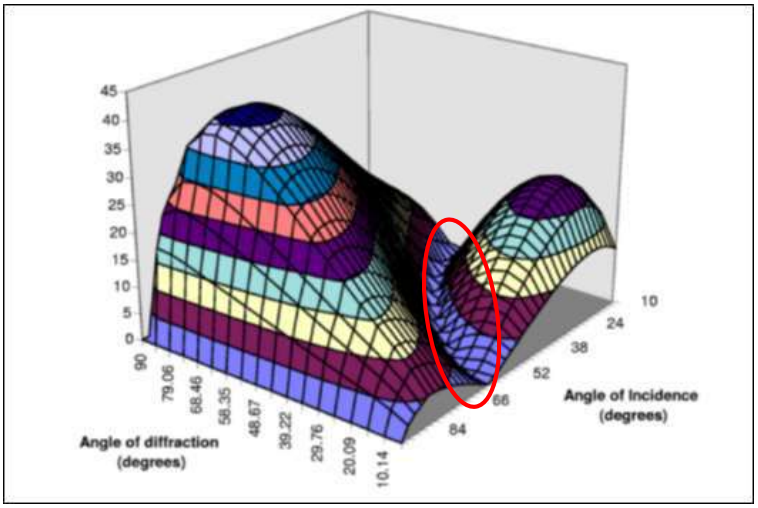
Top- and bottom-edge diffraction amplitudes

Amplitudes from Ogilvy and Temple 1983 paper for all transmit and receive beam angles

Top edge





Bottom edge

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Experimental verification of phase behaviour

Ogilvy's expressions are for a simplified monochromatic model in which phase changes by 180°

Ravenscroft *et al*. (1991) verified the predictions with laser-generated pulses

Results for real probes with finite dimensions and finite pulse length were less clear.

Signal phase behaviour for a real pulse is more complicated than just a 180° flip.

However the Ogilvy expressions are a starting point.

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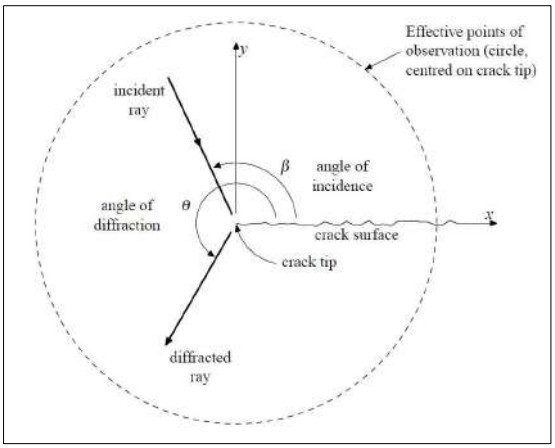
Conditions for phase change

from Ogilvy's L-L diffraction coefficients

$$\sin ½\beta \left\{\sin ½\theta\left(2k_p^2\cos^2\beta - k_s^2\right)\left(2k_p^2\cos^2\theta - k_s^2\right) + 2k_p^3\cos ½\beta\cos\beta\sin 2\theta\left(k_s - k_p\cos\theta\right)^{½}\left(k_s - k_p\cos\beta\right)^{½}\right\} = 0$$



Compression (L) velocity	v_p	5920 ms^{-1}
Shear (T) velocity	v_s	3230 ms^{-1}
Frequency	f	5 MHz
Compression wave vector	$k_p = 2\pi f / v_p$	5.31 mm^{-1}
Shear wave vector	$k_s = 2\pi f / v_s$	9.73 mm^{-1}

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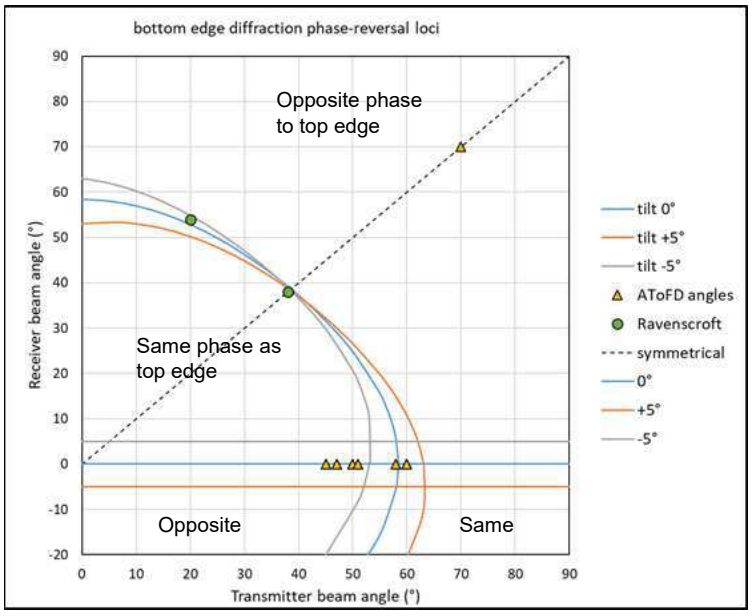

Phase-change loci

Loci of bottom-edge phase-reversal conditions according to Ogilvy expressions

Phase of asymmetric ToFD echoes is not well-defined

Top-bottom phase inversion not reliable for defect characterization

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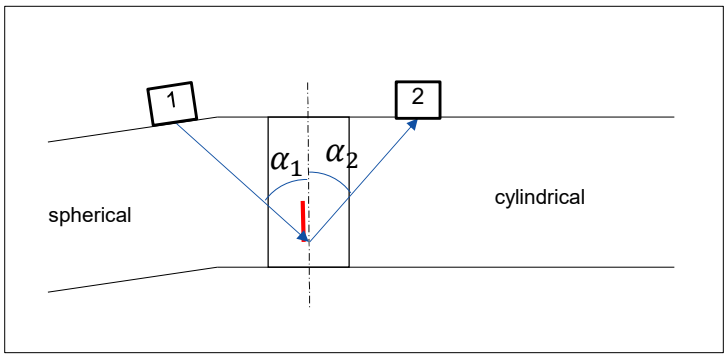
Re-design of ToFD inspection

- Straddling configuration
- Shortest time-of-flight is not symmetrical ($\alpha_1 \neq \alpha_2$)



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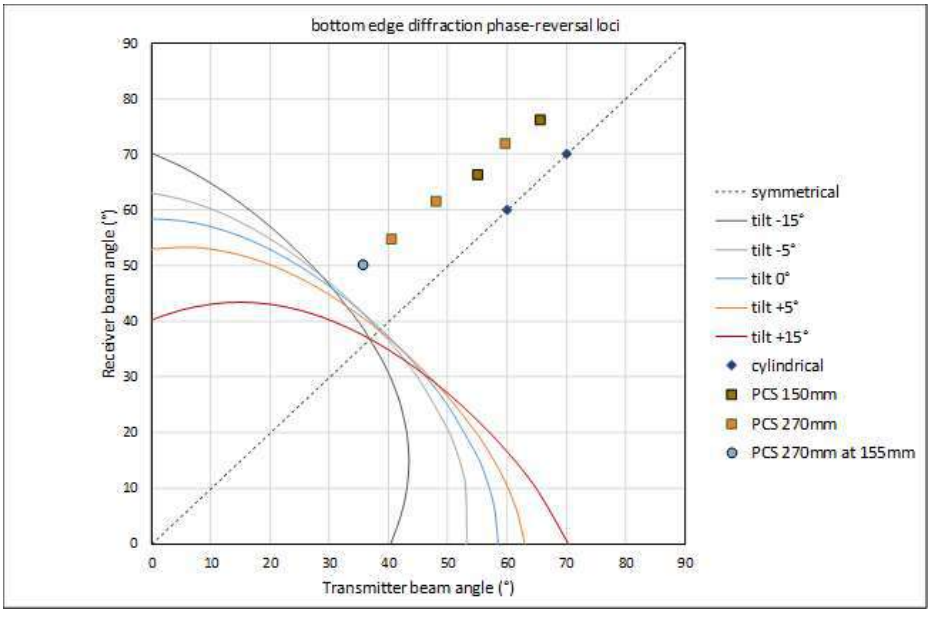
Phase-change loci for new design



PCS and beam angles adjusted to keep (α_1, α_2) outside the arcs

So we can expected top and bottom to have opposite phase

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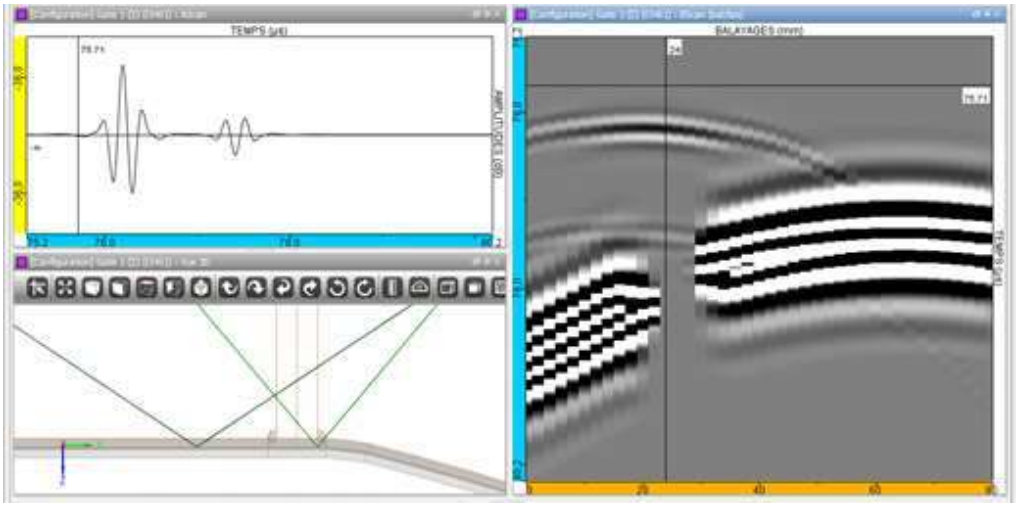
Civa simulation of straddling ToFD inspection

- Near the back-wall; smallest effective beam angles (worst case)
- Top and bottom show opposite phase



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13

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Phase relationships in non-symmetric ToFD

The conclusion is

- If you have a non-conventional, non-symmetric ToFD configuration,
- if you want to use the phase relationship between top and bottom edges to characterize a defect,
- it is worth adjusting PCS and beam angles to ensure that the “bottom edge” incident and diffracted angles are outside the phase-change locus

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14

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Thanks for listening.

Are there any questions?

Laser-induced ultrasonic phased array imaging for non-contact, non-destructive evaluation of tokamak power plant welds

Matthew Riding[1], Yao Ren[2], Don Pieris[1], Peter Lukacs[1], Geo Davis[1], Charles MacLeod[1], Theodosia Stratoudaki[1]
1 University Of Strathclyde, Glasgow, UK
2 RACE United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon Oxfordshire, UK

E-mail address (corresponding author): matthew.riding@strath.ac.uk

Most maintenance and component replacement strategies for tokamak power plants foresee the use of robotic welding tools to form pipe connections remotely in a radioactive environment [1]. Non-destructive evaluation (NDE) is an essential accompaniment to welding in safety-critical applications, and will be necessary to confirm that all remotely fabricated joints meet the strict quality standards imposed by plant operational requirements and nuclear regulation. Relevant NDE techniques must be compatible with remote deployment in the radioactive, high-cleanliness environment of a tokamak power plant, whilst meeting the regulatory requirements for inspection accuracy and sensitivity. Laser-induced ultrasonic phased array imaging is a fully non-contact, couplant-free NDE technique [2]. These characteristics are highly advantageous in the environment of a tokamak power plant when compared with piezoelectric, transducer-based techniques which require physical contact, force, and a form of couplant. In this technique, laser beams are used to generate and detect ultrasound at the surface of a component. The beams are scanned, collecting ultrasonic signals from various locations, which are subsequently used to synthesise an ultrasonic phased array in post-processing. Acoustically reflective sub-surface features can then be imaged using a conventional ultrasonic phased-array imaging algorithm (the total focussing method). The authors present the results from lab-scale experiments testing the capability of laser-induced ultrasonic phased array imaging to detect defects in weld samples relevant to tokamak power plant designs. The technique is shown to be capable of detecting a variety of sub-surface defects in welds covering a range of thicknesses and alloys (such as EUROFER 97, P91 and stainless steel 316). The results motivate future work toward in-situ deployment of the technique via an in-pipe scanning tool, as well as an assessment of the applicability of the technique to other NDE challenges in tokamak power plants, such as the in-situ inspection of plasma-facing components.

Keywords: Laser ultrasonics, welds, tokamak, laser phased arrays, ultrasonic imaging

References:

[1] Kirk, S., Keogh, L., Naidu, L., & Tremethick, T. (2020). In-bore robotic laser cutting and welding tools for nuclear fusion reactors. Lasers Eng., 46, 295-304.
[2] Pieris, D., Stratoudaki, T., Javadi, Y., Lukacs, P., Catchpole-Smith, S., Wilcox, P.D., Clare, A. and Clark, M., 2020. Laser Induced Phased Arrays (LIPA) to detect nested features in additively manufactured components. Materials & Design, 187, 108412.

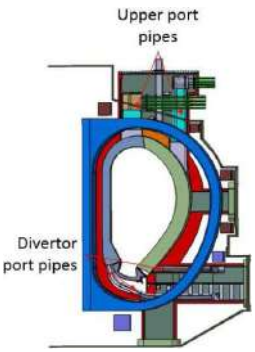
THE PLACE OF USEFUL LEARNING

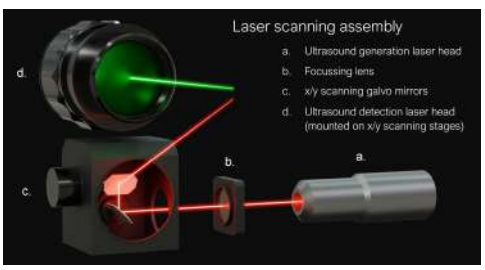
Laser-induced ultrasonic phased array imaging for non-contact, non-destructive evaluation of tokamak power plant welds

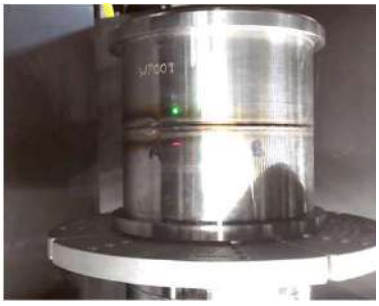
Matthew Riding[1] (matthew.riding@strath.ac.uk), Peter Lukacs[1], Geo Davis[1], Don Pieris[1], Yao Ren[2], Charles MacLeod[1], Theodosia Stratoudaki[1]

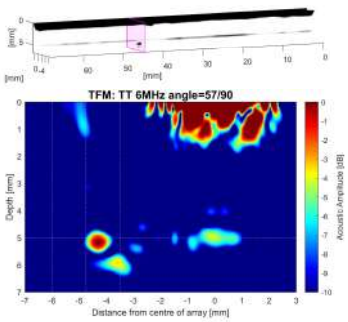
[1]University of Strathclyde, Department of Electrical and Electronic Engineering
[2]United Kingdom Atomic Energy Authority / RACE

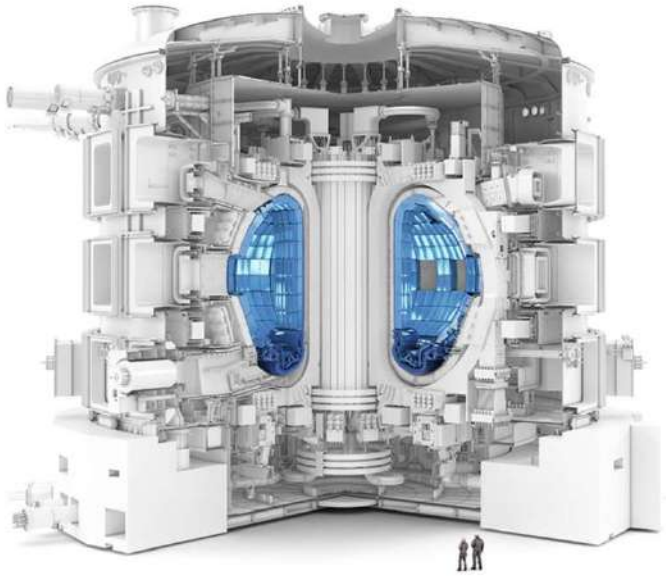
Presentation overview:











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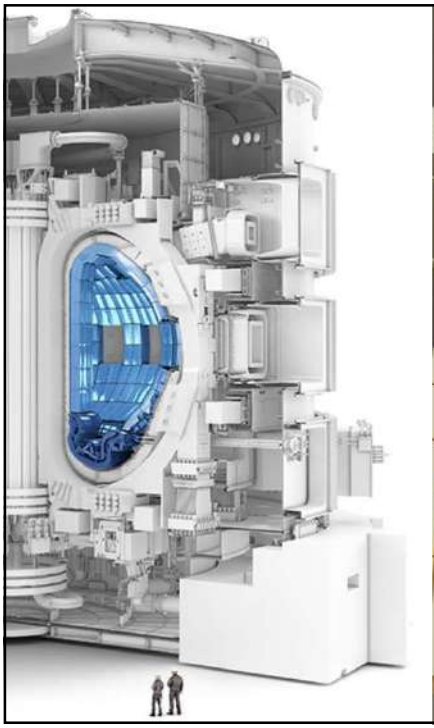
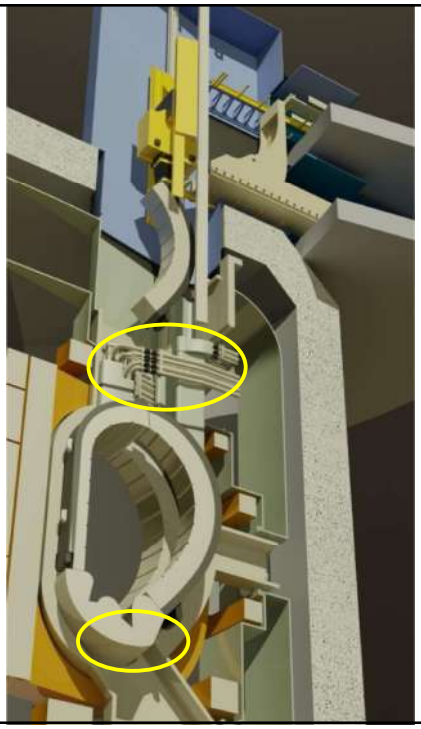


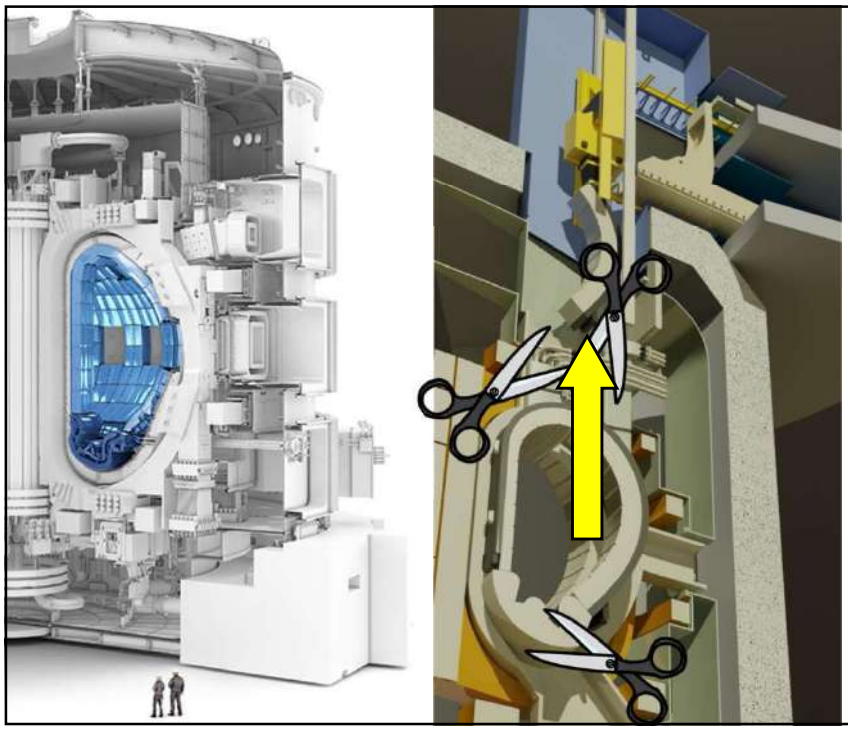


Vertical maintenance concept

Pipes:

For coolant (water, helium) or tritium breeding material (e.g. molten Li, LiPb eutectic)

4

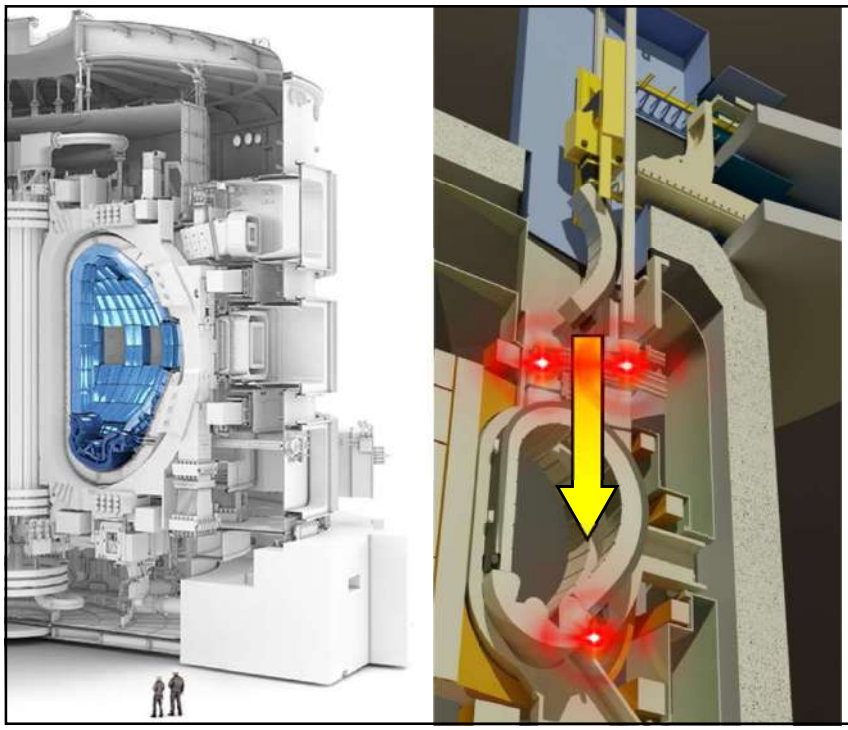


Vertical maintenance concept

Pipes:

Dis-connect: Cutting

5



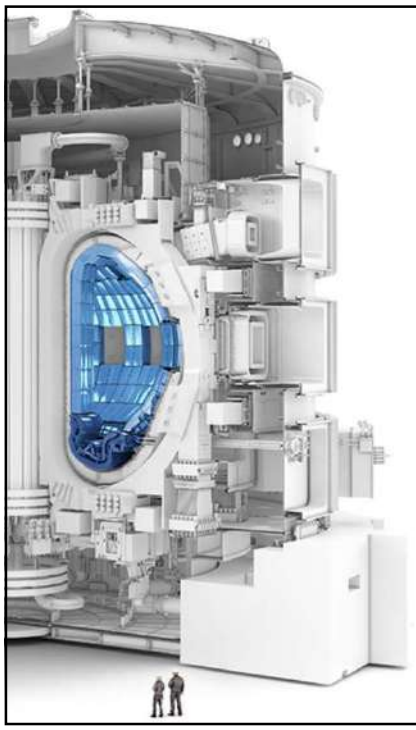
Vertical maintenance concept

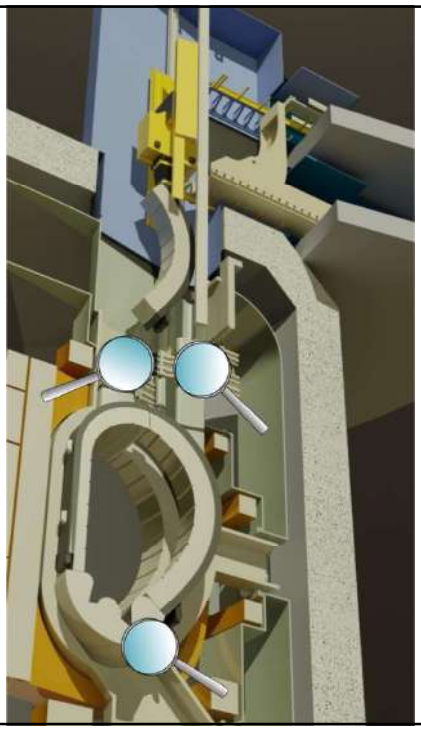
Pipes:

Dis-connect: Cutting

Re-connect: Welding

6





Vertical maintenance concept

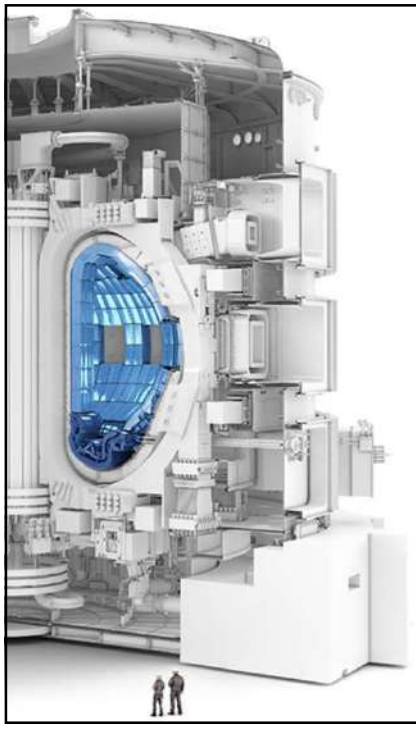
Pipes:

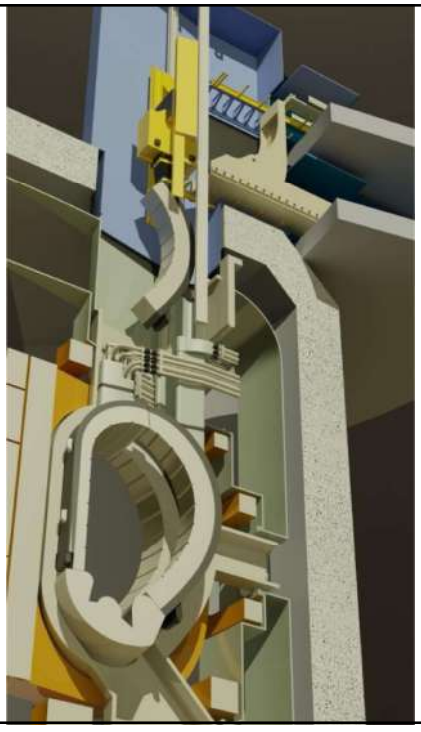
Dis-connect: Cutting

Re-connect: Welding

Post-welding: NDE

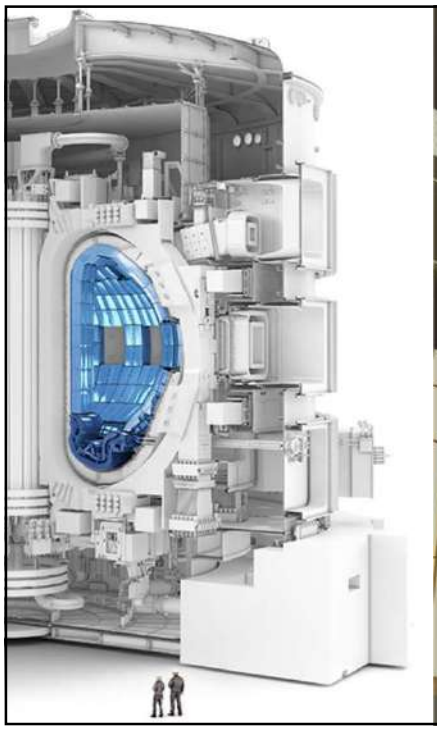
7





Operational environment

8



Operational environment

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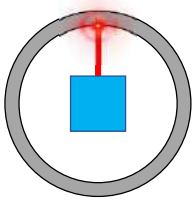
Operational environment

Cutting, welding & NDE constraints

No human access.
Remote, robotic operations only.

In-bore tool access only



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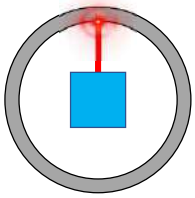
Operational environment

Cutting, welding & NDE constraints

No human access.
Remote, robotic operations only.

In-bore tool access only



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Operational environment

Cutting, welding & NDE constraints

No human access.
Remote, robotic operations only.

In-bore tool access only

May limit applicable NDE techniques (e.g. no couplant)

12

Previous UKAEA/RACE project

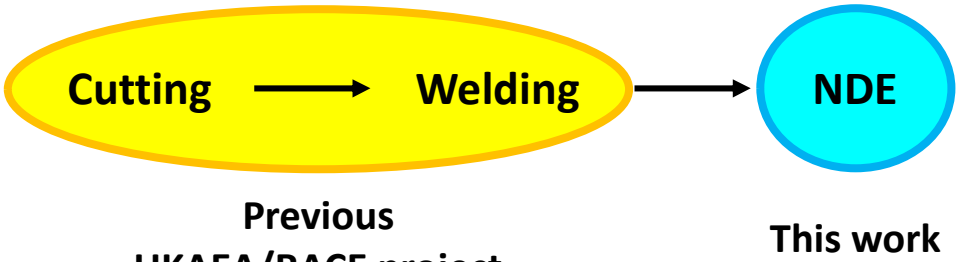
13

Prototype RACE / UKAEA cutting and welding solutions:

14

Prototype RACE / UKAEA cutting and welding solutions:

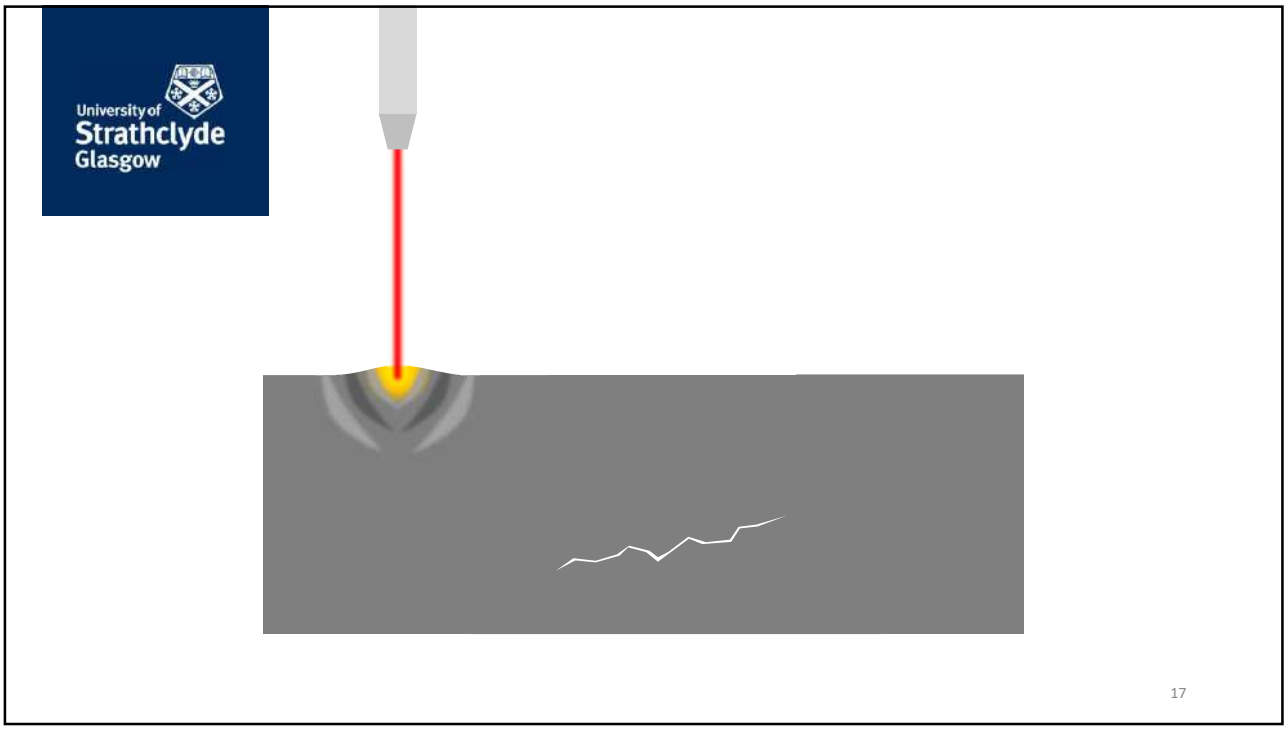
5



Previous UKAEA/RACE project

This work

16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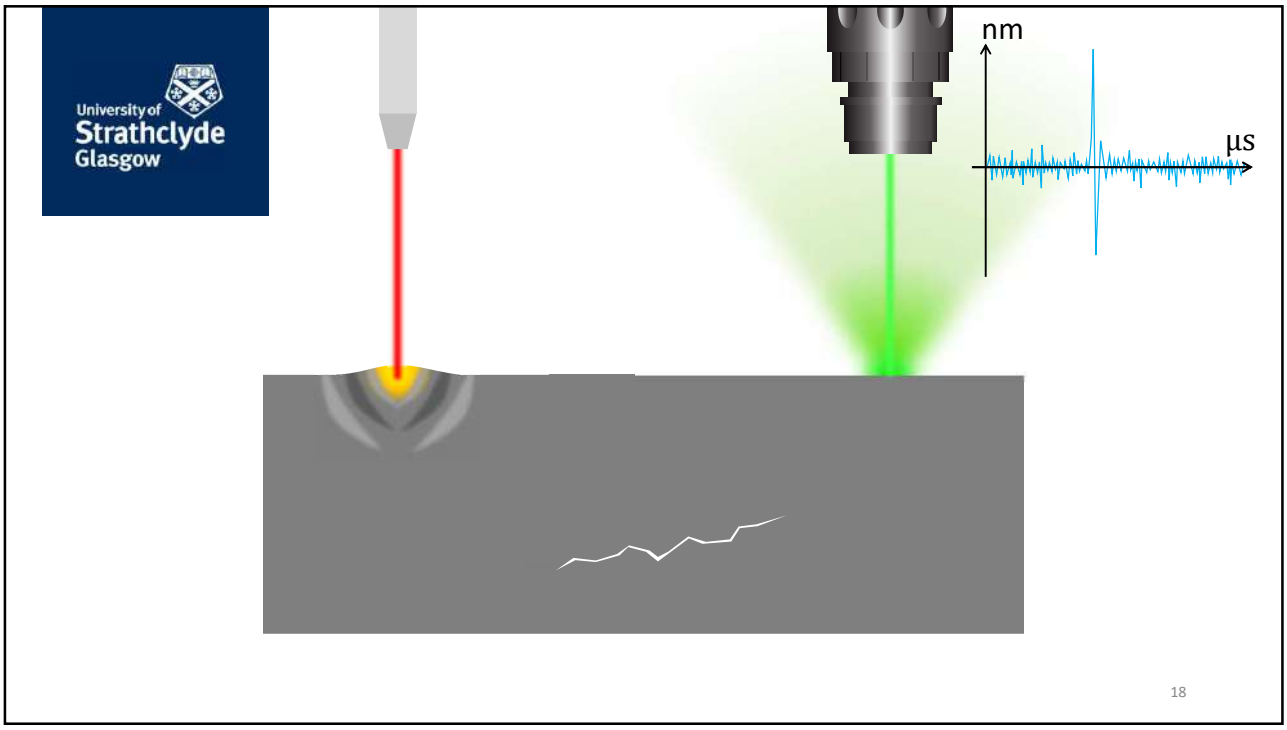
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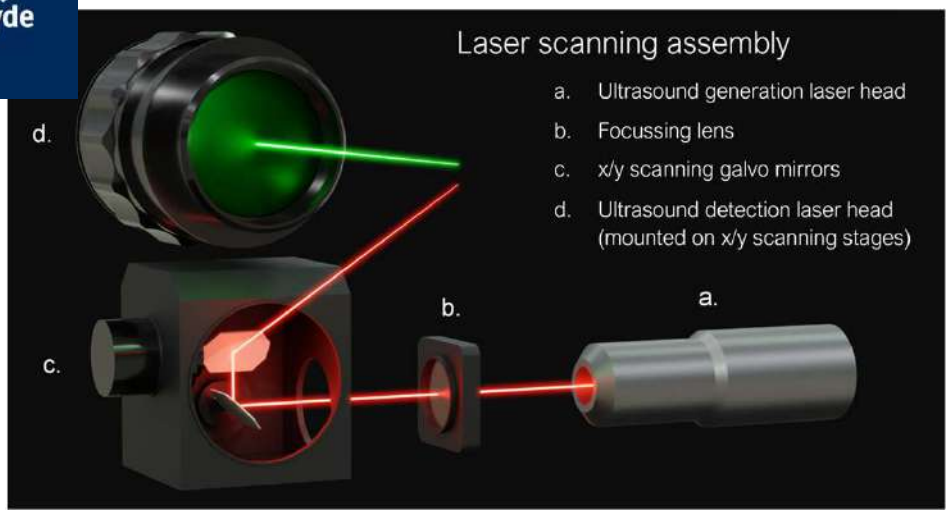

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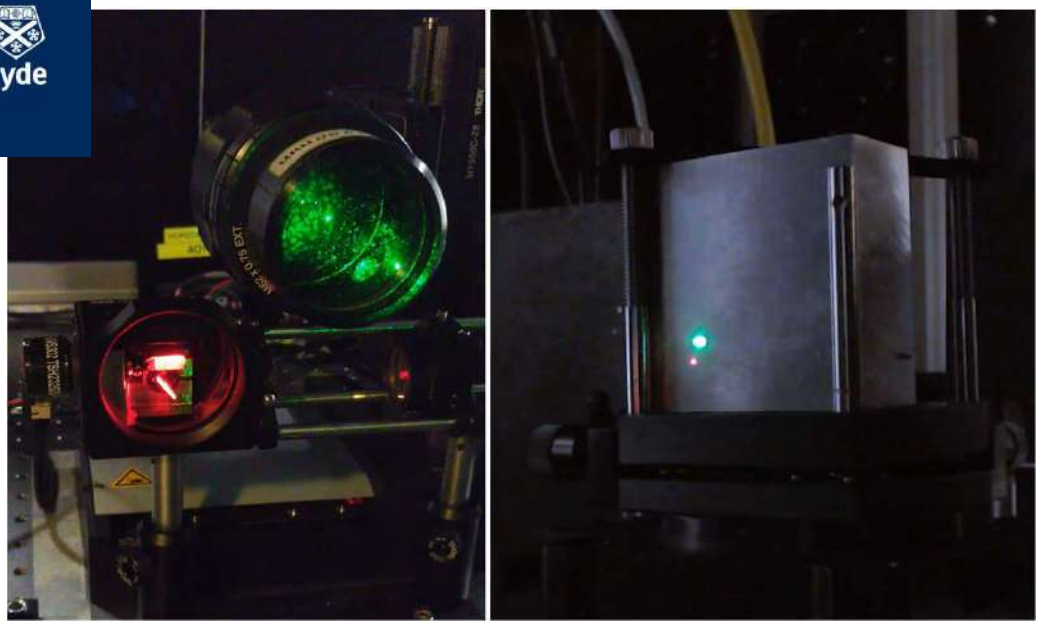

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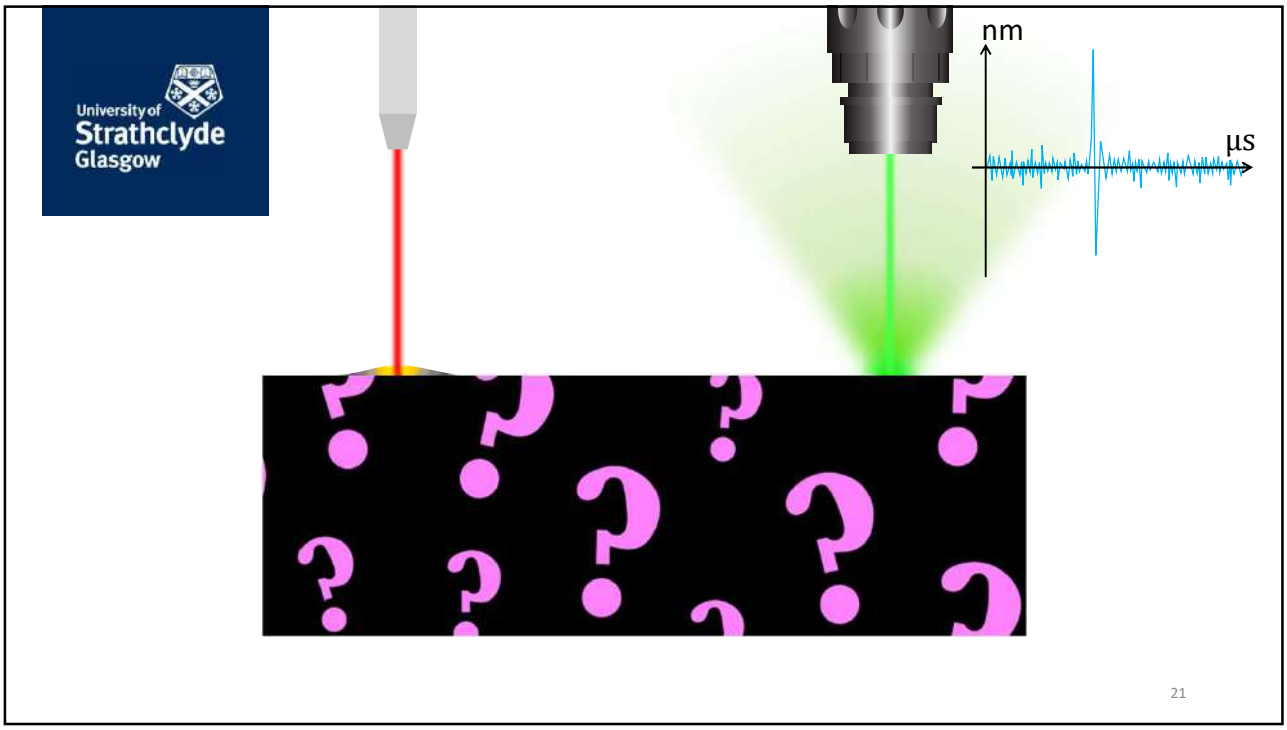
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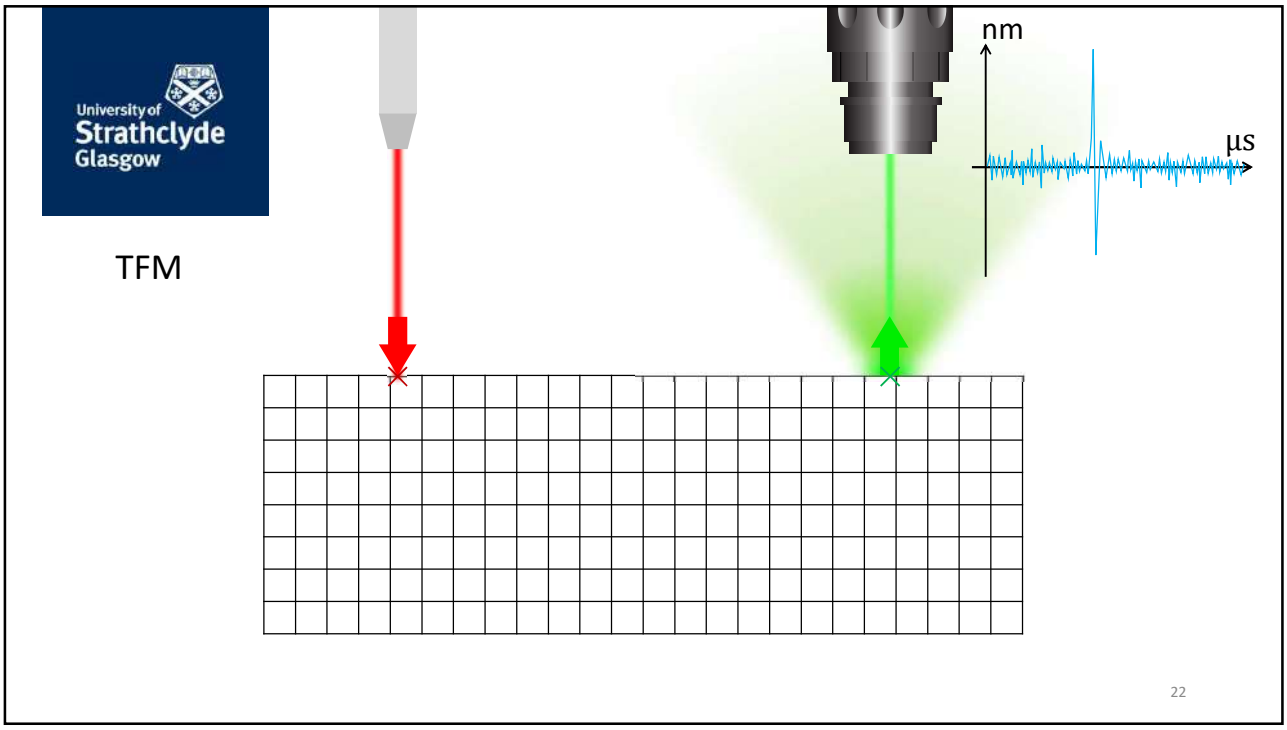
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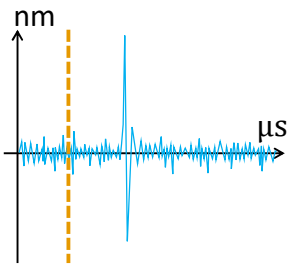

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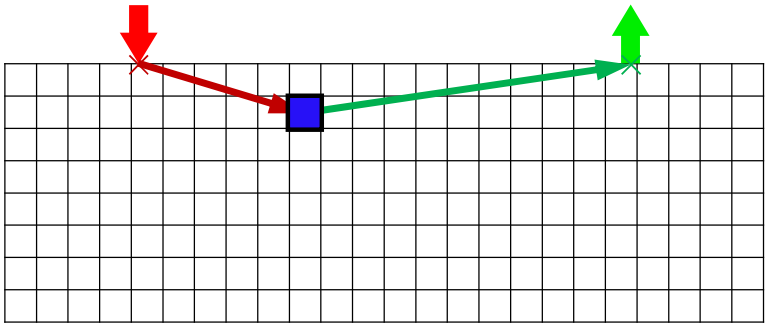

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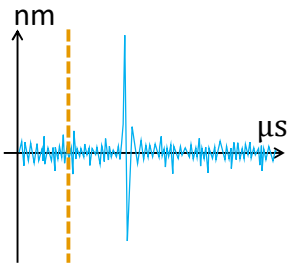

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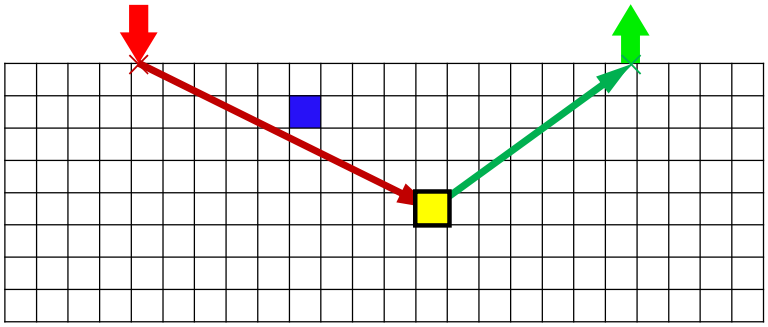

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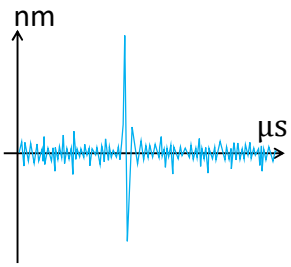

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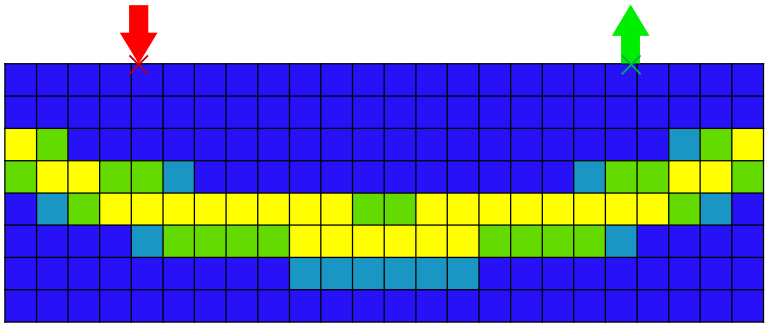

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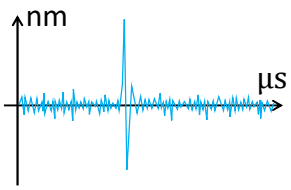

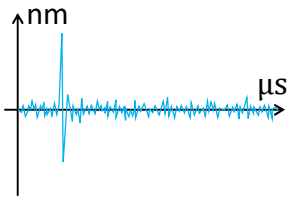

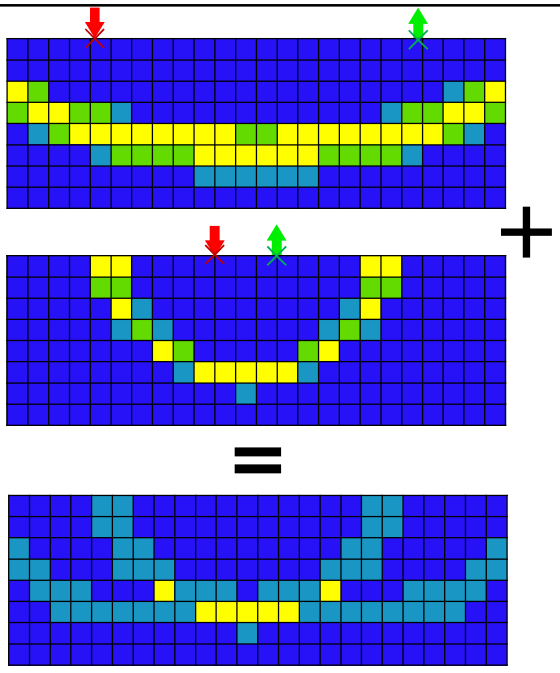

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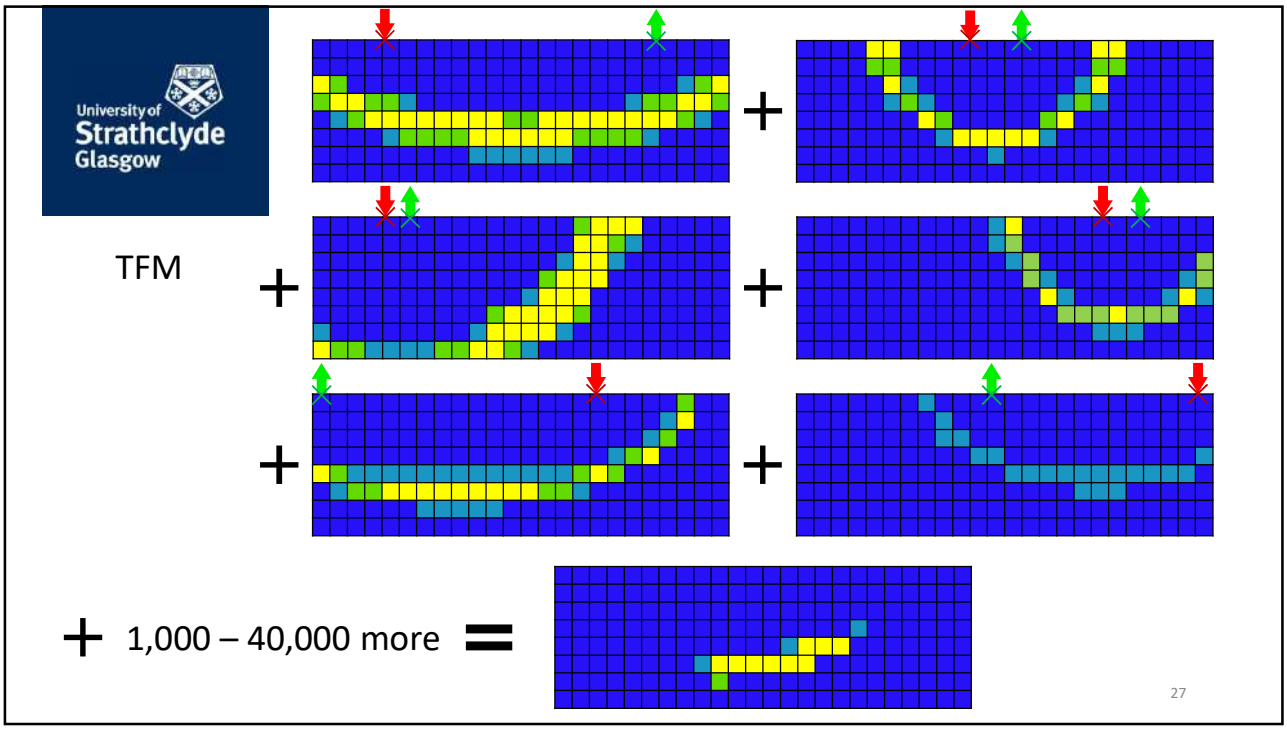
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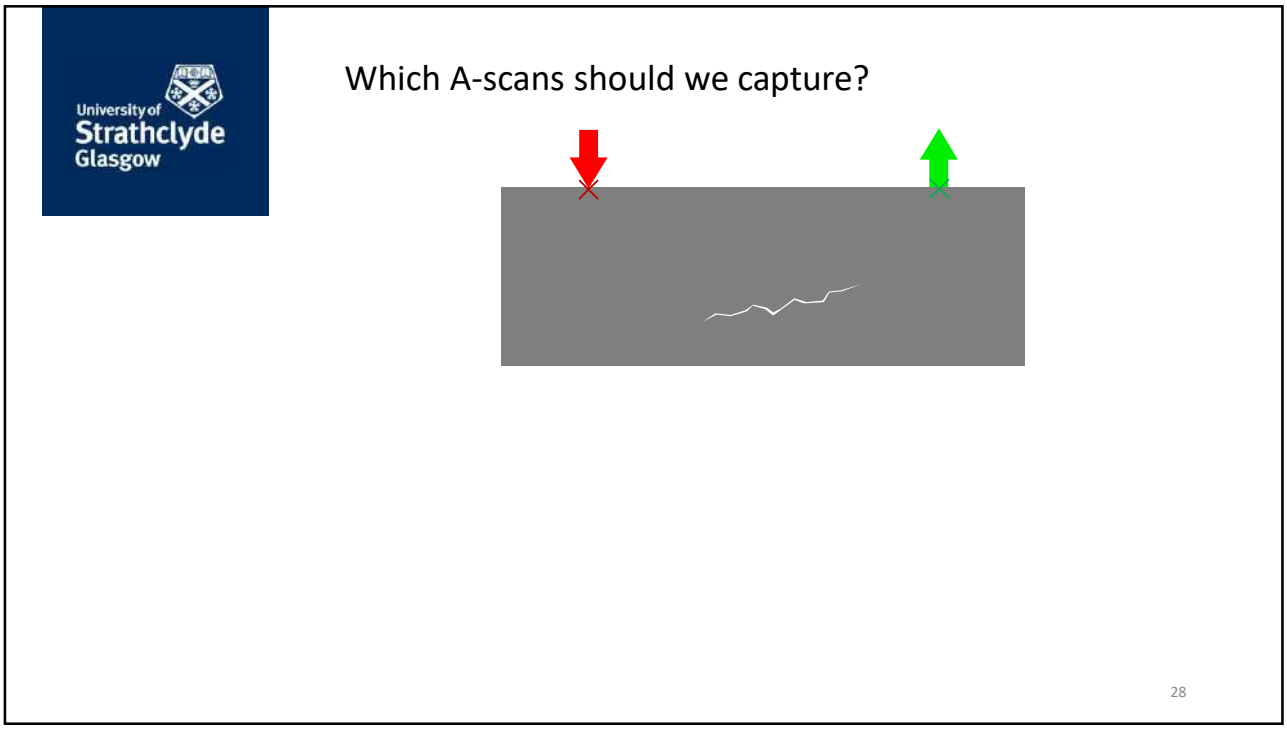
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Which A-scans should we capture?
28

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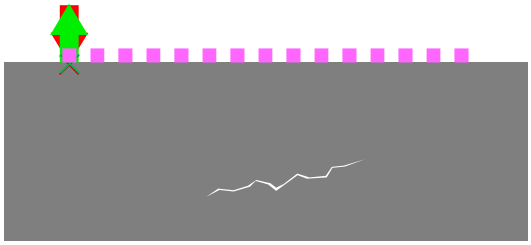
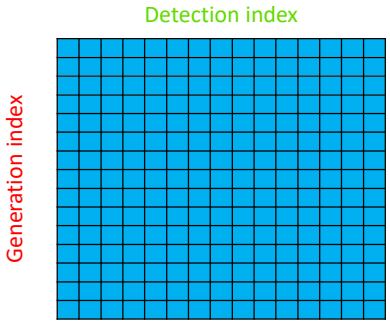
Which A-scans should we capture?

1D Full Matrix Capture (FMC)
Linear, periodic array.



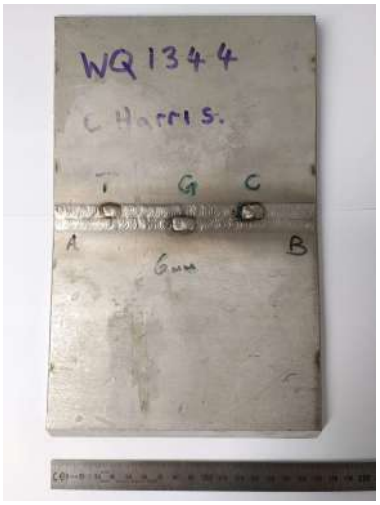


34-element array
→ 1,156 A-scans

29

UKAEA samples:

TIG welded plate
(SS 316)



Laser welded pipe
(CSEF P91)

30

UKAEA samples: Defects

TIG welded plate
(SS 316)

Laser welded pipe
(CSEF P91)

31

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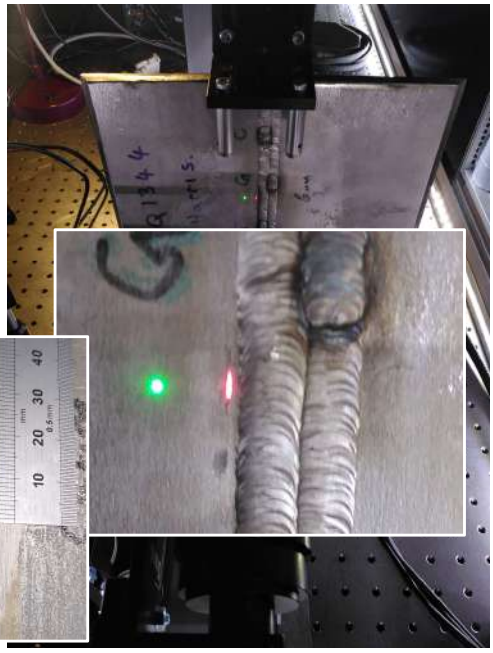
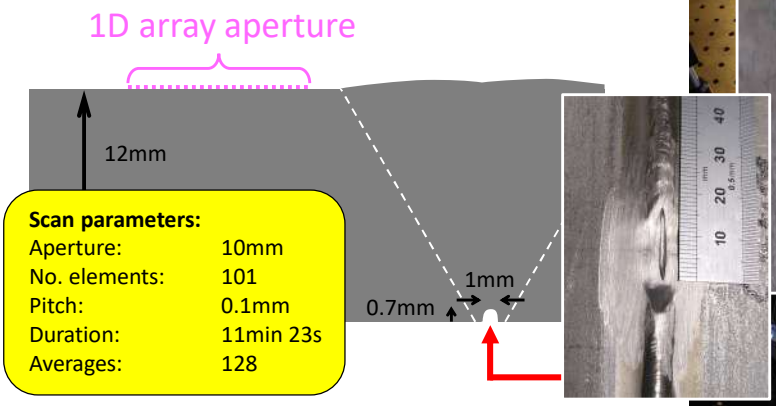
Scanning UKAEA Samples:

Material:
316 stainless steel





Scan parameters:

Aperture:	10mm
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

32

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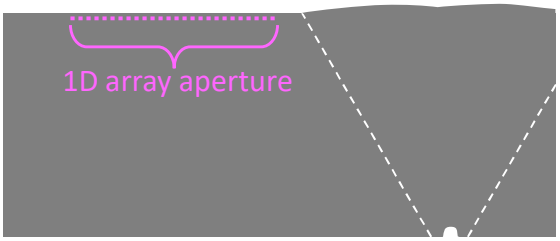
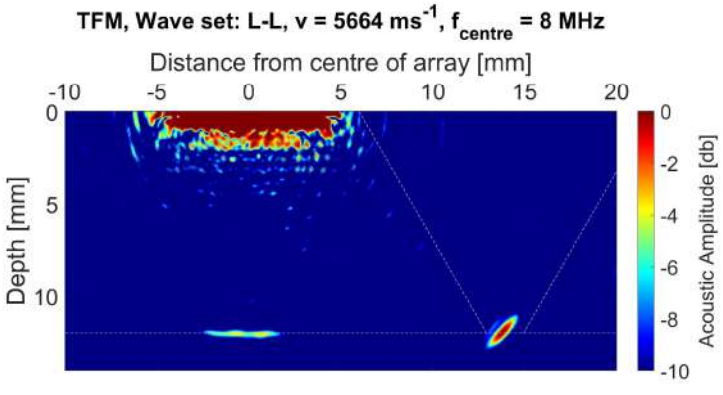
Welded plate TFM images:



Scan parameters:

Aperture:	10mm
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

L-L



33

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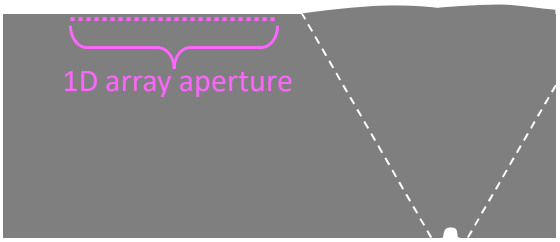
Welded plate TFM images:



Scan parameters:

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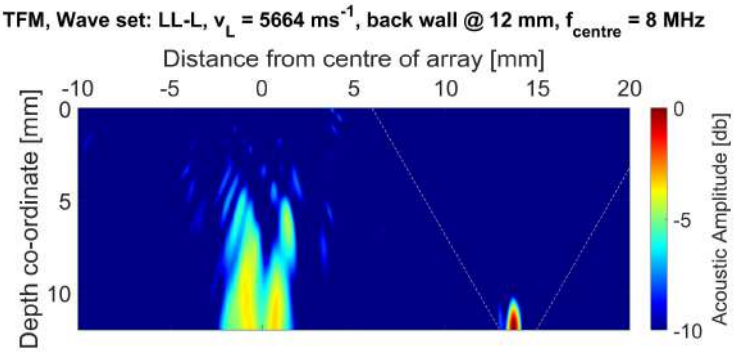
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

LL-L



34

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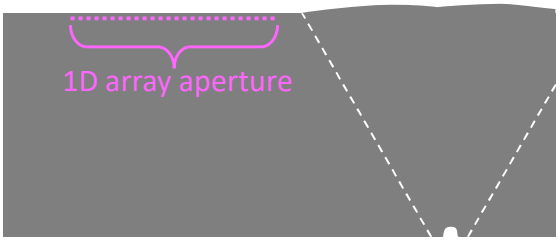

Scan parameters:

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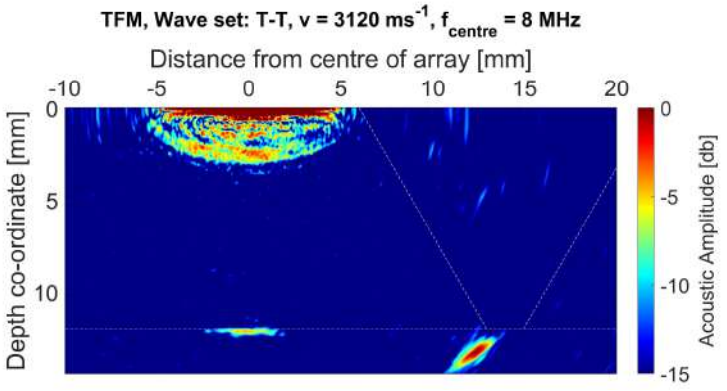
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

T-T



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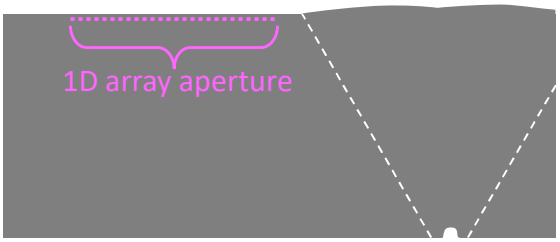

Scan parameters:

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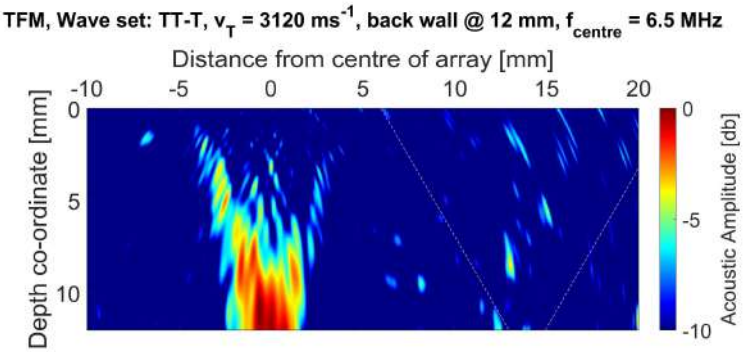
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

TT-T



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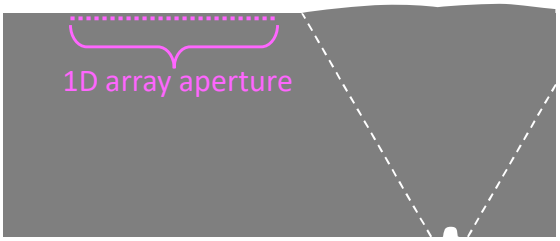
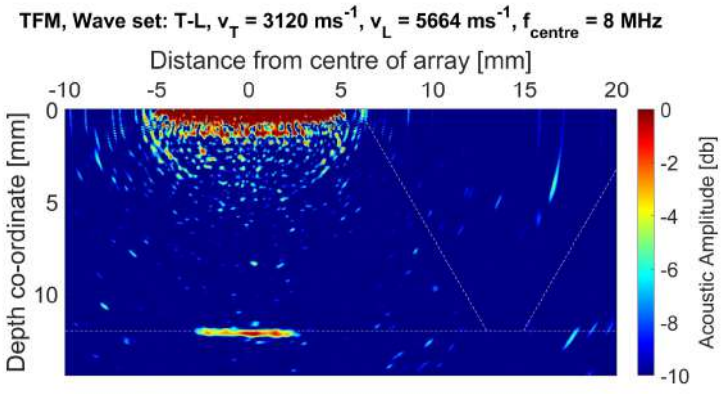


Scan parameters:

Aperture:	10mm
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

T-L



37

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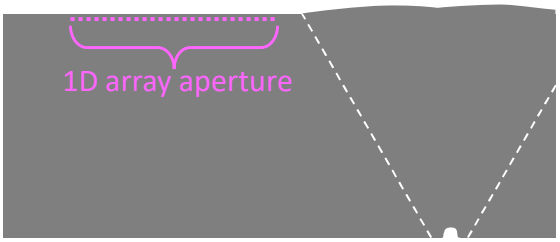

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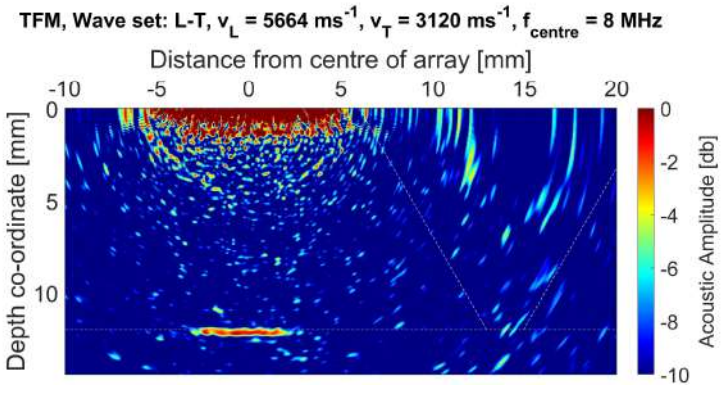
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

L-T



38

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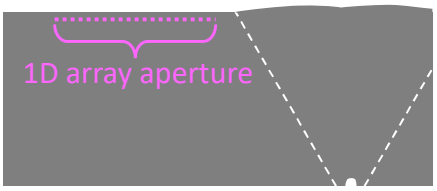

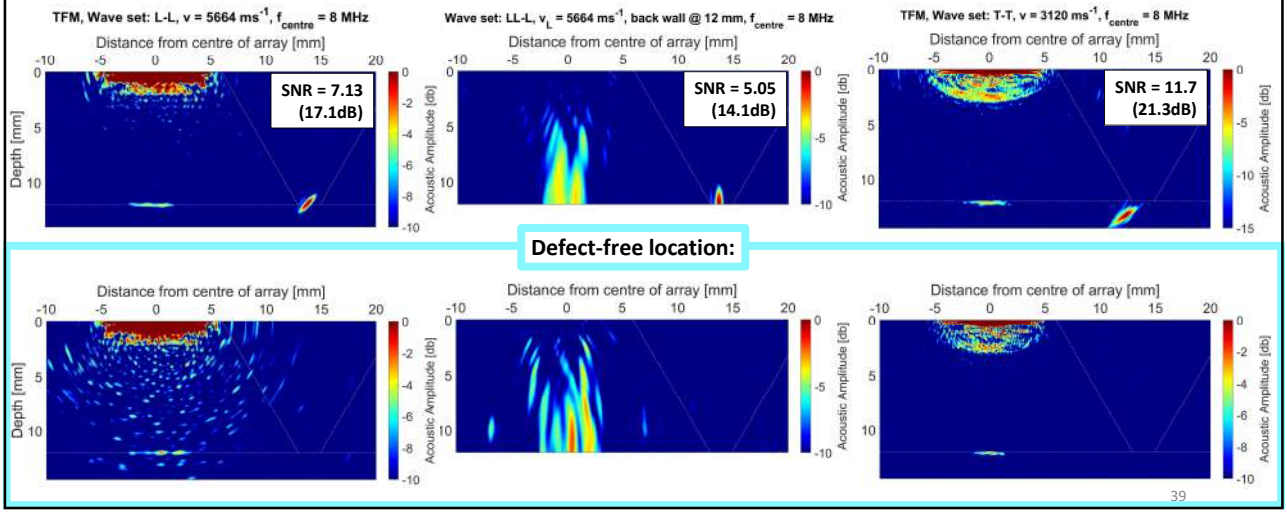

39

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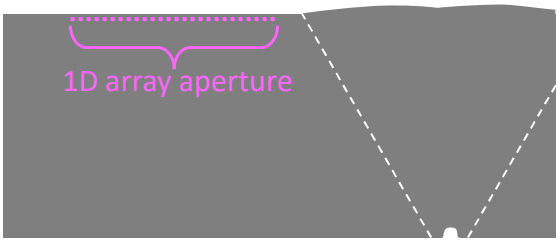

Scan parameters:

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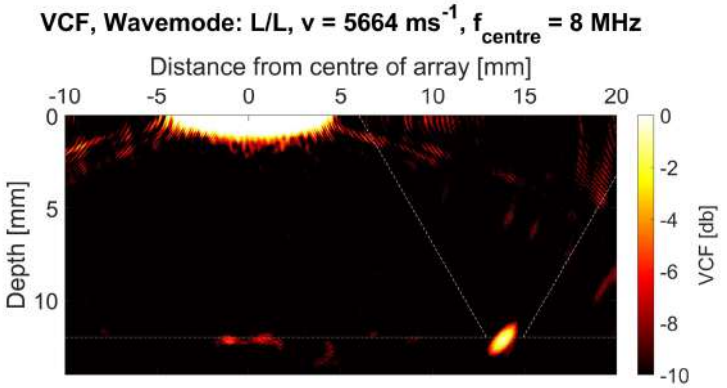
No. elements:	101
Pitch:	0.1mm
Duration:	11min 23s
Averages:	128

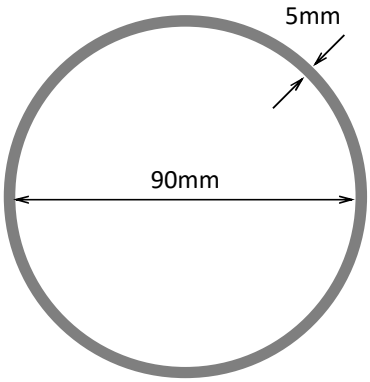
L-L: PCI



40

UKAEA pipe:

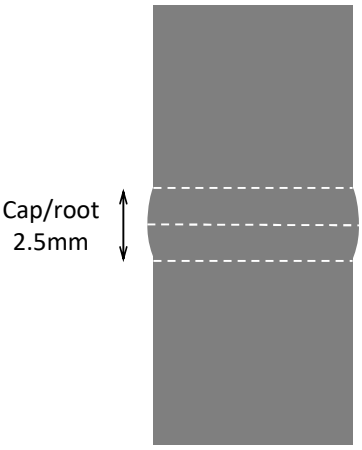
Material:
P91 CSEF steel

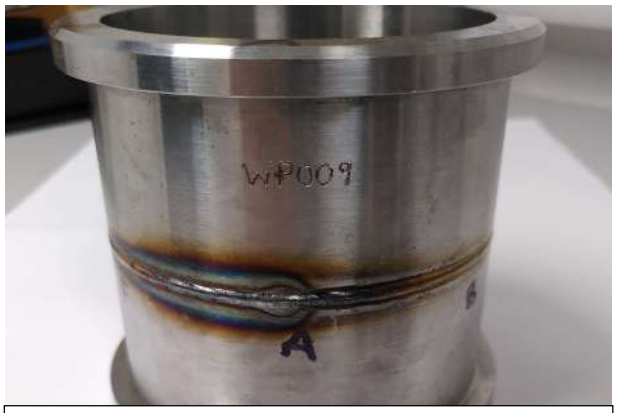


41

UKAEA pipe:

Laser weld





Radiography report:

A-B	lack of fusion and linear/clustered porosity	rejected
B-C	linear/clustered porosity	rejected
C-D	linear/clustered porosity	rejected
D-E	linear/clustered porosity	rejected
E-F	linear/clustered porosity	rejected
F-A	incomplete root penetration, lack of fusion and linear/clustered porotisy	rejected

42

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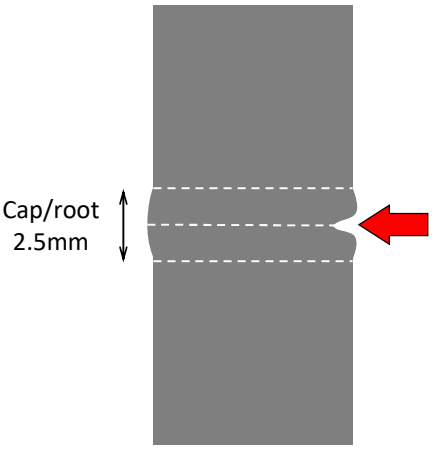
UKAEA pipe:
Laser weld



Radiography report:

A-B	lack of fusion and linear/clustered porosity	rejected
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E-F	linear/clustered porosity	rejected
F-A	incomplete root penetration, lack of fusion and linear/clustered porotisy	rejected

43

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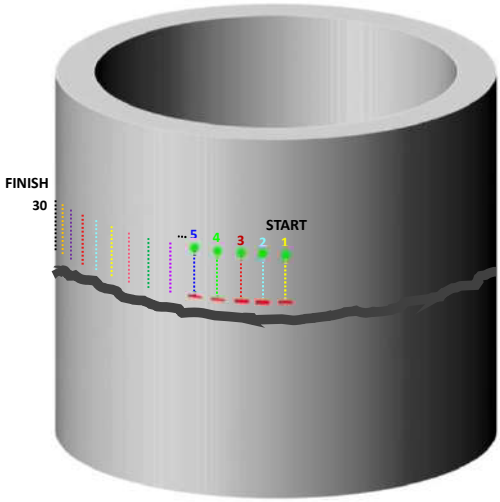
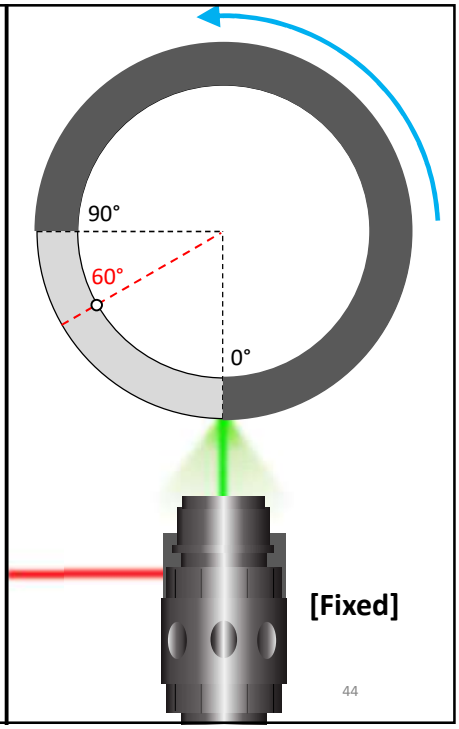
UKAEA pipe: Rotational scanning





44

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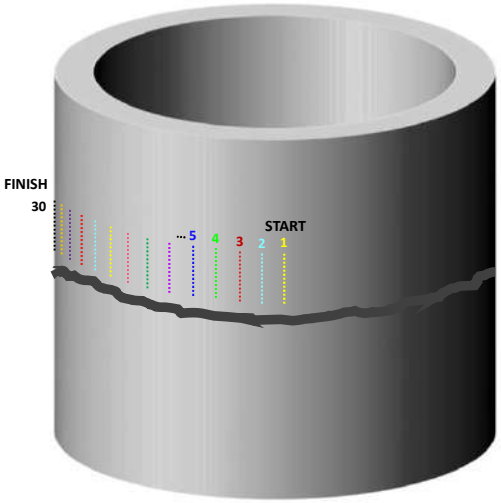
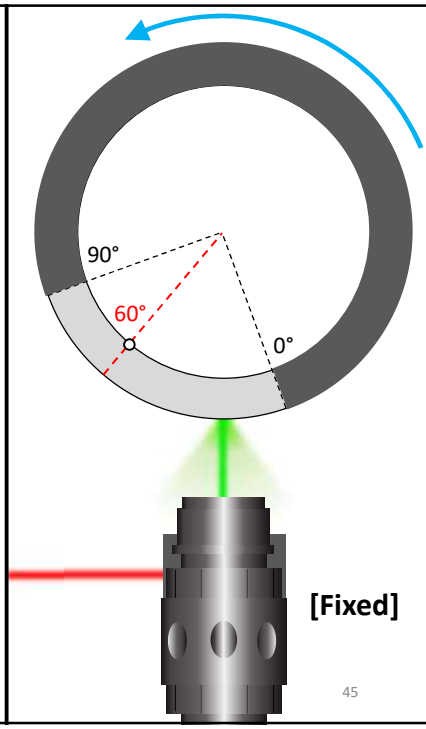
UKAEA pipe: Rotational scanning





45

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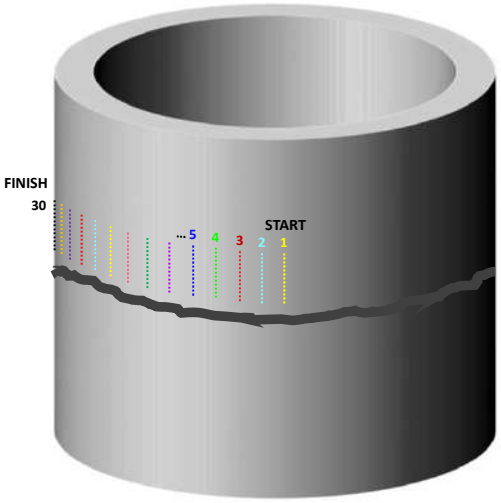
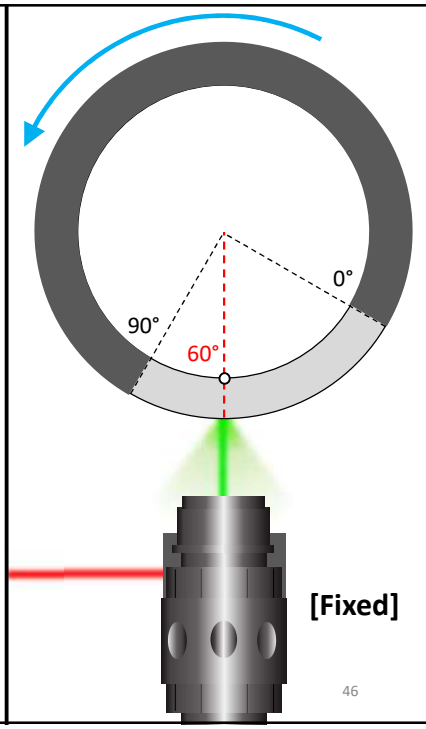
UKAEA pipe: Rotational scanning





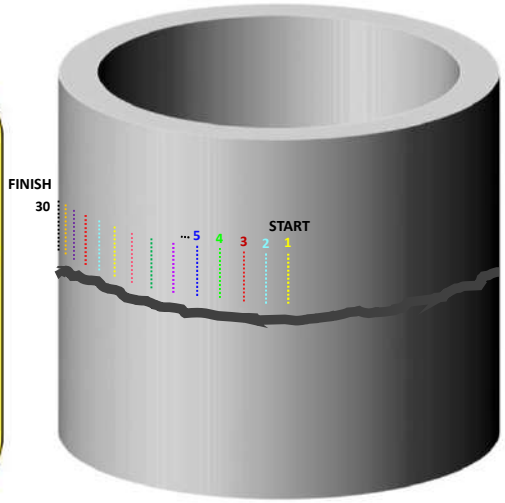
46

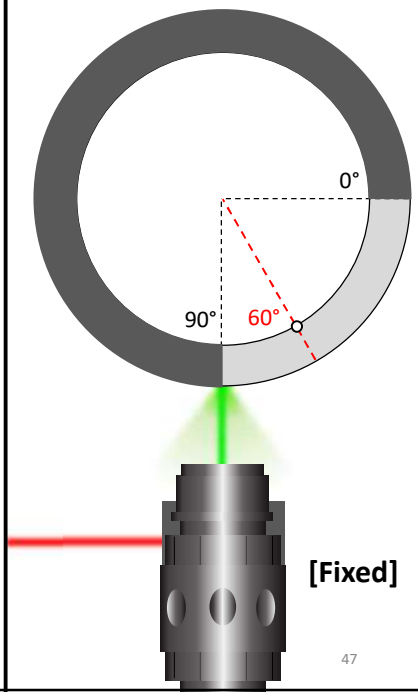
UKAEA pipe: Rotational scanning

Rotational scan 1:

Individual array parameters:
- Aperture: 5mm
- No. elements: 34
- Pitch: 0.152mm
- Time: 1min 46s

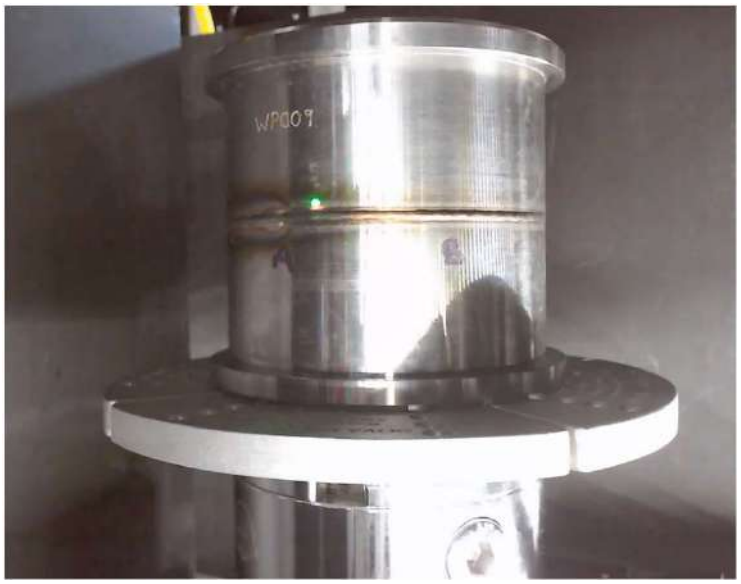
Rotational scanning:
- No. arrays: 30
- Angular step size: 3°
- Angular range: 0 - 87°
- Total time for scan: 53 min





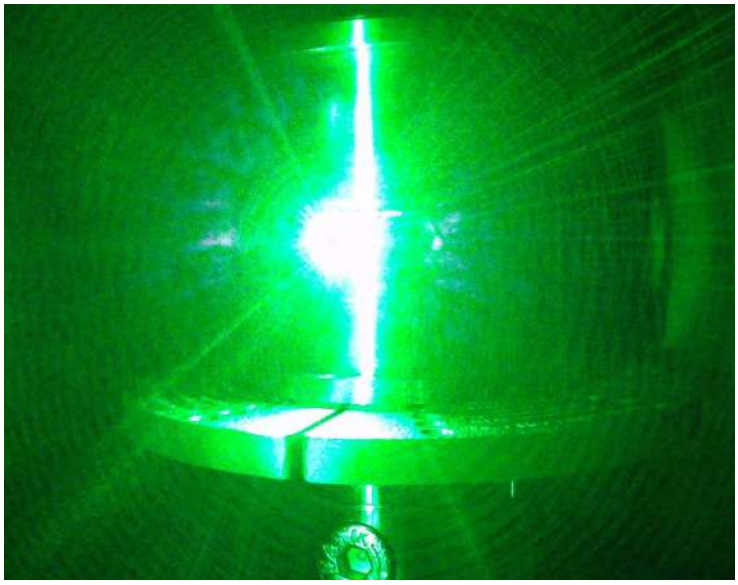
47

UKAEA pipe: Rotational scanning



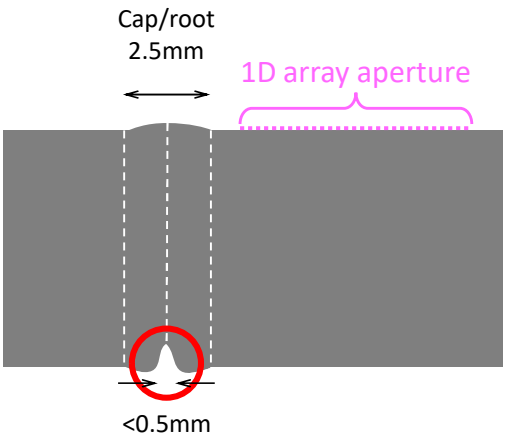
48

UKAEA pipe: Rotational scanning

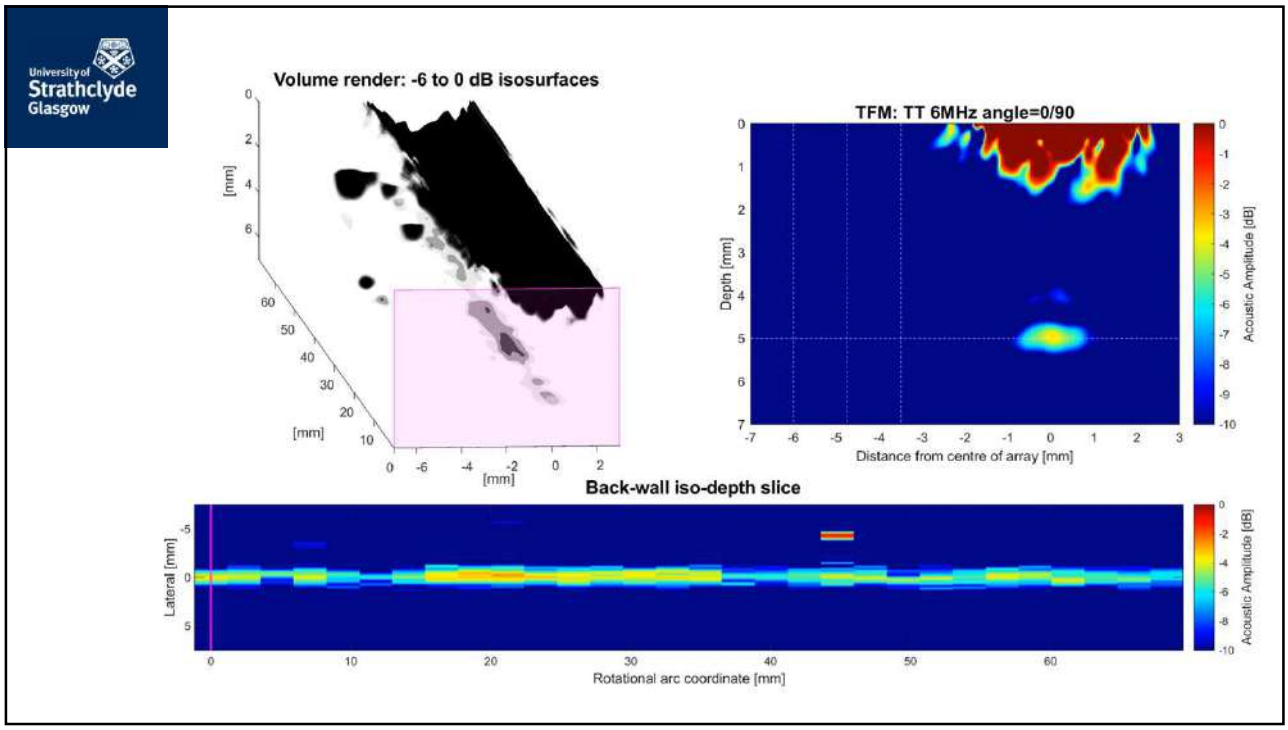


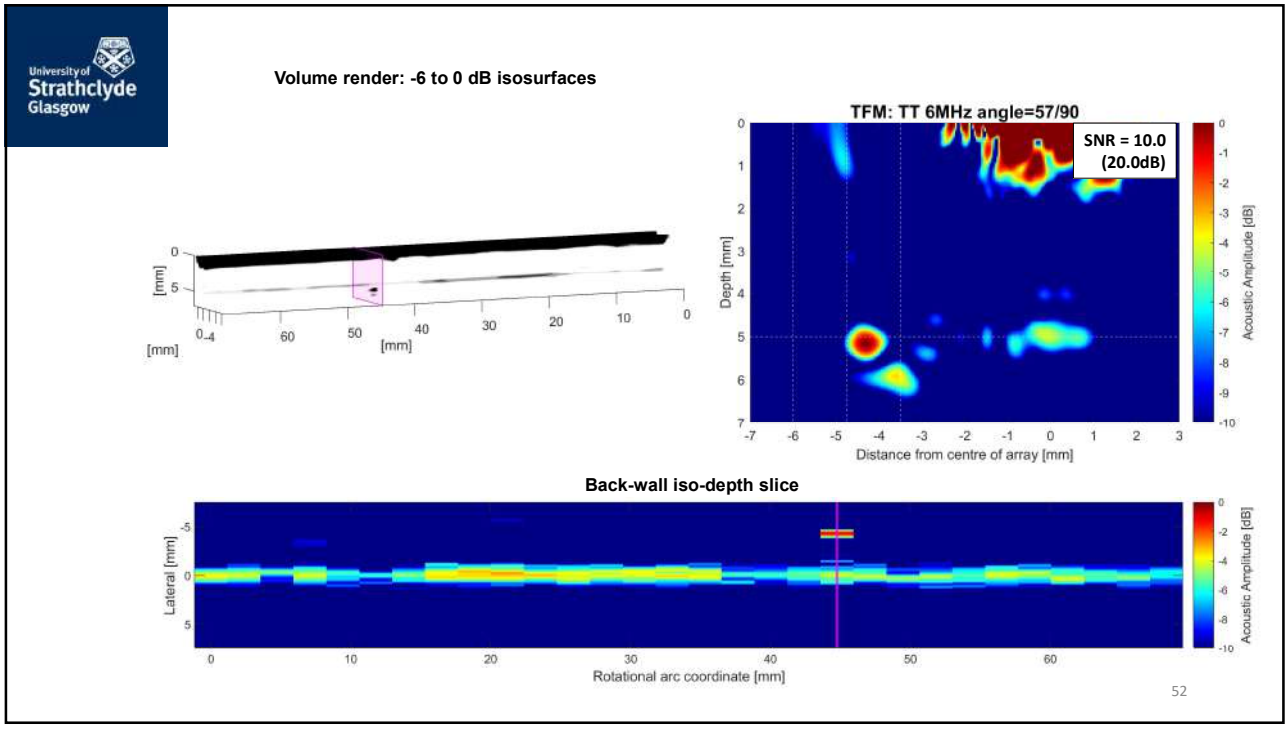
49

UKAEA pipe: Rotational scanning

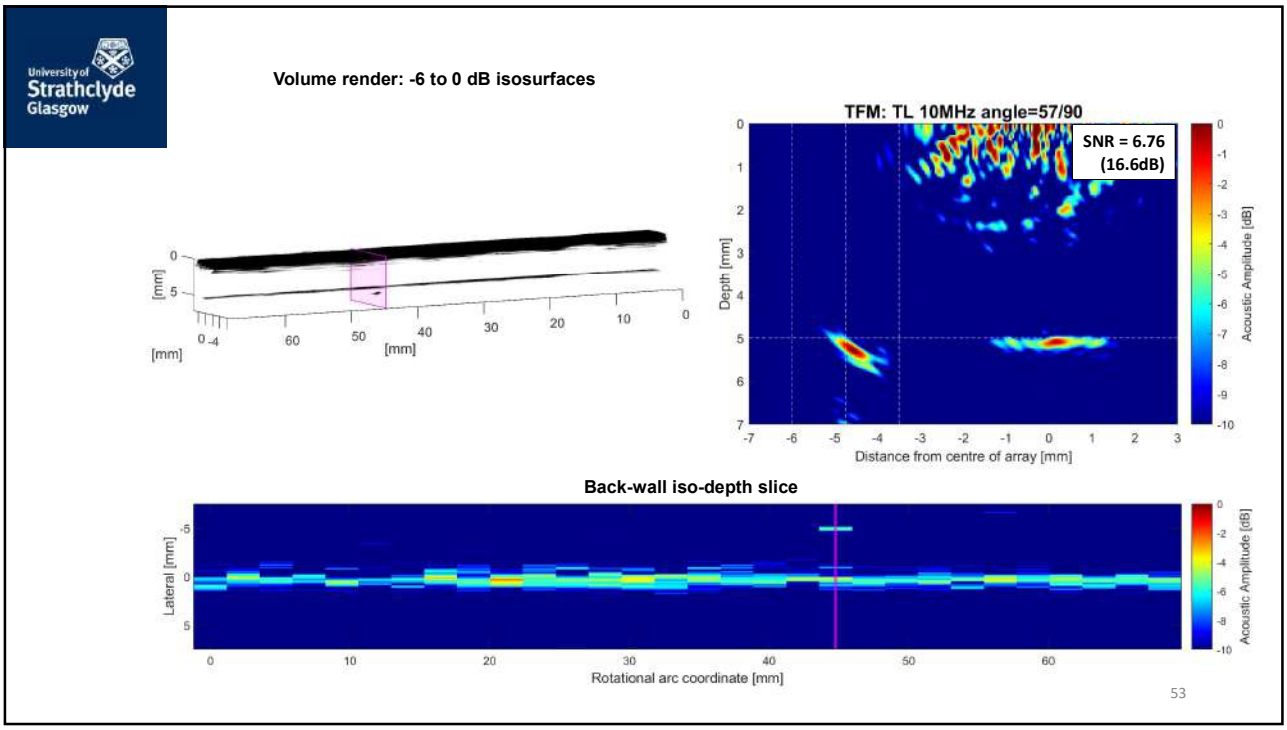


50


Volume render: -6 to 0 dB isosurfaces
[mm]
[mm]
[mm]
TFM: TT 6MHz angle=0/90
Depth [mm]
Distance from centre of array [mm]
Acoustic Amplitude [dB]
Back-wall iso-depth slice
Lateral [mm]
Rotational arc coordinate [mm]
Acoustic Amplitude [dB]


Volume render: -6 to 0 dB isosurfaces
TFM: TT 6MHz angle=57/90
SNR = 10.0
(20.0dB)
[mm]
[mm]
Depth [mm]
Distance from centre of array [mm]
Acoustic Amplitude [dB]
Back-wall iso-depth slice
Lateral [mm]
Rotational arc coordinate [mm]
Acoustic Amplitude [dB]

52



53

Evaluation of results

"For the inspection of tokamak power plant welds…"

Positives

- ✓ Lack of root penetration detected (SNR > 5:1, TT > 10:1)
- ✓ Good defect localisation
- ✓ Relevant materials (SS316, P91)
- ✓ Range of thicknesses (5-12mm)
- ✓ Pipe geometry
- ✓ Non-contact
- ✓ Non-destructive

Limitations

- Impractical capture speed (53min for 90° scan)
- Outer pipe surface
- No bulk defects examined

54

Evaluation of results

"For the inspection of tokamak power plant welds…"

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55

Evaluation of results

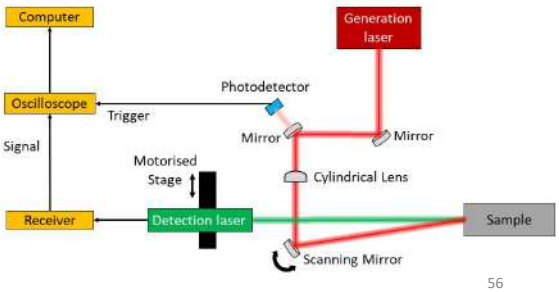
"For the inspection of tokamak power plant welds…"

Limitations

- Impractical capture speed (53min for 90° scan)
- Outer pipe surface
- No bulk defects examined

Future work:

- ➢ Accelerate data capture and scanning



56

Evaluation of results

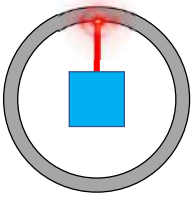
"For the inspection of tokamak power plant welds…"

Limitations

- Impractical capture speed (53min for 90° scan)
- Outer pipe surface
- No bulk defects examined

Future work:

- ➢ Accelerate data capture and scanning
- ➢ Attempt *in-bore* scanning



57

Evaluation of results

"For the inspection of tokamak power plant welds…"

Limitations

- Impractical capture speed (53min for 90° scan)
- Outer pipe surface
- No bulk defects examined

Future work:

- ➢ Accelerate data capture and scanning
- ➢ Attempt *in-bore* scanning

- ➢ Examine a wider variety of defects

Thank you very much for your attention

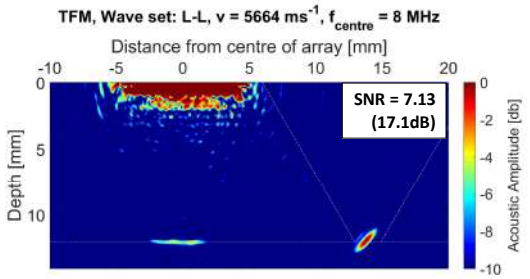
matthew.riding@strath.ac.uk

SNR calculation:

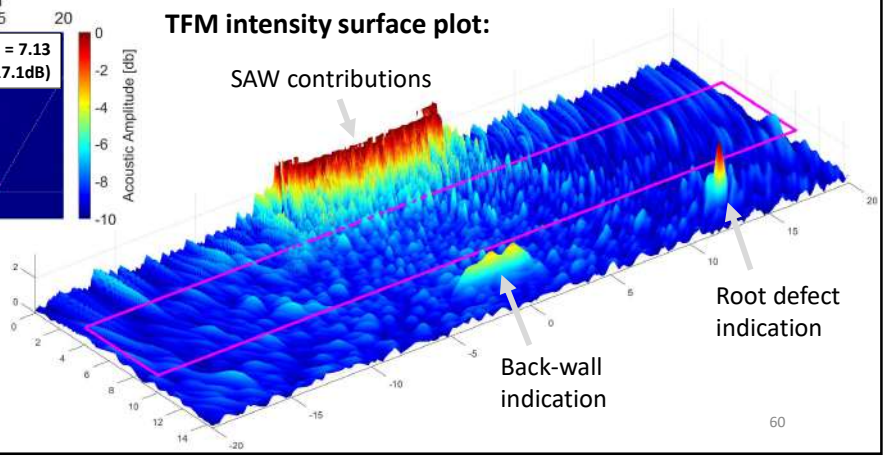
$$\mathrm{SNR} = \frac{q}{\sigma}$$

q = Peak indication amplitude [V]
σ = RMS noise amplitude [V]

σ calculated inside magenta box



TFM intensity surface plot:



60

Show some example raw A-scans and their FFTs

61

VISUALIZATION OF MULTI-FREQUENCY ULTRASONIC DATA

Terrill Massey[1], Mark Dennis[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): tmassey@epri.com

Ultrasonic sensor technology is improving, and transducers can now be built with greater broadband excitation. This technology can result in multi-frequency examinations and potentially provide significant equipment and labor cost savings for (Non-Destructive Evaluation) NDE users, including those in the power industry. Modern UT imaging techniques predominantly map A-scan amplitude, or intensity, to a given color map, which results in individual displays being made for a given transducer frequency and wave mode.

A challenge with this multi-frequency examination approach is viewing the data in a concise, interpretable manner. For example, if three frequencies are used to inspect a component from a broadband probe, currently, a user would need to set up a display mode (that is, a sector scan, B-scan, C-scan, and so on) for each frequency. Interpreting all the data can be time-consuming and could cognitively overload a user.

In this research, an alternative data fusion technique for generating UT images that combine multifrequency data into a single image is tested on laboratory samples. The data fusion technique is pseudo-coloring, an image containing both frequency and amplitude information. With the continued development of UT hardware and software, alternative data fusion techniques will become advantageous for improving the interpretation and reliability for industrial NDE. Next steps for the continuation of this research are also recommended.

Keywords: Non-Destructive Evaluation (NDE), Multi-Frequency UT, Ultrasonic Testing (UT), Data Visualization

.

Visualization of Multi-Frequency Ultrasonic Data

Terrill Massey, EPRI
Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Presentation Outline

1. Motivation for Research
2. Research Objective
3. Experimental Setup
4. Multi-Freq Visualization Approach
5. Observations and Resulting Images
6. Summary

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Motivation for Research and Research Objective

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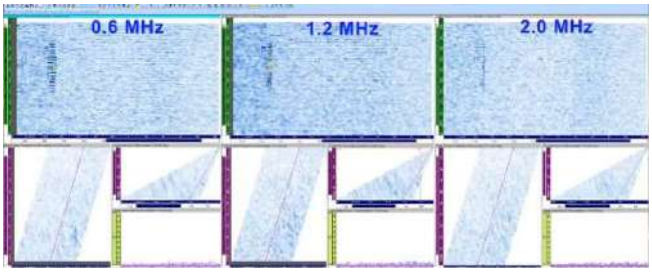
Motivation for Research

- Multi-Frequency and broadband transducer technology is becoming more prevalent in industry. This technology could potentially provide significant equipment and labor cost savings for end users within the power industry.
- Present day UT imaging techniques predominantly map A-scan amplitude, or intensity, to a given color map which results in individual displays being made for a given transducer frequency and wave mode.
- Due to conventional UT imaging techniques, UT data analysis are required to look at multiple A-scan amplitude images(i.e. B-scan, C-scan, D-scan, etc.) at once, one per transducer frequency. This presents a challenge for viewing multi-frequency UT data in a concise and interpretable manner.
- Reviewing multiple images at once for indications of interest may increase analysis time and could cognitively overload the UT data reviewer, thus potentially increasing probability of analysis error.



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Research Objective

- The objective of this research is to investigate an alternative data fusion display technique by combining the information from multiple frequencies into a single display mode (that is a single sector scan, B-scan, C-scan, D-scan, etc.).
- This technique will leverage A-scan spectrum information and pseudo coloring models
- This research will present corrected B-scan images for a variety of specimens and defects utilized in a recent multi-frequency UT data study by EPRI [1].
- This research will also illustrate the concept of pseudo coloring , which is a data fusion technique for combining ultrasonic data captured at various transducer frequencies.
- Utilizing this data fusion technique could potentially provide benefits of workflow streamlining and efficiency of analyzing data for multiple frequency bands.

[1] Assessment of Multi-Frequency Phased Array Ultrasonic Technique EPRI Product ID: 3002021011

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Experimental Setup and Specimens Used in Research

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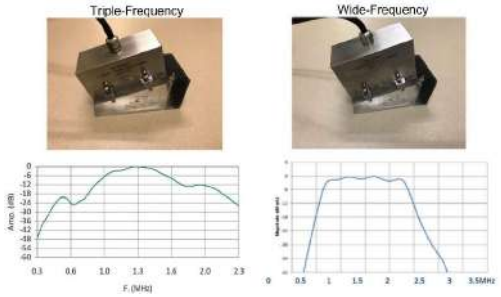
Experimental Setup [1]

- The UT data was collected using two different linear phased array transducers (triple-frequency and wideband frequency) manufactured by Imasonic.
- The triple-frequency transducer provides three distinct center frequencies, whereas the wideband frequency had a center frequency of 1.5MHz.
- The pulse-echo wedge was used by the triple-frequency transducer.
- The pitch-catch wedge combination used the triple-frequency and wide-frequency transducers.
- The UT data was collected with the Zetec Dynarray and the Atco GPS-1000 pipe scanner.

	Triple – Frequency	Wide-Frequency
Manufacturer	Imasonic	Imasonic
Serial Number	13819 1001	13929 1001
Frequencies [MHz]	0.6, 1.2, and 2.0	0.5 – 2.5
Number of Elements	32	64



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Specimens Used for Data Collection

- Three specimens were used in this study with the following characteristics.
- More detail pertaining to these specimens are located in the EPRI deliverable [1].

Specification	Sample #1	Sample #2	Sample #3
Name	325-OP-1-F	347-28-08	710-8-1
Material	SS	CASS	DMW
Short Description	Austenitic SS pipe containing a single v-groove weld with an unground weld face	CASS pipe containing a single v-groove weld with various geometric reflectors	Open practice sample mockup designed as a section from a boiling water reactor N1 outlet nozzle to safe-end connection
Thickness [mm]	68.9	63.52	53.69
Flaw Types	Thermal fatigue	Electro-discharged machined (EDM) flaws	Fatigue

Sample Name	Specification	Defect 1	Defect 2
325-OP-1-F	Orientation	Circumferential	Circumferential
	Length [mm]	43.94	63.50
	Depth [mm] / [%]	32.11 / 49	6.55 / 10
347-28-08	Orientation	Circumferential	N/A
	Length [mm]	56.49	N/A
	Depth [mm] / [%]	19.23 / 40	N/A
710-8-1	Orientation	Axial	Circumferential
	Length [mm]	12.70	46.48
	Depth [mm] / [%]	13.31 / 25	23.29 / 44

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Multi-Frequency Visualization Approach Used in Study

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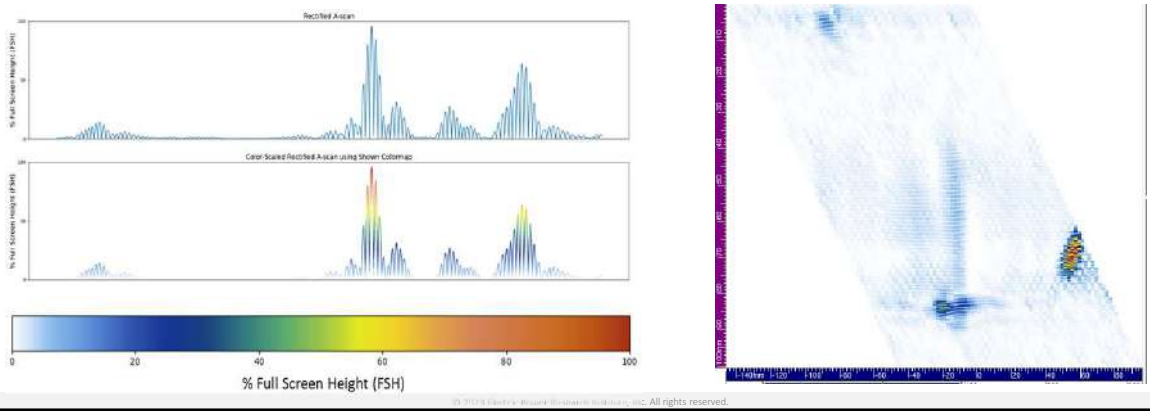
Traditional Visualization Approach for UT Images

- Traditional visualization schemes for UT images aim to produce images that visualize amplitude information within the UT data collected on the specimen.
- This is accomplished through mapping the UT signal (i.e. A-scan) amplitude, or intensity, to a color scale, and combining the mapped intensities of multiple UT signals into the traditional UT images that we are familiar with (i.e. B-scan, C-scan, D-scan, Sector-Scan, etc.).
- Recall: A display mode of UT images is needed for each frequency!



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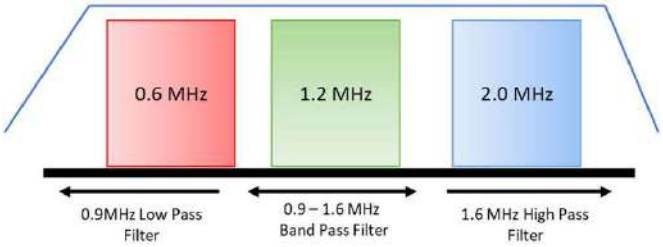
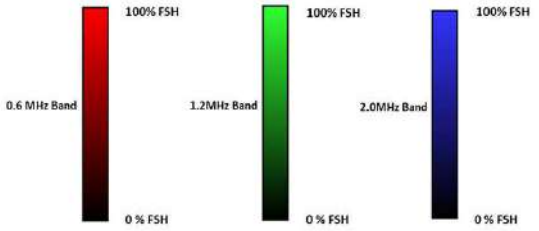
RGB Pseudo Coloring Technique and How It's Used

- The visualization technique used is the Red-Green-Blue (RGB) pseudo coloring technique.
  - This technique can be applied to any UT image (ie. B-Scan, Sector Scan, C-Scan, D-scan, etc.) as well.
- In this study, the UT data is encoded as :
  - **RED:** Low Frequency Range: Less than 0.9MHz (data with a center frequency of 0.6MHz).
  - **GREEN :** Medium Frequency Range: Between 0.9MHz and 1.6MHz. (data with a center frequency of 1.2MHz).
  - **BLUE:** High Frequency Range : Greater than 1.6MHz. (data with a center frequency of 2.0MHz).
- The intensity of the UT signal is considered at each frequency. The lower the intensity of the UT signal, the closer to black the resulting color will be.





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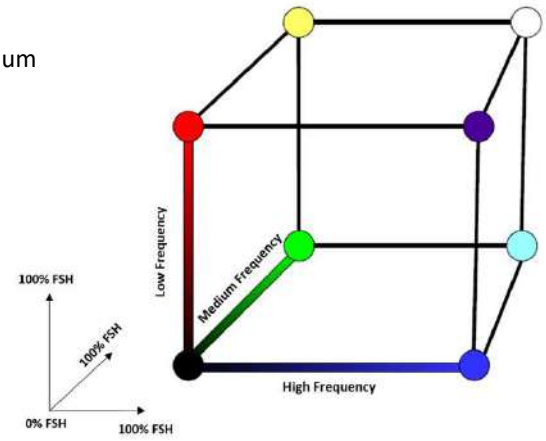
RGB Pseudo Coloring Technique and How It's Used

- In most cases, UT data from multiple frequency ranges contribute to an indication of interest with varying intensities.
- This will cause color mixing(or color fusion) within the RGB pseudo colored B-scan image.
- Utilizing the color code and color intensity map for each frequency, a color mixing scheme can be achieved.
- For example, if UT data that shows maximum intensity for all three frequency channels, the resulting RGB pseudo color will be white.



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Observations and Resulting Images

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RGB Pseudo Images Created During Study

- One set of experiments within the study created traditional B-scans(with traditional color scale) of UT data collected at the three frequency and the RGB fusion counterpart.
- Comparisons were then made between the traditional B-scans and their RGB combined B-scan counterparts.
- These comparisons were made for various indications of interest for all three specimens (recall: SS, DMW, and CASS).

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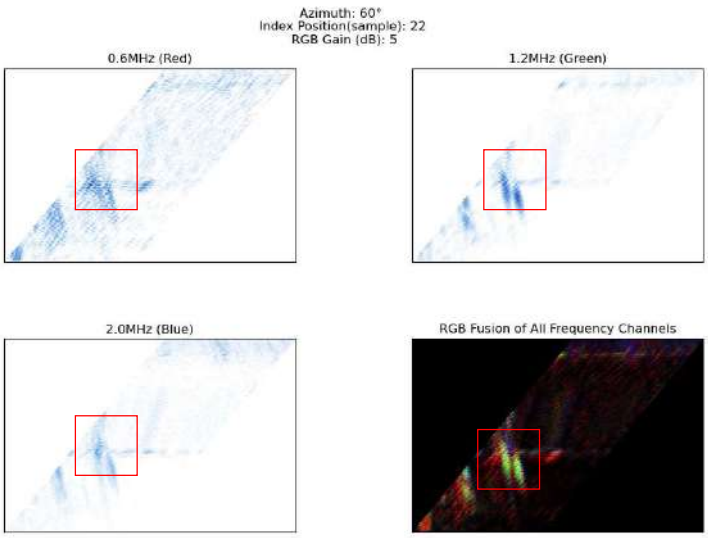
RGB Pseudo B-Scan for 325-OP-1-F Defect 1



- B-scans were produced using the Triple-Frequency Probe with a Ultrasound Beam angle of 60 degrees that is looking downstream at defect 1.
- The yellow tint in the RGB image is given by the combination effect of the intensities provided by center frequencies 0.6MHz and 1.2MHz [i.e. Red(0.6MHz) + Green(1.2MHz)]. These two frequencies dominate the intensity shown at the indication.
- The 2.0MHz center frequency (depicted by a blue color) is slightly contributing to the flaw indication with comparatively small intensity. This slight contribution attributes to the brighter shade of yellow observed in the RGB fusion image.
- This exemplifies the ability of pseudo coloring to contrast the mixing of colors from the frequency content to help display the defect.
- This shows how the RGB fusion image could be used to determine which frequency responses are stronger for a given defect than others.

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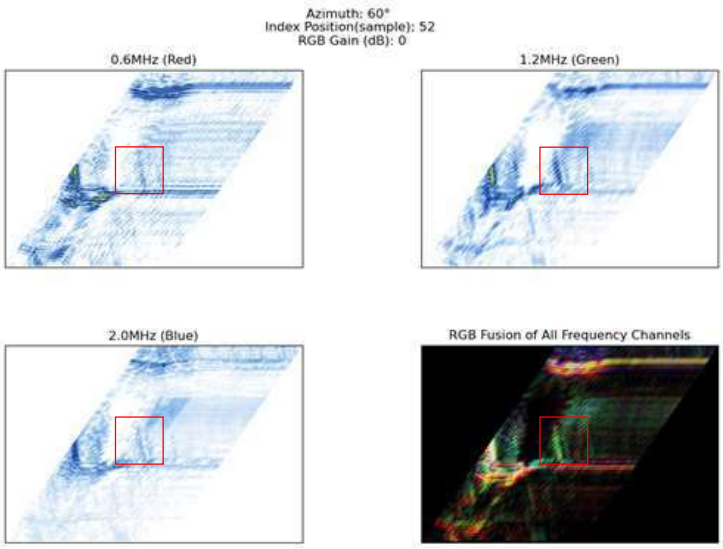
RGB Pseudo B-Scan for 710-8-1 Defect 2



- B-scans were produced using the Triple-Frequency Probe with an ultrasound beam angle of 60 degrees that is looking downstream at defect 2.
- The UT data with 1.2MHz center frequency provides the strongest defect response for defect 2. The 0.6MHz and 2.0MHz center frequencies barely provide a response. This provides a mostly green indication in the RGB B-scan.
- The 0.6MHz center frequency mostly contributes to the weld geometry response with some contribution from 1.2MHz. This is depicted by a mostly red with a yellow tint color in the weld geometry response in the RGB image.
- This RGB image exemplifies how to easily distinguish which frequencies contribute to defect responses and weld geometries within a specimen.

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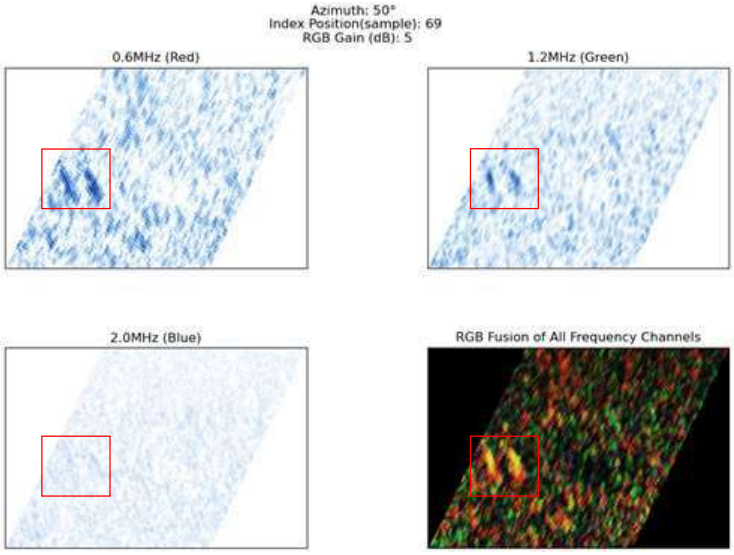
RGB Pseudo B-Scan for 347-28-08 Counterbore



- B-scans were produced using the Pitch-Catch configuration with an ultrasound beam angle of 50 degrees that is looking downstream at the counterbore of the specimen.
- The UT data with 0.6MHz center frequency provides the strongest intensity for the counterbore response.
- UT data with 1.2MHz center frequency provides the second strongest intensity for the counterbore response.
- The counterbore response cannot be seen in UT data with 2.0MHz center frequency. (Typically, features are harder to identify in higher frequency UT data for CASS samples).
- This results in a mostly red with yellow tint response for the counterbore in the RGB image.
- This exemplifies the ability to distinguish which frequencies contribute to certain geometry features even in a noisy environment such as a CASS specimen.

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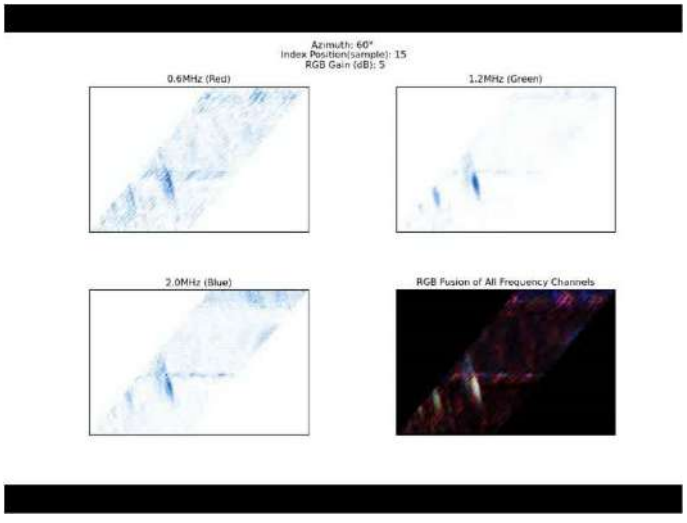
RGB Pseudo B-Scan Response as Transducer Position is Swept



- B-scans were observed as the index position of the transducer was swept across the length of the indication of interest.
- Recall that the yellow tint in the RGB image is given by the combination effect of the intensities provided by center frequencies 0.6MHz and 1.2MHz [(i.e. Red(0.6MHz) + Green(1.2MHz)]. These two frequencies dominate the intensity shown at the indication.
- For some index positions, UT data from the 0.6MHz center frequency provide strong intensities from the responses of weld geometry and noise throughout the specimen. This illustrates a red color in the weld area of the RGB image.
- This shows that the frequency contributions within the UT data can still be distinguished while understanding the flaw response changes as the transducer is swept across the indication area of interest.

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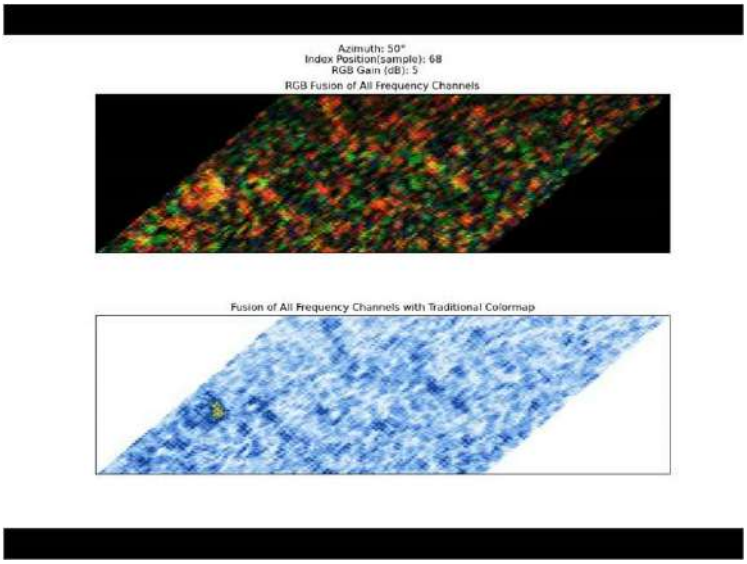
RGB Pseudo vs. Traditional Color Map of B-Scans



- What if we simply overlay the UT data of all three frequency channels into one B-scan image?
- This video showcases the comparison of the RGB fusion image(top) and a B-scan overlay with all frequencies using a traditional color map(bottom).
- The index position of the transducer is swept across the indication of interest(counterbore).
- Recall that in traditional images, only the amplitude information is being displayed and typically signal-to-noise ratio (SNR) is used as an indicator for the likelihood of flaw detection.
- For Pseudo coloring, the ability to mix colors can help provide image contrast that is not possible with amplitude only displays.

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Summary

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Summary

- Multi-frequency and wide bandwidth transducers are being developed and implemented into industrial NDE and further development in transducer technology will only continue.
- Present day UT imaging techniques map A-scan amplitude, or intensity, to a given color map which results in individual displays being made for a given transducer frequency and wave mode.
  - This could create a challenge for the UT data reviewers by increasing analysis time and increasing risk of analysis overload.
- The results in this research indicates that defects and/or specimen geometry were present in pseudo colored RGB B-scans while retaining the frequency information from UT data with multiple frequency ranges.
- Pseudo coloring presents itself as a promising opportunity to possibly simplify interpretation of multi-frequency, industrial UT data.
- Also, pseudo coloring is not limited to multi-frequency data and can be used for other UT applications like combining various wave propagation modes in total focusing method (TFM) images.
- The results of this research will be delivered as a white-paper in November 2022 (EPRI Product ID: 3002023706).

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Reference

[1] Assessment of Multi-Frequency Phased Array Ultrasonic Technique EPRI Product ID: 3002021011

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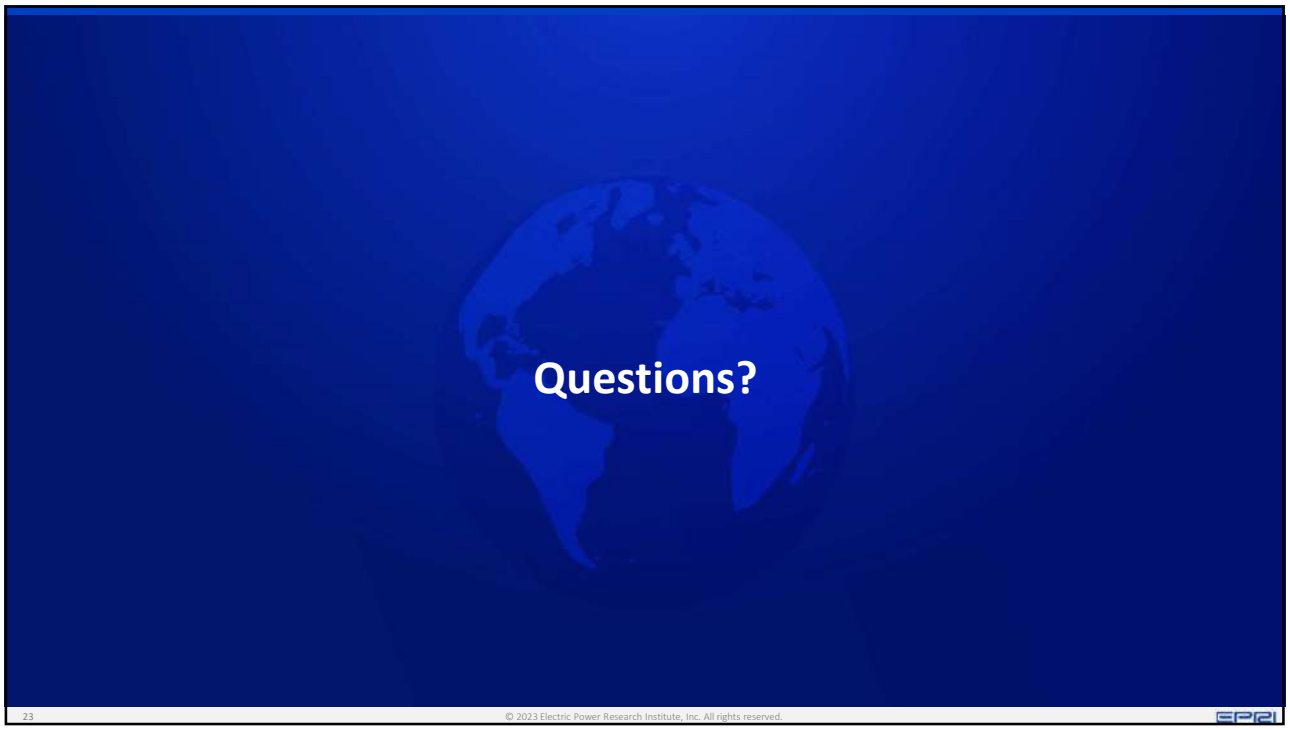

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Appendix

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Opportunities for Future Study

- Next steps for continued research may include:
  - Continued algorithm investigation for pseudo coloring techniques such as HSV pseudo coloring.
  - Laboratory testing of experimental results.
  - Additional studies for pseudo coloring metrics such as contrast-to-noise ratio.
  - User testing with UT technicians and subject matter experts to determine the usability of new display types.

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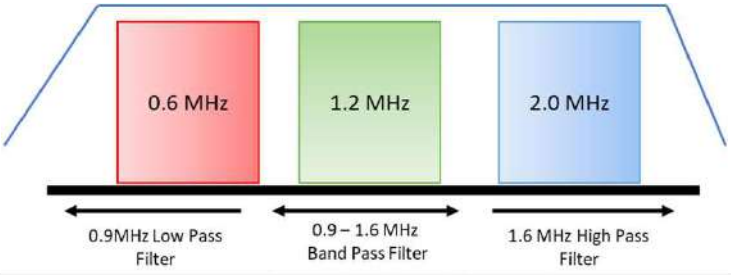
Software Used for UT Data Collection

- UT data was collected using Zetec UltraVision software.
- During the research conducted in [1], an offline post-processing filter tool was implemented in the UltraVision software.
- This filtering tool provided a custom lowpass, bandpass, and highpass filter to be applied to the collected data.
- With this filtering tool, the collected UT data was separated into three frequency ranges with center frequencies at 0.6MHz, 1.2MHz, and 2.0MHz.



Signal-to-Noise Ratio vs. Contrast-to-Noise Ratio

- Signal-to-Noise (SNR) is a metric that is used for determining the likelihood of identifying a flaw within traditional UT data images.
  - This works well for traditional UT images that only contain amplitude/intensity information!
  - This may not work so well with pseudo colored UT images with frequency content as well.
- Contrast-to-Noise ratio could be a metric that showcases the ability of identifying a flaw and determining which frequency content contributes to said flaw.

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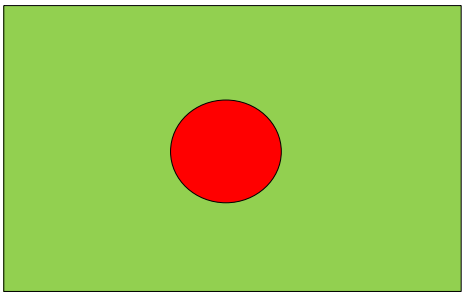
Signal-to-Noise Ratio vs. Contrast-to-Noise Ratio



- Consider a C-scan with RGB pseudo coloring.
- The red area is the flaw, and the green area is considered noise . The intensity of the flaw indication is the same as the surrounding noise.
- By definition, the SNR of the flaw in the A-scan is consider very low.
  - This is because the intensity of the noise is the same as the intensity of the flaw indication.
- However, the contrast to noise ratio is still very high.
  - This is because flaw indication denoted by the red area has a high contrast (and is easily distinguishable) to the noise area denoted by green.
  - The flaw could still be identified although the SNR is very low.

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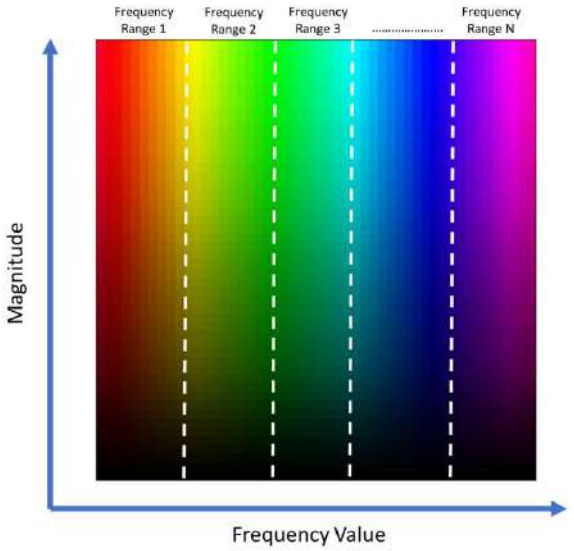
Pseudo Coloring for an Arbitrary Amount of Frequency Ranges

- The RGB model is limited to encoding three frequency bands of interest (low frequency range, medium frequency range, and high frequency range) .
- To encode more than three frequency ranges of interest, a Hue Saturation Value (HSV) pseudo coloring scheme is required.
- The HSV coloring scheme encodes a continuous spectrum of frequencies to various colors instead of considering discrete frequency ranges



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LLT-tandem inspection of thick-section welds using phased-arrays probes

Thomas Bloodworth[1], Mikaël Debroise[2], Dominic Marois[3] & Dirk Verspeelt[3]

[1]Bloodworth Consulting Limited, Wigan, UK
[2]Framatome, 71380 St Marcel, France
[3]Eddyfi, Québec, Canada

…

E-mail address (corresponding author): tbloodworth@btinternet.com

The examination of welds for planar discontinuities whose plane lies perpendicular to the inspection surface is an inspection problem for which tandem ultrasonic testing has long been used as a solution. There exist standards that set out how to design a conventional tandem examination with 45° transverse-wave probes as well as how to design an LLT-tandem inspection in which angled longitudinal waves reflect from the far surface of a component so that they can undergo mode conversion on the face of a defect perpendicular to the surface and return to a receiving probe as transverse waves.

For the End-of-Manufacture inspections of the high-integrity components of Hinkley Point C power station, the LLT-tandem technique has been applied to thick-section welds with internal cladding, by using phased-array probes to create a series of “crossing depth” configurations that cover the thickness of the weld.

The considerations used for the design of the probes are explained. The resulting design covers the thickness with a 5 mm pitch with a single mechanical arrangement of two separate probes. The design enables coverage of welds with thickness exceeding 200 mm.

Other multi-leg reflection modes are possible and the data analysts for these inspections were required to understand and recognise the other modes that could occur. The LLT-tandem inspections form part of multi-technique inspections for a number of high-integrity component welds that have been successfully subjected to Inspection Qualification prior to being used for the final examination of these welds.

Keywords: Ultrasonic testing, tandem testing, LLT, phased array.

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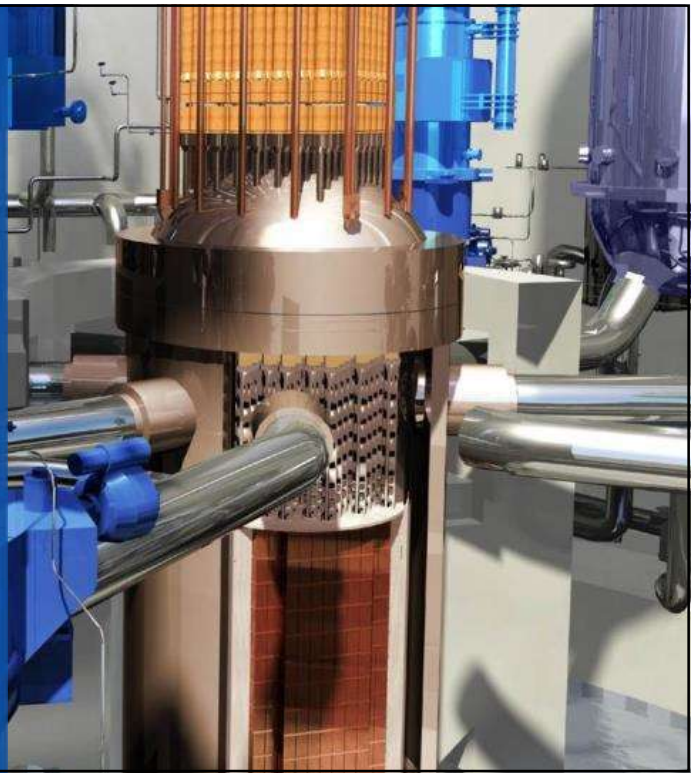
LLT-tandem inspection of thick-section welds using phased-arrays

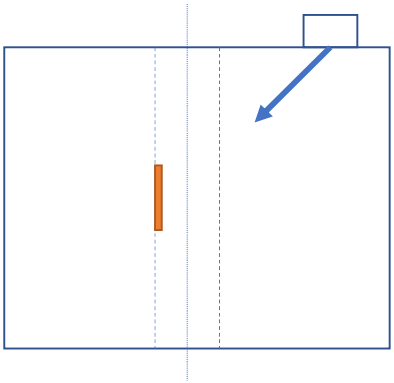
Tom Bloodworth, Mikaël Debroise,
Dominic Marois & Dirk Verspeelt

NDE in Nuclear 2023
Sheffield, June 2023



Defects perpendicular to inspection surface

- Thick-section welds made between parallel preparation faces (chamfers)
- Smooth planar defects (e.g. LoSWF) are therefore oriented with their plane lying normal to the surface and aligned with the weld axis.
- The LLT-tandem technique is optimized for detecting such defects; as described in EN ISO 16826



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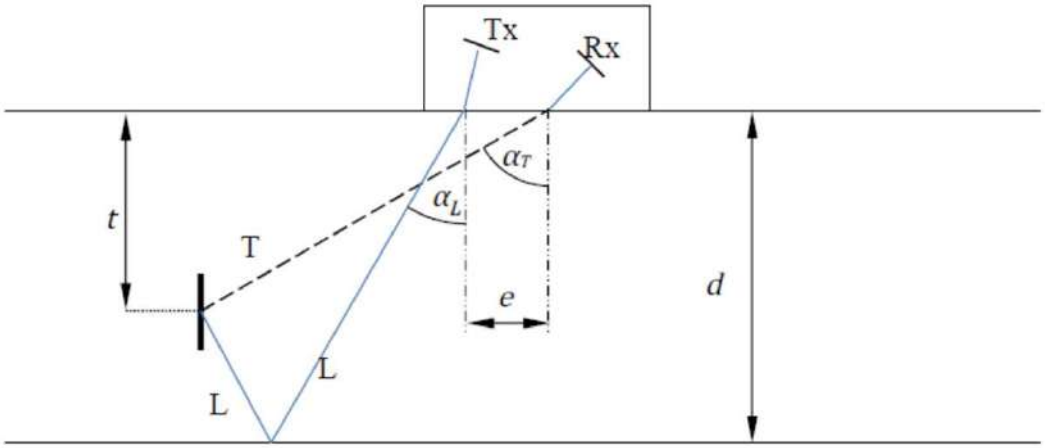
LLT-tandem geometry



$$t = \frac{2d \tan \alpha_L + e}{\tan \alpha_L + \tan \alpha_T}$$

$$\frac{\cos \alpha_T}{\cos \alpha_L} = \frac{c_T}{c_L}$$

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LLT-Tandem key points

- Requires far surface to be parallel to inspection surface
- L-L reflection on far surface
- L-T mode-conversion on defect face
- Crossing point depends on L and T beam angles and probe separation

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Using LLT-tandem for thick welds

- Thick-section welds (150 mm to 250 mm)
  - Requires many LLT-tandem pairs for full coverage
  - So the obvious solution is to use phased-array probes
  - Implementation requires careful design

- Clad on the inside with austenitic steel
  - L-L reflection at clad surface minimizes disruption from the cladding

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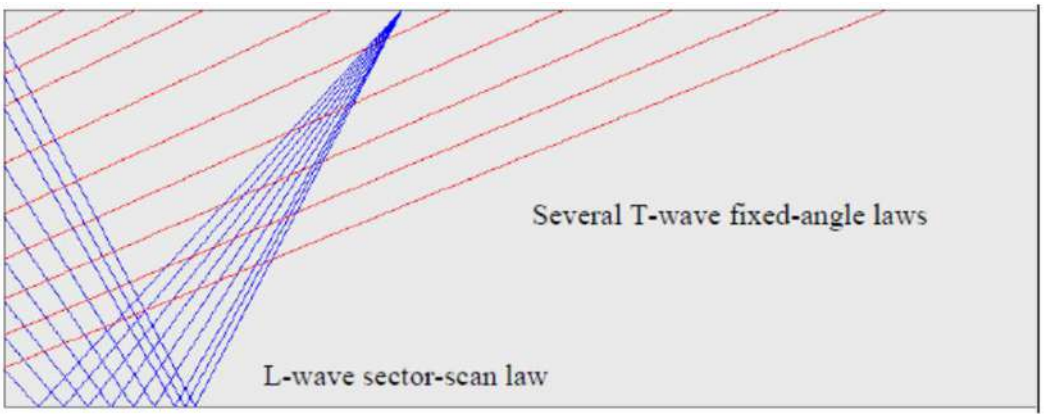
LLT-tandem design - Example 1

L-wave sector scan and many fixed-angle T-wave laws – would need a very long PA probe



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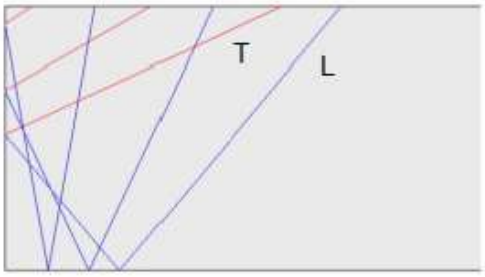
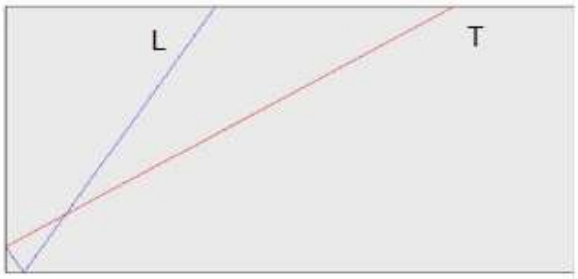
LLT-tandem design - Example 2

Fixed-separation pairs – mechanically more feasible



T in front of L



L in front of T

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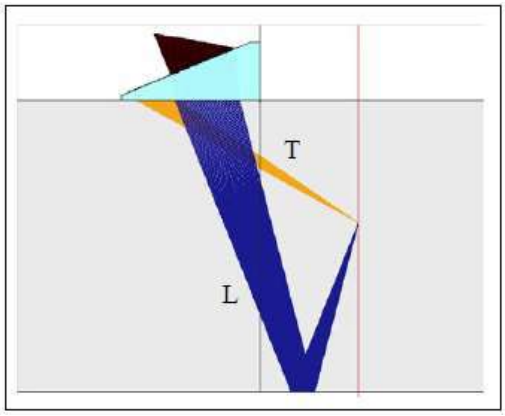
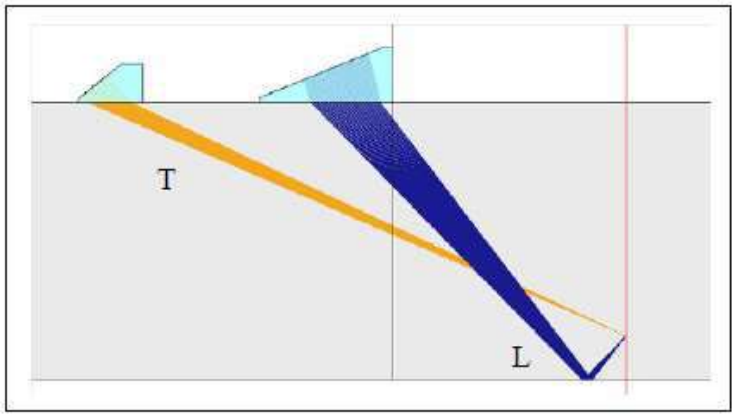
Compromise chosen

- Single-probe option for most of weld thickness
- Two-probe option for deepest region



L and T in single probe



Separate L and T probes

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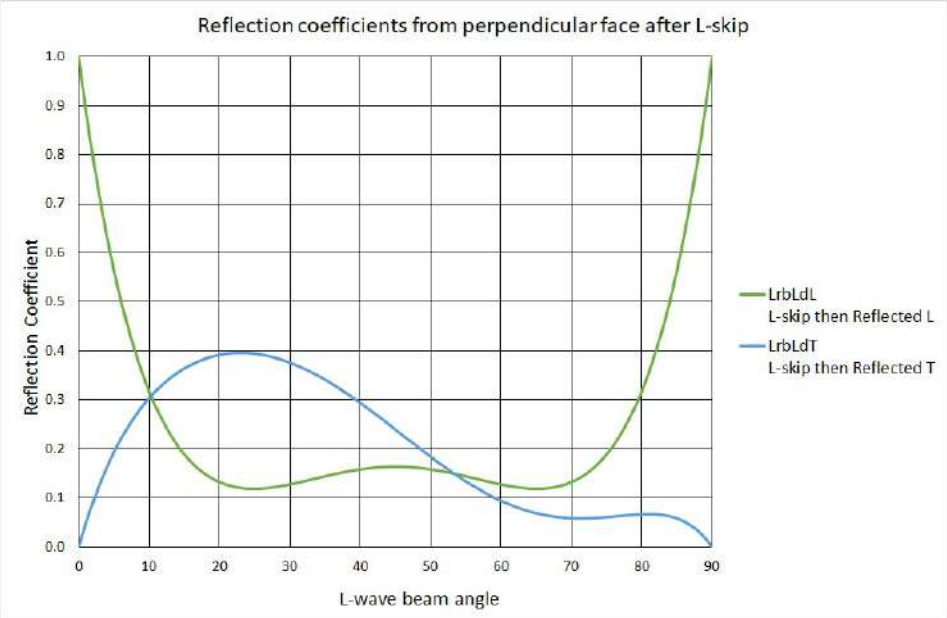
Efficiency of LLT-tandem mechanism



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Single-probe laws

Thickness		165 mm
Refracted beam angles		Separation of index points	Crossing point depth
α_L (°)	α_T (°)	e (mm)	t (mm)
10.1	57.5	-50.2	5
10.2	57.5	-41.6	10
10.2	57.5	-33.0	15
10.1	57.5	-24.0	20
10.2	57.5	-15.4	25
10.2	57.5	-6.7	30
10.1	57.5	2.2	35
10.1	57.5	11.2	40
10.3	57.5	18.7	45
10.2	57.5	28.3	50
11.6	57.7	30.4	55
13.7	58.0	30.1	60
15.7	58.3	30.9	65
17.9	58.7	31.2	70
20.2	59.2	32.1	75
22.4	59.7	33.7	80
25.7	60.5	32.7	85
28.9	61.5	32.9	90
32.9	62.7	32.3	95
36.7	64.0	34.3	100
41.7	66.0	34.9	105

Two-probe laws

Thickness		165 mm
Refracted beam angles		Separation of index points	Crossing point depth
α_L (°)	α_T (°)	e (mm)	t (mm)
13.8	58.0	122.1	110
10.6	57.6	140.8	115
10.8	57.6	148.9	120
12.6	57.8	152.8	125
15.2	58.2	155.5	130
19.4	59.0	156.2	135
26.4	60.7	155.6	140

Nominal deepest crossing point at 140 mm – design limitation of probe size

L-T probe length 64 mm
T probe length 32 mm

framatome

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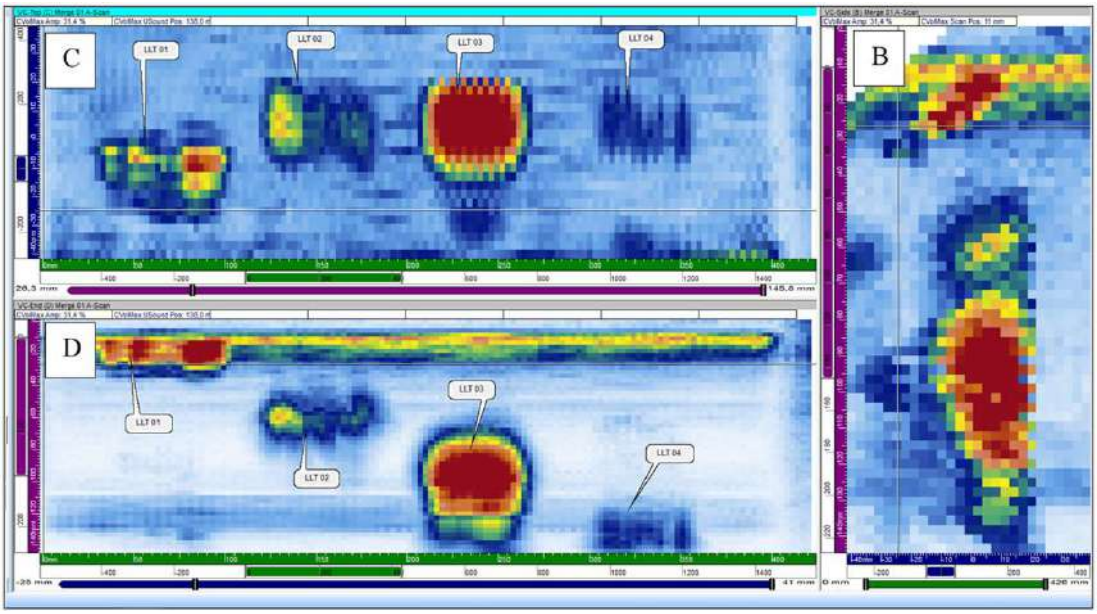
LLT-tandem inspection results (188 mm thick)



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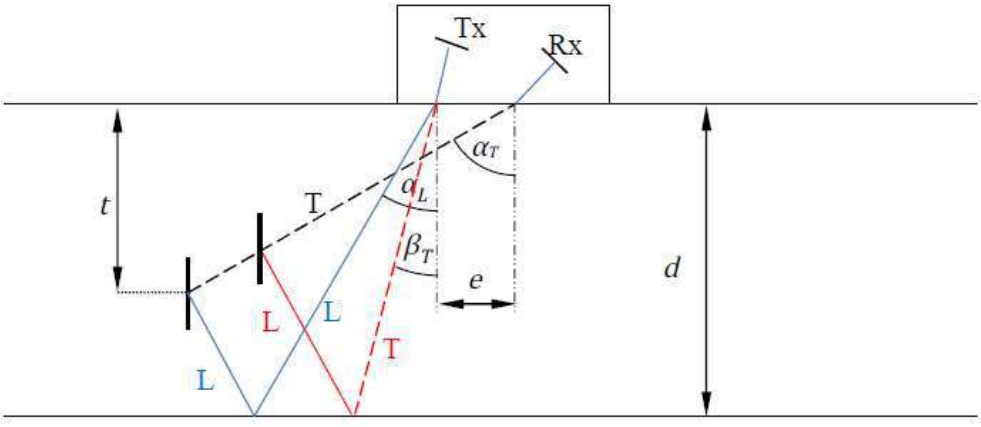
Signal interpretation - Other modes - TLT



- TLT mode at a lesser depth
- Longer time of flight so appears as a deeper “repeat” of LLT

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Conclusions

- LLT-tandem is a powerful ultrasonic technique for detecting planar discontinuities perpendicular to the surface.
- Implementation with phased-arrays allows rapid examination of thick-section welds for such defects
- An example of phased array probes being used where implementation with conventional probes would be unfeasible.

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Thanks for listening.

Are there any questions?

8. Personnel & Human Factors incl. NDE Personnel Training & Certification

The presentations in this session are listed in the table below.

Personnel & Human Factors incl. NDE Personnel Training & Certification	**Chair:** Etienne Martin (EDF)
Using Ultrasonic Simulators to Facilitate Reliable NDE	Josh Stellakis (EPRI)
Human reliability assessment method applied to investigate human factors in NDT: The case of the interpretation of radiograms in the French nuclear sector	Justin Larouze (Mine Paris), Pierre Calmon (CEA), Etienne Martin (EDF)
Development of a Virtual and Synthetic Flaw Modification Process for Training and Qualification	George Connolly (EPRI) et al.
NDE Training and Knowledge Transfer for the Modern Workforce	Scott Hamel (EPRI)

Using Ultrasonic Simulators to Facilitate Reliable NDE

Leif Esp[1], Mark Dennis[1], Terrill Massey[1], Josh Stellakis[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): jesp@epri.com

Over the last few years, the EPRI NDE Program has had ongoing research focused on the development of an Ultrasonic Simulator that can realistically simulate manual conventional examinations of nuclear plant components.

In 2020, the prototype system that provides realistic playback of ultrasonic data on simulated specimens using simulated probes and reference blocks was delivered to the industry. The successful development of this prototype has provided the industry with an additional method for performing training, proficiency maintenance, hands-on practice, and will potentially allow examiners to increase their experience hours using a simulator in lieu of real specimens, instruments, and search units.

The advantage to this is the reduced need for travel for examiners and plant personnel along with a reduction in cost versus purchasing or renting specimens. Another major potential advantage to this is the increased access to specimens that have realistic service induced defects (i.e. IGSCC). Due to the cost reduction pressures being experienced industry wide many examiners are no longer able to practice on these specimens and are missing out on a unique opportunity to maintain proficiency on field removed flaws. The EPRI UT Simulator prototype includes several of these field removed specimens and as such, expands the ability for industry members to get access to these specimens at their facilities or plants without the need for costly travel.

This presentation will provide a summary of the current state of ultrasonic simulator technology as well as an update of in process and future enhancements to the technology.

Keywords: Simulator, ultrasonics, ultrasonic simulator, UT simulator

Using Ultrasonic Simulators to Facilitate Reliable NDE

Josh Stellakis, EPRI
Sr. Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear – Sheffield, UK
June 26 – 29, 2023

www.epri.com

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EPRI VNDE Ultrasonic Simulator

What is it?

- The EPRI VNDE Ultrasonic Simulator is a breakthrough development that overcomes longstanding barriers to ultrasonic examination training and practice. It complements classroom training by providing hands-on ultrasonic examination practice using a fully functional simulator system.

How does it help me?

- Provides a viable option for distance learning and proficiency maintenance for ultrasonic examiners.
  - Helps develop and maintain hand-eye coordination and visuospatial skills needed to be a competent examiner.
  - Provides an opportunity to scan simulated mockups created from real, flawed specimens, some of which are field removed from operating plants with nature-made cracks.
  - Provides realistic examination practice to challenge the skills of the examiner in a risk-free environment.
  - Provides training and hands-on experience anytime, anywhere; without the logistics issues of moving people or heavy specimens

Why is it unique?

- The EPRI VNDE UT Simulator is the first simulator of its type to provide a viable option for recreating manual ultrasonic examinations through a simulated environment while providing a real opportunity for distance learning on par with what you could achieve in a laboratory or classroom setting.

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EPRI VNDE Ultrasonic Simulator

How does it work?

- The integration of software and hardware that simulates a manual ultrasonic examination by "playing back" a recording of ultrasonic examination results
  - "Playing back" is from previously collected/recorded ultrasonic encoded data
    - Encoded data is a result of the acquisition and digitization of the complete A-Scan time base for offline use/review
      - A-Scan time base is an electronic representation of the received ultrasonic energy that propagates the material under examination
        - Received ultrasonic energy is reflected from various material conditions within the mockup
- The entire volume of an existing mockup is examined via high-resolution encoded ultrasonic equipment for future playback by the VNDE Ultrasonic Simulator
- A simulated equivalent of the physical existing mockup is created using various materials and processes
  - As well as procedure-specific calibration standards and transducers
- The simulated transducer is placed on the simulated mockup and every aspect of the transducer's position is tracked through electromagnetics and correlated to the positional information from the recorded encoded data
- Through software, the A-Scan from the previously collected encoded data is *played back* for every transducer position
- The examiner can then simulate an entire ultrasonic examination with the data (A-Scan) being played back for every location and orientation of the transducer

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EPRI VNDE UT Simulator System

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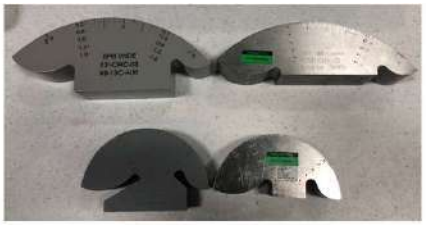
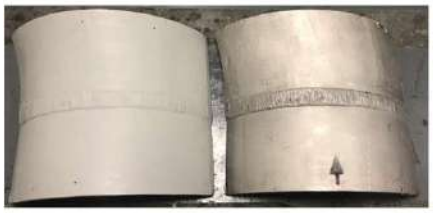
EPRI VNDE Simulated Specimens / Mockups





Molded Specimen Real Specimen

Molded Specimen

Real Specimen

Realistic search units, specimens, and qualified procedures are used to perform the data collection and "playback" to ensure the highest level of realism is obtained in the simulation results

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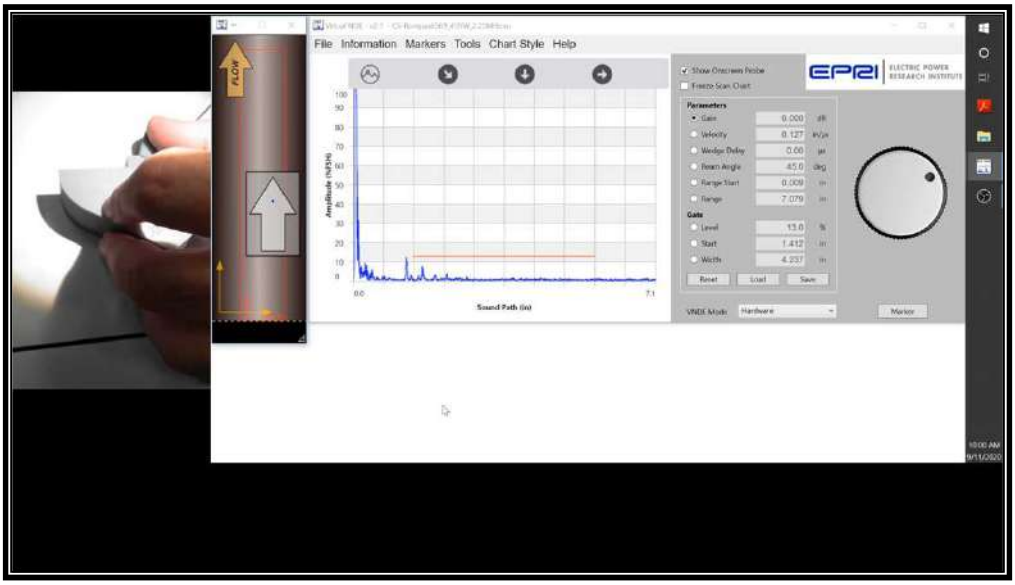
EPRI VNDE UT Simulator Calibration



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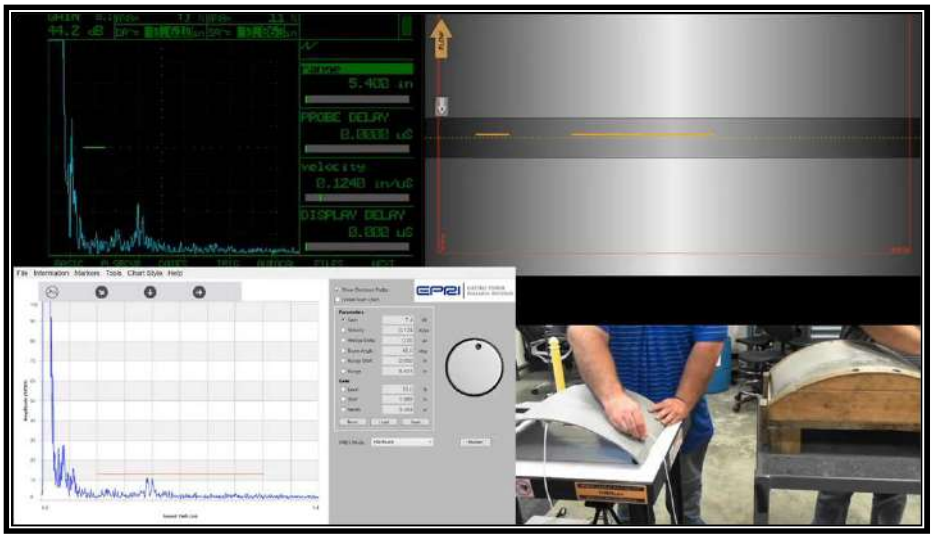
EPRI VNDE UT Simulator Compared to Standard Industry Manual UT Instrument and Equipment



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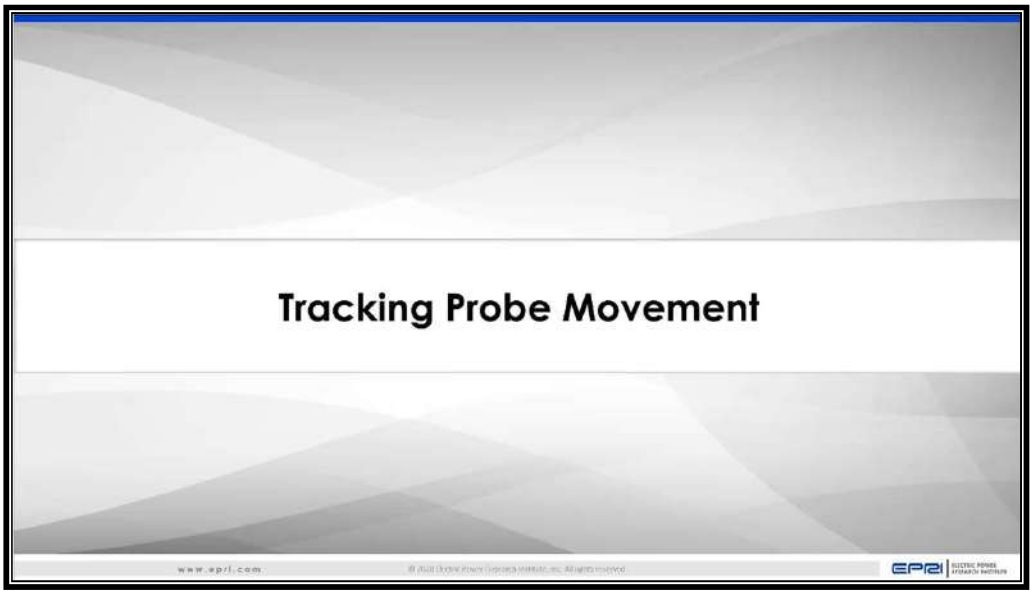
EPRI VNDE UT Simulator Additional Features



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VNDE UT Simulator Future Technology Enhancements

VR-based Simulated Environment

Please Visit the VNDE UT Simulator Showcase Booths to View these Systems

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Questions?

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Human Reliability Assessment method applied to investigate human factors in NDT
The case of the interpretation of radiograms in the French nuclear sector.

Etienne MARTIN[1], Pierre CALMON[2], Justin LAROUZE[3]

[1]EDF – DIPNN – Direction Industrielle, 2 rue Ampère 93200 Saint-Denis, France
[2]CEA LIST, Centre de Saclay Bât. 565, F-91191 Gif-sur-Yvette, France
[3]Mines Paris, CRC, 06904 Sophia Antipolis France

E-mail address (corresponding author): etienne.martin@edf.fr

This paper is intended to share the experience of an approach initiated in France through a National Funded Project (ANR FOEHN) to strengthen the consideration of organisational and human factors in a critical phase of radiographic testing (RT) in the nuclear industry: interpreting radiograms.

Faced with a community of professionals with very different sensitivities and cultural maturity with regard to human and organisational factors, the CREAM method of characterisation and analysis was adapted to the specificities of the activity studied. CREAM is a Human Reliability Assessment (HRA) method that benefits not only from a solid theoretical background but also from numerous operational applications. CREAM emphasises the importance of cognitive processes in human activities and proposes a method for proactively evaluating the probability of error based on the specificity of the tasks to be performed by an operator. The main challenge was to tailor CREAM to the context and specificities of film interpretation through a campaign of non-participant observations and semi-structured interviews in two French nuclear power plants and the two main training centers for the profession of controller, complemented by interviews with experts in the field.

A detailed hierarchical task analysis (HTA) was carried out for the film interpretation phase to break down the activity into elementary subtasks (N=60). The common performance factors (CPC) of the CREAM method were adapted in terms of labels, definitions and their admissible states to reflect the specificities of the profession. The cognitive load profiles for the main subtasks were determined. Finally, the most likely error modes were proposed and validated by RT experts.

Unlike the original intention of the method, our results do not lead to quantifying the probability of errors occurring. Instead, they allow us to highlight subtleties in the reality of the interpreter's profession (e.g. the fact that "interpreting" mobilises the cognitive function of " interpretation" to a lesser extent than might have been expected); they also allow the HOF subject to be discussed in the professional community by providing a common vocabulary and framework. Further work (in particular on the cultural dimensions and the relationship with rules, sanctions and inspections) is in progress.

Keywords: Non-Destructive Examination, Integrity, Reliability, HOF,

NUGENIA
Nuclear Generation II&III Alliance

ENIQ
European Network for Inspection & Qualification
NUGENIA Technical Area 8

eDF MINES PARIS | PSL list CEA tech

NDE in Nuclear 2023

NDE In Nuclear 2023 Sheffield

Human reliability assessment method applied to investigate human factors in NDT:

The case of the interpretation of radiograms in the French nuclear sector

Justin LAROUZEE (Mines Paris, France)
Pierre CALMON (CEA LIST, France)
Etienne MARTIN (EDF – DIPNN, France)

OUTLINE

1/ Context and motivations

2/ CREAM principles and methodology

3/ Adapted CREAM methodology for RT interpretation

4/ Results, discussion

1

CONTEXT & MOTIVATIONS

FOEHN project

NDT AND HUMAN FACTORS

Some shared considerations

- NDT plays a vital role in ensuring the safety of NPP operations and their reliability can be affected by **human performance**
- The importance of **Human and Organizational Factors** (HOF) is unanimously accepted by all stakeholders involved in the design, construction, and operation or decommissioning of these facilities
- Growing interest on HOF in NDT over the world. Several studies carried out and published in the last decade (BAM, NRC, EPRI,...). International WGs on this topic.

FOEHN PROJECT

Organizational and Human factors for NDE reliability assessment

Overall objective: Make progress on the taking into account HOF in NDE reliability assessment.

- Project funded by French Research Agency (ANR) (2017-2020)
- Partnership

Multisectors (Energy, Aerospace) / Gathers NDE & HOF experts

Various directions of research explored by the project

- **On selected cases : Analysis and modelling the HOF and their impact on NDT performance**
- Reflexion on HOF inclusion in a MAPOD methodology
- Monitoring of [manual UT] inspection both to capture variability of gesture and to mitigate HF

ONE INSPIRING CASE OF STUDY (1/2)

- **A bimetallic butt-weld end connection of valve** (ø 3" x 2.77 mm), replaced in 2011, is the subject of an in-service radiographic follow-up examination (48-month periodicity). The sought degradation is mechanical vibratory fatigue cracking.
- **In 2016, 13 months after the last gamma ray inspection, a leak under insulation** led the NPP owner to detect a jet of steam at the bimetallic weld.
- **The weld was gamma-rayed 3 times, interpreted 6 times** by 5 different SQEP (Suitably Qualified Experimented Personnel). **No linear image has ever been recorded**.
- **Re-readings and re-analysis of all the radiographs made on this weld (2012, 2014 and 2015) revealed an image of crack** with circumferential orientation of Lg 70 mm.

➡ Highligting a characterized Human Factor issue

ONE INSPIRING CASE OF STUDY (2/2)

- The first analysis showed different failures to respect the Inspection Procedure.
- So by field enquiries to the operators, **tentative to understand why**, in spite of the proficiency of the operators, the failure of the organisation where 3 inspectors during 3 outages didn't see the image of the defect on the radiographs.
- **In front of the difficulty for operators to respond to an external auditor on such a case engaging personal responsibility, decision was taken not to focus on one specific case but to launch a more general study on HOF in RT.**

NARROWED FOCUS

The present work is part of a wider collaborative research project "FOEHN" (2017-2020) supported by the French National Agency "ANR". It focuses on HOF in the interpretation of RT, in the French nuclear power plants.

RT is one of many NDT processes; French nuclear industry relies on RT films which can be archived and compared over the time to analyze in-progress degradations.

RT implementation encompasses:

- Exposures preparation
- Exposures realization
- Film processing
- **Radiographs interpretation**

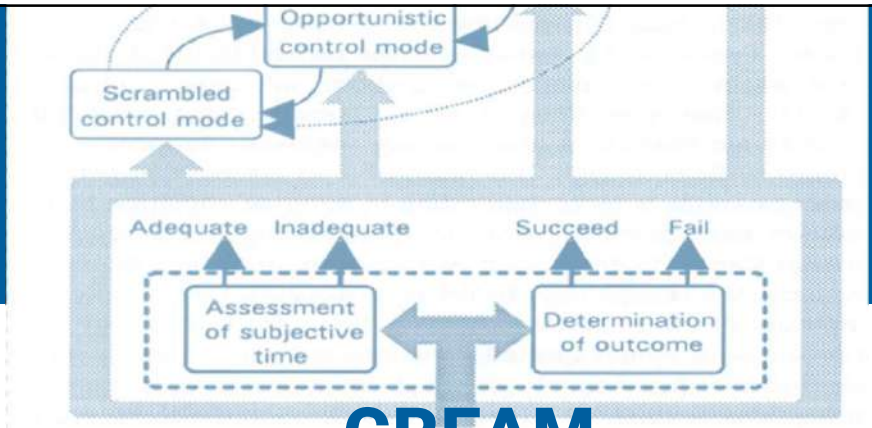
Those tasks being performed by different individuals and often under time pressure.

Different actors (Regulatory – Utility - Vendor); responsibility of the IQB for the qualification of the NDT System; Recognized Tierce Party Organisation (RTPO) for the personnel's certification

A "satisfactory" NDT process relies on:

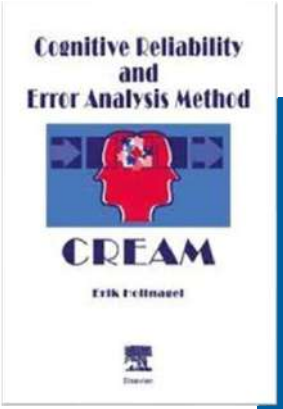
- Capability Statement or Qualification of NDT inspection by an IQB
- Certification of the personnel by an RTPO
- Responsibilities of the vendor to maintain the proficiency of the personnel
- Interactions between NDT vendor and utility customer to ensure the inspectors have all the information they need and minimize interruptions

2



CREAM
Principles & methodology

PRINCIPLES & METHODOLOGY



Cognitive Reliability and Error Analysis Method

CREAM is a Human Reliability Analysis (HRA) Method

Published in 1998 by Erik Hollnagel (safety scientist)

Widely used by both academics and practitionners

The original methodology is divided into:

- A simplified CREAM (mainly intended to **assess working situations**)
- A complex version (intended to calculate **quantiative error probabilities**)

➡ This quantitativity makes CREAM attractive in the context of POD studies

PRINCIPLES & METHODOLOGY

What exactly are we talking about?

HUMAN PERFORMANCE = **SKILLS** (what I can / know how to do) x **CONTROL** (context for using skills)

Depends on:

- 4 **basic** cognitive functions (Observation / Interpretation / Planning / Execution)
- Used at the right time, on the right object, with the right intensity, (etc.) = "human reliability"

Depends on:

- The **context** in which the activity is carried out (influence measured by studying the effects of a limited set of "Common Performance Conditions" or CPC)
- Which determines a control mode + - propitious: (Strategic > tactical > opportunistic > scrambled)

Break down the activity in elementary tasks → Identify the cognitive functions involved → Assess the context of realisation (CPCs) → Determine the control mode (=> Human Error Probability) → Estimation of the probability of success or error of the activity

PRINCIPLES & METHODOLOGY

What exactly are we talking about?

Decompose the activity in elementary tasks → **Assess the cognitive functions involved** → Assess the context of realisation (CPCs) → Determine the control mode (=> Human Error Probability)

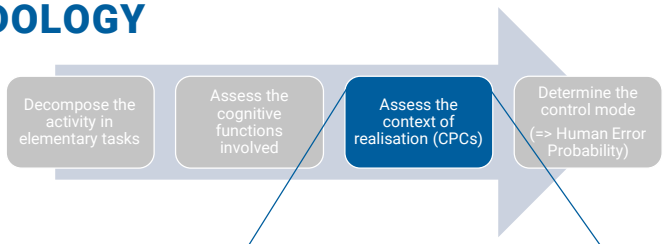
Cognitive function	Generic failure type	Lower bound (.5)	Basic value	Upper bound (.95)
Observation	O1. Wrong object observed	3.0E-4	1.0E-3	3.0E-3
	O2. Wrong identification	2.0E-2	7.0E-2	1.7E-1
	O3. Observation not made	2.0E-2	7.0E-2	1.7E-1
Interpretation	I1. Faulty diagnosis	9.0E-2	2.0E-1	6.0E-1
	I2. Decision error	1.0E-3	1.0E-2	1.0E-1
	I3. Delayed interpretation	1.0E-3	1.0E-2	1.0E-1
Planning	P1. Priority error	1.0E-3	1.0E-2	1.0E-1
	P2. Inadequate plan	1.0E-3	1.0E-2	1.0E-1
Execution	E1. Action of wrong type	1.0E-3	3.0E-3	9.0E-3
	E2. Action at wrong time	1.0E-3	3.0E-3	9.0E-3
	E3. Action on wrong object	5.0E-5	5.0E-4	5.0E-3
	E4. Action out of sequence	1.0E-3	3.0E-3	9.0E-3
	E5. Missed action	2.5E-2	3.0E-2	4.0E-2

Key idea:

- Each cognitive function has a limited number of ways to fail (General Failure Modes).
- Probability values are associated to each Failure Mode (Swain & Guttman)

PRINCIPLES & METHODOLOGY

What exactly are we talking about?



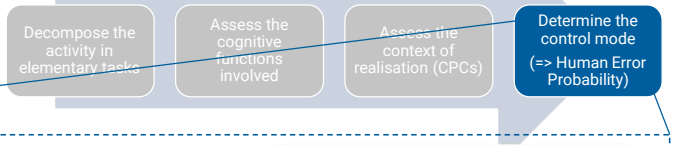
Key idea:

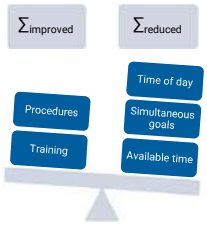
- Analysis of the context : Levels of adequacy aggected to a list of "Common Performance Conditions" (CPC)
- CPC affect (improve/degrade) differently the performance of the ≠ Cognitive Functions

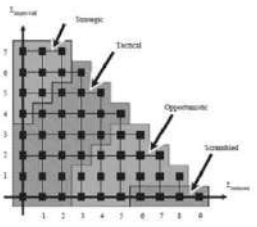
CPC name	Level	COCOM function			
		OBS	INT	PLAN	EXE
Adequacy of organisation	Very efficient	1.0	1.0	0.8	0.8
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.2	1.2
	Deficient	1.0	1.0	2.0	2.0
Working conditions	Advantageous	0.8	0.8	1.0	0.8
	Compatible	1.0	1.0	1.0	1.0
	Incompatible	2.0	2.0	1.0	2.0
Adequacy of MMI and operational support	Supportive	0.5	1.0	1.0	0.5
	Adequate	1.0	1.0	1.0	1.0
	Tolerable	1.0	1.0	1.0	1.0
	Inappropriate	5.0	1.0	1.0	5.0
Availability of procedures / plans	Appropriate	0.8	1.0	0.5	0.8
	Acceptable	1.0	1.0	1.0	1.0
	Inappropriate	2.0	1.0	5.0	2.0
Number of simultaneous goals	Fewer than capacity	1.0	1.0	1.0	1.0
	Matching current capacity	1.0	1.0	1.0	1.0
	More than capacity	2.0	2.0	5.0	2.0
Available time	Adequate	0.5	0.5	0.5	0.5
	Temporarily inadequate	1.0	1.0	1.0	1.0
	Continuously inadequate	5.0	5.0	5.0	5.0
Time of day	Adjusted (day-time)	1.0	1.0	1.0	1.0
	Unadjusted (night-time)	1.2	1.2	1.2	1.2
Adequacy of training and preparation	Adequate, high experience	0.8	0.5	0.5	0.8
	Adequate, low experience	1.0	1.0	1.0	1.0
	Inadequate	2.0	5.0	5.0	2.0
Crew collaboration quality	Very efficient	0.5	0.5	0.5	0.5
	Efficient	1.0	1.0	1.0	1.0
	Inefficient	1.0	1.0	1.0	1.0
	Deficient	2.0	2.0	2.0	5.0

PRINCIPLES & METHODOLOGY

What exactly are we talking about?







Mode	HEP interval
Strategic	0.5E-5 < p < 1.0E-2
Tactical	1.0E-3 < p < 1.0E-1
Opportunistic	1.0E-2 < p < 0.5E-0
Scrambled	1.0E-1 < p < 1.0E-0

- In a **strategic control mode**: the agent can plan, check his plans, communicate, etc.
- In a **tactical control mode**, the agent faces the local situation without being able to produce higher-level strategic plans.
- In an **opportunistic control mode**, the agent reacts to events.
- In a **scrambled control** mode, the agent improvises.

Key idea:

- Human Error Probability (HEP) depends on Cognitive (skills) Control (context) adequation

3

ADAPTED CREAM
Challenges & first results

ADAPTED CREAM

Methodology of adaptation

Observation and interview campaigns were carried out

- (3 NPPs ; 2 training centers ; 30 interviews)

ADAPTED CREAM What exactly is 'interpretation'?

#	TASK	DESCRIPTION
1	Workspace preparation	The interpreter enters the room, sets up, starts and adjusts the equipment
2	Preparation of the interpretation of radiographs	The interpreter ensures that he has his working equipment, procedures, the right number of radiographs
3	Check of the quality of the radiograph	Set of mandatory preliminary checks on radiographs, (optical density, image quality index, general condition, ...)
4	Interpretation of the radiographs	Research of density gradients, comparison with previous radiographs, writing the examination report

ADAPTED CREAM What exactly is 'interpretation'?

#	#	TASK	COMMENT	CF	CFF
1	1	**Workspace preparation** 11			
2	1.1	Enter the room 9	Check that there is no interpretation already in progress	EXE	E2
3	1.2	Free up workspace 18	(if applicable), one work planning per person	OBS	O3
4		22		EXE	E5
	1.3	Turn on the air conditioning if necessary	Too high temperature of the room in summer. The use of several view boxes in a small room requires the use of air conditioning to "lower" the temperature of the room, otherwise the view boxes break down.	PLAN	P1
	1.4	Sitting in front of the illuminator		PLAN	P1
	1.5	Turn on the illuminator, check its conformity	Valid annual verification	PLAN	P1
	1.6	Adjust your working position so that your eyes are slightly above the light beam	Adjust the view box support legs and/or the seat height	OBS	O3
				EXE	E1
	1.7	Check the conformity of the densitometer	Current annual audit		
	1.7.1	Turn on the densitometer		PLAN	P1
	1.7.2	Allow the unit to reach operating temperature and thermal stability for a minimum of 30 minutes.		PLAN	P2
	1.7.3	Check the drift of the densitometer with the working radiograph	At the beginning and end of the interpretation phase (drift)	INT	I1
				EXE	E5
	1.7.4	Fill in the audit report	Name, first name, date, start and end time...	PLAN	P2
				EXE	E5

The overall hierarchical analysis breaking down the activity into 60 subtasks

Characterization performed by 3 groups of field experts who worked independently under the supervision and with the support of a HF specialist.

ADAPTED CREAM What exactly is 'interpretation'?

#	TASK	COMMENT	CF	CFF
2	**Prepare the interpretation of radiographs**			
2.1	Have the review procedure and associated documents available	Check to keep in mind the criteria for scoring, characterization and significant variation.		
2.1.1	Have the characteristics of the area under examination	Type of connection, profile survey, chamfer planning, etc.	PLAN	P2
2.1.2	Have radiographs from previous examinations including end-of-production NDT radiographs		PLAN	P2
2.1.3	To have the operating conditions of the exposure		PLAN	P2
2.2	Have small materials available (transparent ruler, blank examination report, etc.)		PLAN	P2
2.3	Put on the gloves	Personal equipment, cleanfull	PLAN	P1
			EXE	E2
2.4	Take the radiograph packs		PLAN	P2
2.5	Check the adequacy between the radiographs to be interpreted and the area to be examined		OBS	O2
			PLAN	P1
2.6	Check the number of exposures specified by the procedure	Ensure that no exposure is missing	OBS	O3
			PLAN	P1

ADAPTED CREAM What exactly is 'interpretation'?

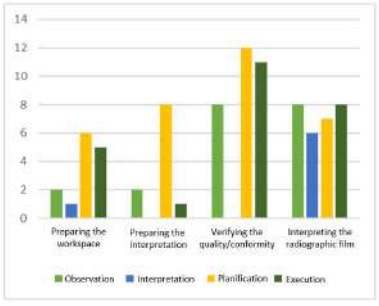
#	TASK	COMMENT	CF	CFF
3	**Check the quality of the radiograph**			
3.1	Taking a radiograph			
3.1.1	Open paper pocket	Start with the one with the "0" mark	PLAN	P1
3.1.2	Remove paper divider	Keeping it accessible	PLAN	P1
3.2	Check the adequacy of the luminous marking, the lead marker with the operating conditions of the exposure		OBS	O2
			PLAN	P1
3.3	Check the quality of radiographs			
3.3.1	Check the general condition of each of the two radiographs	Absence of scratches, stains, marks. Verification carried out in comparison single/double radiograph	OBS	O2
			EXE	E5
3.3.2	Determine the area to be Interpreted	In accordance with the procedure applied	PLAN	P2
			EXE	E3
3.3.3	Check the completeness of the area to be Interpreted		OBS	O2
			PLAN	P1
			EXE	E3
3.3.4.	Check the optical density of the radiograph			
3.3.4.1	Use densitometer	After letting it warm up for at least 30 minutes	PLAN	P2
3.3.4.2	Read the density according to the procedure		PLAN	P2
			EXE	E1
3.3.4.3	Verify the compliance of the optical density with the requirements of the procedure		OBS	O2
			PLAN	P2
			EXE	E1
3.3.4.4	Record the optical density values of the radiograph in the examination report		EXE	E4
3.3.4.5	Check the difference in optical density at the same point of the two radiographs of the same cassette	The difference must be less than 0.3 if Ir 192 0.2 if Co 60	OBS	O1
			PLAN	P2
			EXE	E5
3.3.5	Verify the conformity of the image quality index of the radiograph	In accordance with the procedure applied	OBS	O3
			PLAN	P1
			EXE	E4
3.3.5.1	Record the Image Quality Index (IQI) in the examination report		EXE	E5
3.3.6	Check the conformity of the numbered band (Presence of index, not conform (distance in marks and between index), position, parallelism)		OBS	O3
			PLAN	P2
			EXE	E5
3.3.7	Check that the entire weld has been radiographed (overlap)	Number of views defined by the procedure	OBS	O1
			PLAN	P2
			EXE	E5

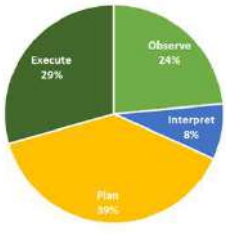
ADAPTED CREAM What exactly is 'interpretation'?

#	#	TASK	COMMENT	CF	CFF
1	4	**Interpretation of the radiograph**			
2	4.1	Place double radiograph in front of the film illuminator		PLAN	P1
3	4.2	Overlap radiographs with precision	Make sure that the marks coincide (movement blur, deformation of the cassette, tiling, ...)	PLAN	P2
4	4.3	Adjust brightness		PLAN	P1
	4.3.1	Acting on the diaphragm		PLAN	P2
	4.3.2	Act on the intensity potentiometer		PLAN	P1
	4.4	Detecting density gradients (images)		OBS INT	O2 I1
	4.5	Sort images		OBS INT	O2 I1
	4.5.1	Note the radiograph defects in the Examination Report's (ER) observations column	Perhaps a draft or the final ER; In the survey report adapted to the procedure	EXE	E1
	4.5.2	Size images that have not been classified as IPU		OBS INT	O2 I1
	4.6	Compare images to scoring and/or characterization thresholds	Have the procedure or codes	OBS INT	O2 I1
	4.7	Locate the images (x, y)		OBS EXE	O2 E1
	4.8	Compare the images with visible or non-visible images from previous visits	This part of the analysis compared with the reference radiographs is fundamental. It is during this part that we can determine the novelty of an indication	OBS INT	O2 I1
	4.9	Categorize images	NT 114 or NT 116 Switch from the image step to the volumetric or non-volumetric indication step	OBS INT	O2 I1
	4.10	Fill in the Examination Report			
	4.10.1	Identify the area being examined on the ROE	Site, slice, Plant Sytem, line number, ISO number and weld number	EXE	E1
	4.10.2	Identify the radiograph (numbered band markings)		EXE	E1
	4.10.3	Rate, by numbering them, the images above the rating threshold according to the rating code (LI, NLI, Artefact)	Specify NAD (Nothing Abnormal Detected) when no images are detected or NSI (No Significant Indication) when images below the scoring threshold are observed.	EXE	E1
	4.10.4	Identify images above the characterization threshold		EXE	E1
	4.10.5	Compare the images at the significant variation threshold	Especially in comparison with radiographs from previous visits	OBS EXE	O2 E1
	4.10.6	Complete the review report		EXE	E4
	4.11	Close the diaphragm	To avoid "flash" phenomena	PLAN	P2
	4.12	Store radiograph in its pocket		PLAN	P2

ADAPTED CREAM What exactly is 'interpretation'?

#	TASK
1	Workspace preparation
2	Prepare the interpretation of radiographs
3	Check the quality of the radiograph
4	Interpretation of the radiograph





Key idea:

- From a cognitive point of view, interpreting radiographs mobilises much more than only 'interpretation' function!
- This is because the interpreter has a lot of preparatory and quality checks to do

ADAPTED CREAM What are the common performance conditions?

#	CPC	DESCRIPTION / ANALYSIS ELEMENTS
1	PROCEDURES & TECHNICAL DOCUMENTATION (CCP, NT, FTR, History of previous exams)	Available, displayed, up to date (indexes, revisions), manufacturing films (archiving), end of manufacturing report, design plan, welding records, etc. Eligible states: Appropriate (+), Acceptable (0), Inappropriate (-)
2	NUMBER OF SIMULTANEOUS OBJECTIVES	Number of welds to be interpreted (possibly number of views per weld). Type of problem (need for additional exposures, meeting). Acceptance or not of films (films conformity). Type of weld (attention when in need to interpret different welds), the diversity of the controlled areas, their geometry. This is related to the organization of work since it is tried to distribute the workload on available interpreters so that they neither use a single procedure overnight nor have change too frequently. Eligible states: Less than capacity (0), At capacity (0), More than capacity (-)
3	LOCAL CONDITIONS OF INTERPRETATION	Interpretation room condition (dark, quiet, wall color, 0-10 LUX, not used as a checkroom, twinned with the lab, multiple interpreters in parallel). Sufficient space to deposit films, to fill out examination reports. Adequate temperature of the room (the use of several illumators in a small room requires the use of air conditioning to lower the temperature, otherwise the illumators might break down. Meanwhile several illumators generate a lot of noise from their fans, which is tiring in the long run). Eligible states: Advantageous (+), Compatible (0), Incompatible (-)
4	AVAILABLE TIME	Number of films to be interpreted, phase of the shutdown. Need to catch up with delays (end of intervention on critical path). Possible pressure to communicate the results quickly and to be able to release the material (sequence of phases). Fatigue. Eligible states: Adequate (+), Temporarily inadequate (0), Continually inadequate (-)
5	QUALITY OF THE HARDWARE	Collective equipment: illumators (with foot pedal to avoid flashes) and densitometers, type of illumator (with adjustable iris, rectangular, LED, etc.). Individual equipment: gloves, ruler, pencil, reading table... Eligible states: Adequate, verified (0), Satisfactory (0), Inadequate (-)
6	TRAINING AND EXPERIENCE	Level of education (level of knowledge in the broadest sense; it is not the level of education that makes the interpreter), years of experience, arrangements and frequency of skill maintenance. Duration of the companionship (rarely respected). Eligible states: Adequate training, experienced (+), Adequate training, little experience (0), Inadequate (-)
7	EFFECTIVENESS OF COLLABORATION / COMMUNICATION	Relations between NPP, internal engineering, technical assistants and the provider. Negotiations on shooting, position, exposure. Collaboration or competition between teams (preparation, shooting, lab, interpreter). Loss of concentration due to the presence of clients in the interpretation room (right behind the interpreter implying a form of pressure). Exercise of free will (avoid the phenomenon of copying/adopting the opinion of another person). Eligible states: Very efficient (+), Efficient (0), Inefficient (-), Undesirable (-)
8	TIME OF DAY (day = 8am to 8pm) PERIOD OF THE WEEK (middle = Tuesday, Wednesday, Thursday)	Favorable end of night (calm, less co-activity), but also more fatigue (monitor the accumulation of weekends worked and the weekly workload). Beginning and end of weeks at risk: long distance driving (from home to work) and/or workload accumulation. Eligible states: Day, mid-week (0), Day, early or late week (0), Night, mid-week (+), Night, beginning or end of week (-)

4

SUMMARY

RESULTS

In Summary:

- We have adapted the CREAM method to NDT (RT)
- Our scope, guided by the accessible terrain, was that of the interpretation of radiographs in French nuclear power plants
- Through this research we produced:
  - A detailed hierarchical task analysis (60 subtasks)
  - An adapted list of CPCs
  - And a sociological analysis of the profession
- Altogether these elements:
  - Help understand some of the factors that make the profession attractive/difficult
  - Help understand how error-provoking situations can be met
  - Provide a quantitative metric to assess the risk of error associated with an NDT system deployment situation, from implementation to analysis

DISCUSSION

- **CREAM** presents a particular interest since **it can offer a metric for evaluating the risk of human error,** considering the cognitive load of the task and contextual conditions
- **This work is a proof of concept** narrowed to interpretation of RT radiographs in a specific context (ISI of French NPP)
  - The benefits of adopting such an analysis in the field must be evaluated, all methods and techniques of NDT, by integrating the invigilation phase by the licensee
  - Work is currently underway to open the thinking to other techniques and industrial sectors through a working group at COFREND
- **One initial intention in FOEHN was to enrich the POD calculations (in particular MAPOD) with human error probabilities. This objective was quickly discarded:**
  - Integrate the risk of cognitive error in a chain of events in order to estimate the probability of failure of a complex task such as detection of defect is not a trivial task
  - Moreover there is no way at this stage to link the probability of cognitive failure to the technical parameters of the NDT process such as the defect size

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Thank you for your attention!
Any questions?
NDE IN Nuclear 2023 Sheffield - J. Larouzée, P. Calmon, E. Martin

Development of a Versatile Virtual Mockup Modification Process for Training and Qualification Purposes

George Connolly[1], Leif Esp[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): gconnolly@epri.com

The modern nondestructive evaluation (NDE) workforce depends upon ongoing training and qualification opportunities to maintain effectiveness and proficiency for safe operation of the nuclear power plant fleet. Currently, the industry invests heavily in procuring and developing a library of physical mockups containing realistic implanted defects, but such specimens are expensive and so relatively few are fabricated.

The EPRI synthetic and virtual mockup project was established in 2013 to support the energy industry by providing a means to electronically generate an array of mockup datasets by modification of existing datasets and synthesis of new datasets. This capability can allow for a diverse library of virtual mockups to be configured and designed for training and demonstration purposes, at a potentially great saving of cost and time. This project has already served six international partners and collaborators for EPRI.

We present an overview of the current state of this research activity with some examples of the modification process and its capabilities and potential, involving both virtual flaws and synthetic flaws. It is envisaged that this tool will be used to generate datasets with virtual flaws in certain configurations to be used in a blind scenario. We also discuss the perspectives on the use of this tool and its qualification progress involving regulatory bodies.

Keywords: Data Manipulation, Flaw Response, Ultrasonic Qualification, Virtual Flaw, Virtual Mockup

Development of a Virtual and Synthetic Flaw Modification Process for Training and Qualification

Tuesday 27 June 2023

George Connolly, EPRI, Inc.
Leif Esp, EPRI, Inc.
Bret Flesner, EPRI, Inc.
Joel Harrison, Pacific Northwest National Laboratory
Aroldo Claus, Nucleoeléctrica Argentina S. A.
Ladislav Horáček, ÚJV Řež, a. s.

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Outline

- Motivation
- Case Study: Access Hole Cover
  - Virtual mockup and synthetic mockup with imported simulated CIVA data
- Ongoing Industrial Partnerships
  - Recent activities and perspectives
- Summary

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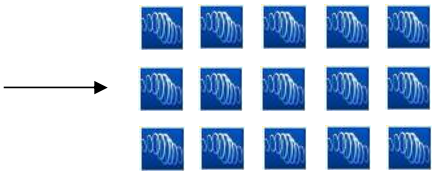
Motivation

- Training, education and qualification critical for the contemporary NDE workforce to develop and maintain skills
- Physical mockups, while important, are expensive to maintain and manage
- Virtual mockups and their datasets can complement physical mockups for training, education and qualification purposes

- We propose to general virtual mockups electronically:
  - Source real data on real flaws and position them appropriately as desired in the virtual dataset
  - Cheaper and quicker than procuring physical mockups
  - Easier to manage with good IT security
  - Can regenerate them every qualification cycle
    - Compromised physical mockup becomes useless; a compromised virtual mockup can be quickly regenerated and replaced

Significant storage and management requirements for physical mockups



Electronic mockups

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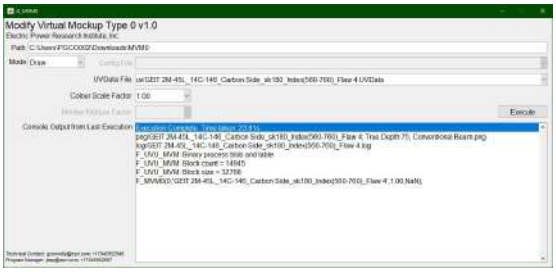
Modification Tool Overview

- Framework of distributable stand-alone executable tools
  - Tool specific to software (e.g., Zetec UltraVision) and to structure of the data volume (depending on software)
  - Support direct read/write to and from the data file
  - Many support direct reading from CIVA (for synthetic flaw)
- Current versions:
  - MVM0 “Modify Virtual Mockup Type Zero”
  - MVM1 “Modify Virtual Mockup Type One”
    - Supports read/write of .BeamData and .UVData files
    - Supports read from CIVA file
  - MVM2 “Modify Virtual Mockup Type Two”
    - Supports read/write of .capture_acq files
- As industrial partnership expands, new tools to be developed in this framework for new software

- Graphical User Interface and User Manual supplied to each industrial partner with worked examples
  - Executable generates graphical visualisation (example on next slide) to aid the user in the modification process



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Case Study: Access Hole Cover

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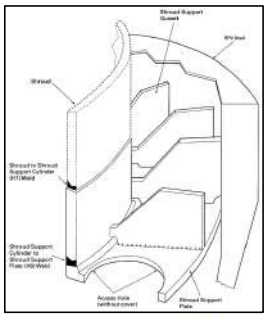
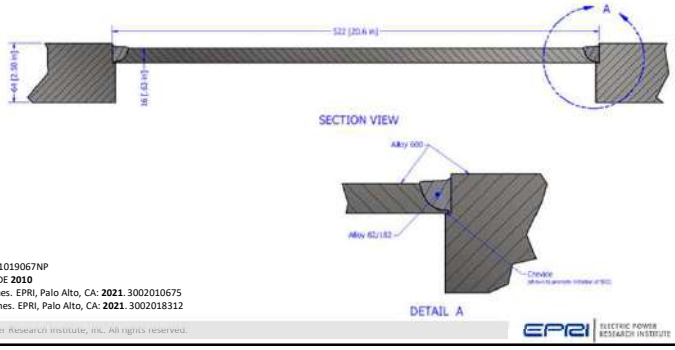
Introduction

Access Hole Cover

- Access Hole Covers (AHCs) [1] seal manways used to access lower internals during construction
  - Welds are highly constrained and are typically Alloy 82/182 with a creviced weld root configuration (schematic shown on right)
- In-vessel UT and EVT-1 (Enhanced Visual Testing [2]) have confirmed very long flaws were present during recent examinations [3,4]
  - Required complex flaw evaluations and one temporary repair
  - BWRVIP Executive Oversight Committee (EOC) action item to determine if weaknesses exist in BWR reactor internals mockup designs as related to current understanding of BWR reactor internals

AHC at bottom left; photograph taken looking down between pressure vessel and core shroud





[1] BWRVIP-217NP: BWR Vessel and Internals Project, Access Hole Cover Repair Design Criteria. EPRI, Palo Alto, CA: **2010**. 1019067NP
[2] Spanner, J. RPV and Primary Circuit Inspection: Nondestructive Evaluation Standard for PWR Vessel Internals in: JRC-NDE **2010**
[3] BWRVIP-03, Revision 20: BWR Vessel and Internals Project, Reactor Pressure Vessel and Internals Examination Guidelines. EPRI, Palo Alto, CA: **2021**. 3002010675
[4] BWRVIP-180, Revision 1: BWR Vessel and Internals Project – Access Hole Cover Inspection and Flaw Evaluation Guidelines. EPRI, Palo Alto, CA: **2021**. 3002018312

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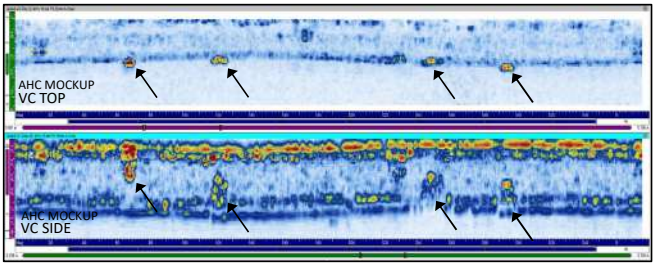
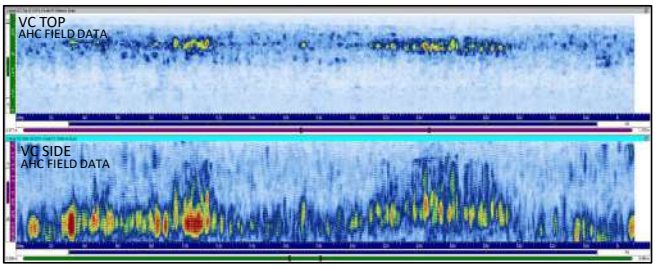
The Mockup Challenge

Access Hole Cover

- Mockups not entirely representative of the actual flaws observed in the field
- AHC Mockup (≈$45k in 2007)
  - 64in. (160 cm) long welds with 13 circumferential flaws
  - Flaw length range: ≈1.0in. (25mm) to 2.25in. (57mm)
  - Majority of mockup weld length is unflawed
  - Flaws stand out from baseline weld noise
- Actual AHC Flaws:
  - ≈64in. (160 cm) long welds with 1 or 2 circumferential flaws in each weld
  - Flawed length circumferential extent 180° to 360°
  - Weak baseline weld noise
  - Fabricating mockups with such long flaws is prohibitively expensive



AHC mockup built in 2007; prominent circumferential flaws identified



AHC field data

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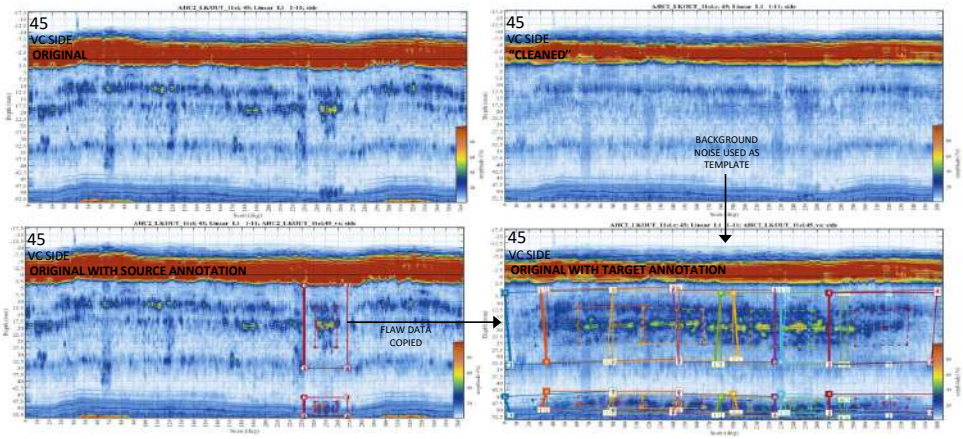
Virtual Flaw Process

Access Hole Cover

- Source data are first relieved ("cleaned") of existing flaws by a statistical suppression process
  - Four prominent circumferential flaws are suppressed prior to virtual flaw implantation
- The strongest circumferential flaw used as data source
  - Source copied multiple times as required with pseudo-randomisation of the target regions along all three axes and amplitude scaling



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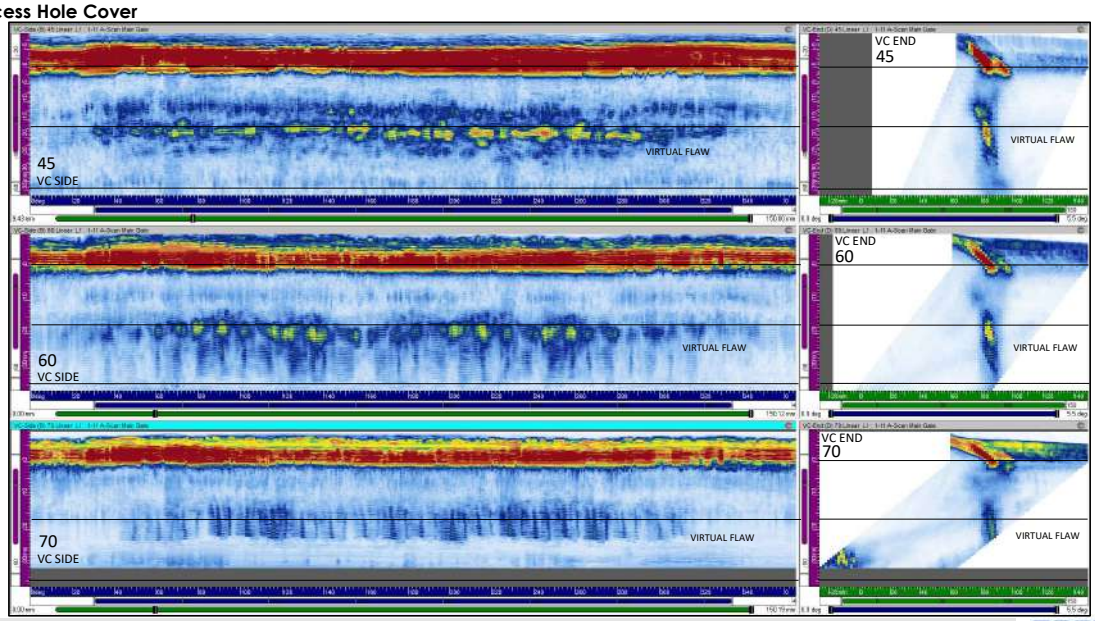
Virtual Flaw Results

Access Hole Cover



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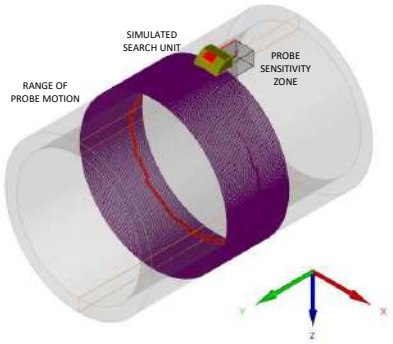
CIVA Simulated Flaw

Access Hole Cover

- Synthetic flaw data introduced from CIVA simulation
  - Flaw comprises 40 rectangular defects 11mm in length
  - Defect height varies pseudo-randomly with taper in the range (0.1-5.0)mm
  - Defect axial position varies pseudo-randomly in the range (138-142)mm
- Simulation settings:
  - Flaw response model: GTD
  - Only three modes to capture corner trap, direct tip diffraction and tip diffraction off skip
- Synthetic volumetric data combined with cleaned mockup with blending
- Typical runtimes: 4h-5h per angle



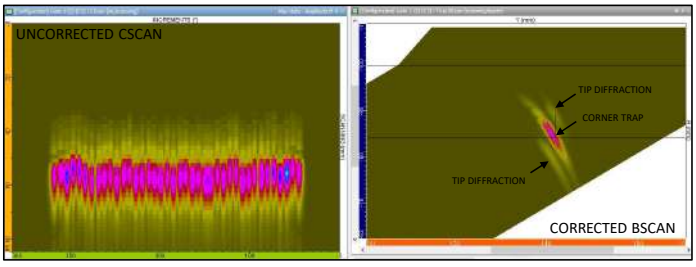
SPECIMEN PROPERTIES

Attribute	Value (mm)
OD	200.00
ID	168.26
Length	300.00

SCAN PROPERTIES

Attribute	Value
Frequency	2MHz
Y Offset*	63.74mm
Y Step	1.597mm
Y Count	53
Θ Offset	0°
Θ Step	0.5°
Θ Count	730

*for the 45° case



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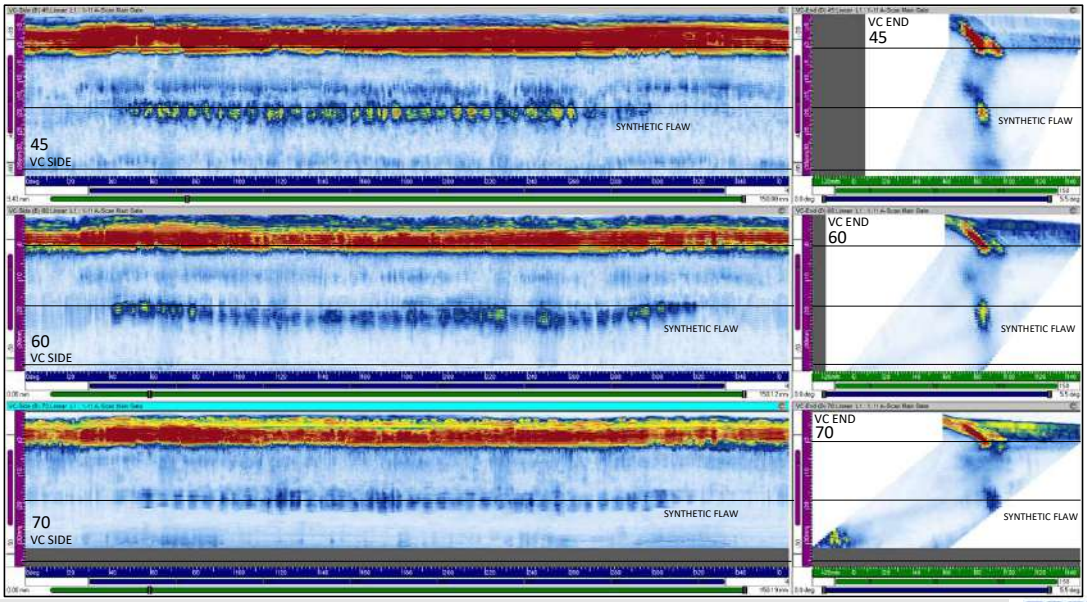
Synthetic Flaw Results

Access Hole Cover



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Industrial Partnerships

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Overview

- We are currently partnered with three EPRI members
  - Provided software tool and user guide documentation with worked examples
  - Feedback and suggestions for improvement are applied to the software tool
- Long-term Aims:
  - Develop virtual flaw and synthetic flaw technology for the benefit of the NDE industry
  - Provide EPRI members and collaborators the ability to generate their own virtual mockups
  - Qualification of virtual flaw and synthetic flaw technology for all training, educational and demonstration purposes

Pacific Northwest NATIONAL LABORATORY
INDUSTRIAL PARTNER

NUCLEOELECTRICA ARGENTINA S.A.
Ministerio de Economía Argentina
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ÚJV
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Industrial Partnership with PNNL

- Since the end of 2022, EPRI is in collaboration with PNNL
  - PNNL is tasked by the NRC to provide technical assessment of digitally-modified and simulated flaw technology
- Collaboration with EPRI will ultimately support NRC assessment of:
  - Appropriate uses of digitally-modified or simulated flaws including applicability for personnel qualification
  - Requirements for ASME code incorporation
  - Regulatory framework needed
- Some key questions to address via the collaborative effort between ERPI/PNNL/NRC:
  - What are the various types of digitally-modified and simulated flaws?
  - Assess whether or not digitally-modified flaws retain the response characteristics of the original flaw but otherwise appear as a unique flaw
  - What are the current and future use of digitally-modified of simulated flaws?
  - Will digitally-modified or simulated flaws provide sufficient challenges for certification or qualification?

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Industrial Partnership with Nucleoélectrica Argentina S. A.

- EPRI collaboration with NA-SA GSPC (Gerencia de Servicios Para Centrales) since 2021
  - Supports UT NDE for Atucha [5] (Siemens PHWR commissioned in 1974)
- Why virtual flaws are of interest:
  - Although they have many mockups of the primary system, they are limited in scope
  - Virtual flaws can augment the mockup library with different flaw types
  - Provide training material for trainee UT data analysts
  - Provide supporting material for inspection qualification efforts
- EPRI provided software tool and ongoing technical support since 2021
- Ongoing work: manufacture of virtual flaws for two cases
  - MK1A (pipe-to-pipe austenitic weld)
  - MK1B (safe end-to-nozzle DMW)
- Physical mockup matching these configurations complete in 2021 to provide baseline noise template

UT array scanning of recently-built mockup

[5] Nuclear Power in Argentina | Argentinian Nuclear Energy | World Nuclear Association url: https://world-nuclear.org/information-library/country-profiles/countries-a-f/argentina.aspx (retrieved May **2023**)

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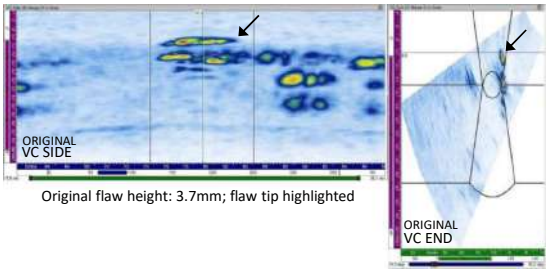
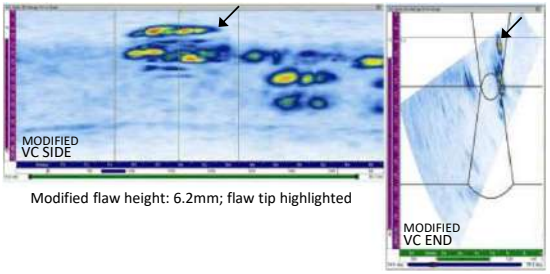
Industrial Partnership with ÚJV Řež, a. s.

- EPRI collaboration with ÚJV since 2020
- EPRI provided software tool and ongoing technical support since 2021
  - Flaw generation for machine learning training sets
  - Training/personnel NDE qualification sets
- Recent progress: Virtual flaw have been implanted in three test assemblies in the VVER-1000 [6] components:
  - Steam pipeline with homogeneous ferritic weld
  - Emergency Core Cooling System (ECCS) validation mock-up with DMW
  - Steam generator collector test assembly DMW
- EPRI software tool has been used to enlarge, diminish and reposition flaws
  - Example shown on right for fatigue crack simulating a service-induced crack
- Longer-term aim: Regulatory acceptance for these techniques in the country



Original flaw height: 3.7mm; flaw tip highlighted



Modified flaw height: 6.2mm; flaw tip highlighted

[6] Nuclear Power in the Czech Republic | Nuclear Power in Czechia | World Nuclear Association url: https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/czech-republic.aspx (retrieved May **2023**)

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Summary

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Summary

- EPRI has a decade of experience in operational and practical application of virtual mockup
- This presentation has demonstrated virtual flaw modification, mockup "cleaning" and synthetic flaw implantation
- Five external collaborators past and present are involved in the EPRI virtual flaw and synthetic flaw project
  - EPRI has distributed modification tool to four collaborators this year (2023) alone
  - Collaboration with regulatory bodies will continue including NRC/PNNL collaboration
- EPRI considers potential collaborators who are interested in the ability to generate virtual mockups in support of a training or demonstration program
  - Collaborator input will also aid EPRI in steering the virtual flaw and synthetic flaw program in a direction that maximises effectiveness and impact in industry
- Additional deliverable planned for this year (**2023**) to present implantation synthetic flaws for previously-recorded data

Reports #3002013152 and #3002023719 publically available at epri.com

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NDE Training and Knowledge Transfer for the Modern Workforce

John Langevin, Scott Hamel

Electric Power Research Institute (EPRI), Charlotte – North Carolina, United States

jlangevin@epri.com
shamel@epri.com

Abstract

New tools and modernized knowledge transfer/retention methods need to be developed to facilitate counteracting the industry's loss of knowledge base and experience through utility personnel attrition. As new resources backfill these voids, experience and knowledge transfer is quintessential to sustaining a safe, efficient, and viable industry. Using modern day technologies, we can effectively execute on knowledge transfer and retention by providing the level of training necessary to bring new or unfamiliar utility staff up to speed, quickly, in support of both the operating and future Nuclear fleet.

Keywords

Non-Destructive Examination, NDE, Training, Simulation, Virtual Reality

NDE Training and Knowledge Transfer for the Modern Workforce

NDE Virtual Reality (VR) Training Containment Building – 4 Loop PWR

Scott Hamel, EPRI
Principal Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Topics

- Background and Impetus
- VR Simulations for NDE Training
- Making of a VR Environment
- The Generic VR Environment/Platform Uses
- Current NDE Training Module Development in VR
- Future NDE Training Modules in VR
- Discussion / Comments

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Background and Impetus

- Impetus
  - New tools and modernized knowledge transfer/retention methods need to be developed to facilitate counteracting the industry's loss of knowledge base and experience through personnel attrition.
  - As new resources backfill these voids, experience and knowledge transfer is essential to sustaining a safe, efficient, and viable industry.
  - Using modern day technologies, we can effectively execute on knowledge transfer and retention by providing the level of training necessary to bring new or unfamiliar utility staff up to speed, quickly, in support of both the operating and future Nuclear fleet.
  - Using Virtual Reality simulations can provide faster and more efficient knowledge transfer of new and learning personnel.

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Virtual Reality Simulations for NDE Training

- VR simulations provide many benefits over traditional training such as…
  - Faster and more efficient knowledge transfer of new and learning personnel
  - Simulations can duplicate real world scenarios from operational experience.
  - Provide just in time training for infrequently performed high risk tasks
  - Provides an immersive experience allowing for learning in an environment free of from distractions.
  - Simulations provide unlimited opportunities to learn by allowing multiple attempts at learning the skills necessary without safety and radiological concerns.
  - Cost benefit in that the training my occur when time permits for the student/leaner. No waiting for scheduled training at offsite facilities.

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Making of a VR Environment (1/6)

- VR environments are primarily made by creating digital assets from LiDAR scanning data or 3D parametric models (Solid Works, Inventor, Etc.)
- The digital assets are brought into a virtual reality engine where the designers use available photos and drawings to adjust or optimize the assets to create the final realistic environment for the simulation.

- Final “digital asset” example shown within the VR environment
- Digital asset is the containment equipment hatch with associated escape hatch

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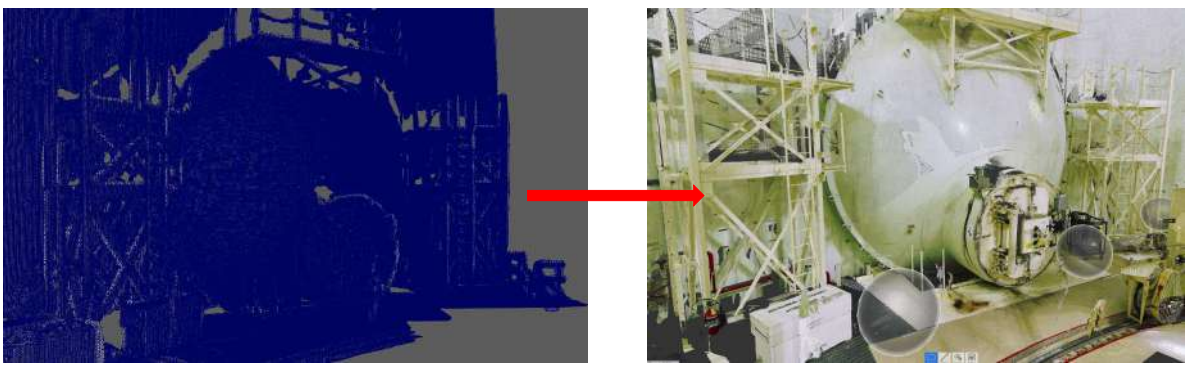
Making of a VR Environment (2/6)

- Step 1 – LiDAR Scanning
  - Data is acquired using laser scanners
  - The data acquired is point cloud data with each point having its own set of Cartesian coordinates, X, Y, Z
  - Shown below on the right is the point cloud data and on the left is the point cloud data with a color photo overlaid onto it.



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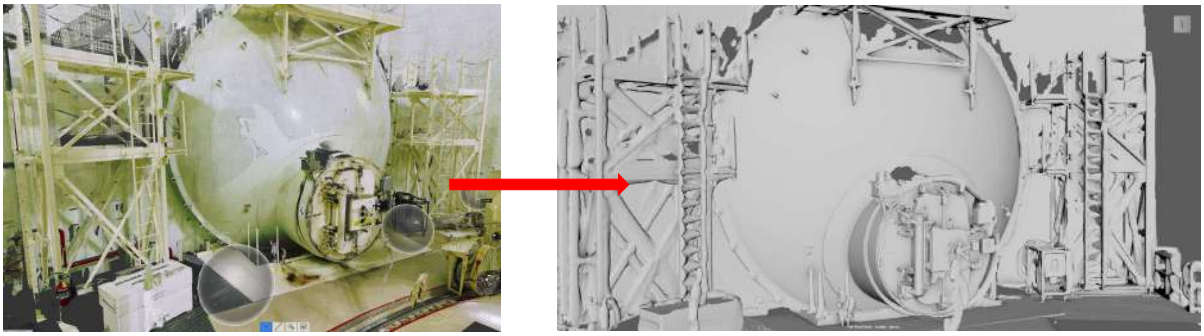
Making of a VR Environment (3/6)

- Step 2 – Point Cloud Reconstructions
  - The point cloud data is reconstructed into polygons by connecting the vertices of the point cloud data. This is the initial “polygon mesh”
  - After the reconstruction varying amounts of detail is available and only a single color applied to all items in what is called a “clay model”



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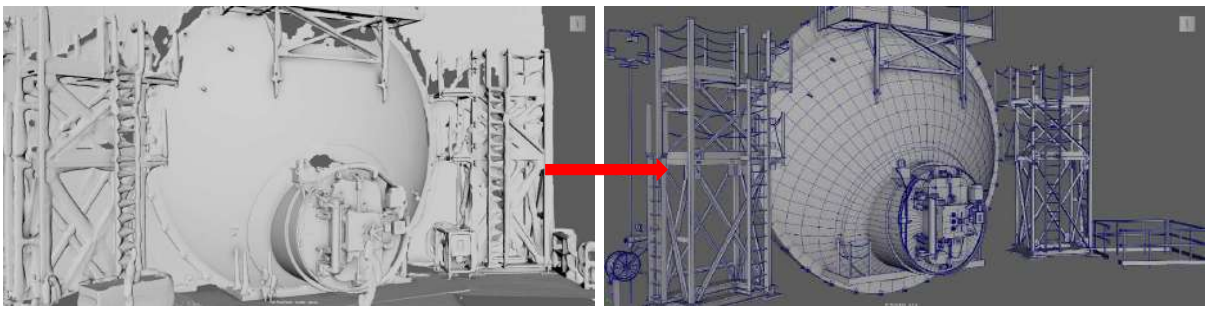
Making of a VR Environment (4/6)

- Step 3 – Polygon Mesh Refinement
  - A 3D modeler will develop a more accurate representative of the items using the initial polygon mesh and any supplementary information from photos and drawings
  - The fully rendered/refined mesh is comprised of evenly distributed quadrangular polygons
  - This step reduces the polygon density of the LiDAR data making the next step called texturing possible.



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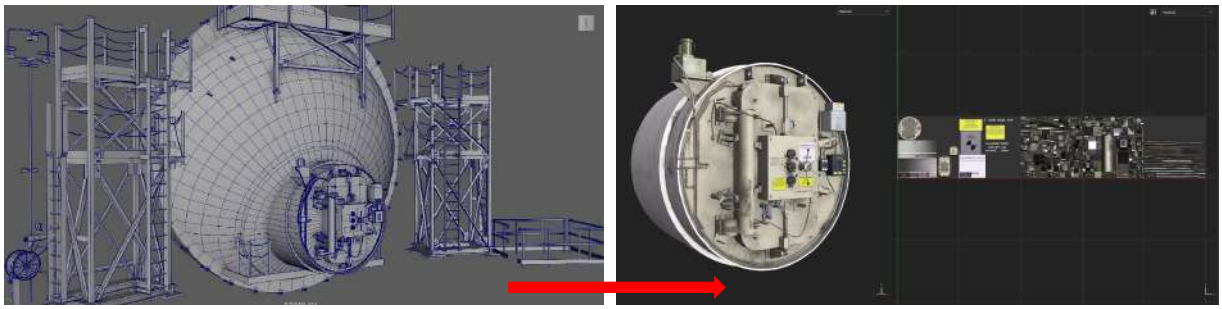
Making of a VR Environment (5/6)

- Step 4 – Texturing
  - Texturing relies heavily on color images of the digital asset to give the asset accurate color and material attributes
  - In texturing, each object is “unwrapped” like how a box would be unfolded, onto a two-dimensional plane
  - The developer can paint onto this 2D plane and store the color and material information as an image
  - The computer then applies this back to the quadrangular mesh for the asset



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Making of a VR Environment (6/6)

- The final product of the LiDAR data capture, polygon mesh rendering and texturing is a digital asset
- The finished digital asset is then brought into the virtual environment engine to create the final virtual reality environment and simulation

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The NDE VR Environment/Platform Uses

- The intent of the NDE VR training project was to create a training environment supporting:
  - NDE Training Course lab activities and modules converted to VR
  - Formal NDE training
  - Supplement On-the-Job training
  - General orientation with plant design and inspection familiarization
  - Adaptation of the NDE UT Simulator platform in future development efforts
- The platform will however have potential uses by other functional areas
  - Radiation Protection
  - Engineering
  - Operations
  - Maintenance

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Current NDE VR Training Module Development in VR (1/4)

- The initial phase of the NDE training simulates a VT-2 system leakage test.
- VT-2 system leakage tests
  - Visual inspections (direct and remote) required by the ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components
  - Carried out to detect evidence of leakage from pressure-retaining components within the covered systems
  - Utilize procedures, drawings and tools to identify pressure boundary leakage within the test boundaries specified.

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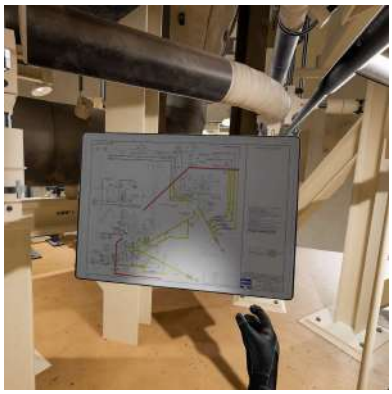
Current NDE Training Module Development in VR (2/4)

- VT-2 VR training simulation examples – tools and info



P&ID

Binoculars

Flashlight

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Current NDE Training Module Development in VR (3/4)

- VT-2 VR training simulation excerpt – leakage

Bolted Connection

Piping Pressure Boundary

Evident at Wall Penetration

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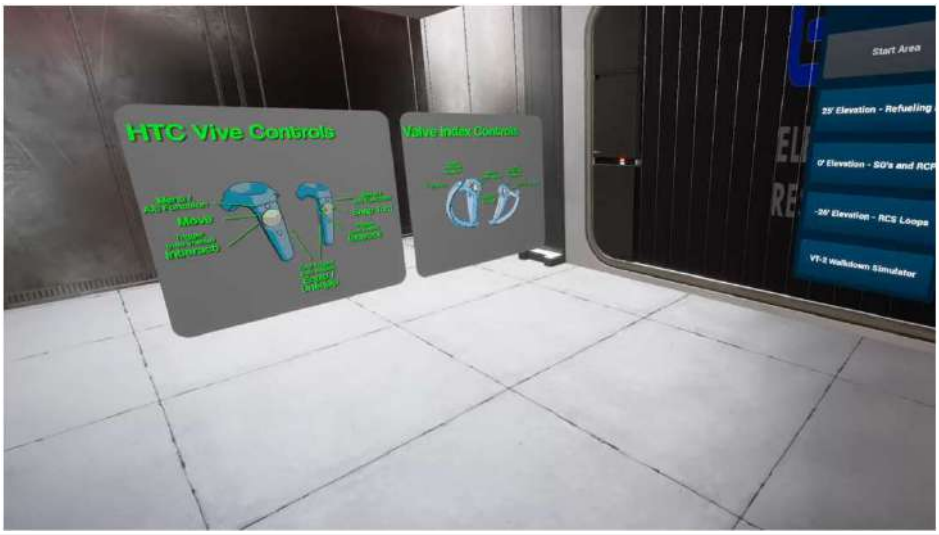
Current NDE Training Module Development in VR (4/4)

- VT-2 VR training simulation excerpt – video



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Future NDE Training in VR

- Future NDE simulations include
  - **VT-1** – Visual inspections for cracks, wear, corrosion, or erosion
  - **VT-3** – Visual inspections for determining the general mechanical and structural condition of components and their supports
  - **IWE** – Containment Liner Surface Visual Inspections
  - **IWL** – Containment Concrete Surface Visual Inspections and Tendon anchorage hardware
  - **Future Integration –** UT Simulator

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Discussion / Comments

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9. Automated Analysis of NDE Data incl. AI / ML (I)

The presentations in this session are listed in the table below.

Automated Analysis of NDE Data incl. AI / ML (I)	**Chair:** Jeff Weed (CANDU Owners Group)
Generative Machine Learning in Ultrasonic Testing – Simulation and Reconstruction Applications	Daniel Algernon, Claudia Thurnherr, Aurélia Muller (all SVTI)
Machine Vision Applications in the Nuclear NDE Industry	Thiago Seuaciuc-Osorio (EPRI), Iikka Virkkunen (Trueflaw)
Flaw Response Simulations using Flaw Profiles Obtained by Destructive Testing	Richard Jacob et al. (PNNL)
Evaluation of a deep learning algorithm trained by simulation to characterize defects from multimodal TFM images in the presence of uncertainties	Roberto Miorelli, Sébastien Robert, Stéphane Leberre and Pierre Calmon (CEA)
Leveraging Machine Learning to Improve Flaw Depth Sizing in Balance-of- Plant Components	Thiago Seuaciuc-Osorio (EPRI)

Generative Machine Learning in Ultrasonic Testing – Simulation and Reconstruction Applications

Daniel Algernon[1], Claudia Thurnherr[1], Aurélia Muller[1]

[1]SVTI Swiss Association for Technical Inspections, Wallisellen, Switzerland

E-mail address (corresponding author): daniel.algernon@svti.ch

Abstract

The application of machine learning-based data analysis has proven its capabilities in various areas of technical applications. Besides broad application areas in the context of general speech or image recognition, great potential is being identified and successfully used for solving complex Nondestructive Evaluation (NDE) tasks. In particular, supervised learning for classification is being increasingly demonstrated for automated defect detection. Besides classification and regression applications, generative modelling is a powerful sub-category of machine learning. It refers to the often highly realistic, though artificial generation of images or data, in general. Algorithms and architectures open new possibilities for the development of surrogate models for the simulation of ultrasonic inspections as well as for the reconstruction of defects or geometries based on ultrasonic data.

Modeling and simulation are important aspects of ultrasonic testing. In particular, in the course of the development of inspection techniques and procedures as well as the planning and preparation of inspections, the use of modeling and simulation is well-established. Traditionally, various numerical and semi-analytical simulation methods are used. As a rule, the aim is to predict actual ultrasound examination results as best as possible; at the same time, the modeling effort and computing time need to be maintained at an acceptable level. Machine learning has significant potential to support traditional simulation methods, make them more efficient and deliver more realistic simulation results. This article clarifies the process of developing a machine learning-based surrogate model and presents the first results. Different approaches and architectures of neural networks are presented, demonstrated and compared. Specifically, the procedure aims to generate ultrasound B-scan images based on input parameters or distinct inspection scenarios. The demonstrated applications relate in particular to the detection and characterization of complex cracks in and on welds. The required amount of training data is immense for the successful generation of a realistic model. Thus, on the one hand, data generated by conventional simulation techniques and, on the other hand, experimentally acquired measurement data are used as a data source.

The image-to-image transformation can not only be used for the artificial generation of ultrasound images based on a defect situation; ultrasound images can also be transferred to the defect situation, which corresponds to a reconstruction task.

The entire training and application process is implemented in user-oriented software, guiding the user through the data import and management as well as selecting and fine-tuning the Neural Network architecture.

Keywords: Ultrasonics, Machine Learning, modeling and simulation, reconstruction algorithms, Generative Adversarial Networks.

Generative Machine Learning in Ultrasonic Testing: Simulation and Reconstruction

D. Algernon, C. Thurnherr, A. Muller

SVTI – Swiss Association for Technical Inspections

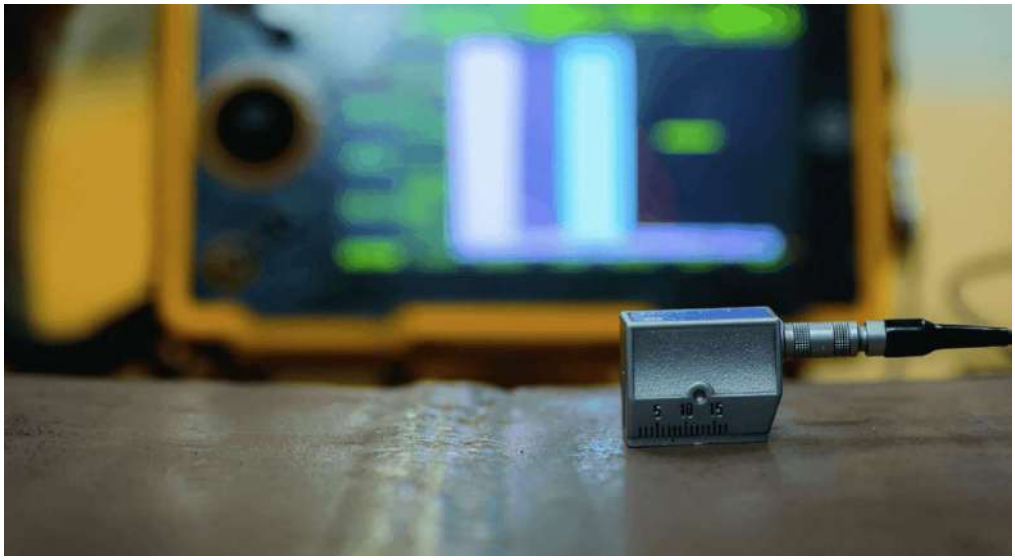
Nuclear Inspectorate

Laboratory for Nondestructive Evaluation (NDE)

- **Artificial Intelligence**
- **Ultrasonic Testing**
- **Numerical / Semianalytical Simulations**

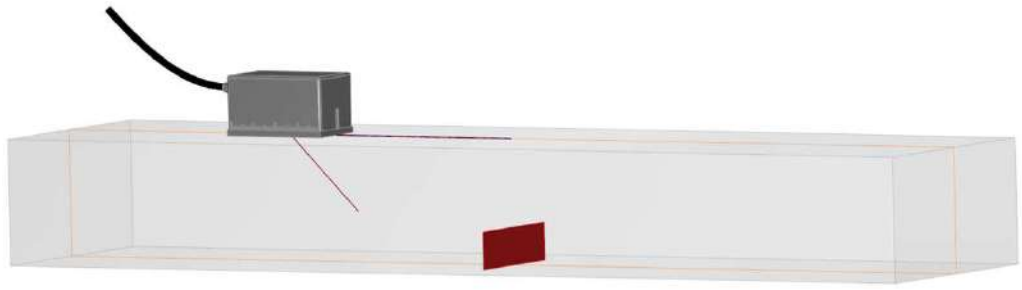
- Ultrasonic Testing

Ultrasonic Testing

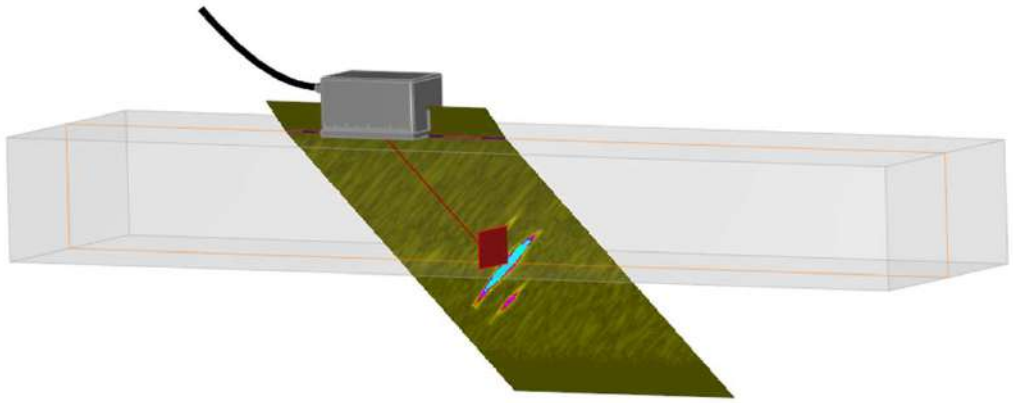


Ultrasonic Testing
Detection

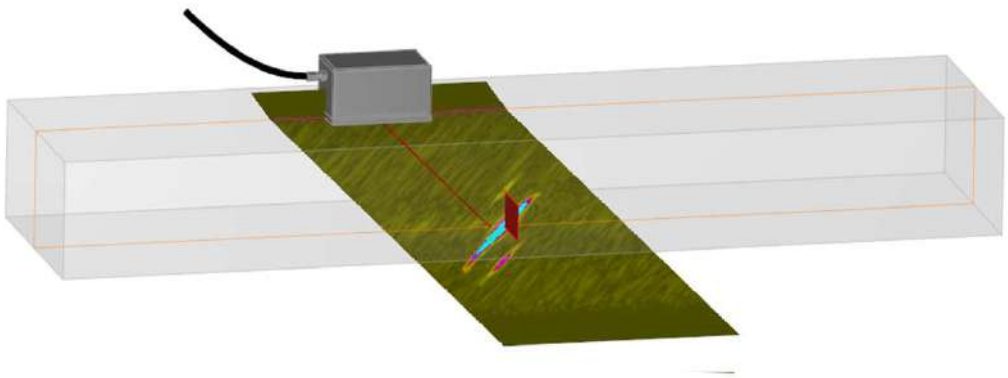
Ultrasonic Testing
Flaw Indications



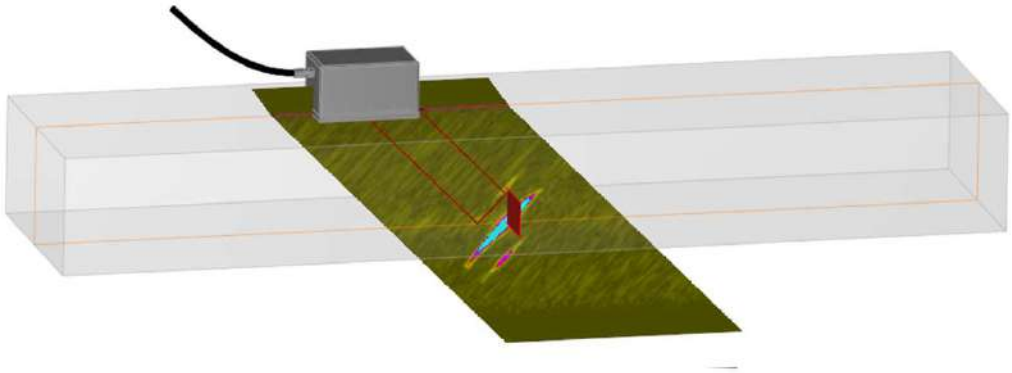
Ultrasonic Testing
Flaw Indications



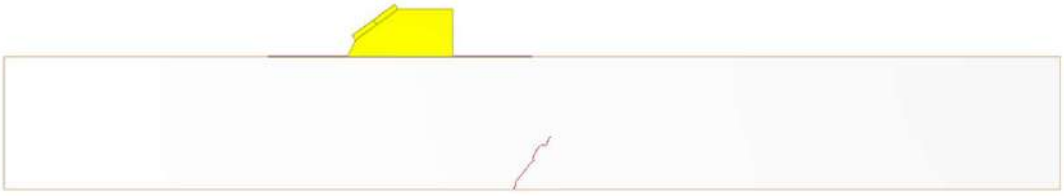
Ultrasonic Testing
Flaw Indications



Ultrasonic Testing
Flaw Indications



Flaw Indications
Quiz



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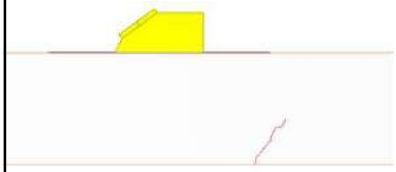
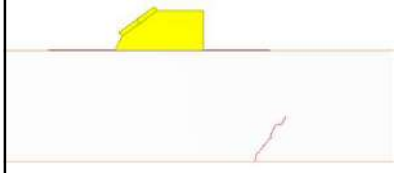
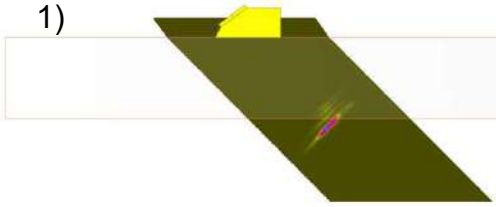


?

Flaw Indications
Quiz



1)



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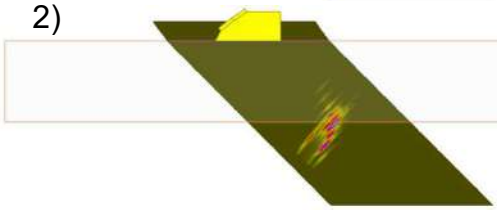

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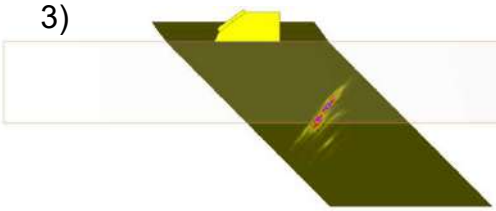
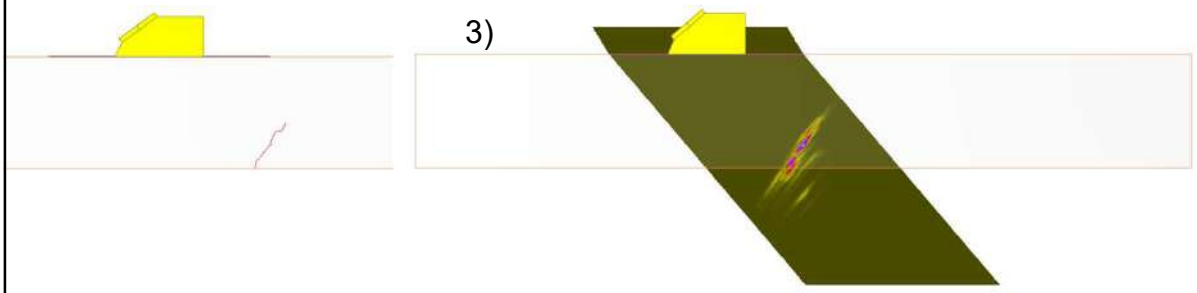


Flaw Indications
Quiz



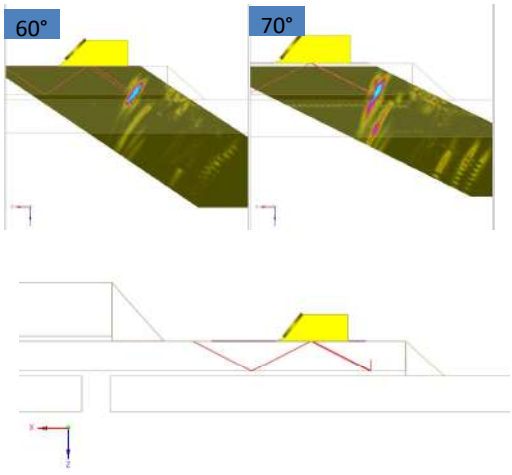
- Artificial Intelligence
- Ultrasonic Testing
- Numerical / Semianalytical Simulations

- **Numerical / Semianalytical Simulations**

Modeling & Simulation
in Ultrasonic Testing

SVTI ASIT

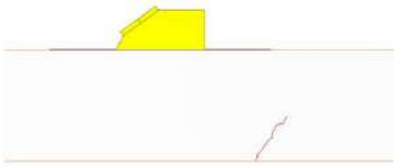
- Important tool in UT
- Inspection planning
- Techique development
- Scenarios
- Analysis
- **Computationally expensive**



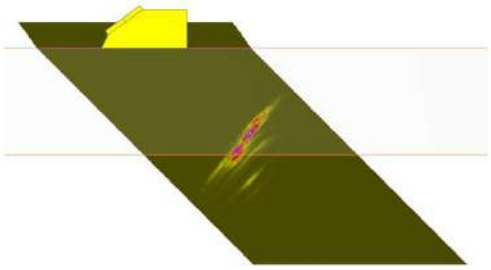
Simulation
„Reality-2-Data“

SVTI ASIT

Input



Output



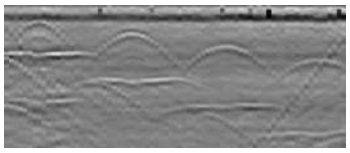
- Model
- Formula
- Program
- Computationally expensive

Solvable by AI?

Reconstruktion
„Data-2-Reality“

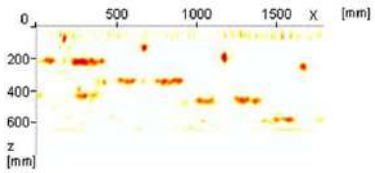
SVTI ASIT

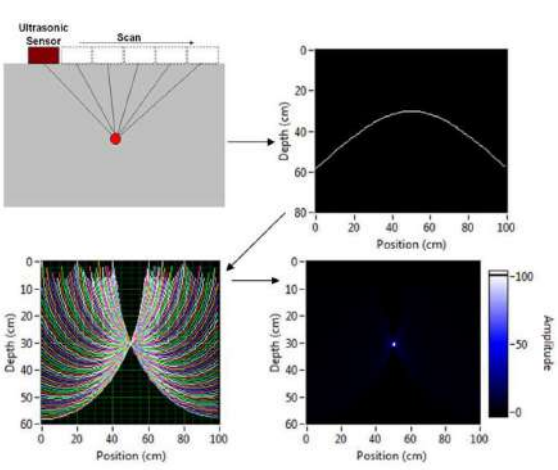
Input



Algorithm

Output





Reconstruction

- Important element of UT
- Increase of contrast, interpretability of UT mages
- Various algorithms
- **Computationally expensive!**

Solvable by AI?

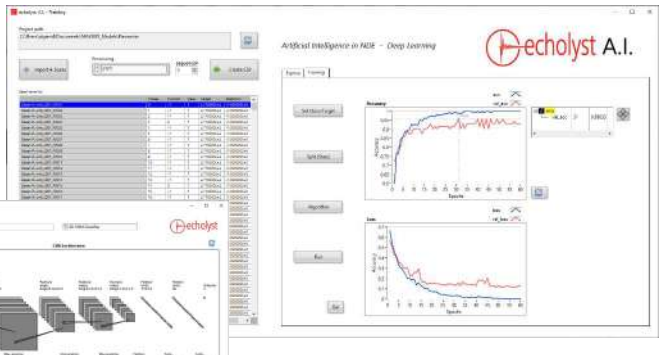
- **Artificial Intelligence**
- **Ultrasonic Testing**
- **Numerical / Semianalytical Simulations**

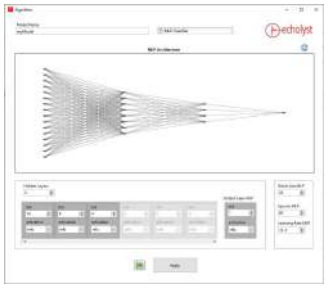
- **Artificial Intelligence**

Artificial Intelligence
ML-Software ECHOLYST A.I.

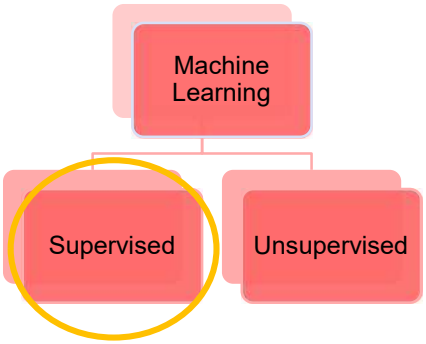
SVTI ASIT

- Transparent implementation of an ML Workflow
- Deep Learning-Architectures





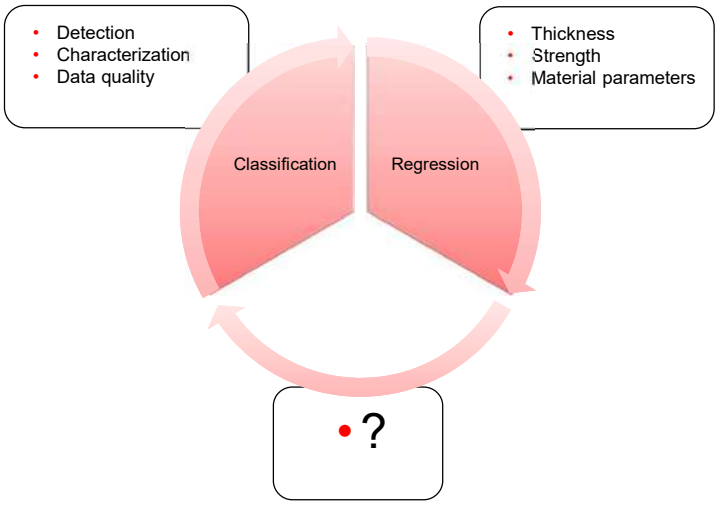
Artificial Intelligence
Machine Learning (Supervised Learning)



Traditional (rule-based) Programing

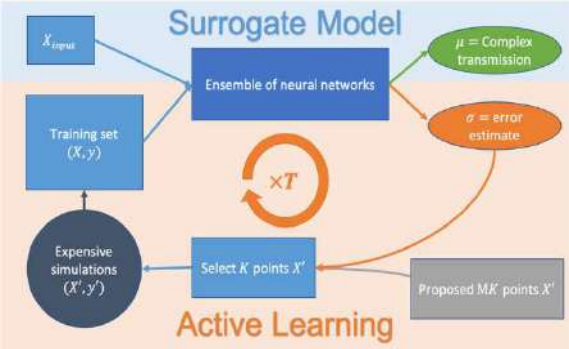
Supervised Learning

Tasks



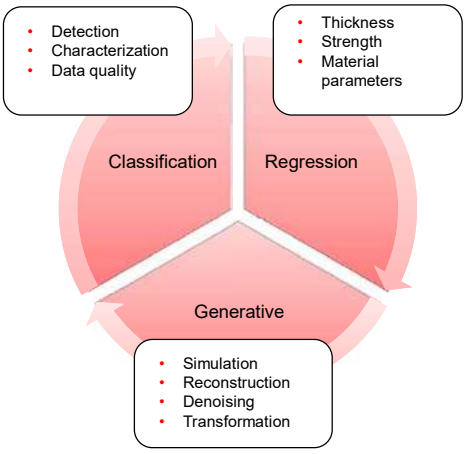
Surrogate Modeling
General

- simplified model
- approximating the behaviour of a complex model
- When original model is computationally expensive
- Tool: Machine Learning
- Training based on data of the original model

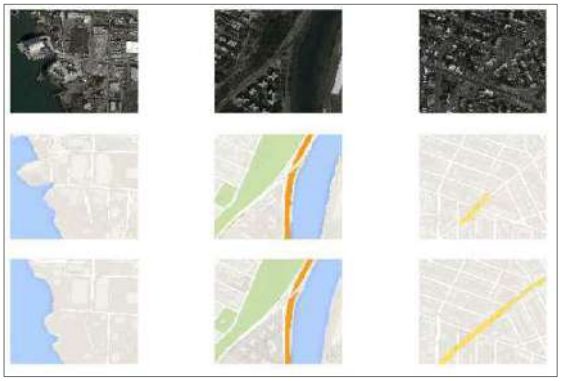


Pestourie, R., Mroueh, Y., Nguyen, T.V. *et al.* Active learning of deep surrogates for PDEs: application to metasurface design. *npj Comput Mater* **6**, 164 (2020). https://doi.org/10.1038/s41524-020-00431-2

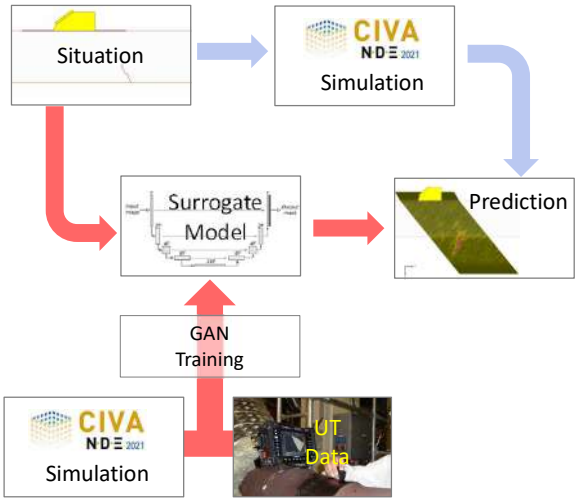
Machine Learning Tasks
NDT

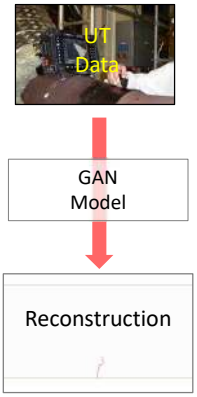


pix2pix



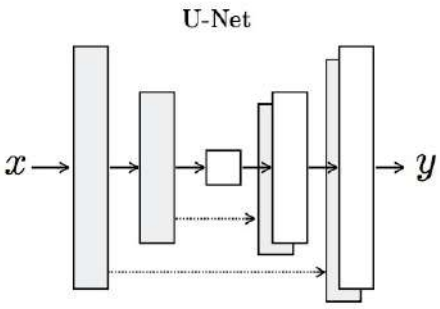
Application for Ultrasonic Testing
Modeling & Simulation / Analysis & Reconstruction





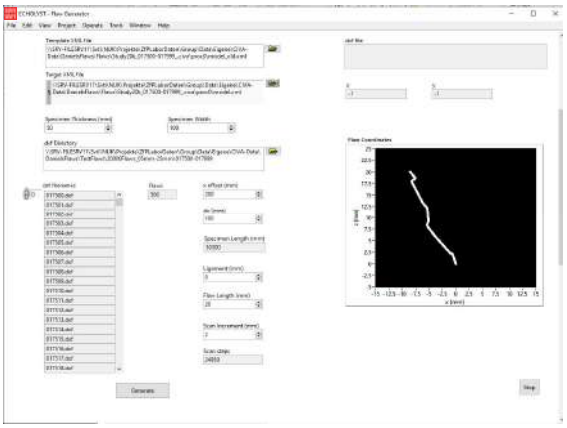
Implementation

- Generate training data based on CIVA-simulations
  - Pairwise: Geometry / Simulation
- Generative Adversarial Neural Networks (GAN):
  - Encoder / Decoder U-Net Architectures
- Implementation in ECHOLYST A.I.
- Generating a surrogate model to predict CIVA-simulations
- Inverse of that task:
- Generate model to reconstruct crack geometries

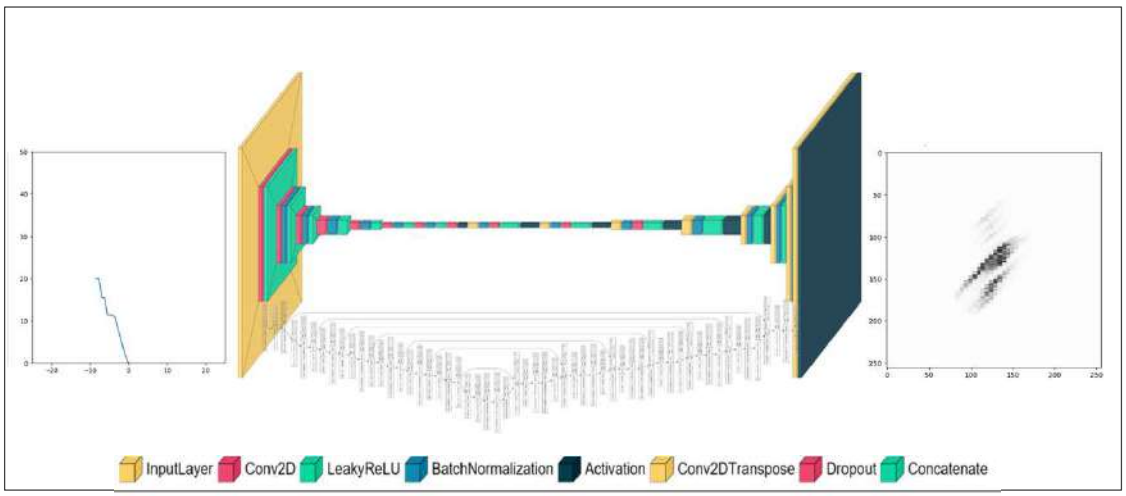


Generating the Data Set

- 2D-Data Set: **20,000 cracks**
- Assumption: surface-breaking at inner surffface (ID)
- **Stochastic modeling of crack geometries**
- **Define range for:**
  - Thruwall extension
  - tilt
  - Facettes
- Automated generation of **DXF-Data**
- **Implantation in CIVA Models**
- CIVA-Simulation
- **Export of CIVA simulation data to ECHOLYST A.I.**
- Implementation of Deep Learning Architectures

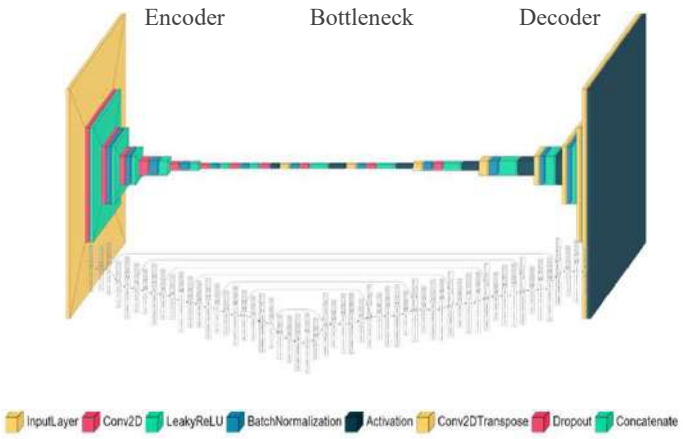


Deep Learning Architecture
Encoder-Decoder Network

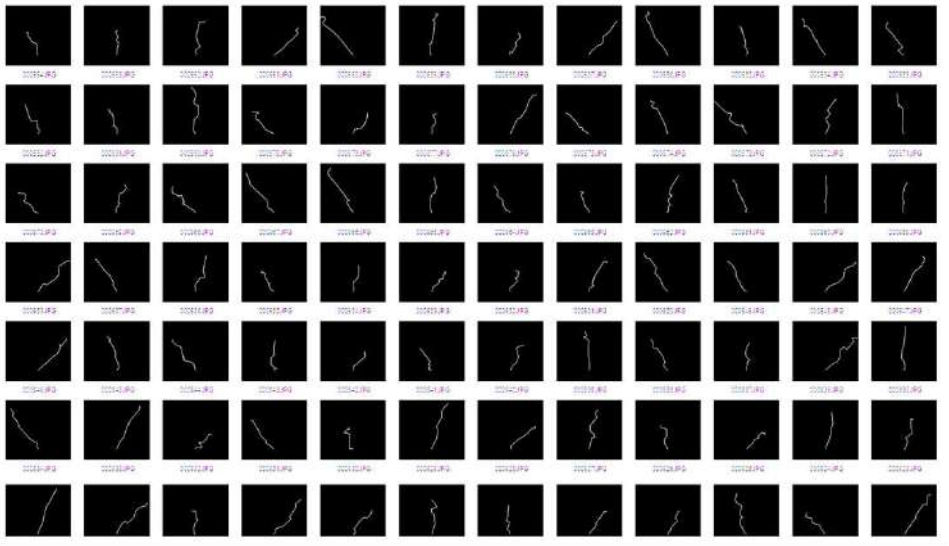


Deep Learning Architecture
Encoder-Decoder Network

- Encoder:
  - Convolutional Neural Network (CNN)
  - Compressing
- Bottleneck;
  - Condensed Version
  - Example: while the input is an entire picture, the bottleneck contains the information „Cat“ or „Dog“
- Decoder
  - Generating the resulting image
  - in „style“ of the target
- Skip Connections
  - Concatenating Layers
  - Flow of information to the decoder



Generating paired data sets
1) Crack Geometry

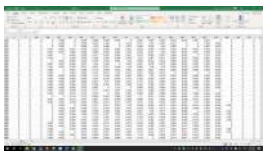


Generating paired data sets
2) Simulated ultrasonic response

Paired Structure

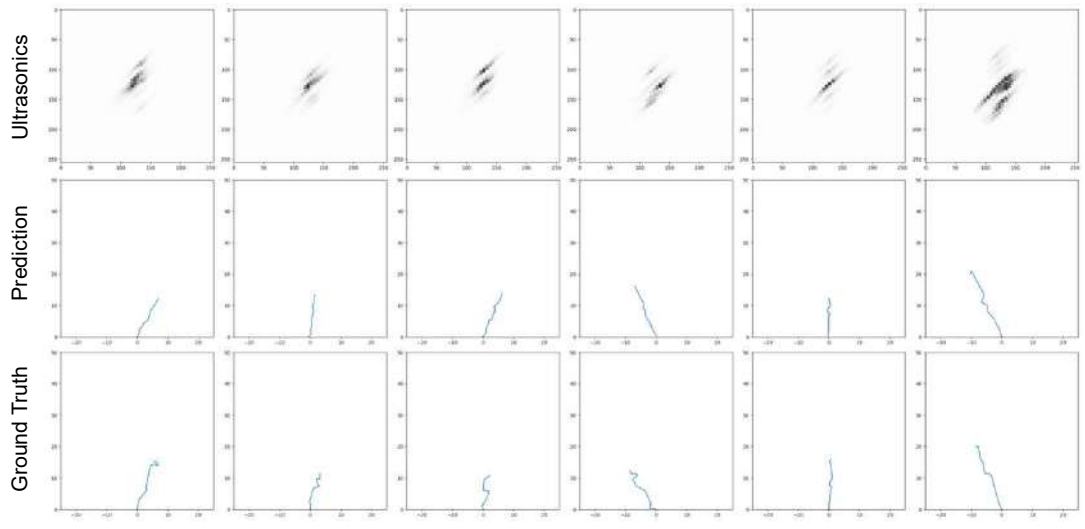
- **Crack Geometry**
  - DXF
  - CSV
  - JPG
- **Parametrized:**
  - Thruwall dimension
  - Tilt
  - Facettes (SD)

- **Simulation Data**
  - Ultrasonics response in terms of B-Scan sections
    - CSV
    - JPG
  - **Probe**
    - 2 MHz, 45°, conventional

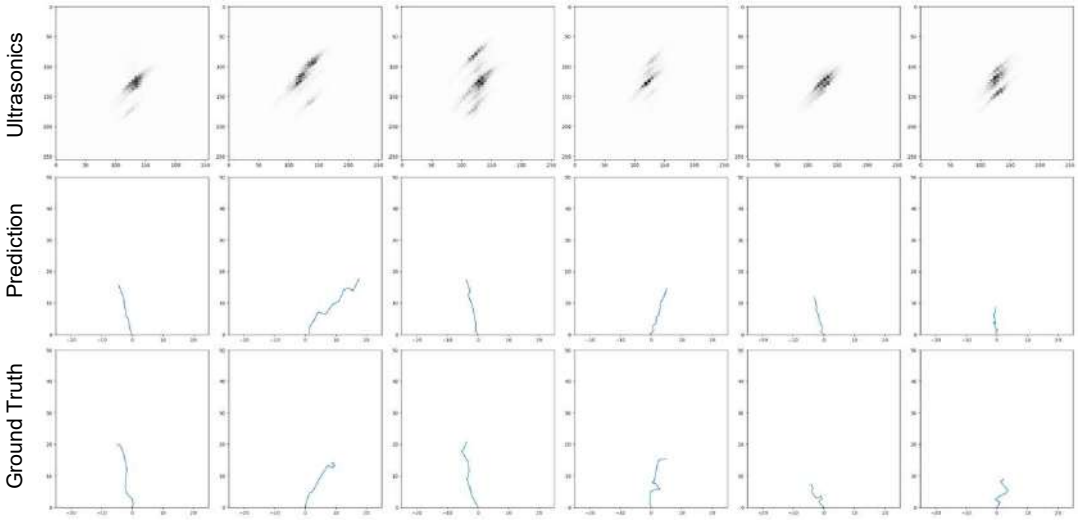


Surrogate Model
Simulation

Surrogate Model
Reconstruction



Surrogate Model
Reconstruction



Conclusion

- Input-Output structure of tasks
  - Modeling and simulation
  - Reconstruction
- Generated a comprehensive data set (20k data pairs)
- Surrogate Model for simulation of ultrasonic responses on cracks
  - Implementation: examples (limited)
- Model for reconstruction of crack geometries
- Demonstration outlining potential

„Data – Algorithm – Model“

Wine Analogy (*considering <u>non</u>-alcoholic wine only*)

Data Source	Organize Data	Algorithm	Validate/ Deploy

Thank you

SVTI Swiss Association for Technical Inspections
Nuclear Inspectorate
Laboratory for Nondestructive Evaluation

Dr. Daniel Algernon

Dr. Claudia Thurnherr

Dr. Aurelia Muller

Leonardo Rössler

Robin Bergande

Machine Vision Applications in the Nuclear NDE Industry

Thiago Seuaciuc-Osorio[1], Brenden Mervin[1], John Lindberg[1], Iikka Virkkunen[2], Oskar Siljama[2]

[1]EPRI, Charlotte, USA
[2]Trueflaw, Espoo, Finland

E-mail address (corresponding author): tsosorio@epri.com

Nuclear power plants perform a variety of non-destructive visual examinations of critical assets; examples vary from reactor components to containment buildings. There are numerous opportunities to leverage machine vision technology in support of inspection activities that usually require a high level of focus from inspectors for prolonged times, the reliability of which are consequently subject to unfavourable human factors. While most of these examinations are recorded, often the necessary data to support the development of machine vision solutions is either scarce or highly sensitive, and mostly unavailable.

In this presentation, the authors will discuss examples of such applications, including the remote visual examination of fuel assemblies, reactor internals, and of concrete containment buildings, as well as different implementation methodologies, from real-time annotation to post-processing and later review. They will share the challenges in each case and some of the potential solutions and approaches being pursued, from convolutional neural networks and synthetic data to more controlled, dedicated transformations and signal detection algorithms. In the process, the presentation will showcase the range not only of potential applications, but also of the potential solution approaches.

Keywords: machine vision, machine learning, remote visual inspection, nuclear fuel assembly, reactor internals

Machine Vision Applications in the Nuclear NDE Industry

Thiago Seuaciuc-Osorio, EPRI
Principal Technical Leader, Engineering

Iikka Virkkunen, Trueflaw
Managing Director

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Some Machine Visions Applications in Nuclear NDE

Fuel Assemblies

Containment Buildings

Reactor Internals

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Some Machine Visions Applications in Nuclear NDE

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Containment Buildings

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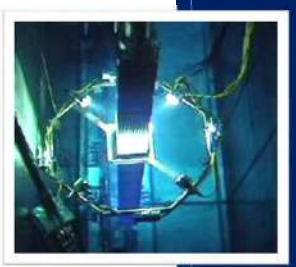
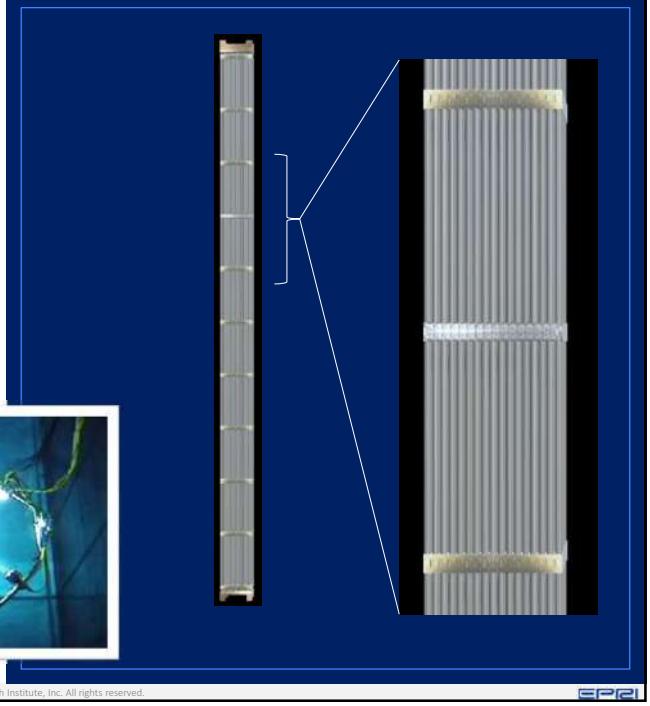
Fuel Assembly Visual Inspections

- Fuel assembly characteristics
  - ~0.2 meters wide and ~4 meters long
- Inspection characteristics
  - High radiation environment
  - Underwater
- Inspection goals
  - Identify abnormalities that may be precursors to a developing issue
  - Prevent re-insertion of damaged fuel
- Inspection process
  - Assembly is raised/lowered in front of camera
  - Engineers watch 4 live stream videos simultaneously, looking for:
    - Scratches/tears
    - Foreign material
    - Abnormal coloration
    - Material displacement





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Example Video

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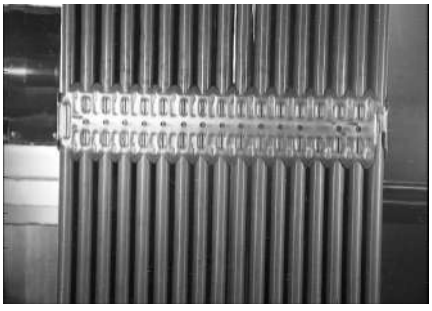
Image Processing for Fuel Assembly Visuals

- **Objective**: Develop an automated computational framework for assessing 4-face fuel assembly visual inspection video in real time to identify anomalies



- **Benefits:**
  - Increased accuracy in identifying anomalies
  - Reduced burden
  - Potential cost savings if visual inspections are on critical path

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Detection Targets

- Scratches
- Cracks
- Displaced material
- Foreign material
- Abnormal surface deposits
- Wear
- Spacing
- Other

Lack of Data

- Scratch vs. Crack
  - No significant database of known truths
  - Need high enough resolution to see depth to differentiate between a scratch and a crack
- Displaced and Foreign Material
  - A few dozen images
  - Very large variety between images
- Abnormal surface deposits
  - "Normal" can be subjective and site-specific
- Wear
  - Different mechanisms yield different wear patterns

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Approach

Lack of data leads to using traditional machine vision solutions

Diversity of targets leads to taking anomaly detection approach

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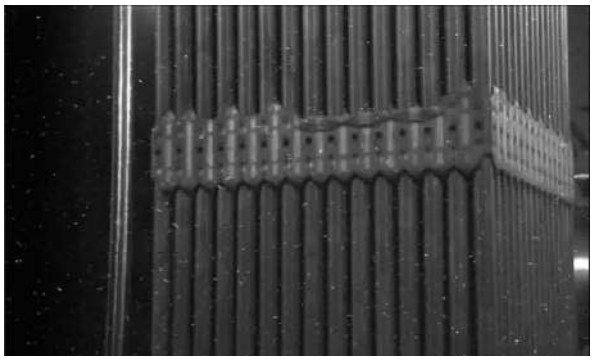
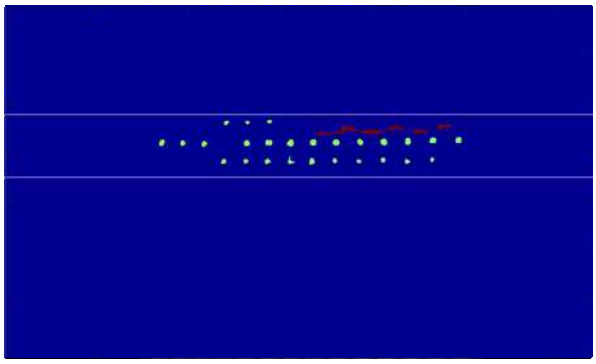
Image Processing in Action

- Remove noise due to radiation
- Isolate primary face
- Rotate and isolate grid
- Mask non-grid region
- Apply shape filters
- Classify results

Before



After



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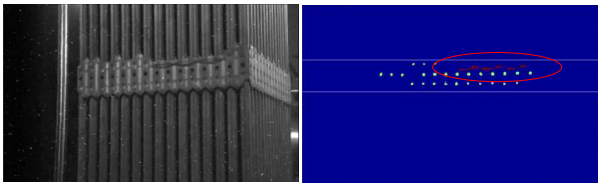
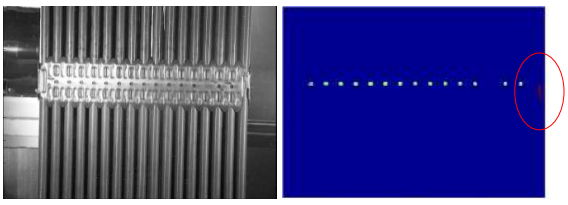
Other Examples from Feasibility Study

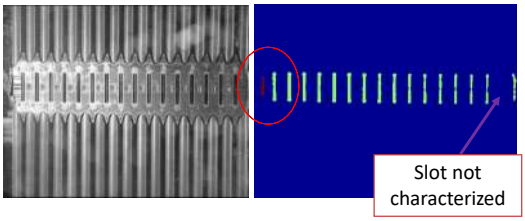
Damaged Spacer Grid



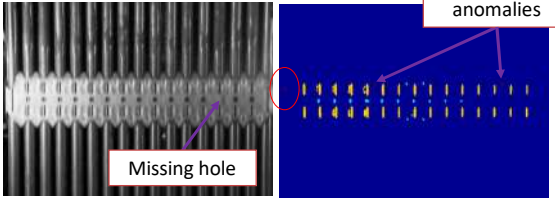
Large Tear



Displaced Material



Small Tear



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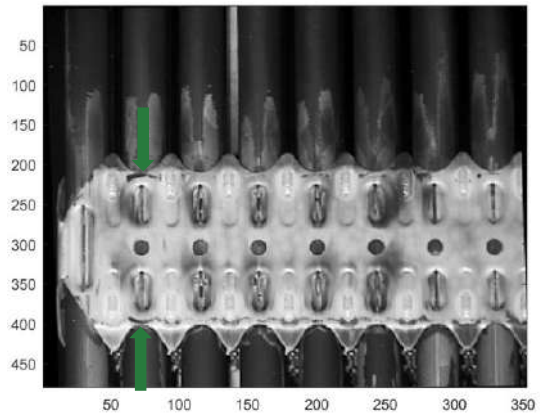
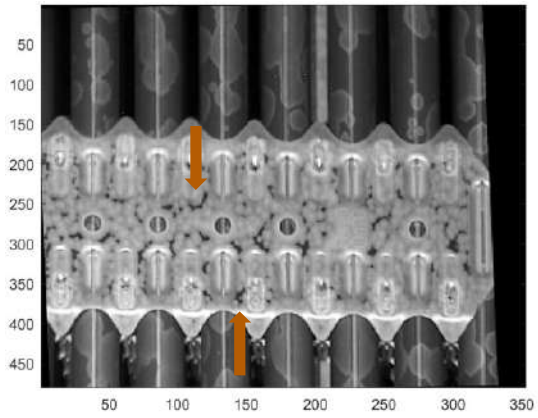
Human & Machines Are Good at Different Things



Grid Wear



Oxide

Easy for a human…not so easy for a computer

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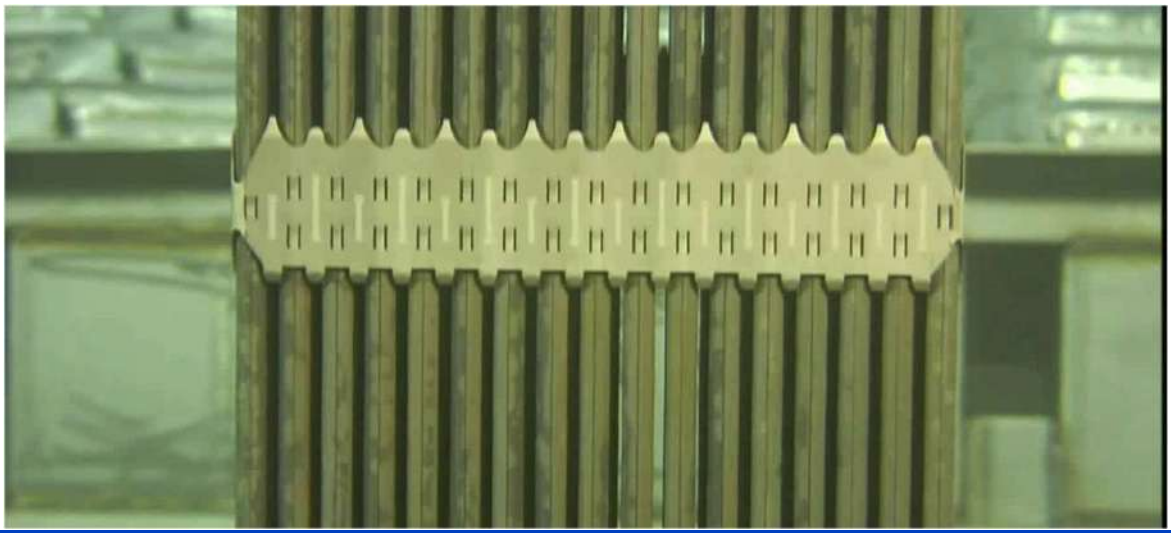
Our Digital Reactor Engineer in Action…



Envisioned deployment: embedded in hardware

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Some Machine Visions Applications in Nuclear NDE

Fuel Assemblies

Containment Buildings

Reactor Internals

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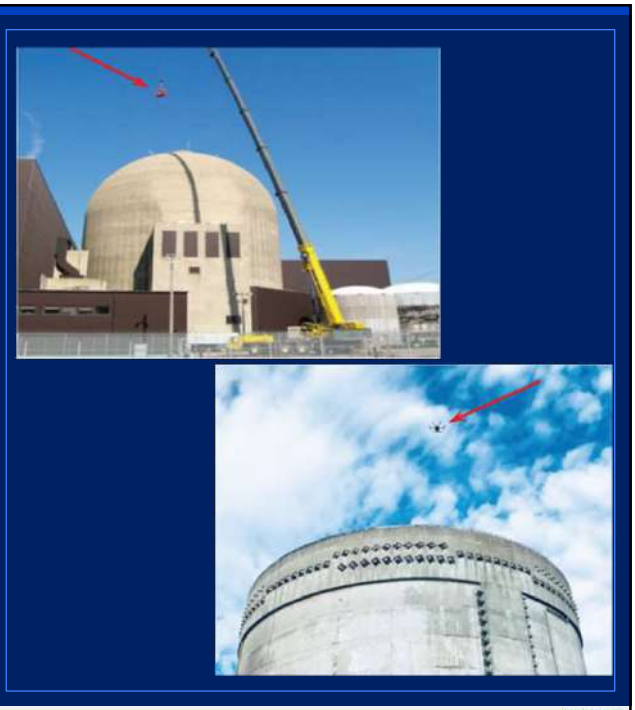
Remote Visual Inspections with Unmanned Aerial Systems

- Benefits during data collection
  - Saves time, reduces costs, increases safety
  - Provides better inspection data record
- Increased burden on analysis
  - Large quantity of monotonous images or videos
- From BCAM (3002021027) & UAS User's Guide for NPPs (3002020913):



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Data, Targets, Approach

- Data from:
  - 3 containment buildings
    - ~2,700 labeled images
  - 2 cooling towers*
    - ~7,000 *un*labeled images
- Approach
  - ShapeMask (Google, 2019)

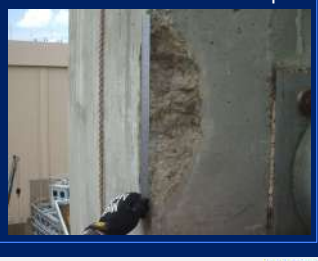
Damage Type
Efflorescence
Crack
Grease Stain
Spall
Corrosion
Pattern Cracking
Abrasion
Honeycomb

Increasing Frequency in Dataset

Crack

Efflorescence

Grease Stain



Spall

** Cooling towers not included in models yet.*

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Example Output

4K image

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Grease Stain Around Tendon Caps

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Cracks and Grease Stain on the Wall

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Cracks

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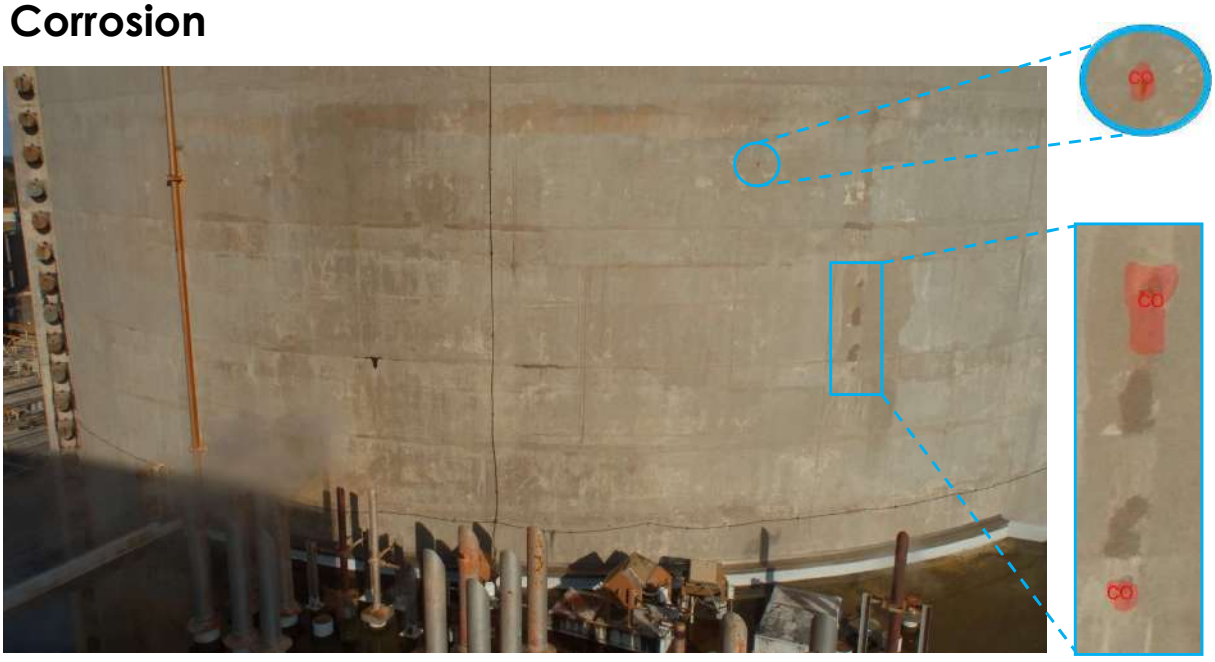
Corrosion



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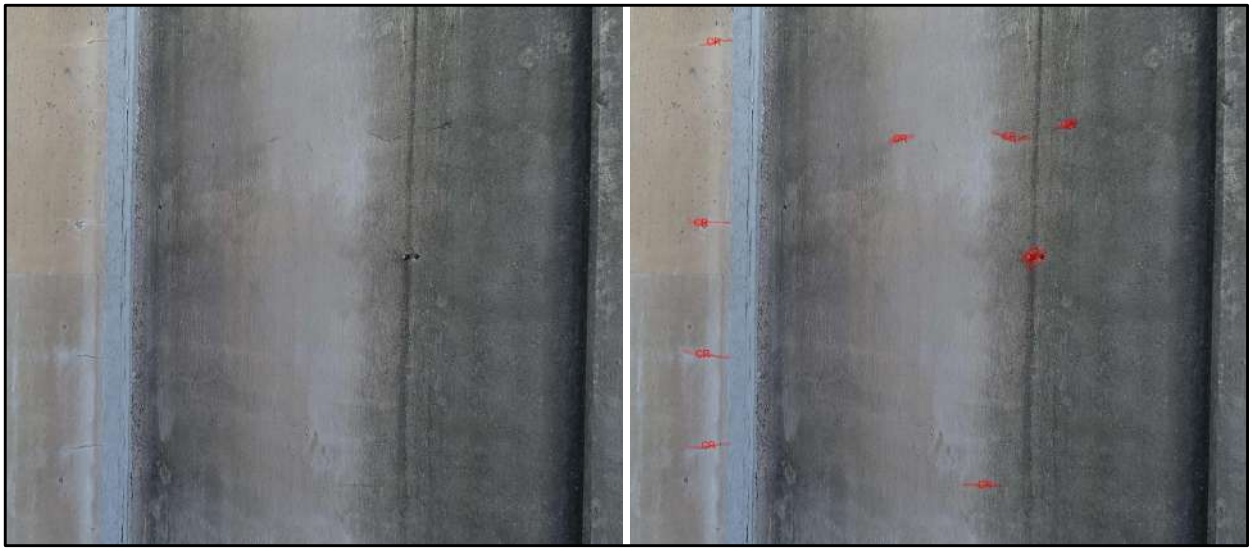
Cracks on Wall



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Efflorescence on Dome

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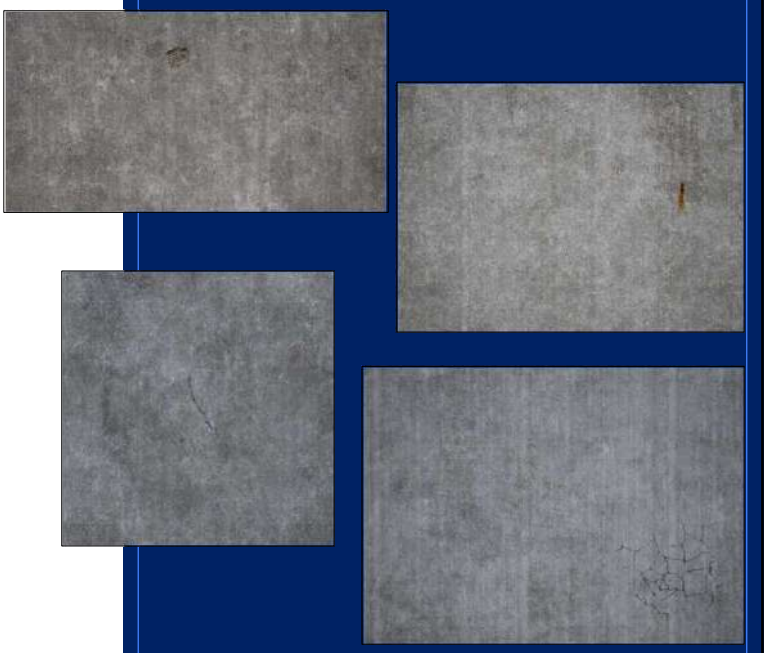
Synthetic Images

- Main targets of interest
  - Crack
  - Pattern Cracking
  - Corrosion
  - Spall
- 7,000 images of each type
- Also investigating GAN-generated images
- Not leveraged in models yet



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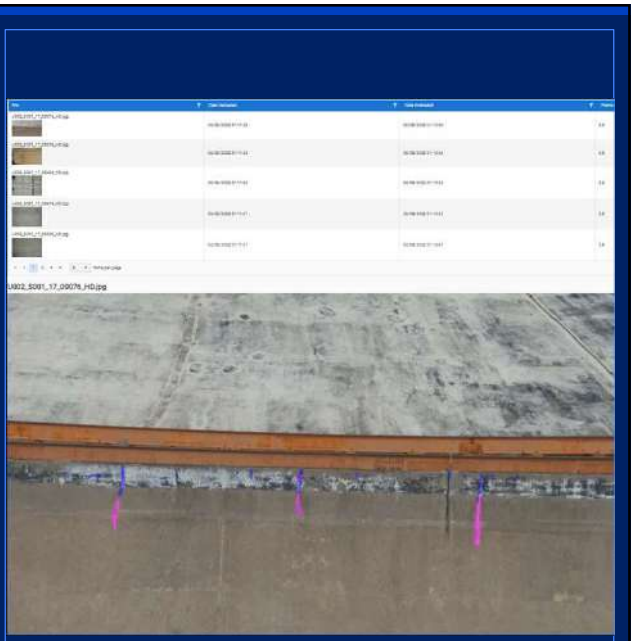
Post-Inspection Analysis

Concrete Defect Detection Tool (CDDT)

- Online tool to analyze images of concrete structures for defects (3002021063)
- Beta version available for testing: https://cddt-test.epri.com/



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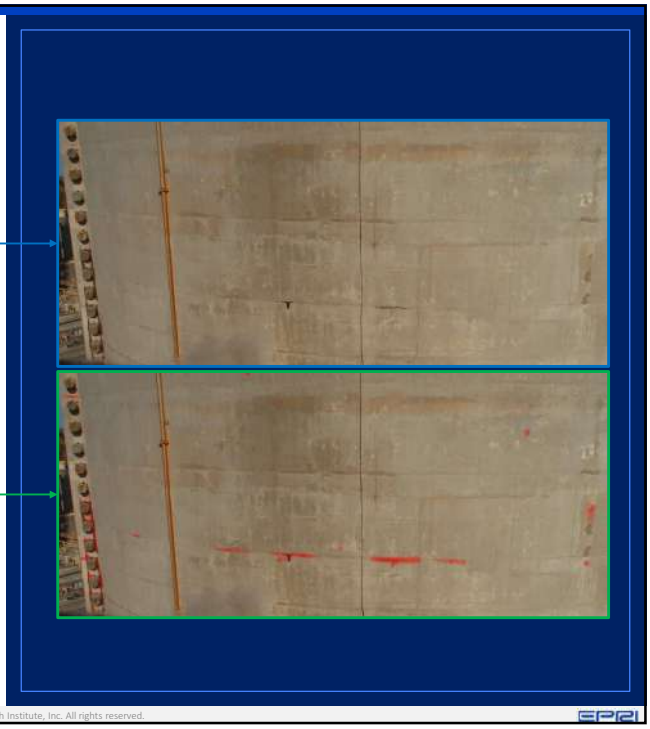
Real-Time Deployment

- Pilot sees regular image
- Inspector sees image with model overlays and guides pilot
- Targeting field demo in 2023



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Some Machine Visions Applications in Nuclear NDE

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Containment Buildings

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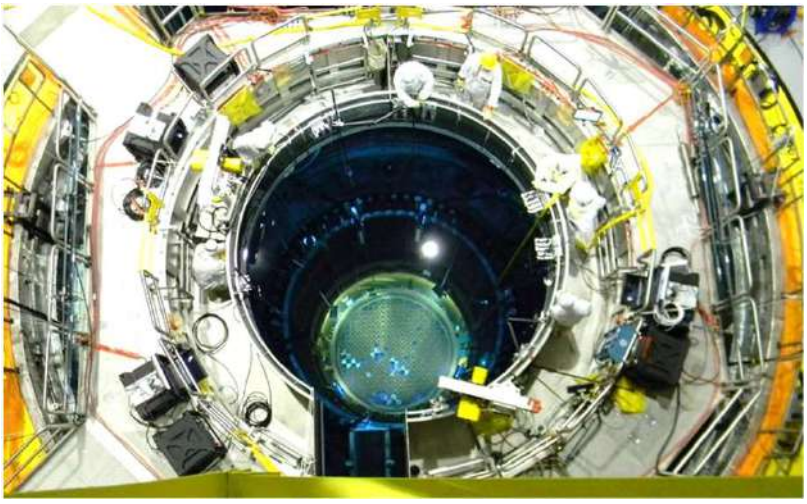
Remote Visual Inspection of Reactor Internals

Data collection
Preliminary analysis
Real time

Data review
Often done at a later time



fatigue

Missed flaws

distraction

Goal: Develop a screening tool that can assist examiners

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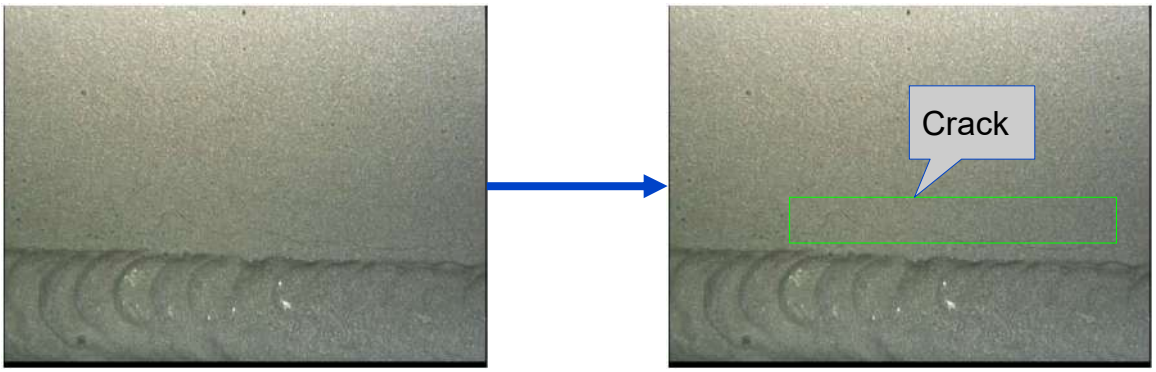
Objectives

- Develop model to detect SCC during remote visual inspection of reactor internals in **real-time**
- Develop SW to enable post-inspection review of results



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Project Overview

Target

- Cracks in reactor internals
- EVT-1 inspection scope

Data

- Field videos (limited)
- Lab specimens
- Virtual flaw technology

Approach

- CNN models trained from scratch

Deployment

- Real-time: edge-computing platform
- SW for post-inspection review

Status

- Initial model development

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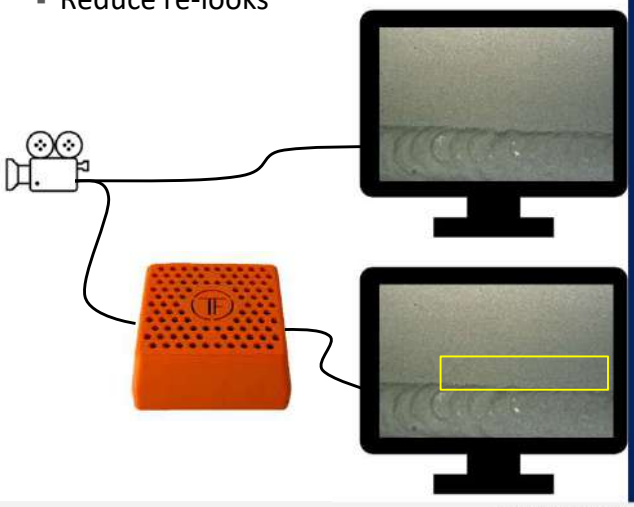
Real-Time Assistance

- Live aid to inspectors
- Reduce re-looks



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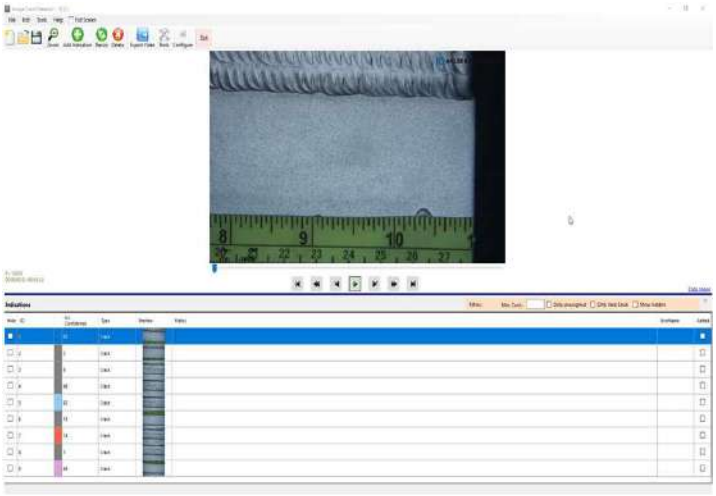
Post-Inspection Analysis



- SW loads video and model results
  - Some further processing of live output
- Level II/III can review/analyze results
- Areas of interest are bounded by rectangles, and highlighted
- Confidence levels, 0-100 are relative
  - Color palates are adjustable.
- User can select/click on detected areas; view and manipulate the data to evaluate and characterize detections.

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Current developments

Standard definition ⇒ High definition

- More benefit from AI
- Limited training data
- Training HD model with predominantly SD data
- Maintain real-time performance with HD data

Varying field data

- Training data from limited sources
- More varied training data will improve generalization and model quality

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Summary

Value in leveraging the best of each actor

- Machines do better at repetitive, monotonous tasks: don't lose attention, don't get tired
- Humans can focus on the "hard" parts

Different approaches

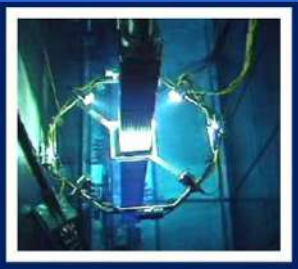
- Traditional machine vision, from scratch

Lack of data

- Different solutions

Different deployment options

- Value in real-time processing ⇒ may limit deployment options
- Edge, embedded in HW, drone, online



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Flaw Response Simulations using Flaw Profiles Obtained by Destructive Testing

Richard E. Jacob[1], Matthew S. Prowant[1], Nicholas A. Conway[1], Chris Hutchinson[1], Aaron A. Diaz[1]

[1]Pacific Northwest National Laboratory, Richland, Washington, USA

E-mail address (corresponding author): Richard.jacob@pnnl.gov

Inservice inspection of flaws through austenitic welds has long been an issue for the nuclear power industry. It is well known that microstructure can significantly attenuate and scatter the sound beam, leading to detection difficulties. The purpose of this study was to determine the predictive value of flaw-response simulations through an austenitic weld model using actual thermal fatigue crack morphologies obtained through destructive testing. After acquiring laboratory ultrasonic scans on five thermal fatigue cracks in three different welded piping mockups, we used destructive testing to characterize the flaw profile, depth, tilt, and ligament (i.e. distance from the flaw base to the mockup inner surface). The flaw profiles were digitized and added to our electron backscatter diffraction (EBSD)-based austenitic weld model. Simulations were run in four different scenarios: (1) with the EBSD weld model and actual flaw geometries, (2) with the EBSD weld model and planar flaws of equivalent tilt, depth, and ligament, (3) with an isotropic (no weld) model and actual flaw geometries, and (4) with an isotropic model and planar flaws (control scenario). The modelling and simulation platform CIVA was used. The empirical and simulated data were quantitatively and qualitatively compared.

Results showed that using full weld models with actual flaw geometries (scenario 1) did not produce more realistic simulation results than the other scenarios. There are several reasons for this finding. First, there were no clear qualitative relationships between the appearances of the empirical scans and the simulation results. For example, signal discontinuities observed experimentally were absent in the simulations. Second, there was no consistency in the quantitative comparisons of the simulated and empirical data, and any correlations or relationships that did appear could have been due to random chance. Third, only one austenitic weld model was used, but there is too much microstructural randomness in welds to be able to model a specific specimen with any reliability. Generating realistic, representative weld models is extremely difficult and time consuming since the infinite array of possible weld microstructural arrangements cannot be easily captured.

Metamodels were run in CIVA to determine what flaw properties had the most impact on inspectability. Results showed that the tilt and length had significant impacts on the flaw-response amplitude but that the ligament did not. Modeling the full range of possible flaw parameters is fast and easy using a metamodel approach. We note that flaw characteristics specified in laboratory mockup documentation typically varied significantly from the true-state, which is a problem for laboratory experiments designed to address specific inspection issues. This has the potential to result in incorrect conclusions being drawn about the inspectability of certain materials.

This study led us to the following conclusions:

(1) The flaw geometry has a significant impact on the echo response, but obtaining the actual flaw

geometry requires destructive testing, which is not possible in field inspection scenarios. Therefore, parametric studies or CIVA metamodels should be used to predict how variations in the flaw shape, depth, tilt, and ligament affect detectability for a given probe and specimen geometry.

(2) Using a complex, EBSD-based weld model and actual flaw geometries did not provide more realistic results than more simplified approaches. Reverting to simpler modeling approaches saves a significant amount of time and allows for running more simulations that can cover a greater range of possible conditions. However, simplifying the model by removing the weld or other microstructure, results in stronger simulated echoes due to the lack of beam scatter.

(3) Flaw depths, tilts, profiles, and ligaments can vary significantly from mockup design specifications. Whenever possible, destructive testing should be included as part of a laboratory study so that erroneous conclusions about flaw detectability can be avoided.

Keywords: Ultrasonic modeling and simulation, flaw response simulations, austenitic weld models, destructive testing, CIVA.

Pacific Northwest NATIONAL LABORATORY

Flaw Response Simulations using Flaw Profiles Obtained by Destructive Testing

Richard E. Jacob, Matthew S. Prowant, Nicholas A. Conway, Chris Hutchinson, and Aaron A. Diaz

Pacific Northwest National Laboratory
Richland, WA, USA
June 2023

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Carol Nove, NRC COR

ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Pacific Northwest NATIONAL LABORATORY

Purpose

- The U.S. Nuclear Regulatory Commission (NRC) inservice inspection regulations require full examination coverage of designated examination volumes
- There are certain examination volumes where this is not achievable due to component geometry or physical obstructions
- This work is part of a series of reports intended to help provide a technical basis for evaluating modeling and simulation, including scenarios where full coverage is not achievable
  - Developing specimen and inspection models
  - Conducting simulations
  - Interpreting and applying results

2

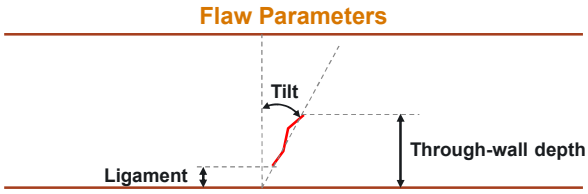
Recent PNNL Reports on Modeling and Simulation

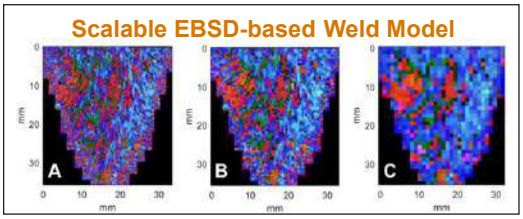
ML17095A969 ML18331A254 ML20122A252 ML22087A127 ML22311A009 ML23005A295

- These reports are publicly available on the U.S. NRC ADAMS web site
- https://www.nrc.gov/reading-rm/adams.html

Objective

- Determine if flaw response simulations are predictive of empirical flaw responses in materials with attenuative and scattering microstructures
  - Cast austenitic stainless steel (CASS)
  - Dissimilar metal welds (DMW) and austenitic welds
- Destructive testing (DT) was used to obtain the flaw true-state parameters, including through-wall depth, tilt, and ligament
- Electron backscattering diffraction (EBSD) was used to develop an austenitic weld model





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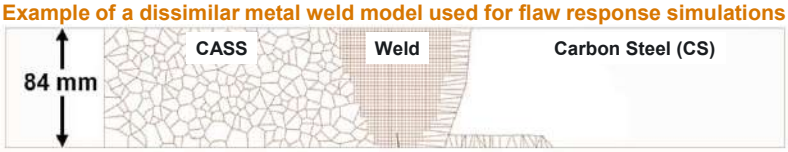
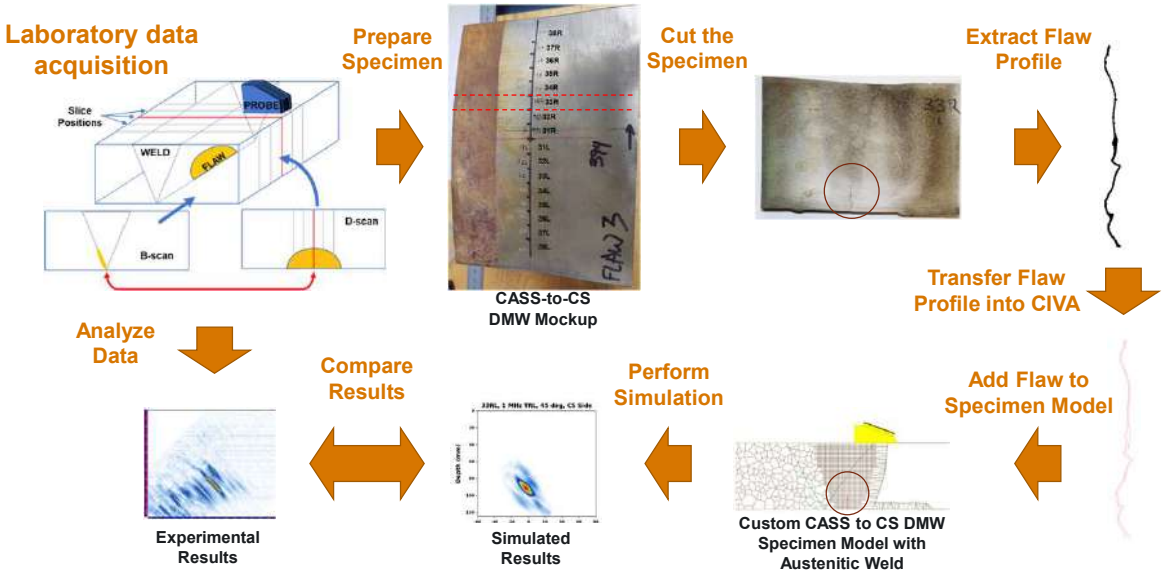
Approach

- Five thermal fatigue flaws were cut after UT scanning in the laboratory
- Flaw profiles were extracted visually or using penetrant testing then drawn in CIVA
- Flaw responses were simulated in four scenarios:
  - Actual flaw geometries (from DT) and a realistic weld model (from EBSD)
  - Planar flaws with the realistic weld model
  - Actual flaws with an isotropic weld
  - Planar flaws with an isotropic weld (control scenario)
- Simulation results were compared to the laboratory UT scans

Example of a dissimilar metal weld model used for flaw response simulations



Workflow

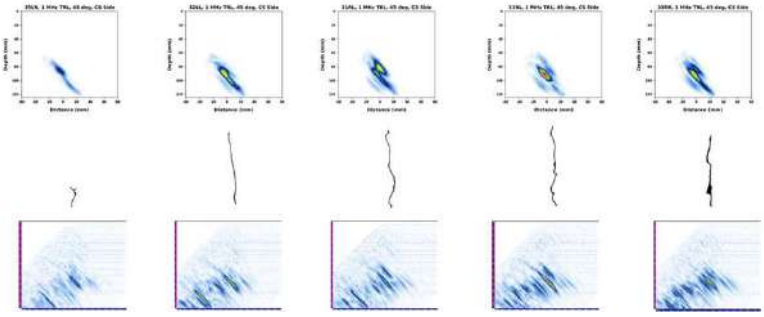


Analysis Approach

- B-scans from each slice position were extracted from the experimental scans
- Data from each scan were grouped and compared to the same group of simulations
  - A “group” comprised the data acquired (or simulated) from a given flaw using a given probe
  - For example, if a flaw was sectioned into five slices, then each group for that flaw would have five simulations and five empirical measurements.

Simulation

Experiment

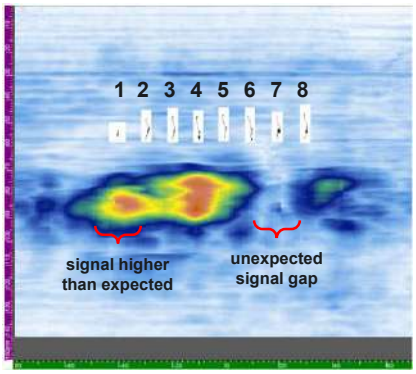


Analysis Approach

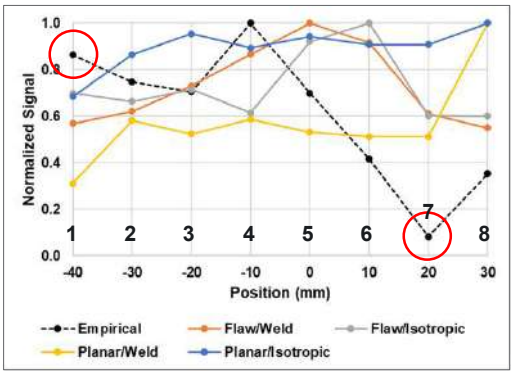
- The peak echo response was measured from each B-scan
- There were no available calibration signals, so data were normalized to the maximum of each group
  - For example, the six simulations were normalized to the simulation with the highest echo, and the six empirical measurements were normalized to the measurement with the highest echo.
- By normalizing each set of data, comparisons in trends could be made
  - If experimental data show that a flaw has a maximum signal at the midpoint and diminishing signals toward the ends, then the simulated data should show the same trend with the same relative amplitudes if the simulations are predictive.
- Results of each of the four simulation scenarios were compared to experiment
  - Actual flaw geometries (from DT) and a realistic weld model (from EBSD)
  - Planar flaws with the realistic weld model
  - Actual flaws with an isotropic weld
  - Planar flaws with an isotropic weld (control scenario)

Results Example

- Experimental results often showed anomalies where signals were higher or lower than expected
- Simulated results did not show similar anomalies

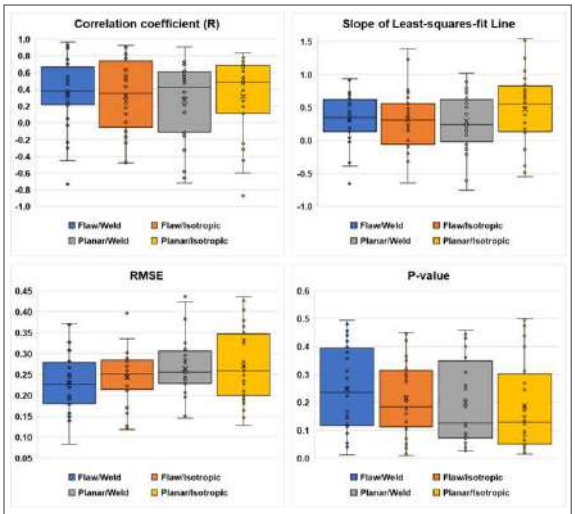


45°, 1 MHz scan of 10% through-wall flaw in 84 mm DMW specimen from the CS side



Key Takeaway #1: Simulation Predictiveness

- Simulations do not account for unpredictable experimental conditions
  - Grain structure
  - Weld fabrication defects
  - Human factors
- Multiple metrics were investigated to determine if any relationships existed between the simulated and experimental results
- Simulations using a complex austenitic weld model and actual flaw profiles were not more predictive than those using isotropic models and planar flaws
- None of the four simulation scenarios were considered to be predictive

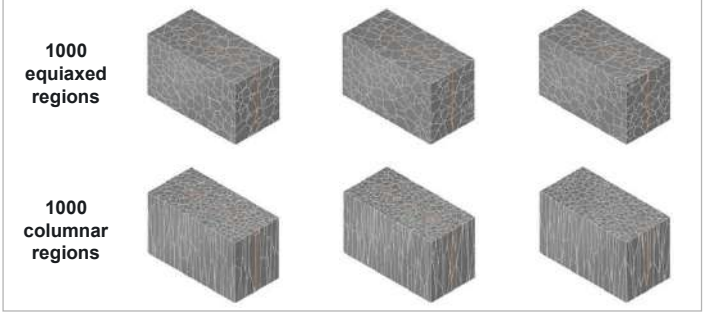


No statistically significant differences were seen between the different simulation scenarios in any of the metrics used.

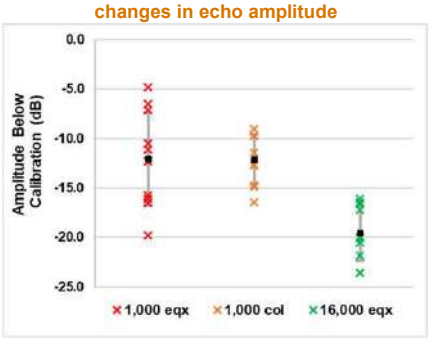
Key Takeaway #2: Model Parameters

- Coarse-grained models in CIVA were tested to see how randomness in grain structures affected results
- A side-drilled hole was used to measure echo amplitude in different random arrangements of Voronoi regions
- Simulation-to-simulation randomness in grain microstructure caused large variations in flaw response, making models with complex microstructure unreliable for flaw response simulations

Examples of randomly distributed Voronoi regions in a 3D model



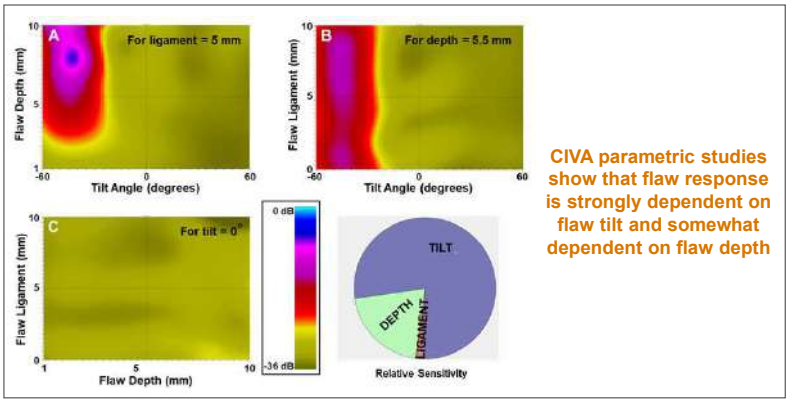
Random simulation-to-simulation changes in microstructure resulted in up to 15 dB changes in echo amplitude



11

Key Takeaway #3: Flaw Properties

- Flaw morphology can only be known through destructive testing, which is not usually an option
- Instead of trying to create the “ideal” defect, flaw response modeling efforts may be better spent focusing on parametric studies of flaw properties, such as tilt, depth, and ligament



CIVA parametric studies show that flaw response is strongly dependent on flaw tilt and somewhat dependent on flaw depth

12

Key Takeaway #4: Flaw True-states

- Flaw true-states found from destructive testing did not always agree with the mockup design specifications reported in the fabrication documentation
  - Through-wall depths varied by up to 4 mm (0.16 in.)
  - Tilts varied by up to ~20°
  - All flaws were supposed to be surface breaking, but ligaments up to 1.8 mm were found

13

Conclusions

- Flaw geometry has a significant impact on the simulated echo response
  - Obtaining the actual flaw geometry requires destructive testing, which is not possible in field inspection scenarios.
  - Therefore, parametric studies or CIVA metamodels should be used to predict how the flaw shape, depth, tilt, and ligament affect detectability.
- Complex specimen models and actual flaw geometries did not provide more realistic results than more simplified approaches.
  - Simpler modeling approaches can save time and allow for more simulations that cover a range of scenarios.
  - However, simplifying the model by removing microstructure results in stronger simulated echoes due to the lack of beam scatter.
- Flaw depths, tilts, profiles, and ligaments can vary significantly from manufacturer mockup design specifications.
  - Whenever possible, destructive testing should be included as part of a laboratory study so that erroneous conclusions about flaw detectability can be avoided.

14

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Thank you
15

Evaluation of a deep learning algorithm trained by simulation to characterize defects from multimodal TFM images in the presence of uncertainties

Roberto Miorelli, Sébastien Robert, Stéphane Leberre and Pierre Calmon

Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France

e-mail address (corresponding author): pierre.calmon@cea.fr

It is agreed that artificial intelligence and in particular Machine Learning have the potential of offering breakthrough tools for the assistance to the expert in the analysis of NDT data. The development of such tools often face both the lack of sufficient amount of representative data and the variability of the influential parameters. To train the algorithms with synthetic data obtained with simulation is a possible way to meet this challenge. In this communication we present a preliminary study aiming at evaluating the capacity of a simulation-driven deep learning algorithm to size crack-type defects in such difficult ultrasonic case. More particularly, the study focuses on defects detected by multimodal TFM imaging. By selecting and combining the most effective ultrasonic modes, this technique can provide an image of the defect giving access to its orientation and size. Nevertheless, the imaging algorithm is sensitive to parameters related to the geometry of the part, which may be only known approximately. In such a case, the image is not easily interpretable by an operator. We study here the ability of a deep learning algorithm to overcome this difficulty. The algorithm is trained on a database of images obtained by simulation, and its efficiency is evaluated on a reduced set of experimental acquisitions by artificially reproducing a lack of knowledge of the geometry. This study has been supported by the Euratom project ADVISE.

Keywords: Ultrasonic imaging, Machine learning, Simulation

Evaluation of a deep learning algorithm trained by simulation to characterize defects from multimodal TFM images in the presence of uncertainties

Roberto MIORELLI, Sébastien ROBERT, Stéphane LEBERRE, Pierre CALMON,

Université Paris-Saclay, CEA, List, Palaiseau, France

Summary

- Introduction
  - Context: The project ADVISE
  - Case of study and objectives: M-TFM and uncertainties
- Methodology:
  - Deep learning architecture
  - Creation of Data set
  - Validation
- Results
- Conclusions and perspectives

Context, objectives

Context: The European ADVISE project 2017-2022

Advanced Inspection of Complex StructurEs

- H2020 Euratom research project
- Coordinated by EDF (Andreas SCHUMM)
- 13 partners from 6 European countries
- 4,55 M€ budget with 4,17 M€ EU funding
- Started on 1 Sep 2017, lasting 48 months

ADVISE
Advanced Inspection of Complex Structures

Eddyfi Technologies, bay, EDF, ktu, framatome, Fraunhofer IZFP, Imperial College London, University of BRISTOL, EXTENDE CIVA, ARTTIC, UJV, CEA, MPA

UT Modelling

N. Leymarie's talk

Material characterization

WP2 — Develop new tools for material characterisation and input data

Transducers & methods

WP3 — Provide advanced inspection methods

Model-based diagnostics

WP4 — Provide defect evaluation methods and assisted diagnostics

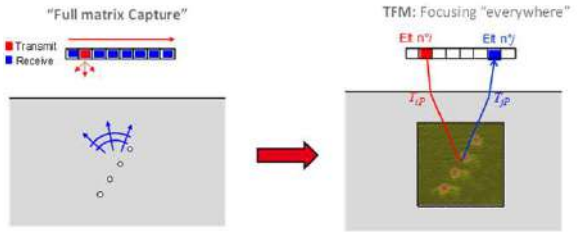
Context: the need to keep on improving Generations II and III reactors' safety and reliability

Overall objectives: to enhance the ultrasonic inspection of complex structured materials

Case of study: Multimodal TFM (MM-TFM)

TFM Array Imaging

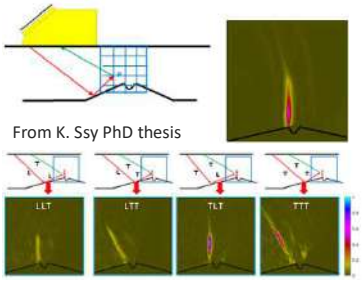
- TFM technique : General principle
  - FMC acquisition: Acquisition of the signals corresponding to all the T-R pairs on the array.
  - TFM imaging: Delay and sum of all the signals at each pixel
  - Assumes direct paths between the array and the pixel



➥ **Based on the computation of Times of flight between the array and the pixel.**

$$I(P) = \sum_{i=1}^{N}\sum_{j=1}^{N} s_{ij}\left(t = T_{iP} + T_{jP}\right)$$

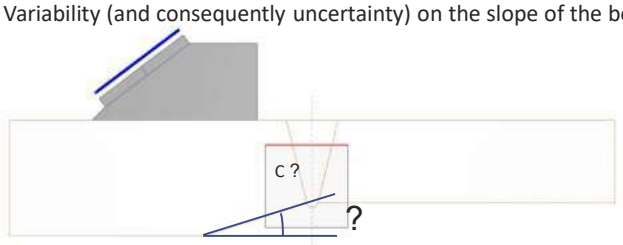
- Multi-modal TFM
  - Generalization of the algorithm in order to account for multiple paths (or modes).
  - Multiple images: computation of ToF for the ≠ modes. One image per mode
  - Well adapted to the detection of breaking crack-like defects from corner echoes.
  - Provided the selection of the suitable mode: Leads to a visualization of the defect giving intuitive access to its size and orientation.



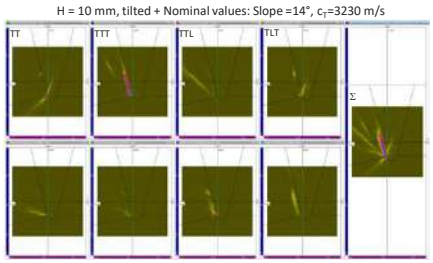
➥ **Times of flight computation requires accurate knowledge on part geometry (among other parameters)**

Case of study: MM-TFM of a welded part + uncertainties

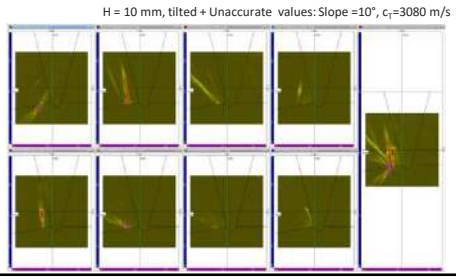
- UT array inspection of a welded part with a bevelled backwall
- Research of crack-like defects initiated on the backwall
- Variability (and consequently uncertainty) on the slope of the bevel



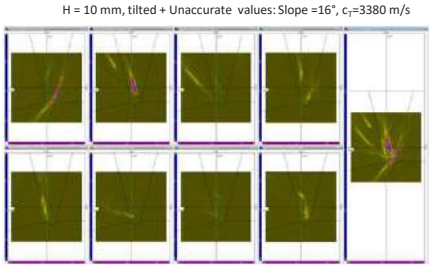
- MM-TFM imaging **without** uncertainties



- TFM imaging **under** uncertainties (lack of knowledge on geometry and/or material)



Lower quality of image and artefacts :
Lower SNR, alteration of echoes, mistaken localization and sizing,



Objectives of the study

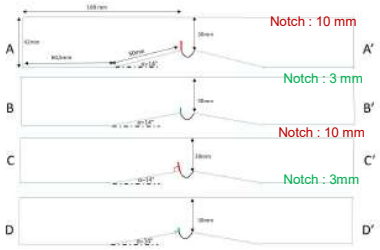
Goal: To evaluate the capability of AI to deal with such problem

- To develop an algorithm based on AI to automatically retrieve size and orientation, from TFM images.
- To overcome the lack of knowledge on influential parameters (slope, celerity).
- To evaluate the potential of simulation assisted AI on this case.

Summary:

- Idea 1: There is information in "erroneous" TFM images even if these images cannot be directly interpreted by an operator.
- Idea 2: To use Machine Learning to extract this information→ ML algorithm can exploit the TFM artifacts and altered echoes as meaningful information.
- Idea 3: In order to overcome the lack of data, to use simulation to train ML.
- Validation of the approach on numerical data and experimental acquisitions.

One mock-up with 4 defects

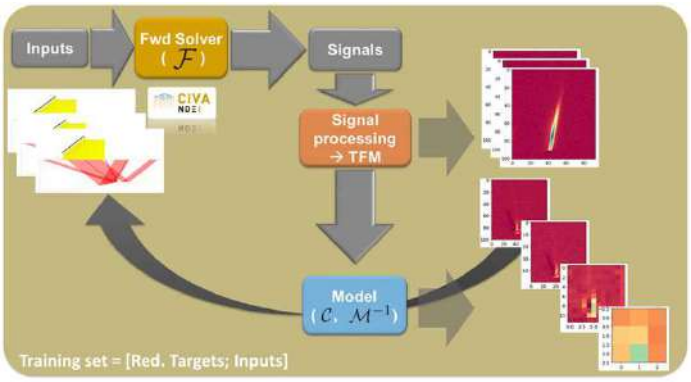


Methodology

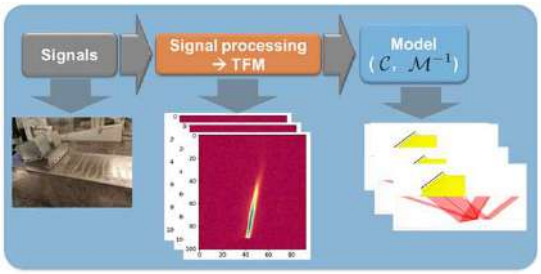
Model driven machine learning

Supervised learning schema [Mio2021a, Mio2021b, Mio2021c Pyle2021, Gra2023]

Offline phase: Dataset generation and ML model training



Online phase: ML model exploitation

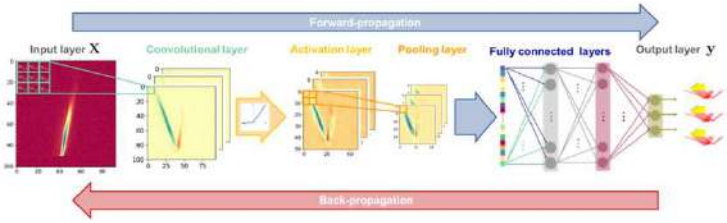


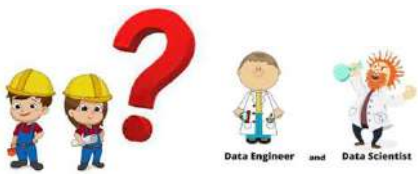
Classification/Regression ML models:
Deep learning → MLPR, **CNN**, RNN, etc.

[Mio2021a] Miorelli et al., "Supervised learning strategy for classification and regression tasks applied to aeronautical structural health monitoring problems", Ultrasonics, vol. 113, 106372 , 2021
[Mio2021b] Miorelli et al., "Defect sizing in guided wave imaging structural health monitoring using convolutional neural networks", NDT and E International, Vol. 122, 102480, 2021.
[Pyle2021] Pyle et al., "Deep Learning for Ultrasonic Crack Characterization in NDE," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 68, no. 5, pp. 1854-1865, 2021
[Gra2023] G. E. Granados, et al., Towards a multi-fidelity deep learning framework for a fast and realistic generation of ultrasonic images in complex geometries with the multi-modal total focusing method. NDT & E Int., 2023

Model driven machine learning

Convolutional Neural Network (CNN) [LeC1998]

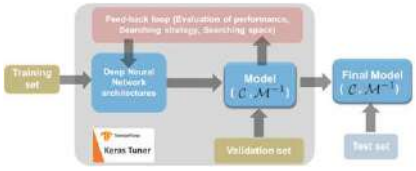




[LeC1998] Y. LeCun, et al., "Gradient-based learning applied to document recognition," Proceedings of the IEEE. 86 (11): 2278–2324. 1998.

Design of the deep neural network architecture & training

1. **Tailored architectures for data at the hand** → both expertise from NDT and data science are needed
2. **Automatic machine learning** (AutoML) procedures → establishing a set of "sufficiently good" networks and choose the most suitable candidate based on "understandable" error metrics (e.g. mean squared error, mean absolute error, accuracy etc.)



Generation of TFM multimode images under uncertainties via CIVA

Dataset generation : TFM images simulated with varying acquisition and reconstruction parameters

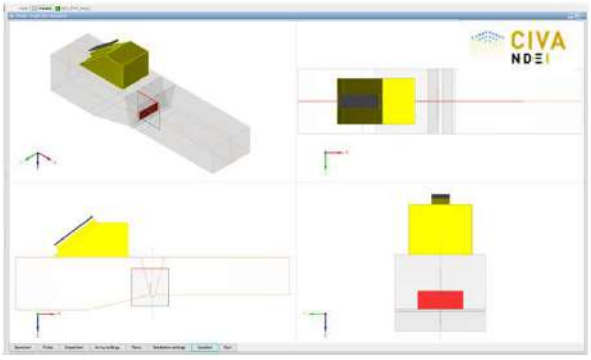
- **Scenarii for FMC acquisition:** Variations on the parameters representing a **set of possible CIVA configurations** including the **parameters to be retrieved**
- **Scenarii for TFM reconstruction:** Variations on the reconstruction parameters for TFM imaging algorithms representative **of possible operator choices.**
- No **a-priori information** on the distribution of dataset parameters is done → uniform PDFs are used

Training ML model on this numerical set of TFM images

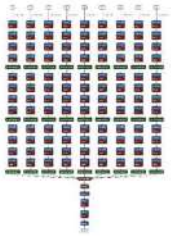
- We **train a single ML model** on a set of the couples MM-TFM images + **parameters to be retrieved**
- **Take into account multiple TFM modes** (up to 9 in this case) without choosing the modes based on the "judgment of an expert"
- Avoid any calibration procedure before training the model → the model is deployed once for all

Generation of TFM multimode images under uncertainties via CIVA

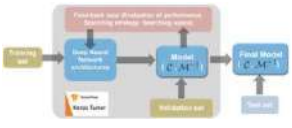
- Simulated configuration : Array 64 elts, 5 MHz, wedge SW 55°
- Creation of data set of TFM images with varying parameters



Tailored deep neural network architecture



AutoML deep neural network architecture



Dataset parameters	
Parameters	**Var. Range**
Flaw height [mm]	[2.0 , 12.0]
Flaw tilt [deg]	[-20, 0]
Backwall slope [deg]*	[10, 18]
Celerity T-waves [m/s]*	[3030, 3380]

	Number of training samples
Database generation	7400 (train) + 500 (valid.)
TFM images resolution	128px x 128px
TFM-modes	TT, TTT, TTL, TLT, TLL, TTTT, TLLT, TTLT, Σ**

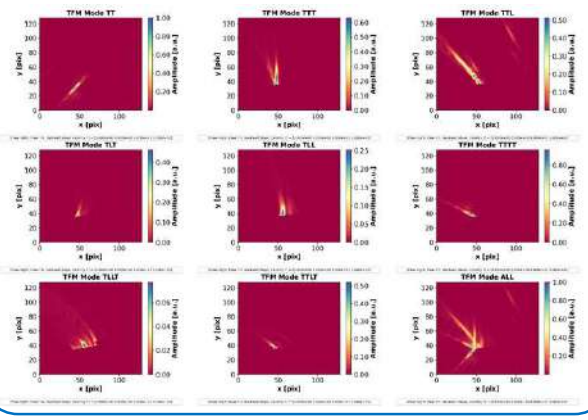
* On the FMC and TFM calculations

** **Σ stands for the maximum pixel-by-pixel for all the considered mode**

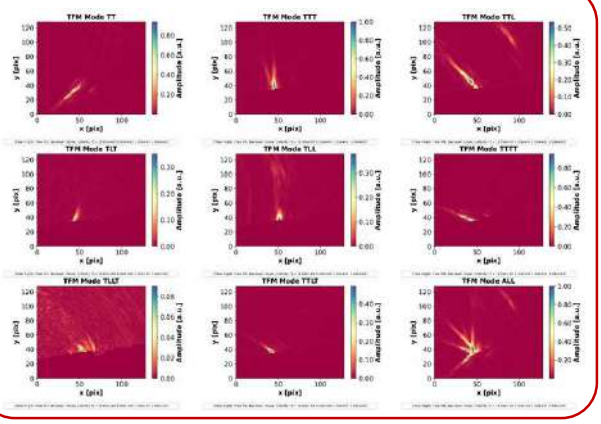
Example of multimodal TFM images under uncertainties

→ Simulations vs. Measurements: [Flaw height, Flaw tilt, **Backwall slope***, **cT***] = [3, 0, 10, 3080] (* on the calculation of ToF, experimental/simulated FMC data obtained with backwall-slope @14° and cT @3230)

Simulations



Measurements



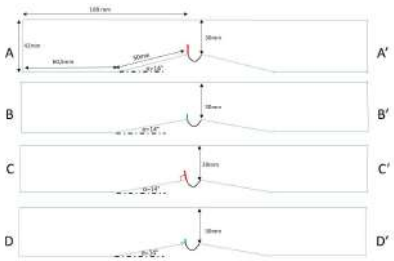
The simulation accurately predicts measured TFM images under uncertainties and artifacts (i.e. images whose reconstruction parameters ≠ acquisition parameters).

Results

Numerical and experimental validation

Numerical validation : Generation of simulated data set of TFM images

Experimental validation: Generation of MM-TFM testing experimental images from the one mock-up

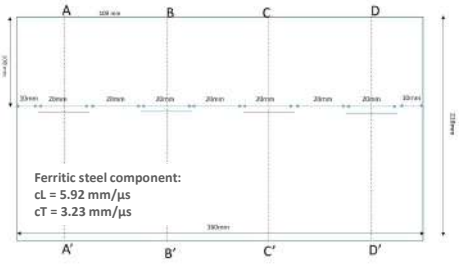


Vertical 10 mm high notch

Vertical 3 mm high notch

Tilted 10 mm high notch

Tilted 3 mm high notch



Experimental test set	
Parameters	**Values**
Flaw height [mm]	**3.0, 4.0**
Flaw tilt [deg]	**-14.0, 0.0**
Backwall slope [deg] (FMC)	14.0
Celerity T-waves [m/s] (FMC)	3230
Backwall slope [deg] (TFM)*	**10.0, 14.0, 18.0**
Celerity T-waves [m/s] (TFM)*	**3030, 3230, 3380**

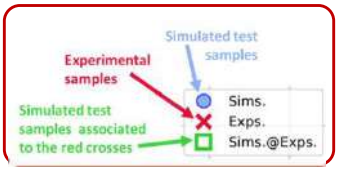
4 FMC acquisitions

X

9 combinations of parameters used for reconstruction

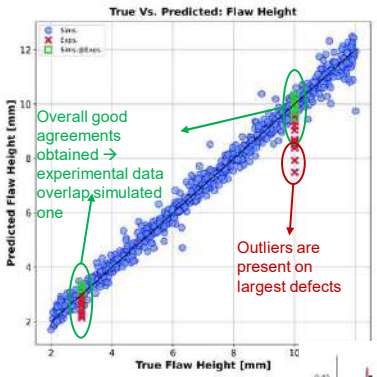
A total of **36 MM-TFM images** have been generated

Validation campaign captions

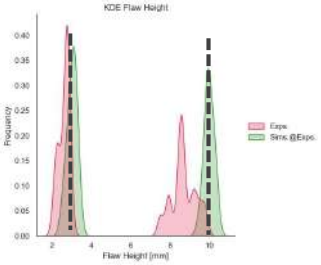


* Used for TFM calculations

Numerical and experimental validation

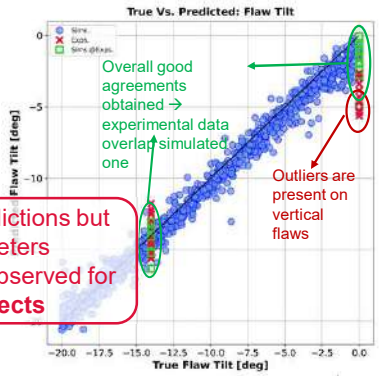


Errors	Flaw Height
MAE	0.65 [mm]
RMSE	0.96 [mm]
R2	0.97 [a.u.]

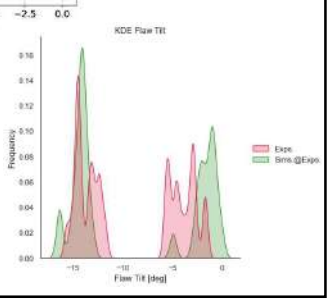


Height

Overall good predictions but Flaw parameters underestimation observed for **largest defects**

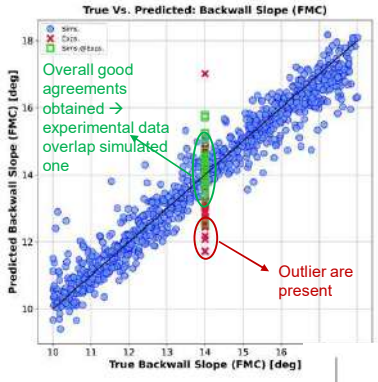


Errors	Flaw Tilt
MAE	0.25 [deg]
RMSE	0.39 [deg]
R2	0.98 [a.u.]



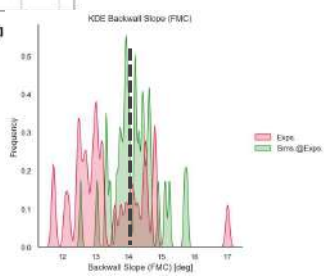
Tilt

Numerical and experimental validation: inversion of backwall slope

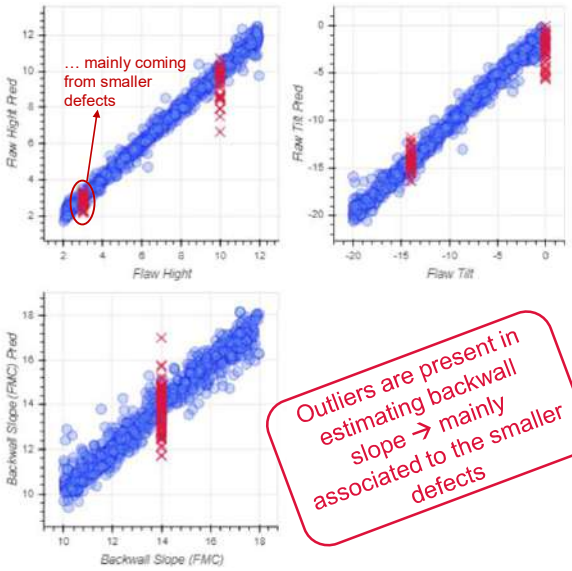


Errors	Backwall Slope
MAE	0.51 [deg]
RMSE	0.70 [deg]
R2	0.91 [a.u.]

Slope



Tracking the outliers…



Outliers are present in estimating backwall slope → mainly associated to the smaller defects

Conclusions & future works

- These results confirm the **wealth of information included in M-TFM images even in case of inaccurate/erroneous reconstruction**. This information can be retrieved by applying relevant algorithms.
- The study demonstrates the **potential of DL algorithms** to assist to the interpretation of such images and more generally **to deal with a complex inverse problem in ultrasonic TFM imaging**.
- The performances obtained by the **simulation trained DL** model on experimental acquisitions are **quite encouraging** for the approach but should be improved.
- Further work is ongoing to deepen this analysis on larger experimental datasets,
- however it is already clear that the challenge is **to design algorithms robust** to unavoidable discrepancies between simulation and experiment. Works are in progress in this direction.
- This study opens the way to the design of **Simulation driven DL tools to aid in the interpretation of complex ultrasonic images**.

Acknowledgments

This work has been carried out under the European Project ADVanced Inspection of Complex StructurE (ADVISE) within the European Union's Horizon 2020 Research and Innovation Program under grant agreement number 755500

Thank you for your attention!

Leveraging Machine Learning to Improve Flaw Depth Sizing in Balance-of-Plant Components

Thiago Seuaciuc-Osorio[1]

[1]EPRI, Charlotte, USA

E-mail address (corresponding author): tsosorio@epri.com

Eddy current (EC) inspections are commonly employed to assess the condition of balance-of-plant (BOP) components in the nuclear industry, such as heat exchanger tubing. While capable of reliably detecting relevant indications, current industry practices can be challenged to provide accurate accurately characterization, especially for certain types of damage such as microbiologically induced corrosion (MIC). On the one hand, poor depth sizing may negatively affect performance if it leads to tubes being unnecessarily removed from service; on the other, it may compromise safety if severely damaged tubes are left in service.

In this presentation, the author will describe the process used both to establish a benchmark for the performance of the industry's current practices in depth sizing inner diameter pits in heat exchanger tubing through eddy current testing, as well as to build machine learning (ML) models for the same purpose. The results show that, when compared to current practices, ML approaches not only provide a performance at least two times better than realistically expected field performance, but also better than an ideal unattainable case obtained with self-calibration. Lastly, the author will show that, although inconclusive due to limited available data, the approach has yielded promising results when used to characterize MIC damage in field-removed samples.

Keywords: eddy current, balance-of-plant tubing, depth sizing, machine learning

Leveraging Machine Learning to Improve Flaw Depth Sizing in Balance-of-Plant Components

Thiago Seuaciuc-Osorio, EPRI
Principal Technical Leader, Engineering

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Motivation

- Eddy current (EC) techniques are commonly used in balance-of-plant (BOP) heat exchanger (HX) tubing inspection
- Current practices are challenged to accurately depth size damage cause by microbiologically influenced corrosion (MIC):
  - Unnecessarily remove tubes from service ⇒ impact performance
  - Unexpected leaks ⇒ impact safety
- Simplistic sizing: mono-parametric approach based on calibration curves typically built on single, specific defect profile.

Can Machine Learning help improve sizing accuracy?

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Approach

- Separate specimen sets for train/test
- ID pits
- Several defect profiles

- Additional frequencies
- Multiple pulls

- Assess performance following current practices
- Multiple calibration references

- Develop models
- Assess performance

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Approach

Develop models for ID pits

Adapt for MIC (see 1013454)

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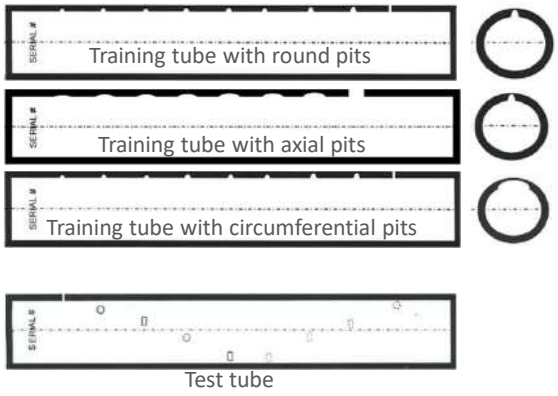
Specimen Inventory

- 19 tubes for train, 4 for test
- 9 flaws per tube
- Flaw profiles:
  - Round pits
    - 5 diameters from 1.59 to 6.35mm
  - Rectangular (axial) pits
    - 5 aspect ratios from 2 to 8
  - Rectangular (circumferential) pits
    - 5 aspect ratios from 1/8 to 1/2
- Training tubes:
  - Aligned defects, all same profile
  - Depths of 10%, 20%, 30%, …, 80%, 100%
- Test tubes:
  - Varied profiles, depths, angular location

Material	304 Stainless Steel
Outside Diameter	1 in. = 25.4 mm
Wall Thickness	0.028 in. = 0.711mm
Length	24 in. = 609.6 mm



Test tube

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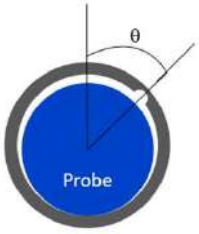
Data Collection

- Absolute and differential modes
- 10 frequencies
  - 4 typically used in EC inspections
  - 6 extras, mainly higher than prime
- 36 pulls at different tube rotations
  - Every 10°



Frequency (kHz)	Prime Frequency Factor
100	0.11
220	0.25
440	0.50
660	0.75
880	**1.00**
990	1.12
1100	1.25
1320	1.50
1540	1.75
1760	2.00

Frequencies typically used in EC

Additional frequencies

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Benchmarking: Manual Sizing

Case	Reference	Target	What It Represents	RMSE (%TW)
Self-Calibration	Same as target	All training tubes	Utopic best-case scenario where reference and target defects match perfectly. Used as a reference for upper limit for performance of manual analysis. Not expected to be achieved in the field.	10%
ASME Calibration	ASME	All test tubes	Performance based on available ASME standard (OD defects), without using any custom reference standards.	24%
ID Pit Calibration	Each of the seamless training tubes	All test tubes	Typical field scenario, where reference defect profiles are not expected to match the unknown target defect. Provides an assessment of variance in performance based on choice of reference standard.	14 – 29%

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Machine Learning Models

- 10 frequencies × 2 modes × 2 signals = 40 waveforms
- Trained on data from several pit profiles, at several angular locations
- 300 total features
  - Amplitude, phase, correlations, frequency analysis components, etc…
- 24 different models
  - Linear, **random forest**, MLP, KNN, SVM
  - Feature selection (statistical, lasso, etc)
  - Multiple strategies
    - **Regression models**
    - Classification for TW holes + regression for others
    - Multi-label classifiers (binned depths)
  - **Absolute** (mm) and relative (%TW) scales
  - Ensemble of top 10 models (mean)

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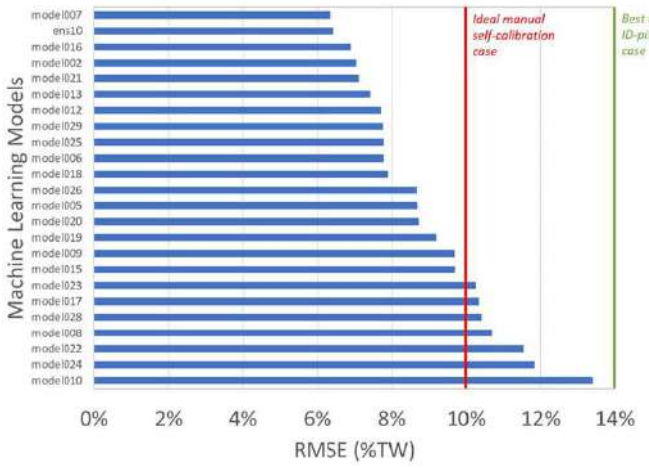
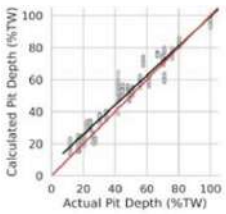
Performance Comparison

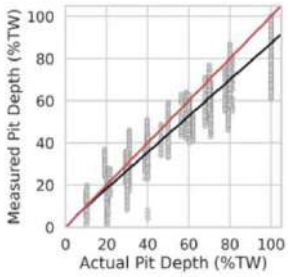
- Machine learning out-performs self-calibration case by 40%



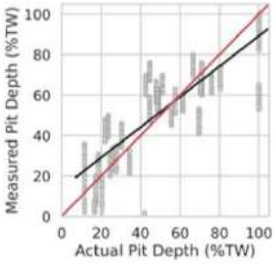
Ensemble ML model
RMSE: 6%TW



Self-Calibration
RMSE: 10%TW



Best ID pit reference
RMSE: 14%TW



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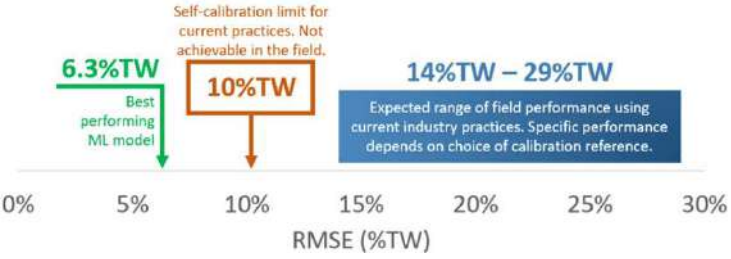
Remarks on ID Pit Sizing

- Performance of current practices vary significantly depending on choice of calibration reference
  - Biased measures observed in some cases
- Results show ML methods to be at least 2× more accurate than expected performance following current practices
  - 40% better than limiting self-calibration case
  - No need to choose calibration reference



Machine Learning to Improve ID Pit Sizing in Balance-of-Plant (BOP) Heat Exchanger Tubes: Target—Type 304 Stainless Steel Tubing (3002021048)

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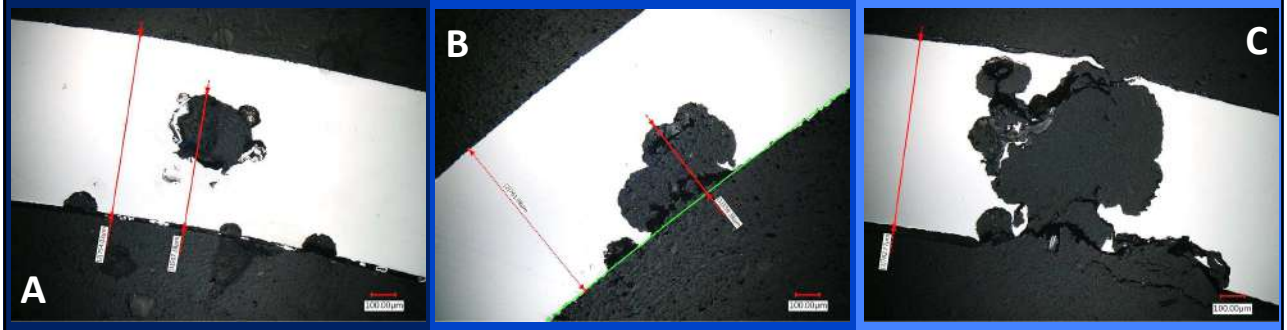
Field MIC Damage

Field-removed tube supplied by member utility



What happens when we apply the models directly to this?

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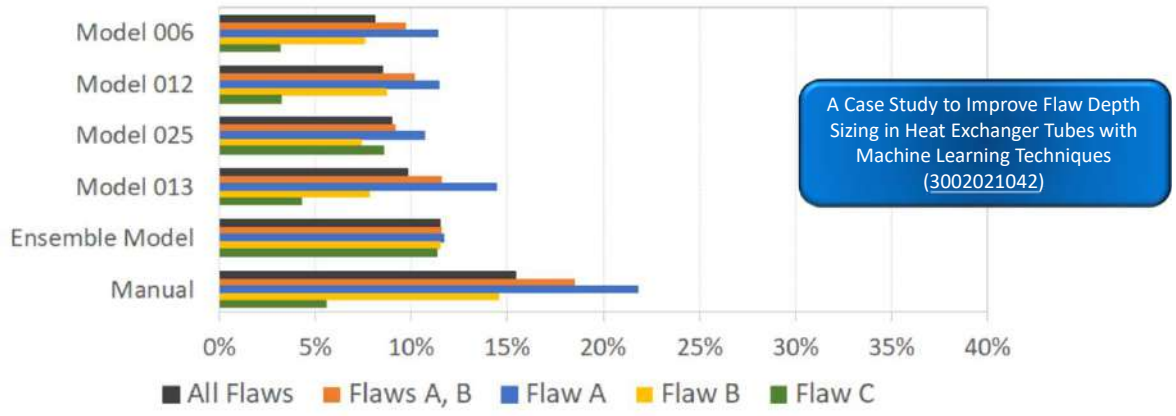
Applying Models to MIC Damage



A Case Study to Improve Flaw Depth Sizing in Heat Exchanger Tubes with Machine Learning Techniques (3002021042)

Top models still out-perform manual by approximately 2×

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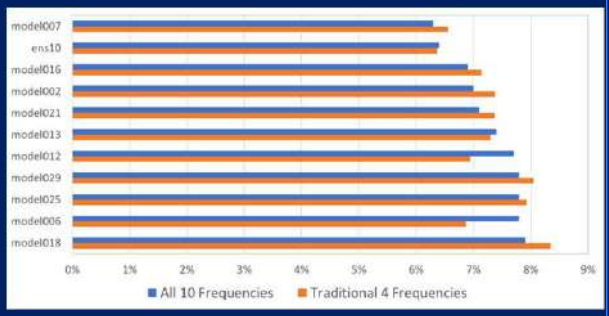
What If We Only Have the Fab-Four?

- Top-10 models re-trained to use only traditional 4 frequencies
  - 1×, 0.5×, 0.25×, 0.125× prime
- ➢ No significant performance degradation observed

Models can be leveraged with current industry data collection practices

Frequency (kHz)
100
220
440
660
880
990
1100
1320
1540
1760



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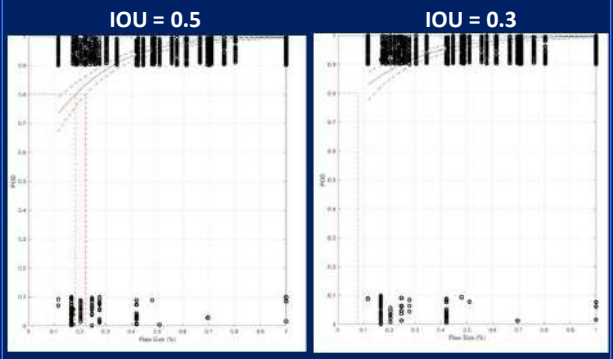
Towards a Fully-Automated Solution

- Preliminary detection model
  - Light Gradient Boosted Machine (LGBM)
  - Point-by-point evaluation
    - Flaw range obtained in post-processing
  - PCA on derivative and its rolling std

IOU	x_{80}	Recall	Precision
0.5	18%TW	0.92	0.96
0.3	8%TW	0.95	0.99

NOTE: This preliminary detection model uses all 10 frequencies.



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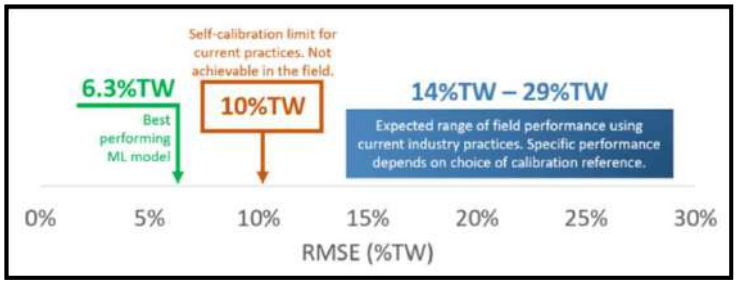
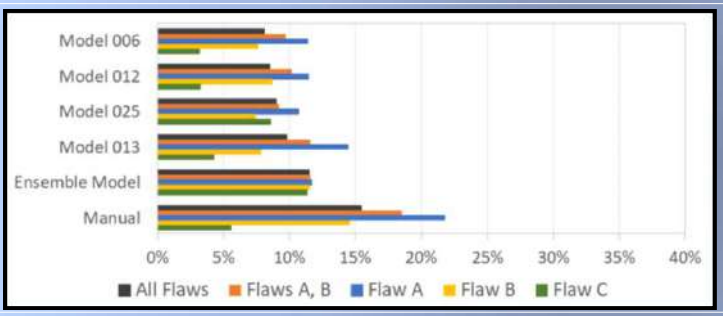
Summary

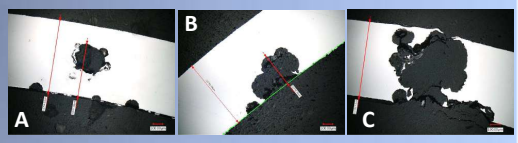
ML approaches offer improvement in ID-pit sizing accuracy when compared to industry practices
(see 3002021048)

Note: ML does not require a choice of reference standard





Direct applications of the models improve MIC depth-sizing as well
(see 3002021042)



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10. R&D and Application of NDE Technologies & Equipment

The presentations in this session are listed in the table below.

R&D and Application of NDE Technologies & Equipment	**Chair:** Oliver Martin (EC-JRC)
Inspection of concrete/steel/concrete pipes affected by corrosion with ultrasound techniques	Thilakson RAVEENDRAN (EDF) et al.
Advanced ultrasonic imaging solutions for the inspection of nuclear assets	Niels Pörtzgen (Applus)
Outage Water Tank NDT inspection	Francisco Javier de la Morena Martínez (Tecnatom)
Beam characterization of a LINAC system for an NDT qualification process	Sylvain Murgier (EDF) et al.
How to research NDE in Nuclear without Nuclear Power Plants	Anne Jüngert (MPA, Univ. Stuttgart)

Inspection of concrete/steel/concrete pipes affected by corrosion with ultrasound techniques

Thilakson RAVEENDRAN[1]*, Arnaud RECOQUILLAY[2], Jean-Marie HENAULT[1], Jean-François CHAIX[3], Guy D'URSO[1], Denis VAUTRIN[1], Vincent GARNIER[3], Jean MAILHE[3], and Philippe BISARAH[4]

[1] EDF R&D, PRISME, Chatou, France
[2] Université Paris-Saclay, CEA, List, Palaiseau, France
[3] LMA, Université d'Aix-Marseille, CNRS, Ecole Centrale, UMR7031, Aix-en-Provence, France
[4]EDF-DI, TEGG, Aix-en-Provence, France

E-mail address (corresponding author): thilakson.raveendran@edf.fr

Non-destructive ultrasound techniques are developed to assess steel thickness in concrete/steel/concrete pipes affected by corrosion. The inspection has to be done from the outside of the pipe.
The steel layer is several millimeters thick and is included between two concrete layers that are several centimeters thick, the external concrete being reinforced. Concrete made of aggregates in mortar acts as a low pass filter for ultrasound due to multi-scattering on aggregates and to visco-elasticity of mortar. Thus, traditional bulk wave ultrasound techniques cannot be used to inspect the steel layer through the concrete layer.
Two types of techniques are studied using bulk waves and guided waves. These techniques are optimized with different samples in laboratory.
For bulk waves, pulse compression methods are studied to maximize the energy and increase the frequency content of the measured signal.
For guided waves, a numerical study enables to identify a mode sensitive to steel thickness, and a specific sensor configuration is proposed to measure it.

Keywords: Concrete/Steel/Concrete pipes, corrosion, ultrasounds.

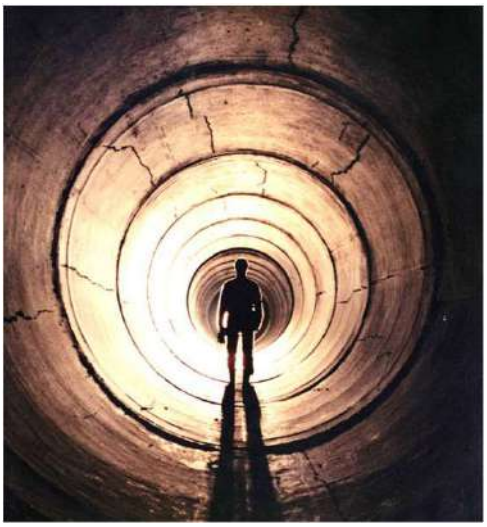
INSPECTION OF CONCRETE/STEEL/CONCRETE PIPES AFFECTED BY CORROSION WITH ULTRASOUND TECHNIQUES

T. RAVEENDRAN, J.-M. HENAULT,
G. D'URSO, D. VAUTRIN, P. BISARAH,
H. LENOURY, **EDF**

A. RECOQUILLAY, **CEA**

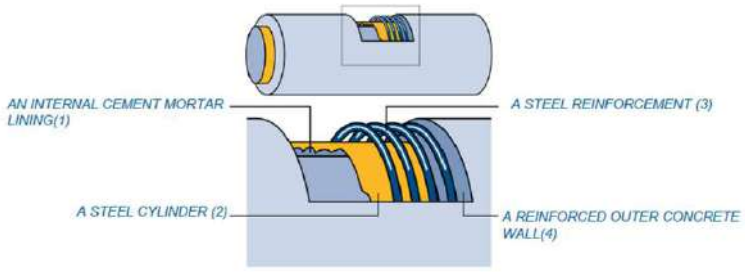
J.-F. CHAIX, V. GARNIER, J. MAILHE, **LMA**

NDE in Nuclear, Sheffield, June 2023



CONCRETE/STEEL/CONCRETE PIPES
STEEL CYLINDER CONCRETE PIPES (SCCP)

- Reinforced concrete pressure pipe with an embedded steel cylinder
- Used in cooling water system pipeworks in nuclear EDF's power plants
- Inner diameter from 250mm to 4 000mm
- Steel thickness from 2mm to 8mm

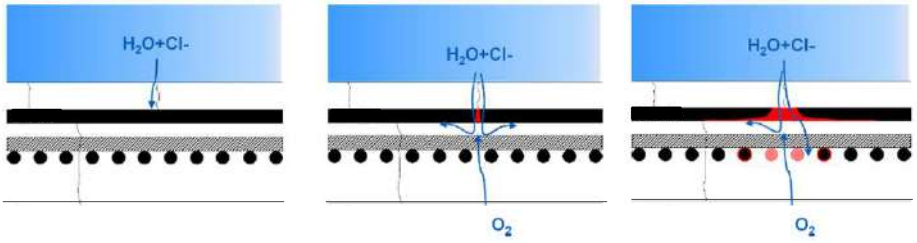


[Bonna TP]

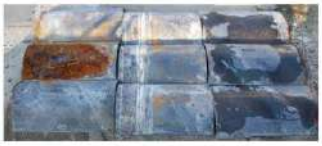
SCCP MANUFACTURING

[Bonna TP]

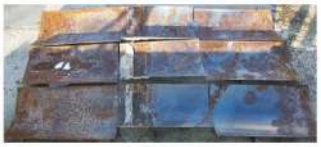
SCCP STEEL CORROSION



Outer steel surface

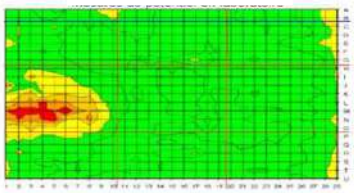
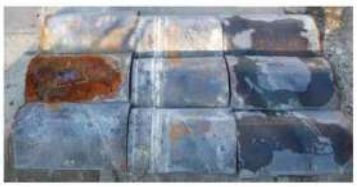


Inner steel surface



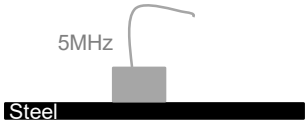
NDT TO INSPECT SCCP

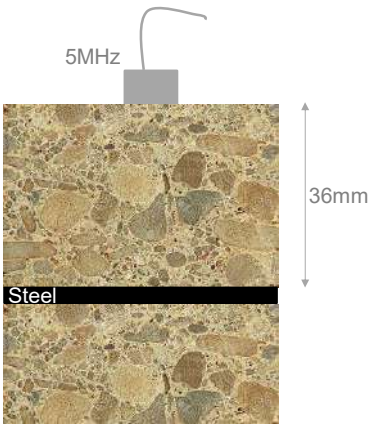
- Electro-chemical potential measurements
- Qualitative results related to corrosion probability
- No information about remaining steel thickness

- Thesis of Thilakson Raveendran (2020 - 2023)
- Collaboration betweeen EDF, CEA and LMA
- Remaining steel thickness assessment with UT
  - body waves
  - guided waves

UT ISSUE

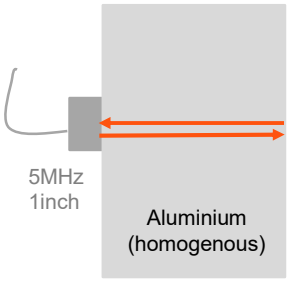


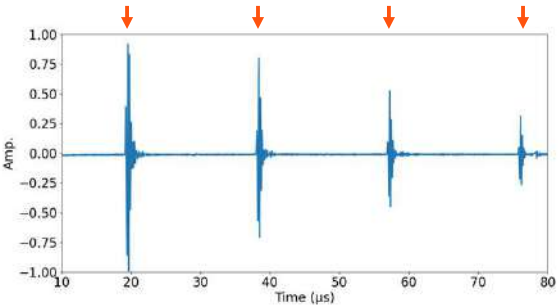


- Concrete
  - Heterogenous medium
  - Aggregates with 8mm diameter max in a mortar matrix
  - Multi-scattering enhanced as the frequency increases / wavelength decreases

→ attenuation of the echoes of interest (coherent part) and structural noise (incoherent part)

PULSE ECHO

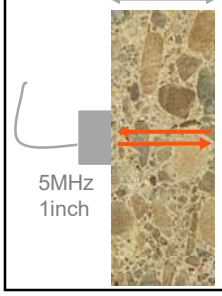


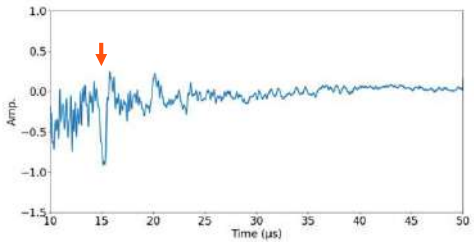


~TOF

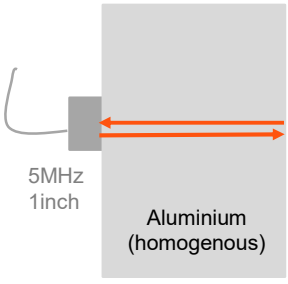
60mm

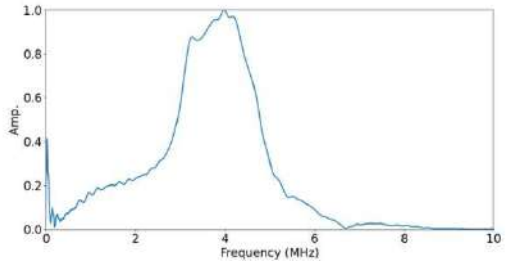
36mm





PULSE ECHO

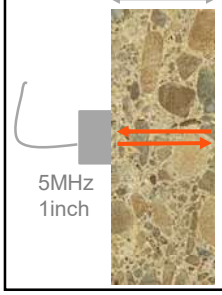


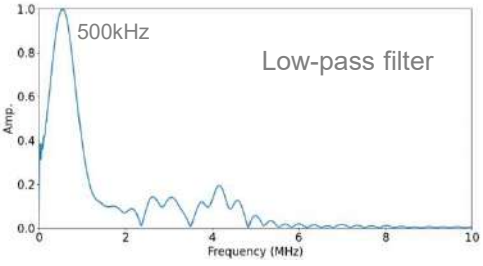


~TOF

60mm

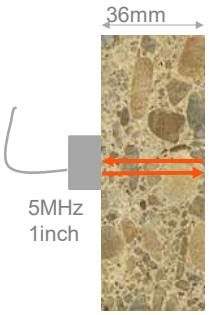
36mm

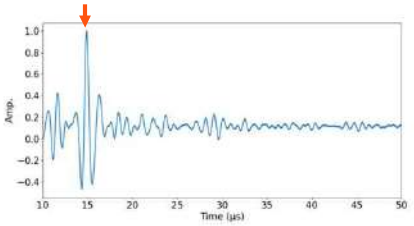


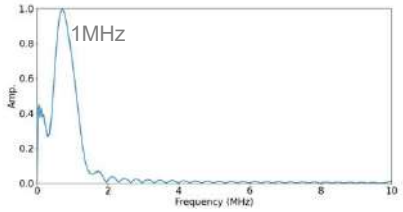


PULSE ECHO → PULSE COMPRESSION

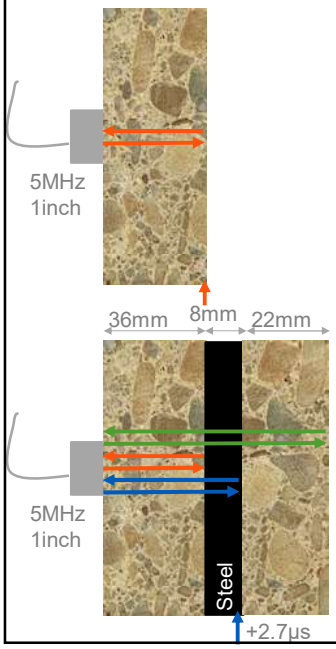
- **Pulse Echo**
  - Voltage pulse to the probe < 1µs
- **Pulse compression – Frequency modulation**
  - Voltage Linear Chirp with frequency increasing linearly with time
  - From 100kHz to 2MHz over a duration of 30ms
  - Auto-correlation

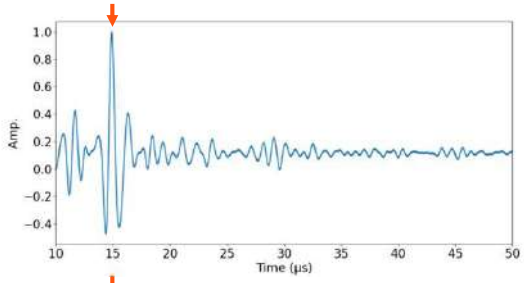


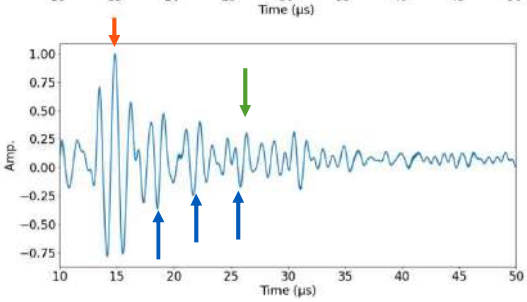




PULSE COMPRESSION – LINEAR CHIRP

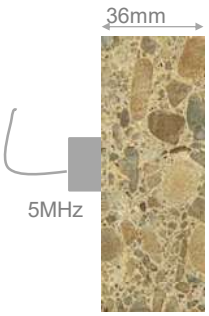


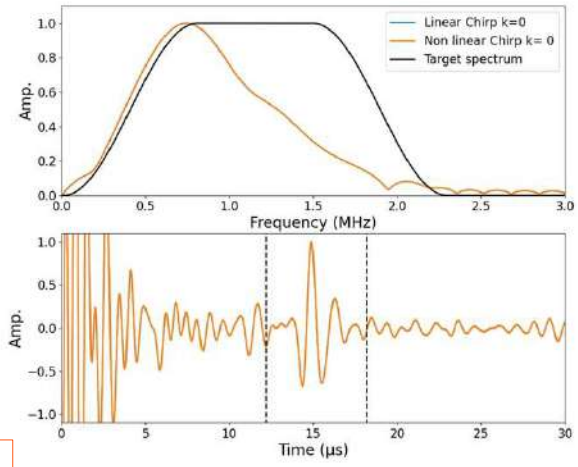




Still need to be improved

PULSE COMPRESSION – NON LINEAR CHIRP

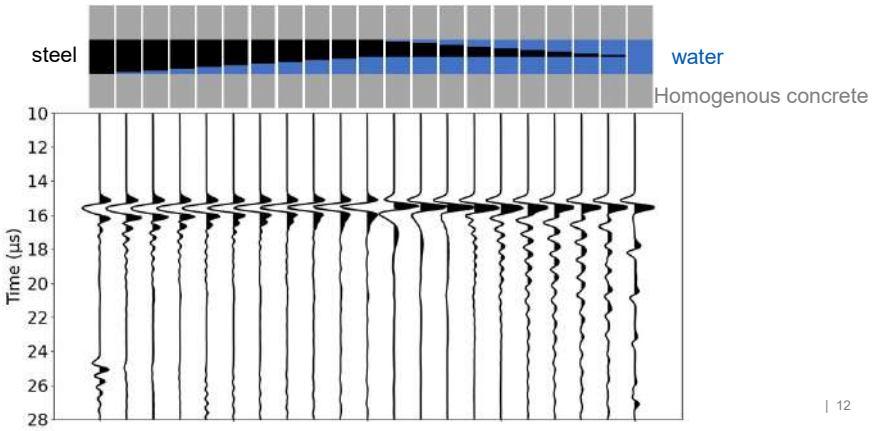




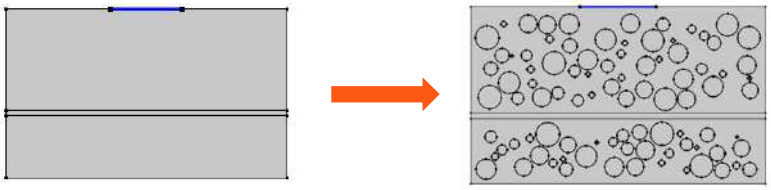
- **Other improvments**
  - Dual probe
  - Local spatial averaging

NUMERICAL SIMULATIONS

- **2D simulations**
- **Elastic (concrete and steel) and acoustic (water)**
- **Different configurations to model a steel/water profile → raw B-scan**



NUMERICAL SIMULATIONS



- **Heterogenous concrete**
  - Aggregates ($Z_{agg} > Z_{mortar}$)
  - Interfacial Transition Zone ($Z_{ITZ} < Z_{mortar}$)

→ **Reproduce the structural noise**

CONCLUSION AND PERSPECTIVES

- **NDT inspection of SCCP**
- **Remaining steel thickness**
- **UT**
  - Multi-scattering in concrete → attenuation and structural noise
  - Pulse Echo method not adapted
  - Pulse compression method promising (Chirp and auto-correlation)
  - Improvments with dual probe and spatial averaging
  - Use of numerical simulations
  - Developments in lab on plate samples → SCCP samples
- **PEC**

THANK YOU FOR YOU ATTENTION

ANY QUESTION ?

Advanced ultrasonic imaging solutions for the inspection of nuclear assets

Niels Pörtzgen niels.portzgen@applusrtd.com

Rotterdam, the Netherlands

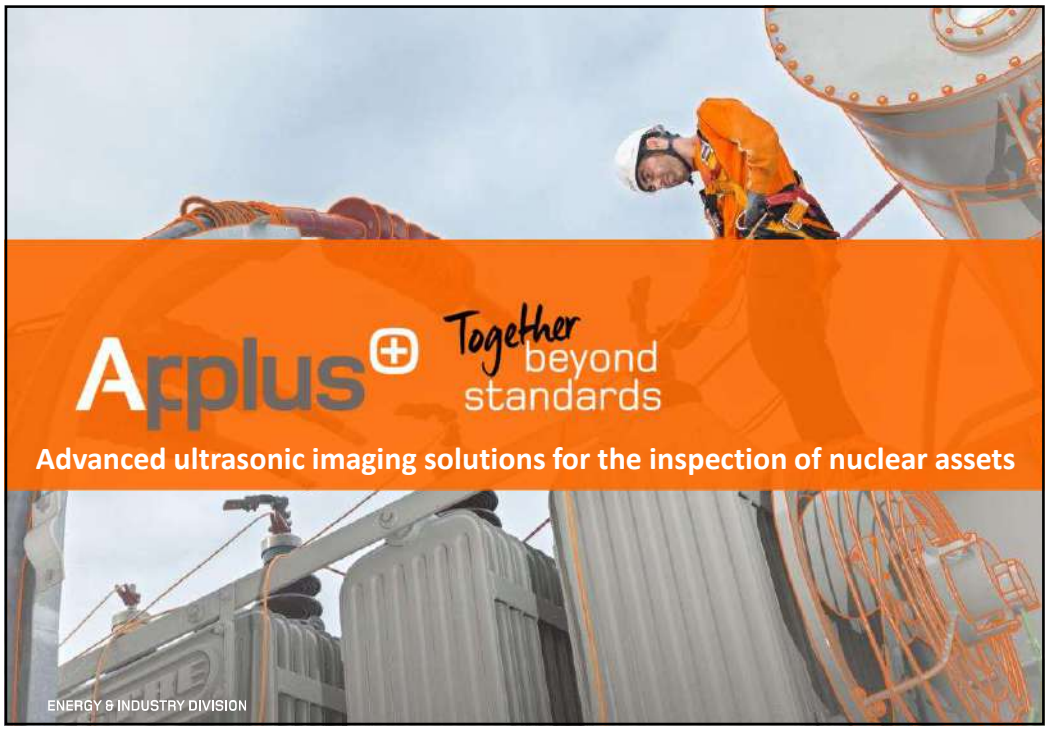
Abstract text (1/2 – 1 A4 page)

For a safe and productive operation of nuclear power plants, reliable and accurate inspection strategies are crucial. The inspection of nuclear assets such as piping systems, boilers, the reactor hull and dome etc., still rely largely on traditional non-destructive testing (NDT) methods like manual ultrasonic testing, (magnetic) penetrant testing and radiography. Traditional inspection methods have been used ever since the introduction of nuclear power plants and their performance and limitations are well understood over the years. Best practices have been developed to optimize such performances and to mitigate the shortcomings by being conservative in data interpretation and avoidance of risk by redundant inspection and plant shut downs.

Due to advances in sensor technology and computer and software developments, new and novel inspection methods have been introduced which potentially supersede the performance of traditional inspection methods. One of the latest innovations in non-destructive testing is based on imaging of ultrasonic data using a reconstruction algorithm. Such data is acquired with ultrasonic arrays and is known as a full matrix capture (FMC) data set, which can be compared to a fingerprint. The fingerprint contains unique information regarding the material properties, the geometry of the component, the presence of potential indications together with its location, shape and size. With the reconstruction algorithm (e.g. the total focusing method (TFM) or IWEX), such information can be positioned in a comprehensive 2D image.

In this paper/presentation, we will review some common traditional NDT strategies for the inspection of nuclear assets. We will discuss their limitations and why improvements are desired like accuracy and consistency of defect sizing. Then, we will present the principles of ultrasonic imaging and how this potentially can improvement the inspection of nuclear assets. Furthermore, we will illustrate the improvement with a use case. The use case involves the inspection of a thick dissimilar girth weld in a stainless-steel pipe. Ultrasonic inspection of such a weld is notoriously challenging due to the unfavorable material properties of the material (coarse grained) and the weld (dendrite structure). We will present the strategy to obtain a representative ultrasonic 2D image by using multiple travel paths and wave modes (longitudinal and transverse). We will conclude with recommendations for best practice and discuss the possibilities for adaptation of ultrasonic imaging technologies in the nuclear industry.

Keywords: nuclear assets, ultrasonic inspection, 2D imaging, FMC TFM, IWEX.



Content

Applus

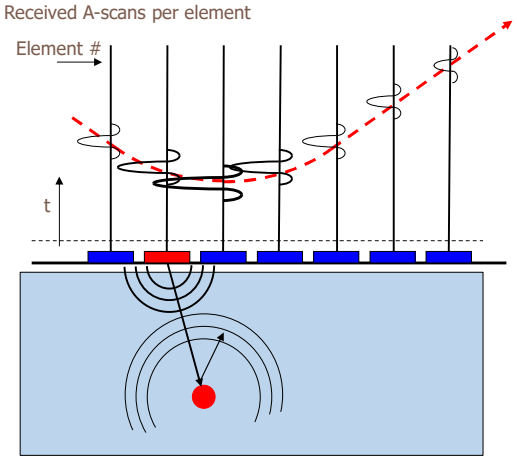
- Basic concepts
  - Traditional non-destructive testing strategies
  - Inspection challenges
- Principles of ultrasonic imaging
  - Full Matrix Capture (FMC) data
  - Image calculation (Inverse Wavefield Extrapolation)
- Examples from practice
  - Inspection of Inconel weld
  - Heavy walled dissimilar welds with CRA layer
  - Critical weld from stainless steel

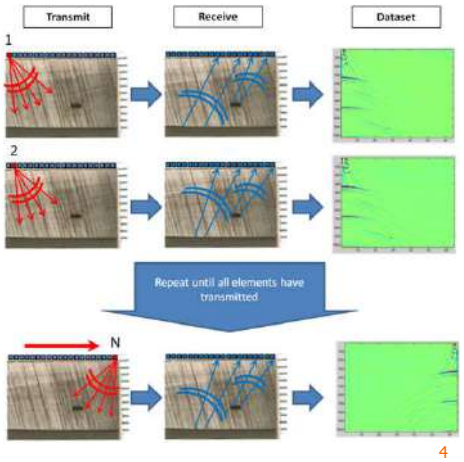
Traditional ultrasonic inspection

- Radiographic and ultrasonic testing are mostly used
- Traditional NDT requires expertise and experience
- Detection depends on conditions such as material properties
- Data display and interpretation can be ambiguous and not accurate
- For safety and efficiency, ultrasonic testing is often preferred

Principles of ultrasonic imaging

- Ultrasonic (phased) array technology is readily available
- Recording of an ultrasonic 'fingerprint' → Full Matrix Capture (FMC) data
- 2D image can be calculated with a reconstruction algorithm
- Different implementations are possible → PWI, PCI, TFM, IWEX





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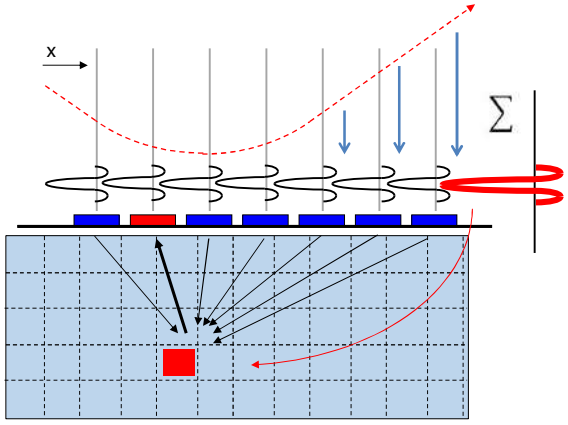
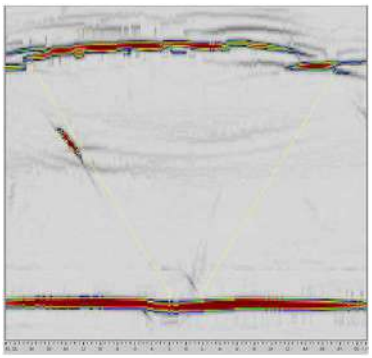
Principles of ultrasonic imaging

- Reconstruction is based on time shifting and summing of responses
- Different travel paths are taken into account → imaging modes
- A comprehensive 2D image is obtained





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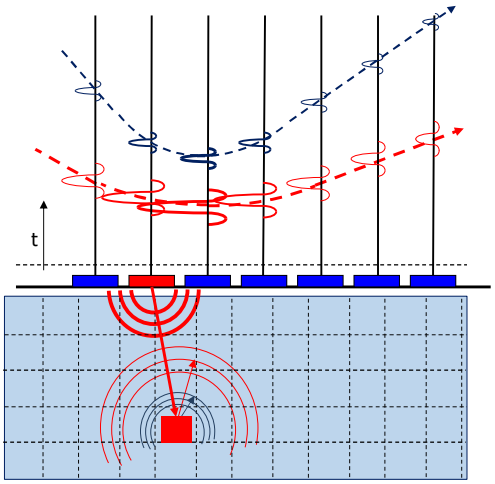
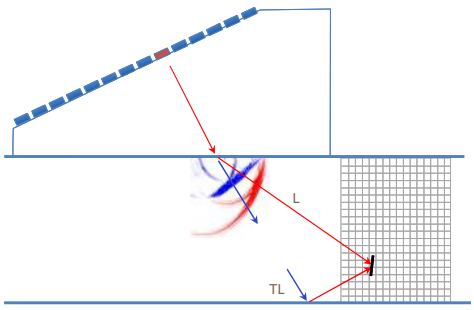
Principles of ultrasonic imaging

- Different wave types (longitudinal, shear) can also be used
- Attenuation of waves can cause poor SNR in the resulting image
- Imaging modes based on long waves have benefits for coarse grained welds





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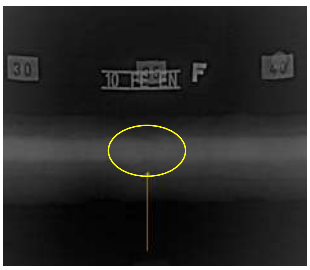
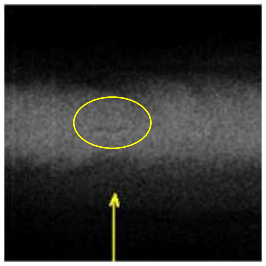
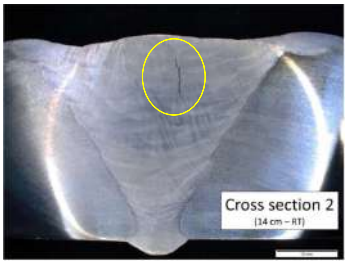
Use case 1 → inspection of Inconel welds

- During periodic inspection cracks were identified with RT
- Height and depth location of the cracks could not be determined by RT
- There were concerns that cracks were missed
- Risk to keep facility in service → weld was cut for further investigation

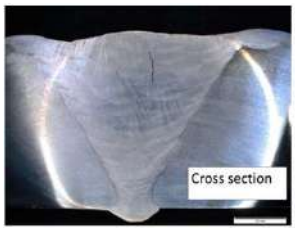


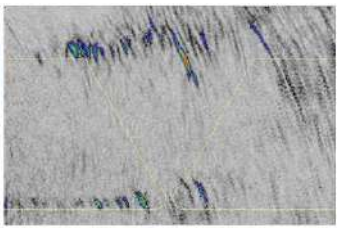


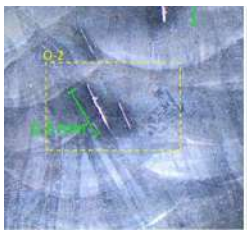


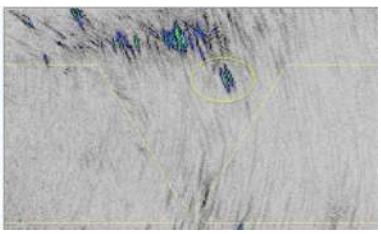
Use case 1→ inspection of Inconel welds

- The remaining welds were inspected with IWEX
- Other cracks were unambiguously identified, which were missed by RT
- Based on the IWEX data, a reliable integrity assessment was possible



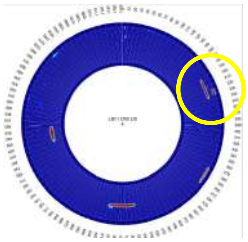


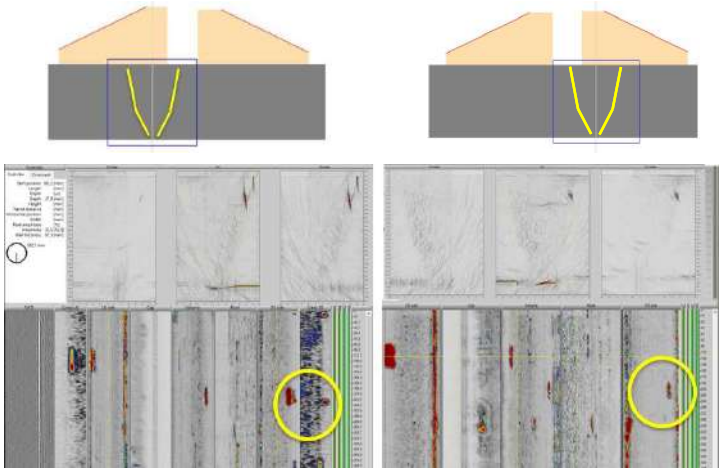




Use case 2 → Heavy walled weld with CRA Layer

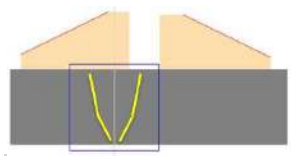
- The inspection strategy was based on 2x offset scans (cap was flushed)
- A combination of imaging modes was applied an additional ToFD and creep
- A qualification program was required with IUT and macro sectioning

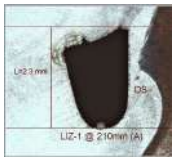


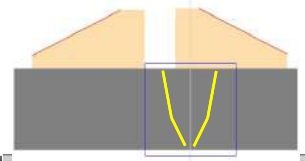


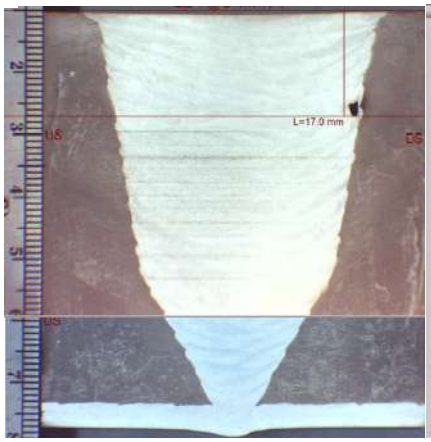
ENERGY & INDUSTRY DIVISION

Use case 2 → Heavy walled weld with CRA Layer





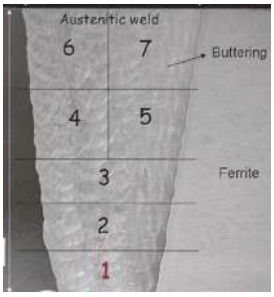


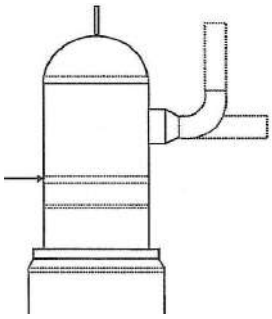


ENERGY & INDUSTRY DIVISION 10

Use case 3 → Critical weld in super heater

- Critical weld from austenitic stainless steel
- Monitoring of indications (crack growth)
- 63,5 mm wall thickness
- Mock-up piece with seeded indications
- Cap ground flush





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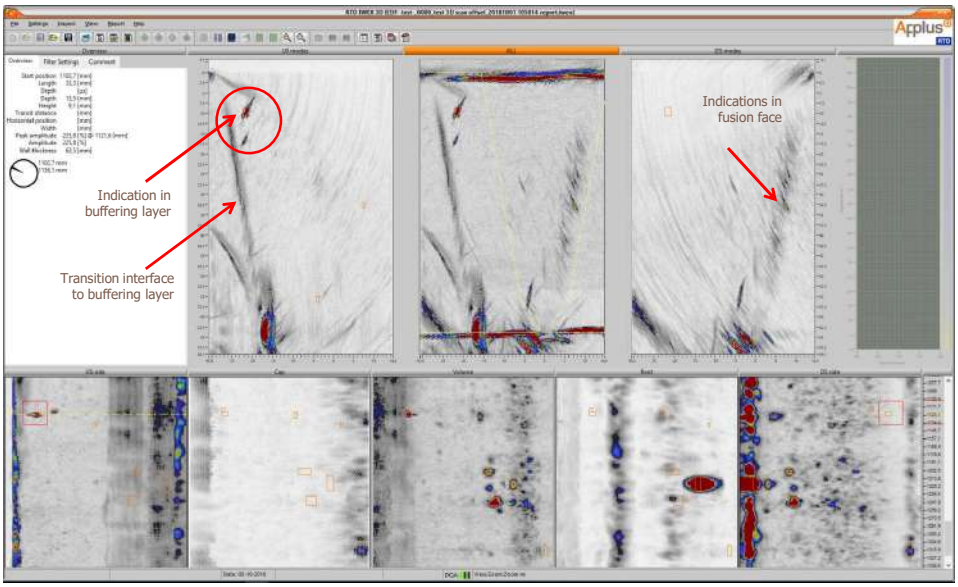
Use case 3 → Critical weld in super heater



ENERGY & INDUSTRY DIVISION

12

Applus

Together beyond standards

Discussion and questions

Applus
Together
beyond
standards

Outage Water Tank NDT inspection / paper

Francisco Javier de la Morena Martínez, Luis Lopez Lopez, Francisco J. Fernández Muñoz, Jose Amador Sillero Marín

Tecnatom has performed the inspection of the Outage Water Tank, as part of the requirements for the Long-Term Operation (LTO) in the Spanish NPP (PWR and BWR reactors). By the time that the requirement was stablished, the available inspection systems requires that the tank was in empty conditions what is considered as an important handicap for the schedule of the inspection into the outage activities.

Tecnatom has develop an entire system based in two equipment (RITA® & SIBIU PRO ®) which allows the Non-Destructive Test inspection of the tank with no need of draining. The inspection requirements meet with the guidelines stablish in the document EPRI 3002003071 (Guideline for tank inspections). The scope of the inspection comprises the measure of the thickness of the base of the tanks by means of PAUT (Phased Array Ultrasonic Technique) and the inspection of the surface of the inner walls by means of Remote Visual Testing.

RITA® is the manipulator designed and manufacture in Tecnatom to perform the inspection of the bottom of the tank. This remotely operated crawler can be introduced into the tank through the manhole in the upper part of the tank and it has been designed with special emphasis in covering the maximum accessible area. The designed include key characteristics for this specific inspection such as the resistance to the radiations, omnidirectional wheels and sufficient cable length to perform the acquisition from a clean zone.

The PAUT technique can be used in stainless steel, carbon steel or aluminium tank floors. The postulated defectology is the thickness reduction in the bottom of the tank due to internal or external corrosion. The measurement can be performed over painted surface until 400 µm of thickness with an accuracy of 1 mm. Painted surfaces with a greater thickness are feasible with a reduction in the accuracy.

SIBIU PRO® is a small dimensions submarine develop from a commercial submarine and adapted to the radiological environment and the VT inspection requirements. Both manipulators, RITA and SIBIU PRO, can be operated simultaneously.

Tecnatom has extensive experience in the execution of the inspection of the Outage Water Tank in which has acquired relevant experience in terms of time of execution, reliability, and cost-effective approach.

E-mail address (corresponding author): fjdelamorena@tecnatom.es

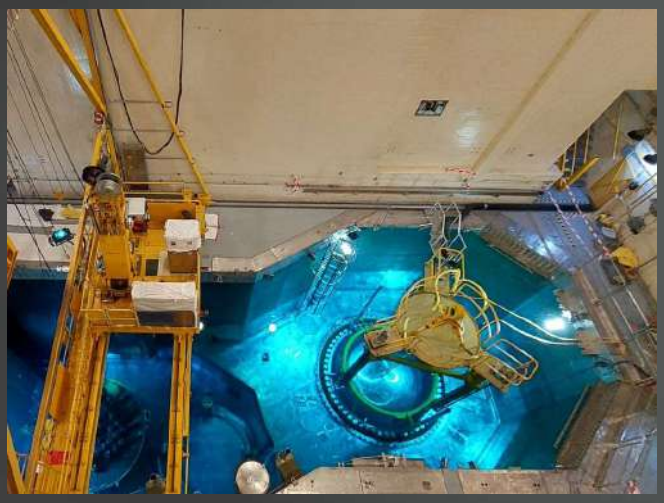
Keywords: NDT, Inspection, PAUT, Outage Water Tank,

NDT inspection

F. Javier de la Morena
Technology and Innovation Project Director
fjdelamorena@tecnatom.es

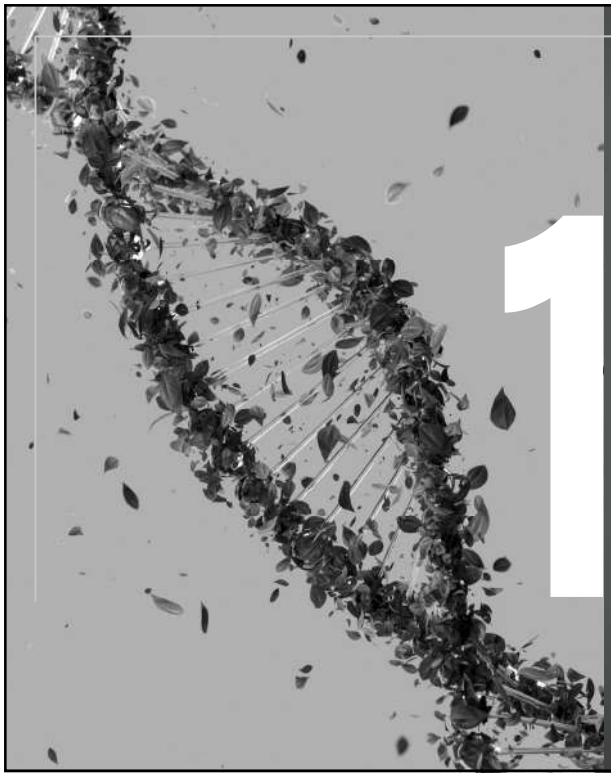
June, 27th , 2023

REACTOR CAVITY



Where is the water….?

Outage Water Tank NDT Inspection



1

SCOPE AND CONDITIONS

Inspection target and the conditions associated

Component: Refuel Water Storage Tank

- STORAGE OF THE WATER OF THE REACTOR CAVITY
- COMPONENT LOCATED OUTER TO THE CONTAINMENT ZONE
- LTO PROGRAM & SPANISH REGULATOR REQUIREMENT (CSN)
  - CORROSION OF THE FLOOR IN THE COMPONENT
  - SURFACE STATE OF THE INNER WALLS AND THE CEILING

5

Component: Refuel Water Storage Tank

- ALARA

Refrigerant from the primary system

- ACCESIBILITY

Tank never completely empty

Access through a man hole

- INSPECTION QUALITY

Wall thickness mapping

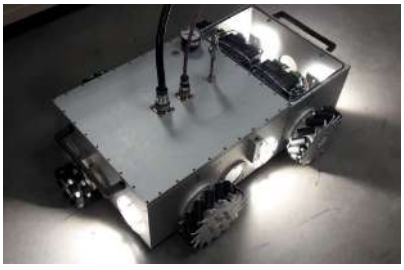
Remote visual Inspection

6

2 INSPECTION SYSTEM

Manipulators and NDT techniques used

INSPECTION SYSTEM

	BASE MATERIAL	INNER SURFACE
		
TECHNIQUE	AUTOMATED PAUT	REMOTE VT-1
MANIPULATOR	RITA®	SUBMARINE ROV

8

BASE MATERIAL MANIPULATOR: RITA

High mobility

Omnidirectional wheels

Manual or programming trajectory

Immersion proof

Cameras for positioning

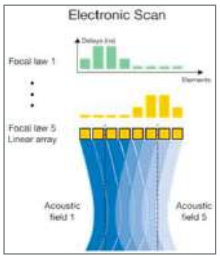
9

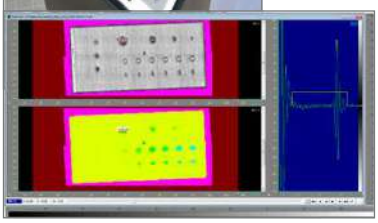
BASE MATERIAL TECHNIQUE: PAUT

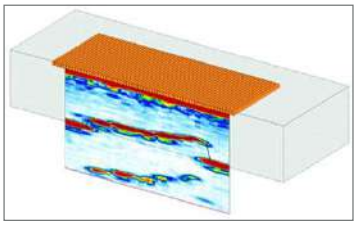
Objective:
Wall Thickness mapping

Equipment:
PA 1D – 64 elements
HW: Sonia UT
SW: Inspectview

Accuracy:
1 mm in depth
1 mm equivalent diameter







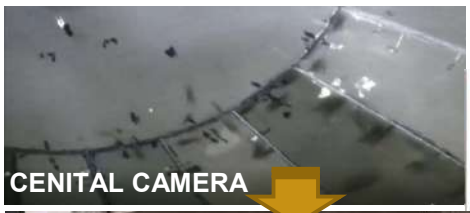
10

INNER SURFACE MANIPULATOR: SUBMARINE ROV

- Compact size
- Based on commercial submarine
- Hight mobility and intuitive operation
- Batteries or external power supply
- Clamps to collect Foreign materials

11

INNER SURFACE TECHNIQUE: REMOTE VT-1



CENITAL: 2065 x 1533

FRONTAL: 1920 x 1080

UPPER CAMERA FOR THE INNER SURFACE OF THE FUEL TANK COVER

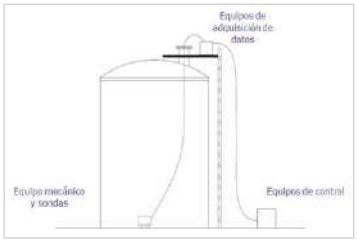
SPECIFICATIONS BASED ON VT-1

12

3 INSPECTION SYSTEM ON SITE

How the whole system is deployed on the field.

INSTALLATION

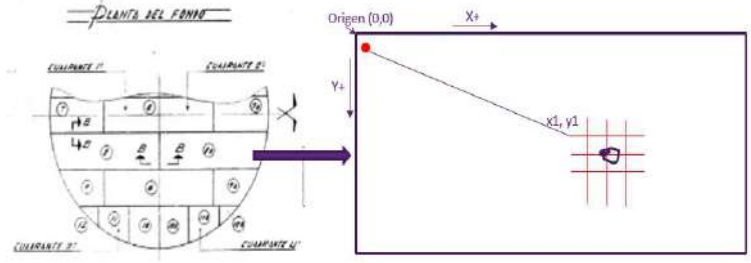


- Radiological island
- Installation by Truck crane
- RITA & Submarine through manhole
- Acquisition on the floor
- Operation

14

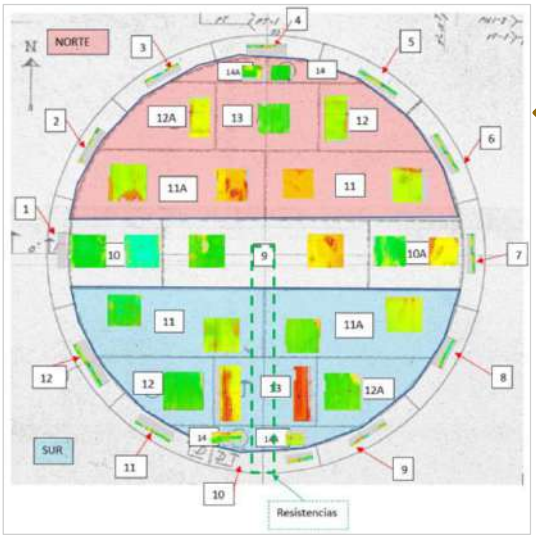
ACQUISITION

- Acquisition team on the ground
- Submarine gives support to RITA
- RITA is located in relation to the plate
- Automated Inspection
- In parallel: VT and UT



15

RESULTS



PAUT FLOOR INSPECTION

VT INNER SURFACE

16

4 CONCLUSION

Understandable and quality results for the customer

CONCLUSION

CONVINIENCE INSPECTION SYSTEM FOR THE OUTAGE WATER TANK

- COMPLETE SOLUTION FOR THE LTO INSPECTION OF THE WATER REFUEL TANK
- OPTIMAL RADIOLOGICAL CONDITIONS
- ADVANCE PAUT TECHNIQUE
- SOLUTION DEPLOYED IN ALL SPANISH NPP

18

5 EXTRA

RITA in action!

VIDEO

Questions & Answers
Thanks!

www.tecnatom.com

Beam characterization of a LINAC system for an NDT qualification process

Nicolas DOMENJOUD[1], Lionel WOISEL[2], Florian DECOEUR[3], Sylvain MURGIER[1],
Arnaud VAN DE LOOCK[2], Justine LARCHEVEQUE[3]

[1]EDF Industrial Direction, 2 rue Ampère, 93211 Saint Denis, FRANCE
[2]TENEO, 113 Boulevard Jacques Tête, 95300 Pontoise, FRANCE
[3]EDF Technical Operational Unit, 1 Avenue de l'Europe,77144 Montévrain, FRANCE

E-mail address (corresponding author): sylvain.murgier@edf.fr

Industrial radiography mainly uses gamma sources. Despite all the inherent problems regarding radioprotection, availability, and usability, the characteristics of gamma sources are well known and provide a reliable entry point for qualifying an NDT process. However, gamma sources have limitations in terms of wall thicknesses examination, with theoretical limits higher in the context of an accelerator. Linear accelerators, on the other hand, are mainly used for specials NDT applications, where only the energy level characteristics are mentioned in the various construction codes. Nevertheless, linear accelerators can provide high energy levels with high dose rate, effectively reducing the exposure time of the radiographic examination, improving the control of radiation safety, and usability. Up to date, linear accelerators are complex machines, mostly bulky, with a high level of configuration of different parameters and are practically unusable for NDT qualification purposes. The bulky factor alone is sufficient to justify the restrictive use of the accelerators in manufacturing plants for large parts. New generation technology will change the usability factor in the relatively near future, and it could be envisioned that the accelerator will be compact and practical enough to replace cobalt, iridium or selenium on work sites.
The main problematic of the "accelerator" remains: are they able to be a part of the radiographic qualification process? Are we able to precisely control and monitor this complex system with repeatability and knowledge of the effects of defined parameters on the formation of the accelerator beam? EDF owns a set of MINAC (miniaturized accelerator) and we have worked with TENEO to answer a very simple question: what do we know about the X ray beams from our units? Further, we confirmed the compatibility of the wall thicknesses crossed with current accelerator heads. What dose rate can we achieve behind the marketing characteristics of our units? Is there a way to predict the beam characteristics, and from one work site to another, can we achieve repeatability? What is the influence of parameters on the radiographic sensitivity? Are there parameters that impact sensitivity? In a way, we wanted to know and affirm whether it was possible to consider linear accelerators in an NDT application as another simple and well-known gamma source... and the answer is undoubtedly YES, as we will try to convince the public.

Keywords: LINAC, qualification, beam (max. 5).

EDF Industrial Direction:
- Nicolas DOMENJOUD
- Sylvain MURGIER

TENEO:
- Sylvain DIDIER-LAURENT

Beam characterization of a LINAC system for NDT qualification process

Sheffield – NDE 2023

Summary

1. French NDT regulation context
2. MINiatuized ACcelerator: MINAC
3. Challenge
4. Strategy
5. Results
6. Conclusions and perspectives

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1 French NDT regulation context

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1. French NDT regulation context

With regard to French practices, according to the order of November 10, 1999 relating to the monitoring of the operation of the primary and secondary circuits of PWR (known as "*Arreté d'Exploitation*" or "AREX"), "*The non-destructive testing procedures employed within the framework of the inspections planned [...] on the devices are subject, prior to their use, to a qualification issued by an entity chosen by the operator.*"

The NDT processes which concern the primary or secondary circuits must therefore be **qualified**.

NDT process qualification **primary objective is to provide evidence and assurance** that the NDT process is capable of meeting specified requirements.

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2

MINiatuized ACcelerator: MINAC

An American history X(-Ray)

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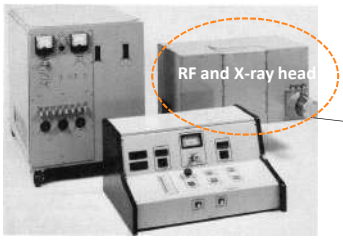
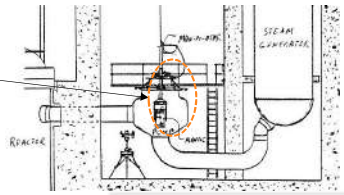
2. MINiatuized ACcelerator: MINAC



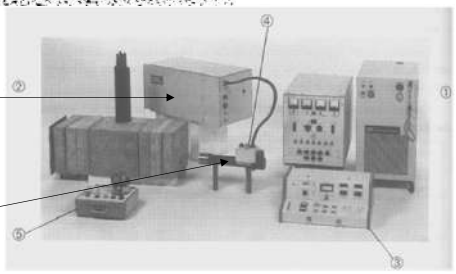
1978 :First generation : Portable Accelerator Development Project instigated by EPRI



1983 : MINAC 3: the X-ray head becomes separated from the RF head in order to improve usability and operability

RF head

X-ray head



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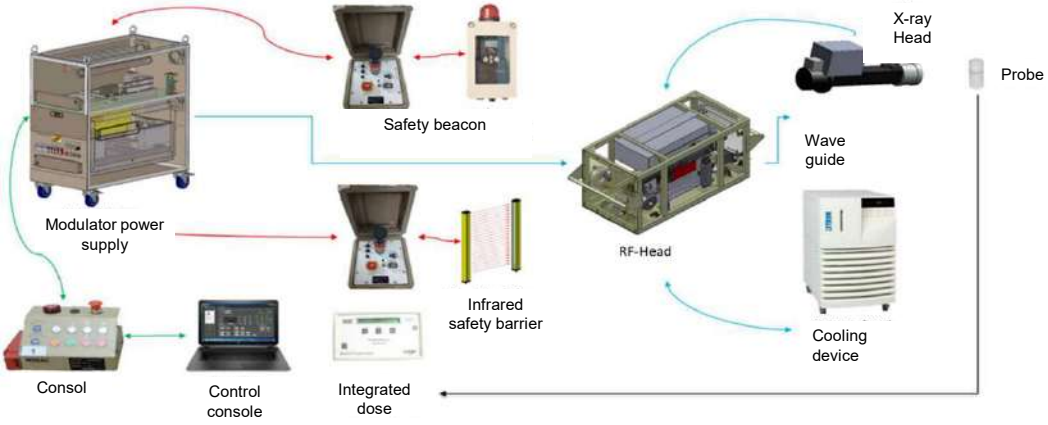
2. MINiatuized ACcelerator: MINAC

Nowadays, MINAC is looking quite different:



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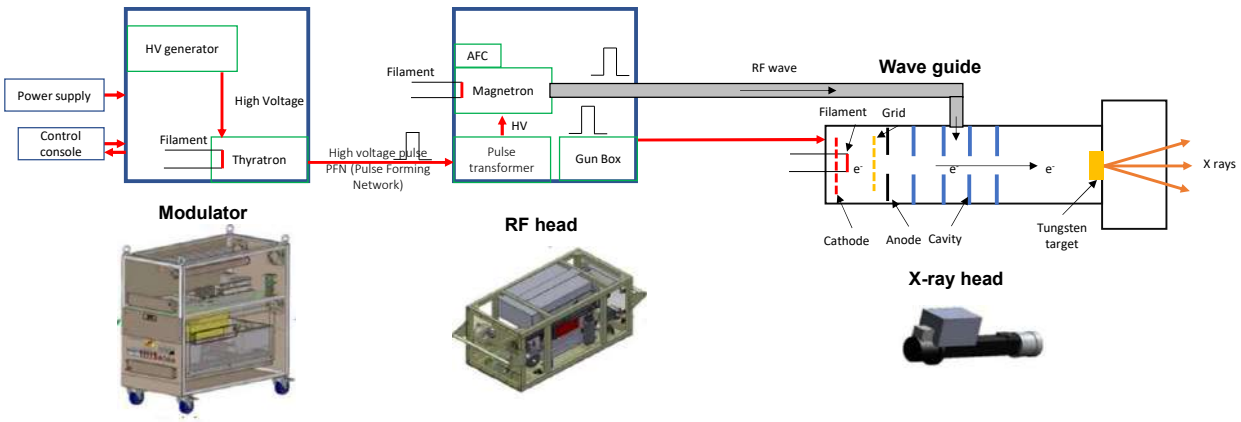
2. MINiatuized ACcelerator: MINAC

And can be schematized as follow:



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3

Challenge

X-ray generators NDT applications has never been qualified before

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3. Challenge

In the case of a radiography examination using radioelements, the following influencing parameters are treated:

- ✓ Nature of the radioelement: Se^{75}, Ir^{192}, Co^{60}
- ✓ Dimension of the radioelement

In the case of a X-ray beam, and moreover in the case of a high energy X-ray beam from a linear accelerator, the characteristics of the beam (energy, dose rate, homogeneity of the beam) must be **determined and their impact on the sensitivity of the application** must be evaluated.

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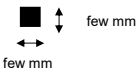
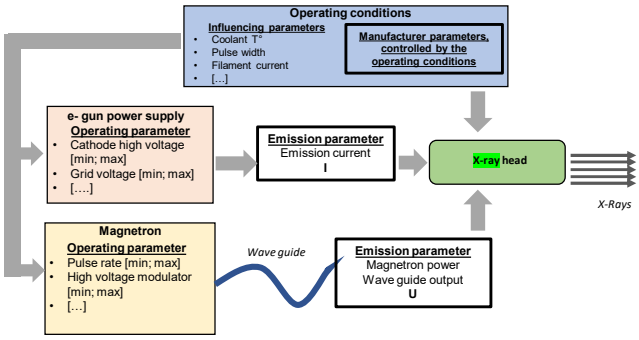
3. Challenge

Radioelement g



Influencing parameters:
- Nature
- Size of the radioelement

MINAC



Influencing parameters:
- At first glance, too long to be listed

But…

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4 Strategy

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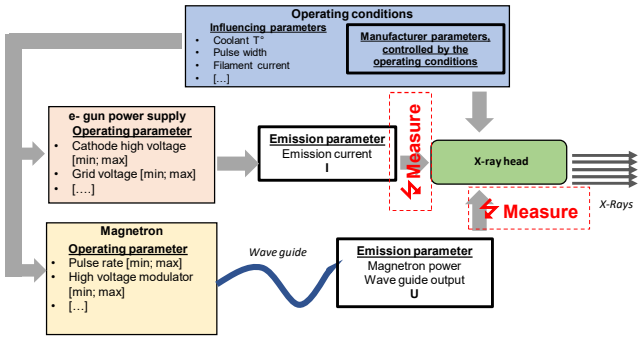
4. Strategy

Eventually, all the MINAC components are designed to provide sufficient power through high frequency wave (X-band, 9,3Ghz) to the X-ray head, in order to generate the appropriate X-ray beam.
As the RX head is (mostly) a passive device - in theory - the same electrical input signal would generate the same X-ray beam.
So, with an appropriate X-ray head input instrumentation, as simple as a current and voltage measurement (« ϟ Measure » on the following figure), it becomes possible to control and predict the X-ray beam characteristics, henceforth, making formal qualification of a linear accelerator possible.



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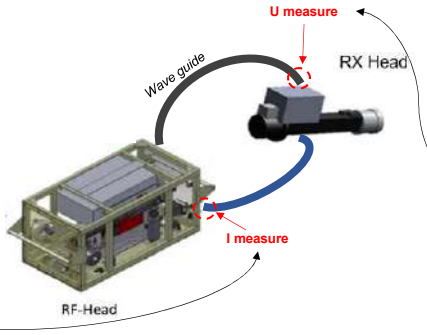
4. Strategy

Instrumentation devices positioned as close as possible from the X-ray Head.

E-gun current measurement using a current transformer on RF head output



High Frequency incident wave power measurement with a directionnal coupler associated with a diode directly on the X-ray head

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4. Strategy

Testing all the possible MINAC set up:
- Waveguide specifications : length, general shape
- Several RF heads,
- Electrical input (gun box current, magnetron power)

In order to assess:

1. The minimum and maximum I and U parameters values required to **achieve an industrial dose rate** (**Part 1**)

2. Full **compatibility and safe operation** of MINAC equipment and X-ray head within I and U obtained previously (**Part 2**) for the concerned thicknesses

3. The **potential effects on the radiographic images** within the range of I and U defined on part 1 (**Part 3**)

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5 Results

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5. Results – Part 1

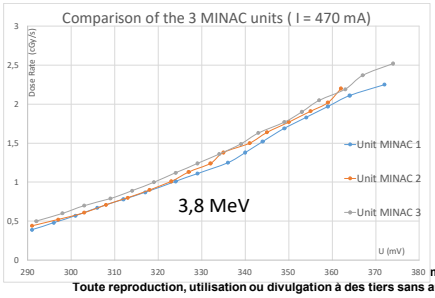
Between U and I, the results show **that U is more impacting than I** on the Dose Rate value.
All the tests performed permitted us to greatly improve the operational knowledge of the MINAC devices, for example, we see that a specific e-gun value led to a maximum dose rate, going further decrease it.

I_{EM} (mA)	U_{UT} (mV)															
	291	297	303	308	313	318	323	327	332	335	341	345	350	355	359	362
400	22%	25%	29%	33%	37%	42%	46%	51%	57%	62%	67%	74%	79%	85%	91%	95%
470	20%	24%	28%	32%	36%	41%	46%	51%	56%	63%	68%	75%	80%	87%	92%	100
550	21%	25%	29%	33%	37%	42%	46%	53%	57%	64%	70%	77%	82%	89%	92%	98%

Optimum

3,8 MeV – unit MINAC 1 – Dose rate evolution (%dose rate max) with the I and U parameters

For a given X-ray head, whatever the used RF heads, for a same couple of I and U, we observe a similar Dose Rate.



➔ **The 3 RF head are commutable**

mations qu'il contient.
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5. Results – Part 1

For each X-ray head, we can define an **operating range of U and I ensuring an industrial Dose Rate**:

X-ray Head	Emission parameters		Dose Rate (cGy/s at 1 m)
	I (gun box current) mA	U (magnetron power) mV	
3 MeV	360 - 480	310 - 350	1,0 - 2,2
3,8 MeV	400 - 540	320 - 360	0,9 - 2,2
6 MeV	290 - 410	330 - 370	0,4 - 1,7

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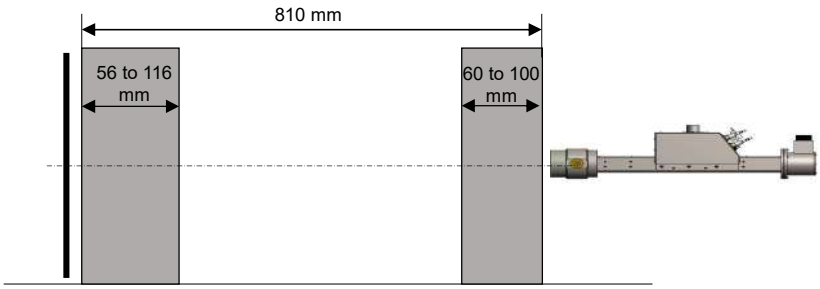
5. Results – Part 2

For each X-ray head, execution of radiographic exposures following those parameters:
- U and I Max (High Dose rates)
- Focal distance: 810 mm
- Thicknesses: from 116 to 216 mm
- C2 films, Cu^{29} screens
- Film density: 3,5
- Use of penetrameters (classical and duplex)
- Radiograms are digitalized



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5. Results – Part 2

Whatever thicknesses, the film **density distribution is similar**. The same result is achieved for the 3 X-ray heads

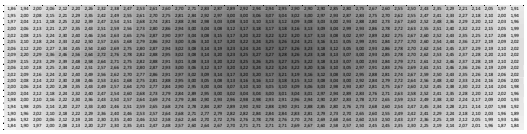


Illustration: measurement of the density along the radiogram – 3,8 MeV RX Head

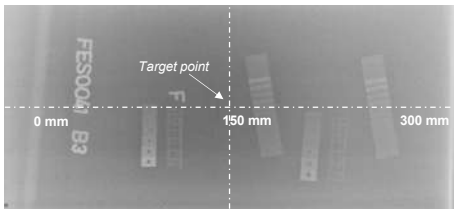
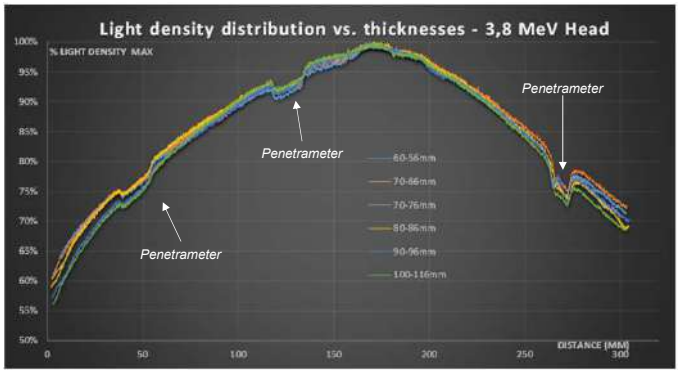


Illustration: measurement of the density along the radiogram



Density distribution – Example for the 3,8 MeV Head

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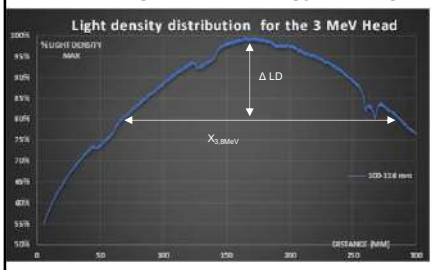
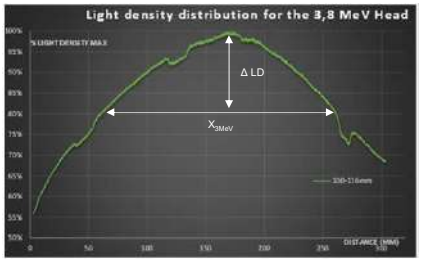
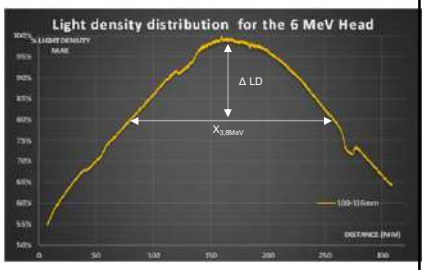
5. Results – Part 2

The **higher the energy, the tighter the distribution of densities**.







Under optimal operating conditions (Dose rate max), the 3 X-ray heads allow the examination of the range of thickness considered (**116 – 216 mm) while maintaining an industrial exposure duration**.

	3 MeV Head	3,8 MeV Head	6 MeV Head
Thicknesses	Exposure time (min)		
60-56mm	5	6	2
70-66mm	9	9	/
70-76mm	13	11	4
80-86mm	/	19	/
90-96mm	39	29	9
100-116mm	96	76	18

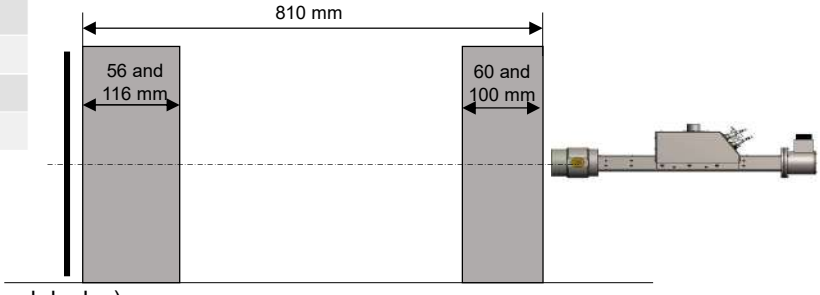
21

5. Results – Part 3

For each X-ray head, execution of radiographic exposures following those parameters:

- Various emission parameters:

I	U
I_{min}	U_{min}
I_{min}	U_{max}
I_{max}	U_{min}
I_{max}	U_{max}



- Focal distance: 810 mm
- Thicknesses: 116 and 216 mm
- C2 films, Cu^{29} screens
- Film density: 3,5
- Use of penetrameters (classical and duplex)
- Radiograms are digitalized

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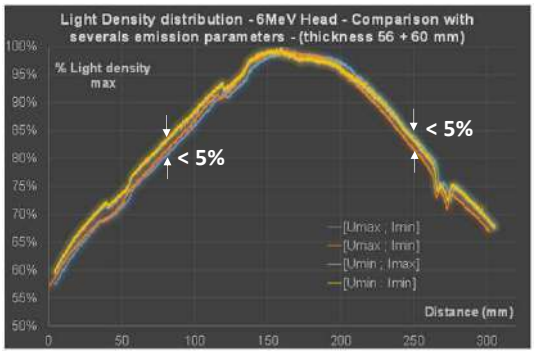
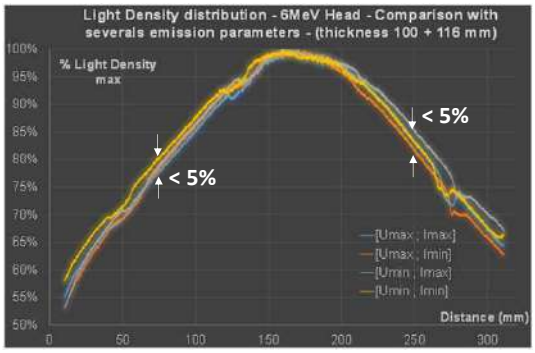
22

5. Results – Part 3

Example for the 6 MeV X-ray Head:





Whatever the emission parameters U and I, within the specified ranges, for each X-ray head (3, 3,8 and 6 MeV), there is **no evidence of influence on the optical density profile** on the radiograms, and *a fortiori* on the X-beam spectrum.

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6

Conclusions and perspectives

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5. Conclusions and perspectives

It is possible to control in a **reliable, simple and repeatable** way the electrical parameters generating the X-ray beam in the accelerating head, **significantly simplifying the apparent complexity of a LINAC** type system. LINAC is **no longer a "black box"** for NDT users.

The upstream chain has no impact provided the U and I measured values remain identical.

The density profile is known for the 3 X-ray heads and allows to know in advance the capacity in terms of area coverage.

Whatever the emission parameters U and I, for each X-ray head (3 MeV, 3.8 MeV and 6 MeV) there **was no evidence of influence on the optical density profile** on the radiograms, and *a fortiori* on the X-beam spectrum.

An accelerator with these 2 parameters (U and I) monitored, can **be considered as a gamma source**, subject to the establishment of **suitable and controlled operating parameters**.

Then, it becomes **possible to consider the qualification of NDT process using linear accelerators**.

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Contacts

EDF – Industrial Direction– 2-4 rue Ampère, 93206 SAINT DENIS
- MURGIER Sylvain: sylvain.murgier@edf.fr
- DOMENJOUD Nicolas: nicolas.domenjoud@edf.fr

EDF – Operational Technical Unit – 1 Avenue de l'Europe - 77144 MONTEVRAIN
- DECOEUR Florian: florian.decoeur@edf.fr
- LARCHEVQUE Justine: justine.larchevèque@edf.fr

TENEO - 200 Rue Barthélemy Thimonnier, 69530 BRIGNAIS
- WOISEL Lionel: lional.woisel@teneo.eu
- DIDIER-LAURENT Sylvain: sylvain.didier-laurent@teneo.eu
- VAN-DE-LOOCKE Arnaud: arnaud.van-de-loock@teneo.eu

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How to research NDE in Nuclear without Nuclear Power Plants

Jüngert, Anne[1], Stefan Keuler[1], Martin Werz[1]

[1]Materials Testing Institute University of Stuttgart, Stuttgart, Germany

E-mail address (corresponding author): anne.juengert@mpa.uni-stuttgart.de

Although Germanys remaining nuclear power plants (NPP) will be shut down in 2023, research in nuclear safety remains an important topic. New technologies, reactor designs or innovative testing techniques applied in reactors worldwide have to be assessed with regard to the safety of all citizens. Thus, Germany will still be funding application-oriented basic nuclear safety research, even though it does not own NPP any more.

This paper presents the ongoing research activities at the Materials Testing Institute (MPA) at the University of Stuttgart with focus on topics related to non-destructive testing (NDT). The MPA at the University of Stuttgart has a long history of nuclear safety research and still offers some unique test facilities. In NDT the MPA focuses on ultrasonic testing and reliability of NDE for lightwater reactors. For this purpose, a large amount of test specimens with artificial and realistic cracks in differents welds were created in the last years. These test specimens are now used to quantify the reliabilty of NDT and address certain influences like human factors. The special challenges during testing of austenitic weld material are another active research area.
Another research focus are advanced manufacturing techniques, where the adaption of NDT techniques has to be investigated and the damage mechanisms of typical flaw have to be understood. Therefore, th MPA hosts a junior research group about types of very small modular reactors (vSMR) since 2022. The research group deals with all aspects of the safety of SMR using metal-cooled heat pipes, beginning from safe manufacturing with advanced techniques, materials behaviour at high temperatures, during dynamic loads or exposed to corrosive media. The development of NDE techniques for all safety relevant components with regard to the different damage mechanisms in various load scenarios is an important topic and a great challenge in this research group.

Keywords: ultrasonic testing, reliablity, light water reactors, SMR

How to research NDE in Nuclear without Nuclear Power Plants

Anne Juengert

Materials Testing Institute University of Stuttgart

Germany shut down the last NPP in 2023

Germany is surrounded by NPP

⇒ Germany needs experts in nuclear safety

⇒ Funding of research and young researchers programs

Outline

Materials Testing Institute (MPA) in Stuttgart

Nuclear research history at MPA

Current research in NDT in nuclear

Possibilities of cooperation

Materials Testing Institute

Who are we?

- founded by Carl von Bach in 1884
- central institute at the University of Stuttgart
  - chair of „Construction Materials“
  - chair of „Materials Testing, Materials Science and Strength of Materials“
- about 270 employees (technical and scientific staff)
- long history in nuclear research

Research History in nuclear engineering at the MPA

1960

- Burst tests of pressure vessels
- Testing of RPV for first German NPP

1970

Research:
- underclad cracks
- component safety
- RPV materials

→ Basic safety concept

1980

After Tchernobyl focus on safety related research
- NDT and assessment of austenitic welds

2000

Research:
- UT Probability of Detection
- Fracture mechanics
- Weld assessment

UT qualification at RPV

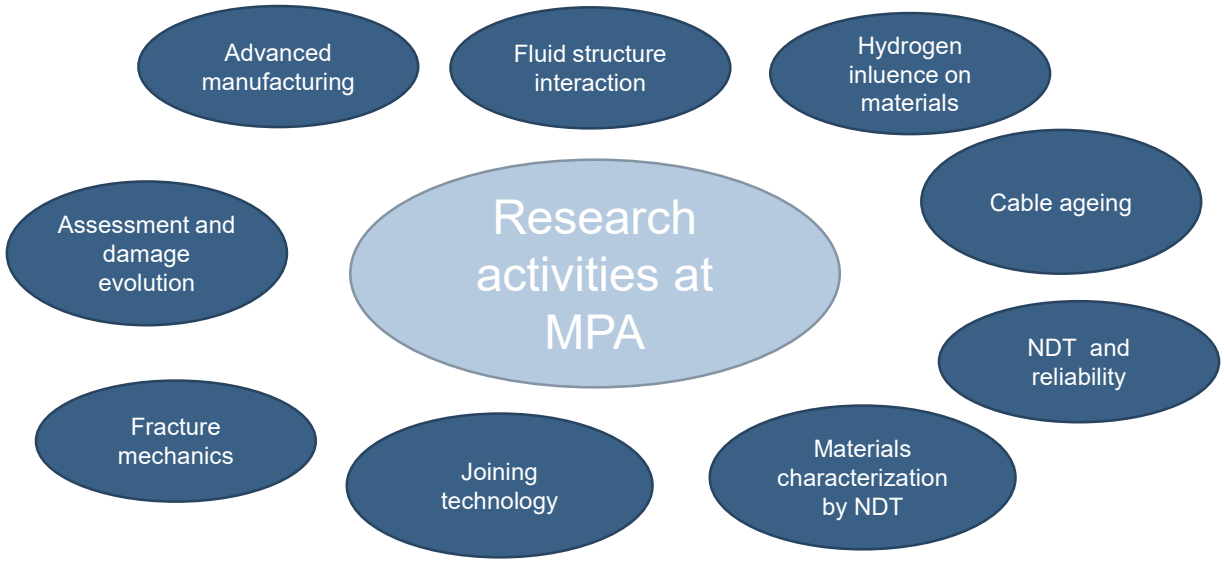
2010

Research:
- Influencing microstructure during welding
- Probability of Detection

Today

- Advanced Manufacturing
- Reliability of NDT
- Component reliability
- Aged materials
- SMR
- …

Current Research Topics at MPA



NDT Reliabilty: Validation of NDE

In the OECD NEA **Project SMILE**, aged material is harvested from the reactors in Oskarshamn and Ringhals, Sweden.

NDE is performed on **harvested material,** e.g. the core support structures, which contain austenitic welds.

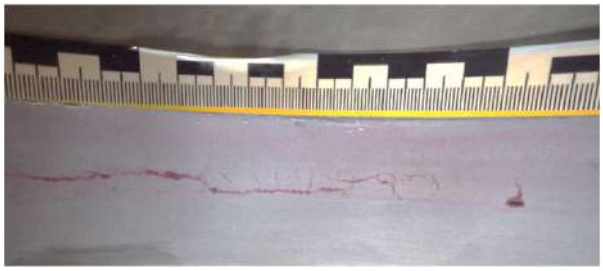
We compare the **results from the NDE** to results from former inspections to validate NDE results by real flaw data.

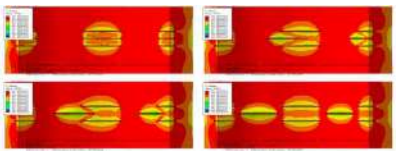
We perform analyses of the **microstructure of A600/A690** to validate the current risk assessment.

Reliability Assessment and NDT

Project aim: Reliability assessment for welded components in NPP, including:

1. **Material parameters** from fracture mechanic tests
2. NDT reliability by **POD curves**
3. **Realistic crack** geometries

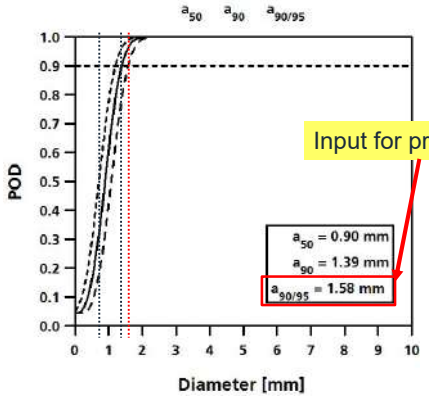




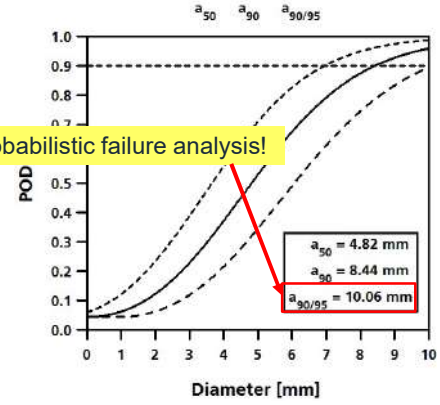
Reliability Assessment and NDT

PoD-curve for austenitic material from experiments and simulations at specimens with artificial flaws

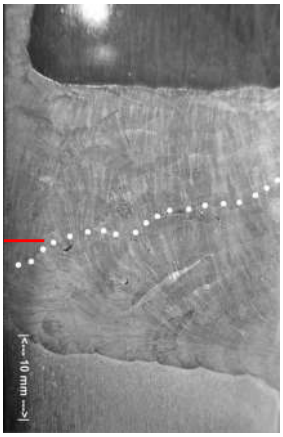
PoD curve for base material



PoD curve for weld material



Input for probabilistic failure analysis!

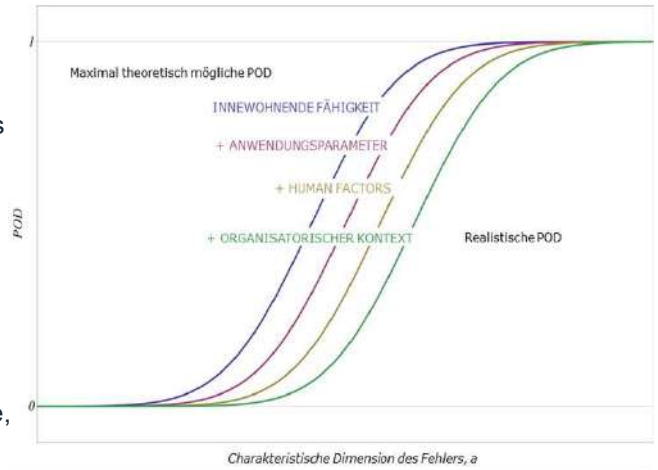


Human Factors in NDE (project starting 2024)

Experimental study on human factors during manual UT at ferritic pipe welds in NPP

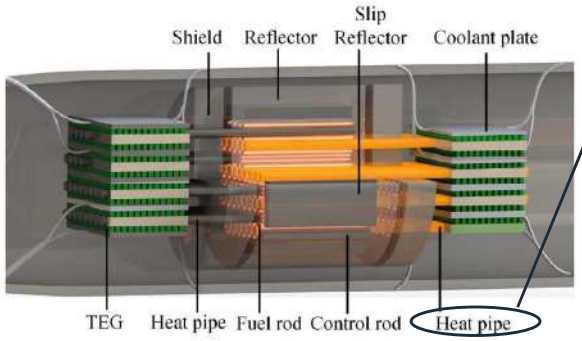
- Design of test specimens with flaws
- Experiments including 80 -120 UT examiners Level II or III
- Variation of factors:
  - Quality of information
  - Quality of written an oral instructions

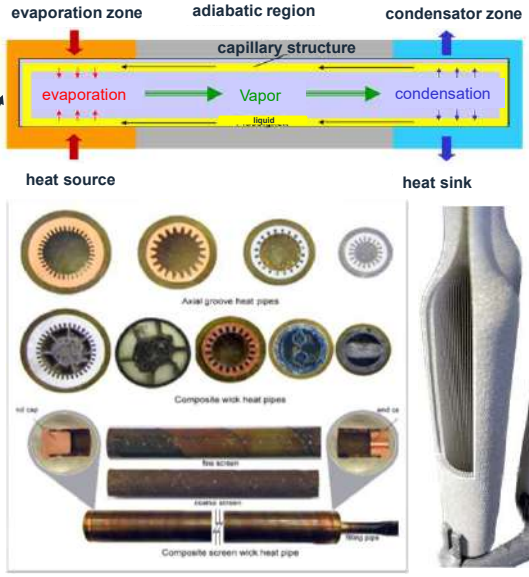
Projects partners:
BAM, MPA, TÜV Nord Ensys, SVTI, Framatome, MuM



Young researchers group: SiFeKo

vSMR concept using heatpipes

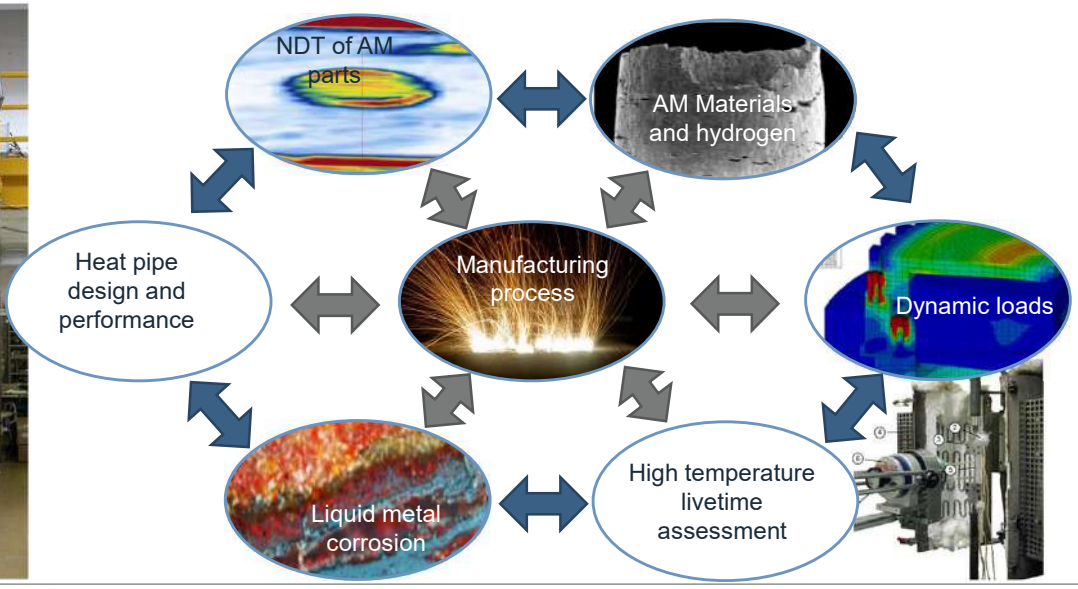




Heat pipes consist a complex capillary structure on the inside.

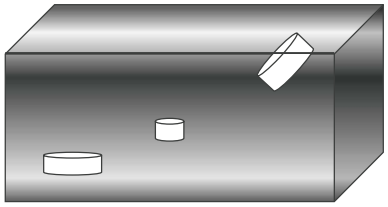
Can this heatpipes be manufactured by laser powder bed fusion?

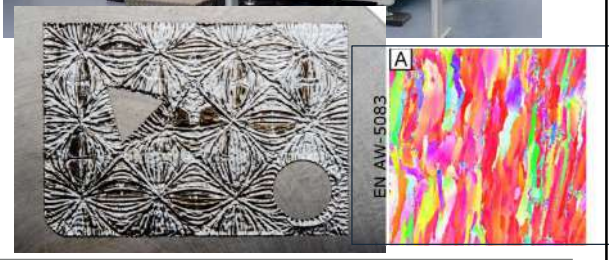
Young researchers group: SiFeKo



SiFeKo NDT: UT testing of AM parts

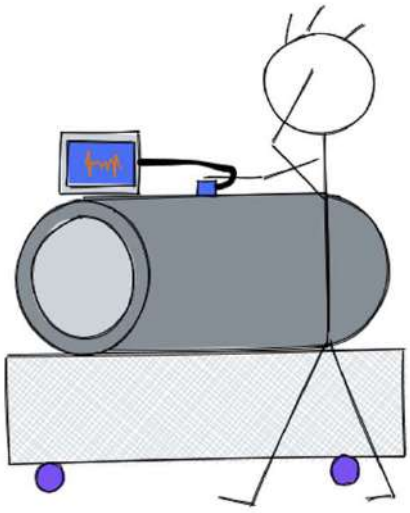
Selective laser melting (SLM)



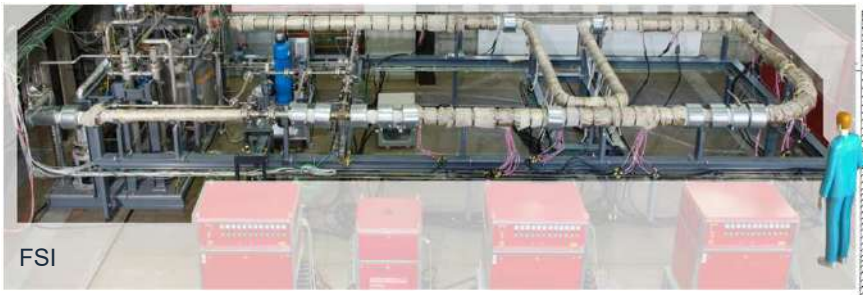


What about
- Surface structure of inner surfaces?
- Poweder filled flaws?
- Printing of angled reflectors?
- Microstruktur?

Possibilities of cooperation

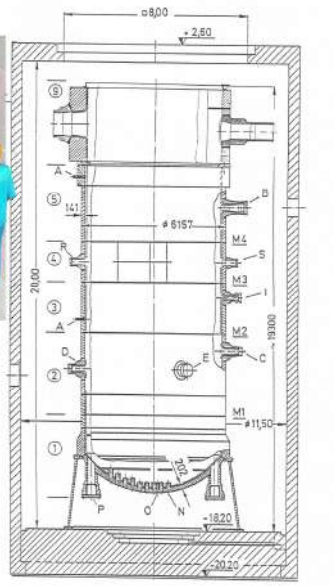


Unique test facilities



Test loop for fluid-structure interaction

- Cyclic thermal loads
- Medium influence
- Leak rates
- …



Full scale RPV with different artificial and realistic defects for qualification of NDT

Test specimens: austenitic welds

Bar shaped specimen
Wall thickness 30 mm
U-welds, V-welds, X-Welds

Defect types:
- stress corrosion cracks
- fatigue cracks
- notches
- drilled holes

Austenitic pipe welds segment with varying grain structure in U-weld

Wall thickness 30 mm

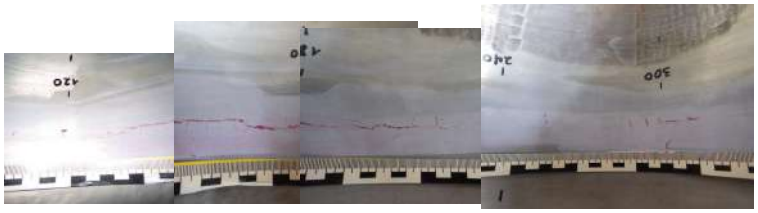
Defect types:
- notches

Test specimens: dissimilar weld specimens

Bar shaped specimens
Wall thickness 40 mm
Partly cladded

Defect types:
- stress corrosion cracks
- notches

Dissimilar pipe welds
30 mm wall



Defect types:
- stress corrosion cracks
- notches

RPV test blocks

Several **cladded blocks** with:

- underclad cracks
- weld defects
- SCC under cladding
- notches under cladding

My message to you!

Germany shut down its NPP, but we are still here and still doing research in nuclear !

Examples of **past and current projects**:

- Reliability of NDT
- Human Factors in NDT
- Young researchers group about safety aspects of vSMR

We offer **unique testing facilities** and a variety of test parts

We are looking forward to grow our international network!

Thank you!

EU-funded Project: iWeld

Project Advise Sep 2017 – Aug 2021

Partners: EDF, CEA, Extende, intercontrôle, M2M, Imperial College London, University of Bristol, Fraunhofer IZFP, MPA Stuttgart, Bay Zoltan, Kaunas University, UJV Rez, Arttic

- Improving Simulation of UT
- Development of CIVA Module for anisotropic welds

Results presented in Training School Feb 2021 https://www.advise-h2020.eu/media

Project iWeld Oct 2022 – Sep 2026

Partners: EDF, University of Southampton, Imperial College London, CEA, Transvalor, MPA Stuttgart, Kaunas University, Extende

- Adapting of the ADVISE results to other industries

11. NDE of Concrete & other Non-Metallic Materials

The presentations in this session are listed in the table below.

NDE of Concrete & other Non-Metallic Materials	**Chair:** Anders Lejon (Ringhals AB / Vattenfall)
Ultrasonic Monitoring of Irradiated and Thermally Aged NPP Cable Sheets	Yasemin Inc (VTT)
Guided Wave Inspection of Inaccessible Regions of Prestressed Concrete Containment Vessels (PCCVs)	Jay L. Fisher (Southwest Research Institute) et al.
Cargo Inspection using Muon Tomography for Nuclear Security	Akanchha Fnu, Pankaj Wahi, Prabhat Munshi (India Tech)
Natural NDE for Nuclear: Muography Case Studies for Waste and Infrastructure Inspection	David Mahon (Univ. Glasgow)
Nonlinear Ultrasonic Inspection of Concrete Slabs Containing Embedded Steel Liners Subjected to Accelerated Corrosion	Markus Nilsson (Lund Univ.) et al.

Ultrasonic measurements on irradiated and thermally aged NPP cables

Yasemin Inc[1)], Konsta Sipilä[1)] , Oskari Jessen-Juhler[2)] , Jari Rinta-aho[3)]

[1]VTT Technical Research Centre of Finland, Espoo, 02150, Finland
[2] Sweco Oy, Helsinki, Finland
[3] Codento Oy, Helsinki, Finland

E-mail address (corresponding author): yasemin.inc@vtt.fi

Abstract

Cables are vital components in Nuclear Power Plants (NPPs), with twenty-five thousand cables on average connecting many terminals in an NPP. Cables are subjected to irradiation and elevated operating temperatures, that cause aging and potential cable failure. Therefore, monitoring the integrity of the cables is important for safe operation of the plants. Destructive Testing (DT), generally tensile test and elongation at break, is typically used to determine the condition of cables. However, Non-Destructive Testing (NDT) methods offer a more flexible approach to monitoring the aging.

Ultrasonic Testing (UT) is used for condition monitoring of metallic components and can be applied in studying materials properties. This work utilizes the UT pulse-echo technique to measure the mechanical properties of the cables. The Time-of-Flight (ToF) and sound path were measured, and the ultrasound velocity in a cable was calculated accordingly.

The experiments were carried out on crosslinked polyethylene (XLPE) sheets with different aging conditions, and the measured sound velocity was correlated to the cable condition. The used UT setup is described, and the results are presented and discussed. The correlation between ultrasound velocity and irradiation or thermal degradation was evaluated.

Keywords: Ultrasonic Inspection, cables, aging

Ultrasonic Monitoring of Irradiated and Thermally Aged NPP Cable Sheets

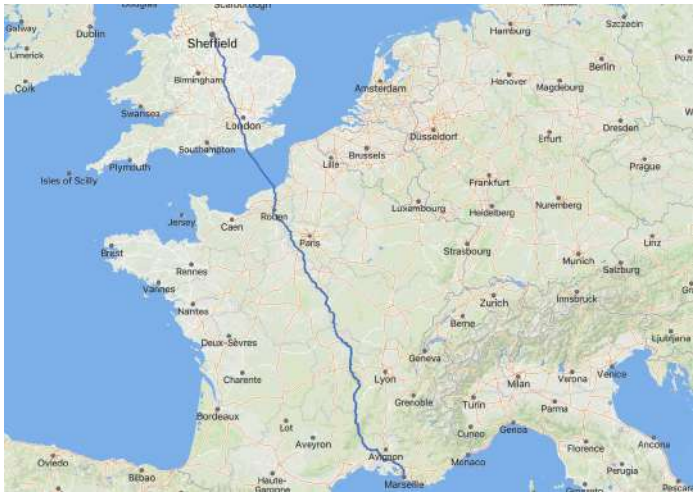
Yasemin Inc

Content

- Cables in Nuclear Power Plants
- Importance of Ultrasonic Measurement
- Experiment Setup and Design
- Experimental Results
- Conclusion

Cables in Nuclear Power Plants

- Cables play a crucial role in the operation of NPP, including power transmission, control and instrumentation
- ~1,500 km of electrical cables in every section - including the reactor
- *Harsh aging conditions* – Mechanical stress, irradiation and temperature. These factors can lead to degradation in the cable insulation, loss of electrical conductivity, increased cable resistance, and potential failure
- Up to 60 years of lifetime requirement!



Importance of Ultrasonic Measurements

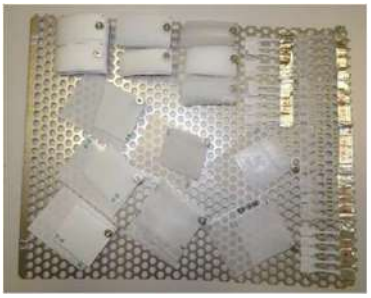
- The acoustic velocity is the speed at which ultrasonic waves travel through a material.
- The well-known behavior of elastic solids, the velocity of a longitudinal wave is a function of density, Young's modulus, and Poisson's ratio.
- Since the density stays constant while the material ages, all the differences in sound velocity are caused by differences in elastic properties
- The tensile testing was used as an indication to compare the sensitivity of the technique toward aging detection

Experiment setup

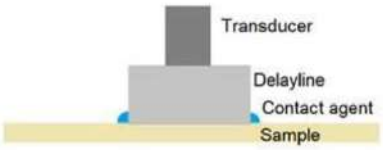
High Dose Rate
400Gy/h
Medium Dose Rate
60 Gy/h
Low Dose Rate
8.5 Gy/h

@130° C
@110°C
@87°C
87°C+ Low dose rate

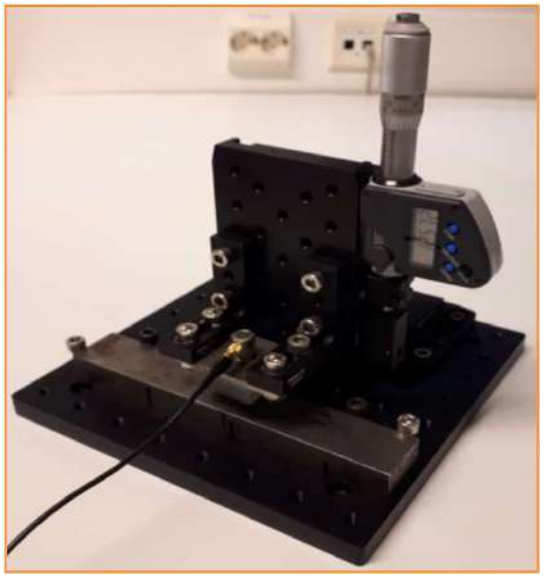
- 7 different sheets with crosslinked polyethylene (XLPE) and anti-oxidants
- 7 different aging conditions
- 5 different arbitrary duration for each condition (7 months to 2 years total)



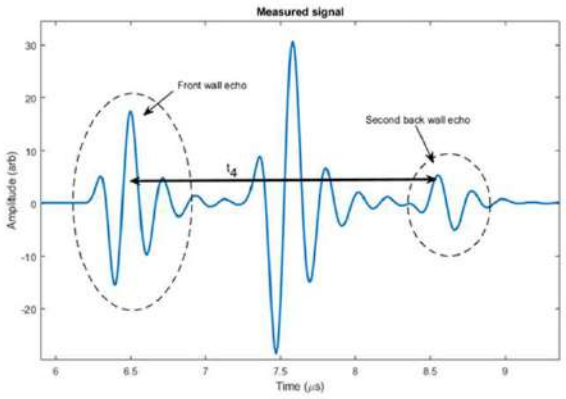
System Design



- 5Mhz contact transducer
- 22mm acrylic wedge
- Mitutoyo digital micrometer
- Dynaray Lite Instrument
- Matlab for signal analyzing



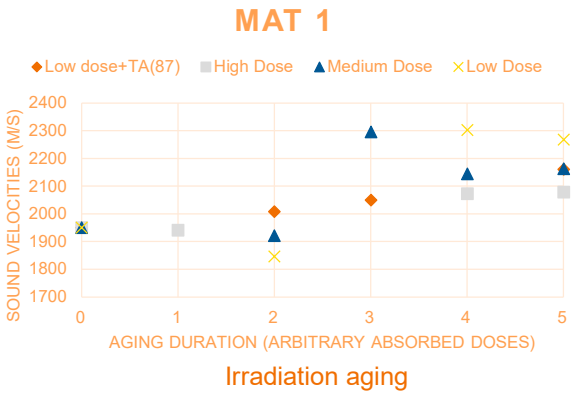
Measurements



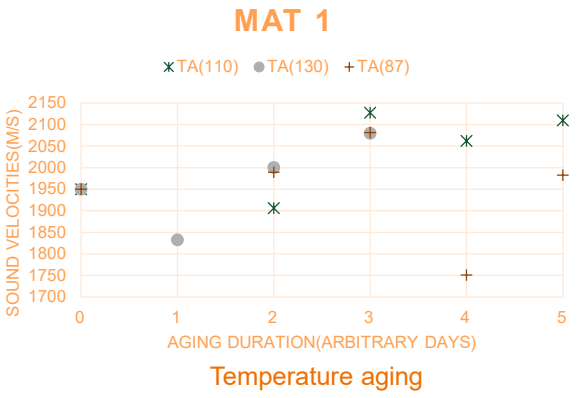
Using the second back wall echo reduced the relative error in velocity calculations significantly!

$$sound\ velocity = \frac{sound\ path\ length}{time\ of\ flight}$$

Experimental Results – *Velocity&Aging*
Material 1- *Silane crosslinked PE*

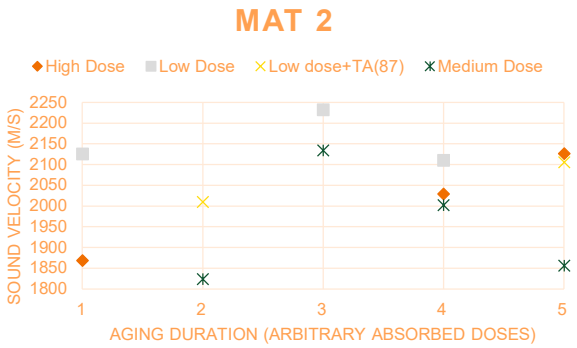


Irradiation aging

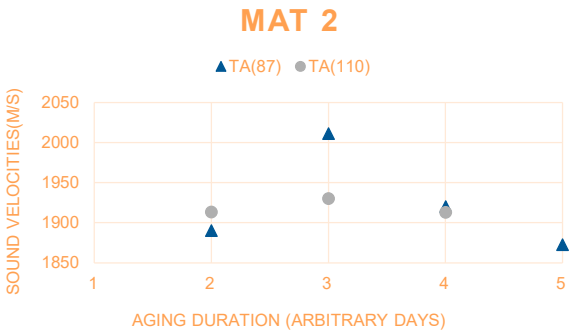


Temperature aging

Experimental Results – *Velocity&Aging*
Material 2- *Silane crosslinked PE + 1phr of a phenolic AO*

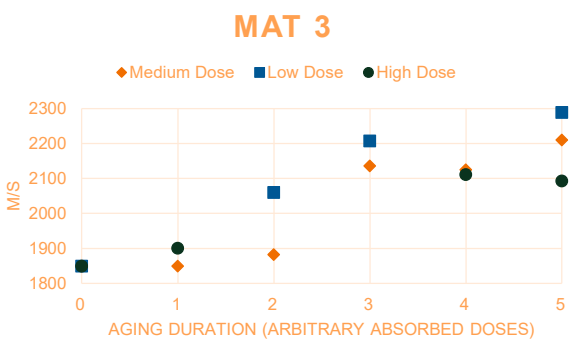


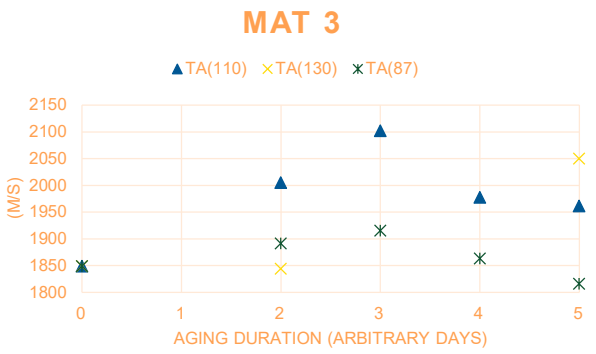
Irradiation aging



Temperature aging

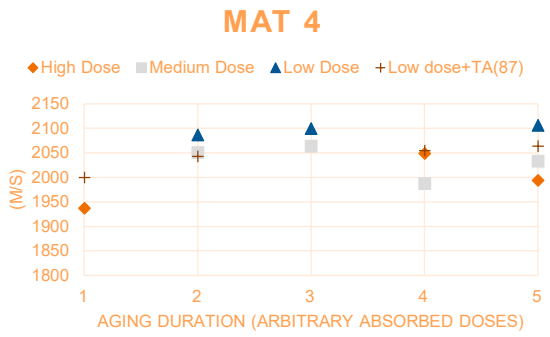
Experimental Results – *Velocity&Aging*
Material 3- *Silane crosslinked PE + 1phr of a thioether AO*

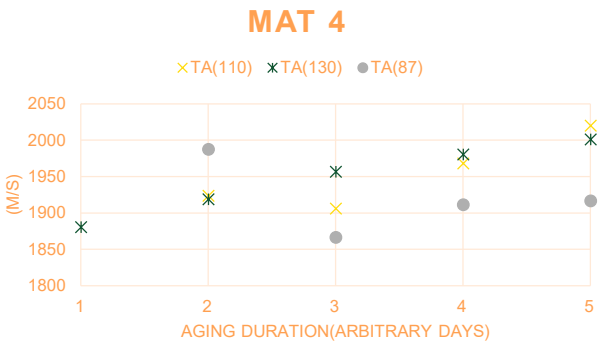




Experimental Results – *Velocity&Aging*

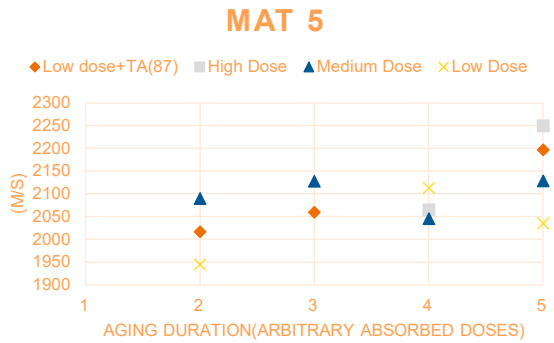
Material 4-*Silane crosslinked PE + 1phr of a phenolic AO + 1phr of a thioether AO*

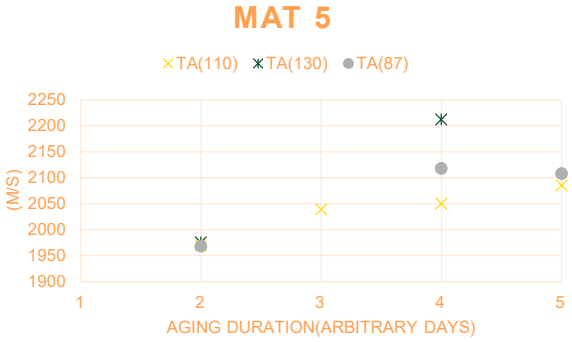




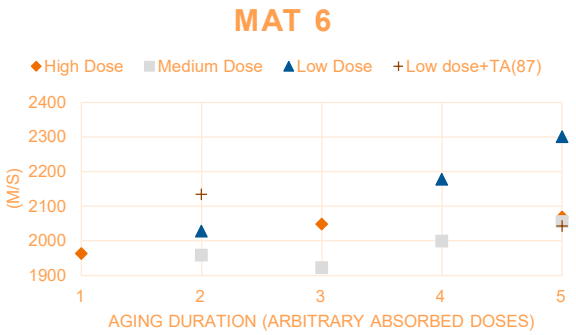
Experimental Results – *Velocity&Aging*

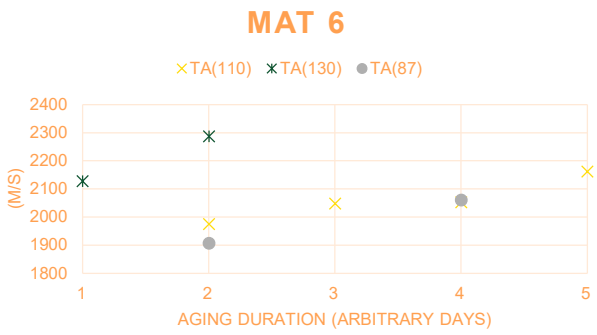
Material 5- *Silane crosslinked PE + 25phr of ATH*



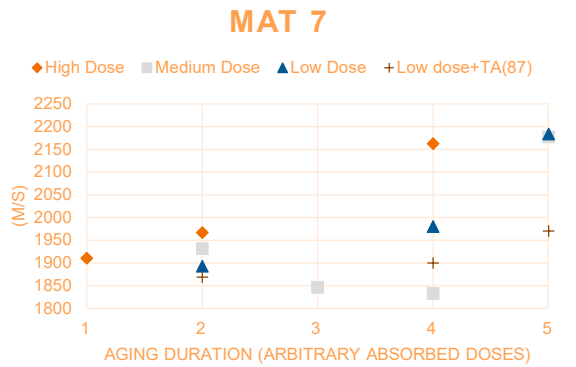


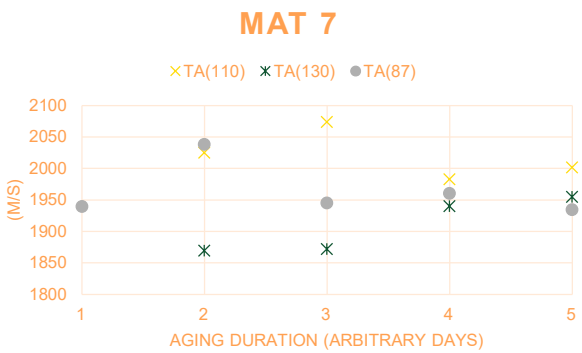
Experimental Results – *Velocity&Aging*
Material 6- *Silane crosslinked PE + 50phr of ATH*



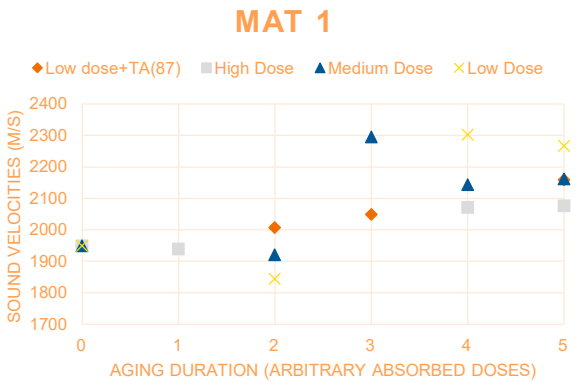


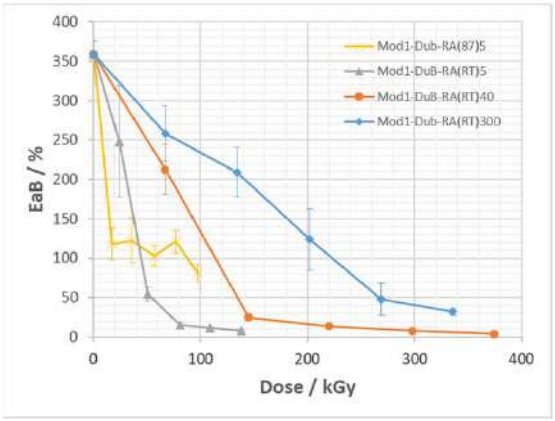
Experimental Results –*Velocity&Aging*
Material 7- *Silane crosslinked PE + 50phr of ATH + 1phr of a phenolic AO + 1phr of a thioether AO*





Example of Sound Velocity & Elongation at Break (EAB) Comparison





Conclusion

- The sound velocity changes as the samples aged. Especially severe aging can be differentiated from less aged samples more easily.
- The consistent changes were found on sheets without an antioxidant (Mat1,5,6)
- Irradiation is more effective on the velocity change than the temperature.
- Sound velocity measurement was challenged by the sheets' thickness (1-1.5mm), sample deformation, and surface roughness.
- In the nuclear industry, it is still an open subject to monitor cable conditions by ultrasonic sound velocity measurement.

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Yasemin Sahin Inc
yasemin.inc@vtt.fi
+358 50 596 83 34

@VTTFinland

www.vtt.fi

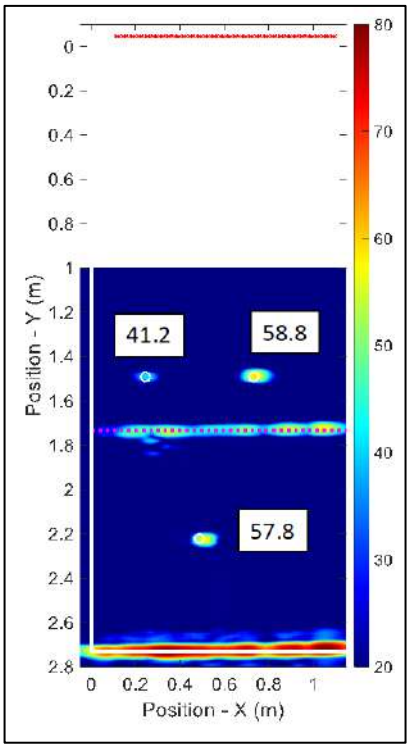
Guided Wave Inspection of Inaccessible Regions of PCCV Liners

Jay Fisher[1], Adam Cobb[1], Junichi Akagawa[2], Ryosuke Katsumata[2]

[1] Structural Engineering Dept., Southwest Research Institute®(SwRI®), San Antonio, TX, USA
[2]Plant Service Division, Nuclear Engineering Ltd. (NEL), Osaka, Japan

E-mail address (corresponding author): jay.fisher@swri.org

Many nuclear power plants include prestressed concrete containment vessels (PCCVs) as the final barrier for radiation release. These vessels have steel liners, typically 6 to 10 mm thick, on the inner wall to act as a leak tight barrier. In the U.S., there have been at least 5 known incidents of externally initiated corrosion, with at least 3 known cases of through-wall corrosion [1,2]. Unfortunately, there are many areas of the liner where the surface is not directly accessible for inspection, including regions below the basemat floor, as well as regions behind air conditioning and other equipment that are mounted on the containment vessel (CV) wall. To address this challenge, SwRI and NEL are developing an ultrasonic guided wave system to allow inspection of hidden areas of the liner, including welds and bulk plate material. The system includes a hand-held sensor designed to inspect a 6.4-mm thick liner for up to 3 m from the sensor. The sensor is an electromagnetic acoustic transducer (EMAT) that uses magnetostriction to generate and receive shear horizontal (SH) guided waves. The EMAT consists of an electromagnet to produce an adjustable bias field, and a printed circuit EMAT coil with transmitter windings to generate a pulsed field and separate receiver windings. EMAT coils designed to produce wavelengths of 9.5 mm and 16 mm have been manufactured and tested on a PCCV liner mockup. Both the fundamental SH mode, SH_0, and the first order mode, SH_1, have been investigated with these coils. Data are acquired by moving the sensor along a straight line, with the ultrasonic beam propagating normal to this line. A Synthetic Aperture Focusing Technique (SAFT) algorithm is used to combine the data into a 2D image showing the locations of any geometric reflectors. The image to the right shows sample results using the SH_0 mode with a 16-mm wavelength (at 200 kHz) collected on a PCCV liner mockup. The numbers in the boxes indicate the measured signal-to-noise ratio (SNR) in decibels (dB), for notch defects that are 20% and 40% through wall, where the two 57+ dB correspond to the 40% through wall flaws. There is also a strong reflection from a weld, denoted by the magenta dashed line. These and other results are discussed in detail, including a comparison of results with SH_0 and SH_1 wave modes.



Keywords: PCCV Liner, Containment Vessel, Guided Wave, Inspection, NDE

[1] Darrell Dunn, April Pulvirenti, and Paul Klein, https://www.nrc.gov/docs/ML1121/ML112140119.pdf

[2] Jason P. Petti, et al, *Nuclear Containment Steel Liner Corrosion Workshop: Final Summary and Recommendation Report,* SANDIA Report SAND2010-8718, July, 2011

Guided Wave Inspection of Inaccessible Regions of Prestressed Concrete Containment Vessels (PCCVs)

Jay L. Fisher[1], Adam Cobb[1], Junichi Akagawa[2], Ryosuke Katsumata[2]

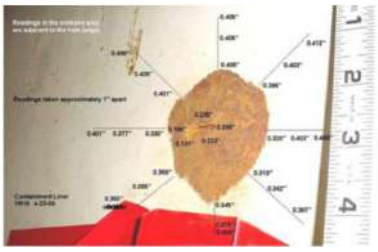
Jay.fisher@swri.org

[1] Southwest Research Institute
San Antonio, Texas, USA
[2] Nuclear Engineering, Ltd.
Osaka, Japan

NDE in Nuclear 2023

Background

- Many nuclear power plants use prestressed concrete containment vessels (PCCVs) as the final barrier for radiation release
- PCCVs have steel liners, typically 6 – 10 mm thick, on the inner wall to act as a leak tight barrier
- In the U.S., there have been at least 5 known incidents of externally initiated corrosion in the liner, including 3 that were through wall
- Much of the liner is not inspectable with conventional techniques (leakage testing and VT in the U.S.)
- Regions of interest for inspection include where equipment is mounted to the CV wall and where the liner is hidden in concrete
- Similar problem exists with metal containments



Perforation in Beaver Valley 1 Containment Liner 2009 (USNRC)

Motivation

- For large structures, guided wave techniques have the potential to 1) inspect larger portions and 2) perform inspections must faster than conventional NDE
  - These advantages are offset by reduced inspection sensitivity and characterization capability
- There is a need to develop a guided wave inspection approach that reduces these disadvantages while allowing the inspection of areas not accessible using conventional approaches

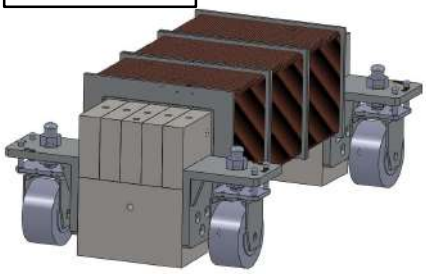
Previous Development History

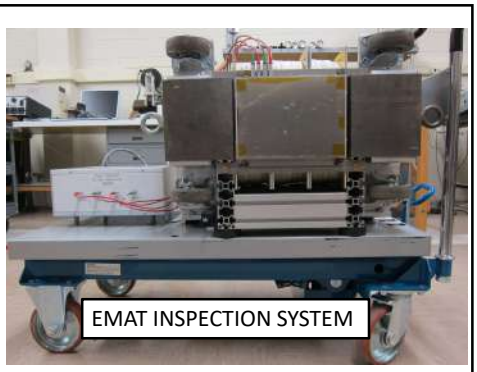
- 2002: D.J. Naus (ORNL/NRC/LTR-02/02) surveyed inspection approaches and recommended development of magnetostrictive sensor guided wave inspection, based on previous testing results by SwRI under EPRI sponsorship
- 2009 - 2015: Inspection of 38 mm thick metal PWR CV
  - Laboratory demonstration and successful field trial
  - Equipment developed (2013) for plant inspection
  - Inspection in 2015 outage
- 2013 - 2017: Inspection of 30 mm thick Mark I PCV
  - Laboratory development, plant demonstration and access studies were performed
  - Spherical bottom of PCV inspected
- 2017 – present: Inspection of Hanford Site Double Shell Tanks
  - used to store nuclear waste
  - Robotic system delivers EMAT sensors to region outside of primary tank

Guided Wave Sensors: EMAT and MsT

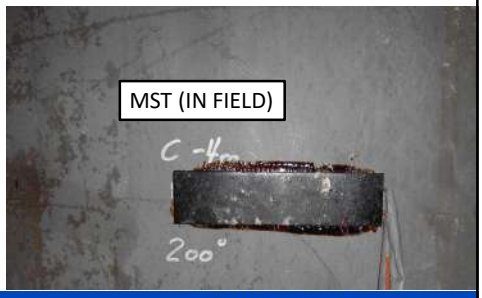
- Electromagnet acoustic transducers (EMATs)
  - Generate sound waves directly in material under test using either Lorentz forces or magnetostrictive effects
  - Typically have periodic spatial patterns to reinforce a given wavelength
  - Pros: no coupling fluid, work through coating layers, better mode selectivity
  - Cons: large sensor size and heavy because of low frequencies used
- Magnetostrictive Sensors (MsS) and Transducers (MsT)
  - Special EMAT - acoustic waves generated in a thin strip of a magnetostrictive material and coupled to the part using adhesive (MsS) or couplant (MsT)
  - Highly efficient at generating shear-horizontal motions in plates
  - Pros: small / low weight sensor
  - Cons: Consistent coupling (especially on real structure) can be difficult - process is difficult on plates where many sensor positions are required

EMAT (CONCEPT)





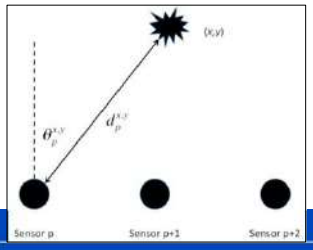
EMAT INSPECTION SYSTEM

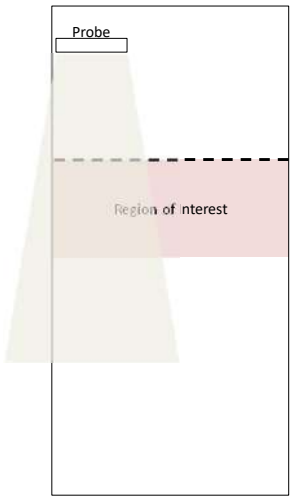


MST (IN FIELD)

Data Collection and Analysis Strategy: Synthetic Aperture Focusing Technique

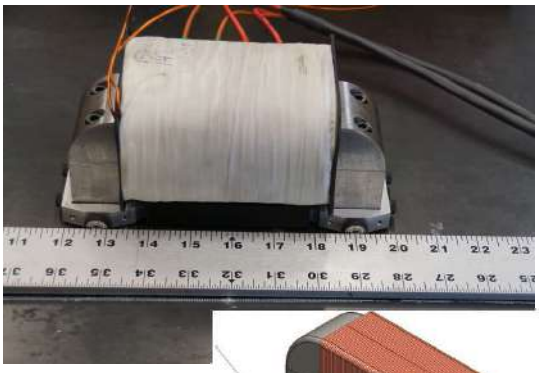
- Scan sensor at a constant vertical height around the vessel, sending sound to the inaccessible areas
  - Acquire data at regular intervals (25-50 mm)
  - Divide the structure into a grid of x-y locations
  - For each x-y location, add up all waveforms together:
    - Use portion of waveforms that corresponds to propagation distance (d) from x-y location to each sensor
    - Scale the amplitude based of each waveform based on sensor directivity and angle to the analysis location (Θ)
  - Repeat for all grid locations to create image

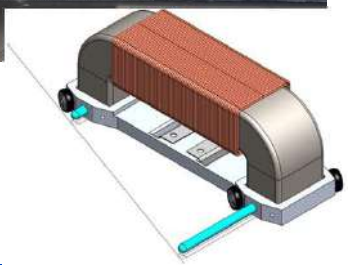




Small EMAT Design for PCCV Liners

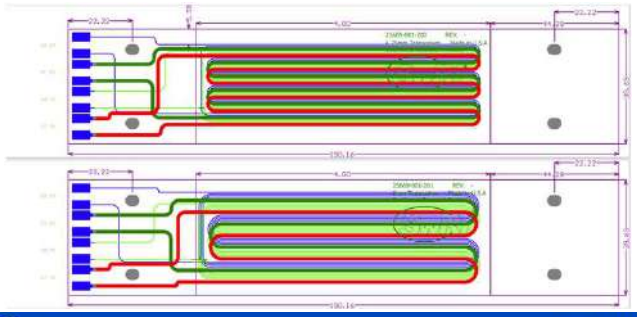
- Size 8 in x 2.9 in x 2.8 in (20 cm x 7.4 cm x 7 cm)
- Weight 7.5 lb (3.4 kg)
- Designed to produce at least 20 Oe magnetic field throughout entire thickness of liner, even on thicker liners
- Wheels to help slide along linear guide
- Pins can be inserted to change beam angle from 0 degrees to ±20 degrees



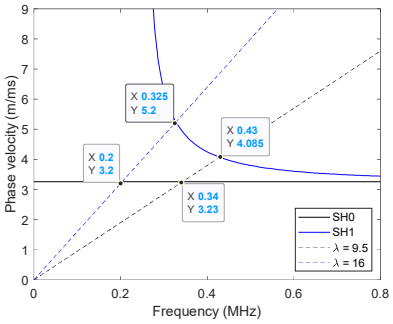


EMAT Sensor Coil

- Flexible printed circuits
- Two transmitter coils spaced ¼ wavelength apart and and two receiver coils spaced ¼ wavelength apart, with the signals excited and received out of phase to enable direction control.
- Multiple parallel traces to increase current in transmitter coils and increase voltage in receiver coils as well as to match amplifier impedance
- 9.5 mm and 16 mm wavelength designs



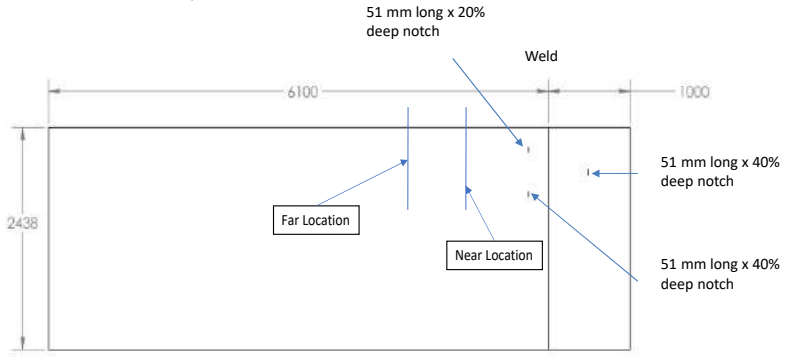
Dispersion Curves



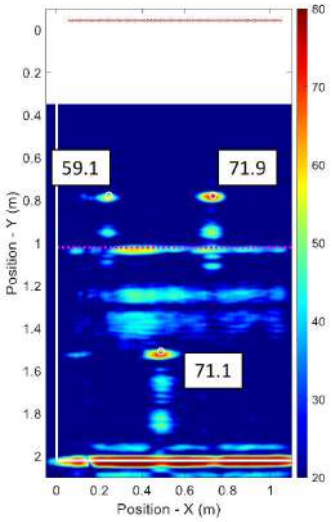
- Planned for testing SH0 and SH1 modes
- SH0 at 200 kHz for 16 mm wavelength and 340 kHz at 9.5 mm wavelength
- SH1 at 325 kHz for 16 mm wavelength

Mockup

- Steel plate 6.4 mm thick
- Three notches; one behind a weld
- Two scan paths ("Far Location" 1.7 m from the weld and "Near Location" 1 m from the weld)

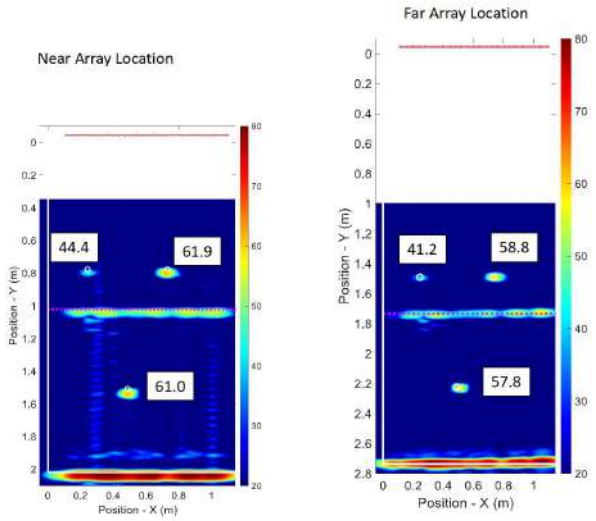


SH0 results at 340 kHz from Near Location

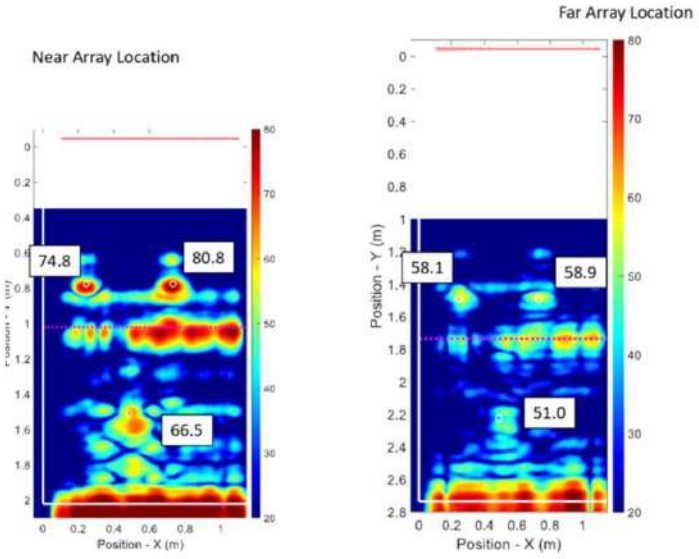


- Red x's indicate probe positions
- Numbers in white box indicate SNR in dB
- Dotted red line is weld location
- Additional indications are from reflections off of edges
- Big red line near the bottom is direct reflection from plate end

SH0 results at 200 kHz



SH1 results at 325 kHz



Conclusions

- 16 mm wavelength advantages
  - Less attenuation (lower frequency)
  - Able to detect larger defects in a weld using an angle beam, which depends on off-axis reflection from short defects to avoid weld reflection
- 9.5 mm wavelength advantages
  - Less beam spread – better at range
  - Higher order modes are less dispersive
- SH1 vs SH0
  - SH1 SAFT algorithm needs improvement, but has potential for 20+dB SNR improvement and better detection of gradual defects (separate work has confirmed that SH1 can detect gradual wall loss defects better than SH0)

Conclusions

- The 9.5 mm wavelength sensor had electronic noise, but that can be improved by increasing the number of parallel traces
- The16 mm wavelength sensor had lower SNR near weld but higher SNR away from weld, probably because the larger wavelength has less beam spread
- SH1 mode had higher SNR than SH0 for both sensors, but SH1 had many regions of coherent noise.
  - SH1 wave packets are long in time because of large dispersion
  - The existing SAFT algorithm does not take dispersion into account
- The 16 mm wavelength has less attenuation than 9.5 mm sensor, probably due to its lower frequency
- The 16 mm sensor should be able to detect larger defects in a weld using an angle beam, which depends on off-axis reflection from short defects to avoid weld reflection
- Effects

Two point scattering algorithm for Cosmic ray Muon Tomography

Akanchha Fnu [1], **Pankaj Wahi** [2], **Prabhat Munshi** [3]

[1]**Nuclear Engineering and Technology Programme, Indian Institute of Technology Kanpur, India**

[2]**Department of Mechanical Engineering, Indian Institute of Technology Kanpur, India**

Department of Mechanical Engineering and Computer Science and Engineering, Indian Institute of Technology Jammu, India

E-mail address (corresponding author): prabhat.munshi@iitjammu.ac.in

Abstract

Muons produced by cosmic rays are extremely penetrating charged particles in the Earth's upper atmosphere, which are detectable at sea level with a flux of around one muon per square centimeter every minute. They primarily interact with matter through Coulomb scattering. Muon tomography utilizes these properties of cosmic ray muons to scan the internal structure of shielded objects in a variety of applications where conventional imaging techniques, such as X-rays, are ineffective. By employing the multiple Coulomb scattering of muons as a radiographic probe, the method of cosmic ray muon tomography is seen as a potentially useful approach for locating high-Z materials and Special Nuclear Materials. In this imaging technique, the Point of Closest Approach (PoCA) and the Expectation-Maximization reconstruction methods are the most common types of algorithms used for image reconstruction. The reconstructed images, however, are quite noisy because of an unstable maximum likelihood estimation of the scattering parameter. Due to the low flux rate, this approach necessitates a long exposure period and has a low position resolution. In addition, a complicated method is required because the course of the ray is not straight due to the multiple Coulomb scattering that occurs.

In this paper, we propose a two-point scattering approach, in which two scattering points are used rather than one, and the image is reconstructed using the Algebraic Reconstruction Technique (ART) algorithm. The choice of the two scattering points in this approach depends on the boundary of the object to be investigated which has been obtained from the image generated using the POCA technique. When compared to the image acquired by applying the PoCA technique, the image that was reconstructed using the results of the two-point scattering approach has been found to be of better resolution.

Keywords: Muon Tomography, PoCA, ART, Coulomb scattering.

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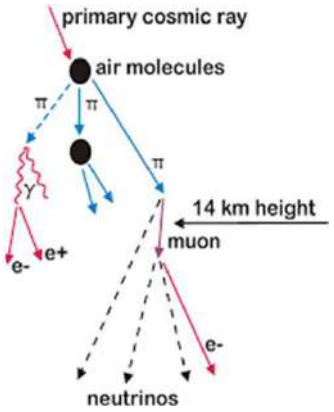
Cargo Inspection using Muon Tomography for Nuclear Security

Akanchha1 Pankaj Wahi 1 Prabhat Munshi1,2

1 Indian Institute of Technology Kanpur
2 Indian Institute of Technolgy Jammu

Introduction to Cosmic Muons

- Muons are elementary particles belonging to the family of leptons.
- They are about 200 times more massive than electrons.
- Muons have an electric charge and are affected by electromagnetic forces.
- Cosmic muon produced by cascade of reactions induced by cosmic rays in the upper atmosphere
  - Flux: ~150 /m²/s ~ $\cos^2\theta$ (maximum in zenith direction)
  - Mean energy: 4 GeV
  - Life-time: 2 μs
  - Natural and harmless radiation



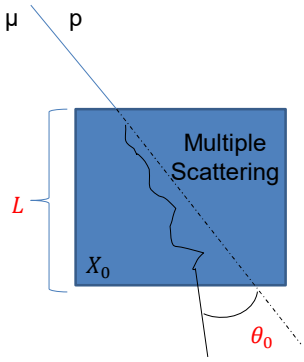
$\pi^+ \rightarrow \mu^+ + \nu\mu$
$\pi^- \rightarrow \mu^- + \bar{\nu}\mu$

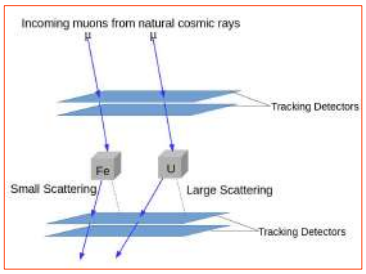
2

Muons Interaction with matter: Multiple Scattering

- Coulomb scattering deviates the direction of muons when crossing matter.
- Scattering angle depends also on the Z, density, and size of the material.
- Multiple Coulomb scattering to 1st order produces Gaussian distribution of scattering angles θ with width σ = θ_0 :

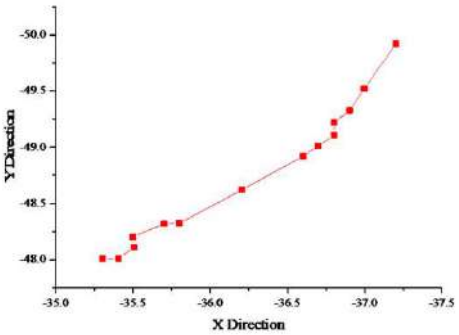
$$\theta_0 = \frac{13.6}{(pc\beta)} \times \sqrt{\frac{L}{X_0}} \times [1 + 0.038\ln(\frac{L}{X_0})]$$



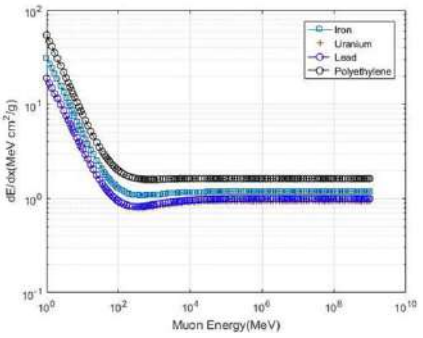


3

Mean Free Path and Energy Loss



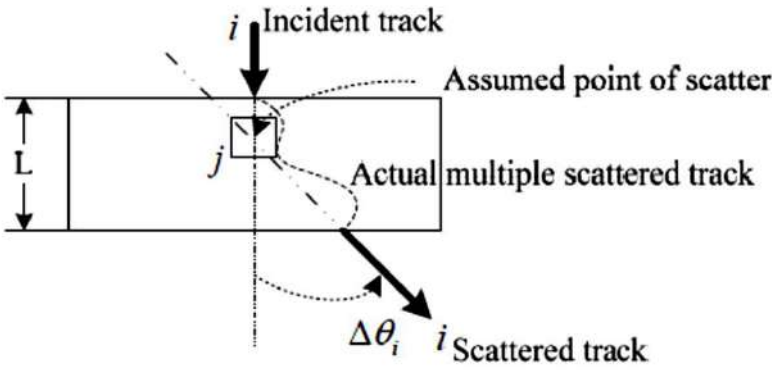
Mean free path of muon travelling inside a uranium block



Energy loss in elements as a function of muon energy

4

Point of Closest Approach concept



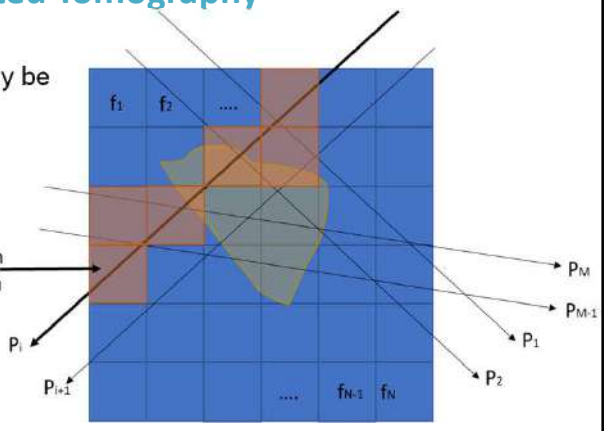
5

Algebraic based Computed Tomography

- For a given ray, the projection may be expressed as:

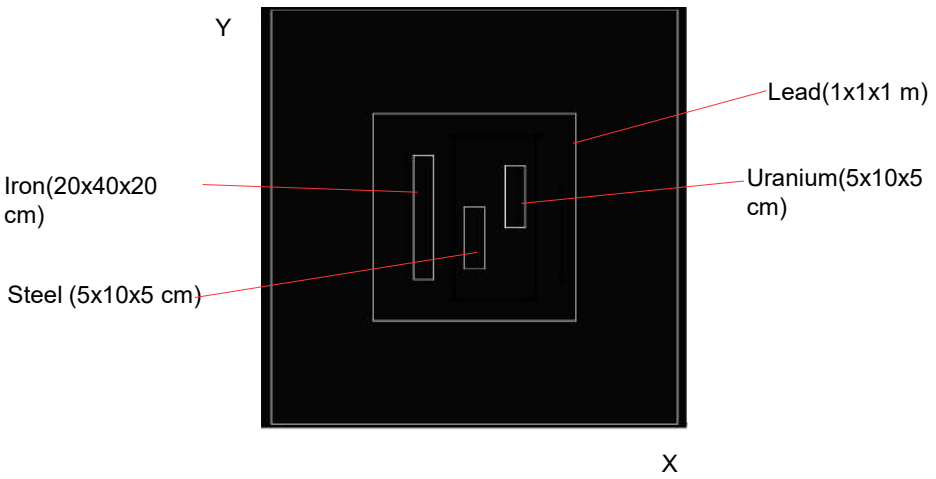
$$P_i = \sum_{j=1}^{N} w_{ij} f_j$$

w_{ij} = pathlength of ray i through cell j



6

Original Geometry

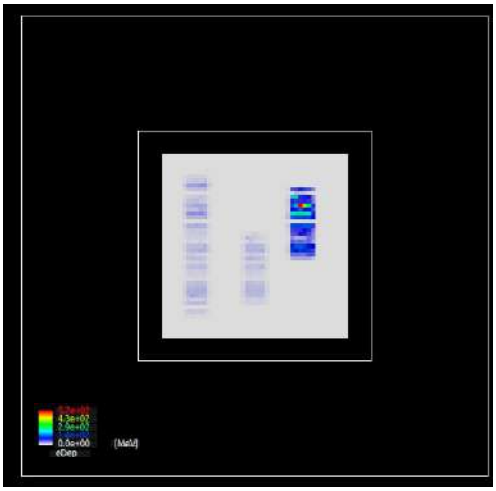


7

Simulation with 10^4 muons with single scattering using PoCA

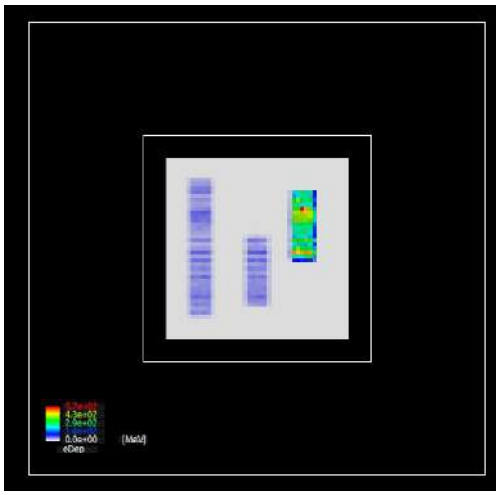
8

Simulation with 10^4 muons with double scattering using ART



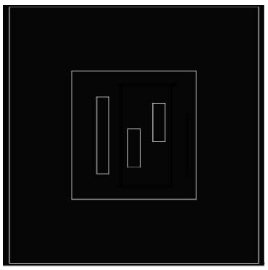
9

Simulation with 10^7 muons with double scattering using ART

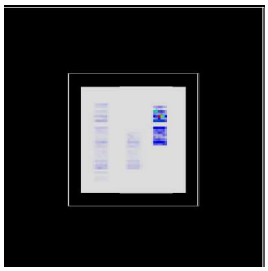


10

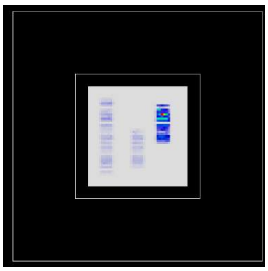
Comparison of PoCA and ART with original geometry



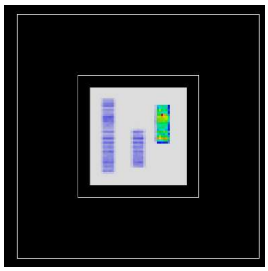
(a) Original Geometry



(b) PoCA reconstruction



(c) ART reconstruction



(c) ART reconstruction with increased flux

11

Comparison of RMS value for the with original geometry

Algorithm	PoCA	ART	ART with increased flux
RMS value	0.0144	0.0119	0.0058

12

Conclusion

- Use of Algebraic Reconstruction Technique (ART) based reconstruction methods for reconstructing the projected information stored in the detector bins.
- The ART algorithm gives slightly better results than PoCA but this can be highly beneficial in detection of special nuclear materials.
- This work can be further extended by using MART based algorithms for reconstruction purpose.

13

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14

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THANK YOU

Natural NDE for Nuclear: Muography Case Studies for Waste and Infrastructure Inspection

David Mahon[1,2], John Annand[1,2], Anthony Clarkson[1,2], Simon Gardner[1], Paul Naidoo[2], Ernst Niederleithinger[3], Matthew Ryan[4], Dan Wright[2], Guangliang Yang[1, 2]

[1]School of Physics & Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK
[2]Lynkeos Technology Ltd., University of Glasgow, Glasgow, G12 8QQ, UK
[3]Bundesanstalt für Materialforschung und -prüfung (BAM), 12205 Berlin, Germany
[4]National Nuclear Laboratory, Chadwick House, Warrington, WA3 6AE

E-mail address (corresponding author): David.Mahon@Glasgow.ac.uk

The Earth's upper atmosphere is under constant bombardment from cosmic rays that produce showers of subatomic particles. One constituent of these showers, the muon, can be harnessed to provide a powerful, new NDE capability for a wide range of industrial applications. By tracking the paths of muons through objects of interest using position sensitive detectors, a millimetre-resolution 3D density map can be reconstructed of the internal composition of complex engineered structures and containers.

The University of Glasgow, its spinout Lynkeos Technology, and the National Nuclear Laboratory have pioneered the development of muography for nuclear waste package inspection under Nuclear Decommissioning Authority (NDA) and Innovate UK funding. This resulted in the first, and to date, only, installation of a muography system within the global nuclear industry on the Sellafield site in 2018. This Lynkeos Muon Imaging System has subsequently been used for a range of nuclear waste management research applications. Several case studies will be presented in this talk:

- Imaging of uranic material within 500 litre concrete-filled stainless-steel drums,
- QA inspection of GeoMelt® in-container vitrification product blocks produced at the NNL pilot plant, and
- Condition monitoring and inspection of 3m^3 boxes containing sludges retrieved from the Magnox Swarf Storage Silo plant.

These confirm the potential of muography to play a significant role in global nuclear waste management for a variety of different containers and encapsulation techniques, and to underpin the safety cases for long-term waste storage.

Currently, Lynkeos Technology is funded as part of the NDA's Remote Monitoring of Sensitive Sites programme to develop a muography capability for point-of-inspection analysis of ageing reinforced concrete infrastructure. Results from a collaboration with built infrastructure NDE experts at Bundesanstalt für Materialforschung und -prüfung (BAM), exploring the capability of muography for the passive inspection of reinforced concrete will be presented. These experimental results are compared with radar, ultrasound, and X-ray laminography methods, and confirm the significant potential for muography to image the condition of steel reinforcement bars, voids, and tendon ducts within thick concrete.

Keywords: muography, passive inspection, NDE, built infrastructure, nuclear waste.

Natural NDE for Nuclear:
Muography Case Studies for Waste and Infrastructure Inspection

Dr David Mahon
Business Development Manager
Lynkeos Technology Limited

Lecturer in Nuclear Physics
University of Glasgow

NDE in Nuclear 2023
NDE of Concrete & other Non-Metallic Materials
27th June 2023 (4:55PM)

LYNKEOS TECHNOLOGY LTD · NATIONAL NUCLEAR LABORATORY · University of Glasgow

Cosmic-ray Muography

Muons are naturally-occurring particles, produced in the upper atmosphere by cosmic rays

Present at sea level with a flux of $1cm^{-2}min^{-1}$ and energies from keV to TeV (average of 3.35GeV)

Muons can penetrate heavy shielding and large thicknesses of rock and concrete

Muographic imaging is 100% passive and can produce 2D and 3D images based on material density and atomic number, Z

Field made headline news in 2017 with the discovery of a 'Big Void' in the Khufu Pyramid

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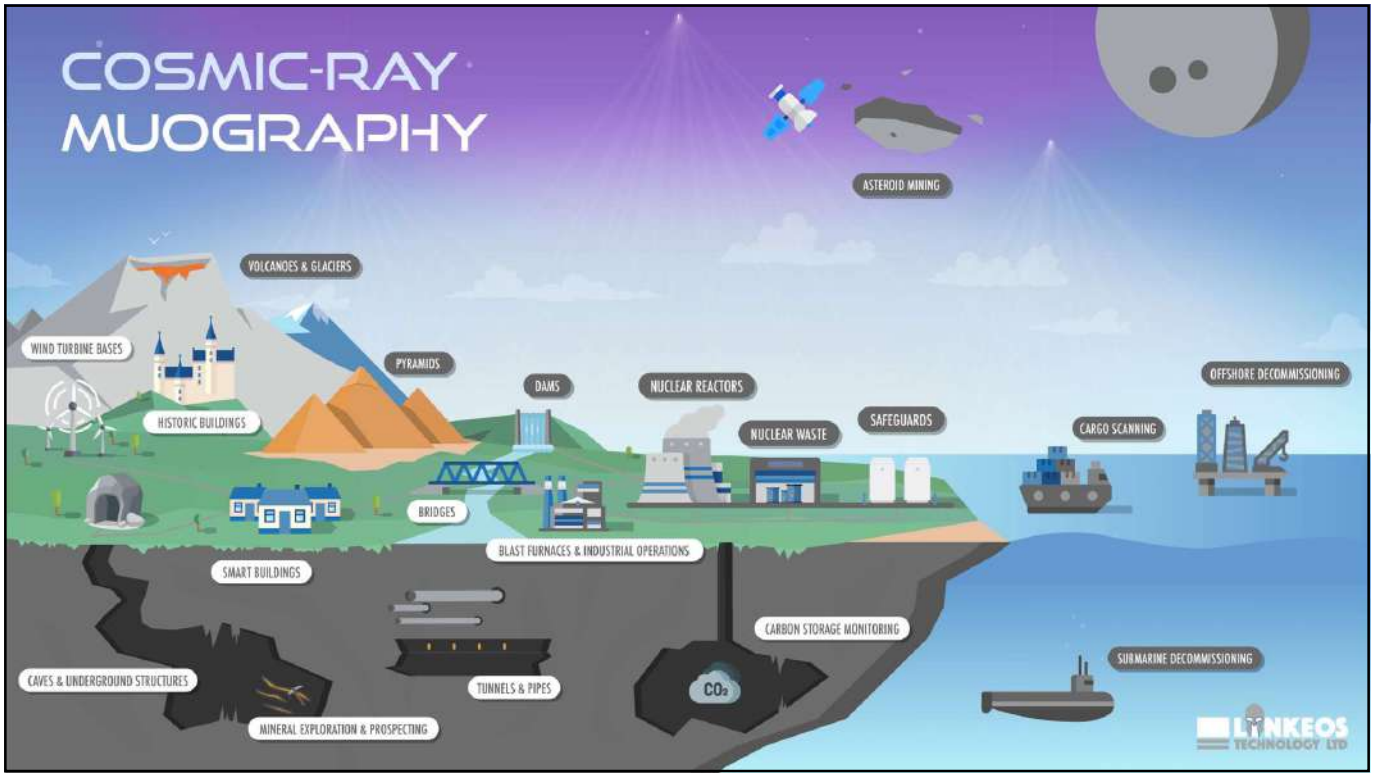
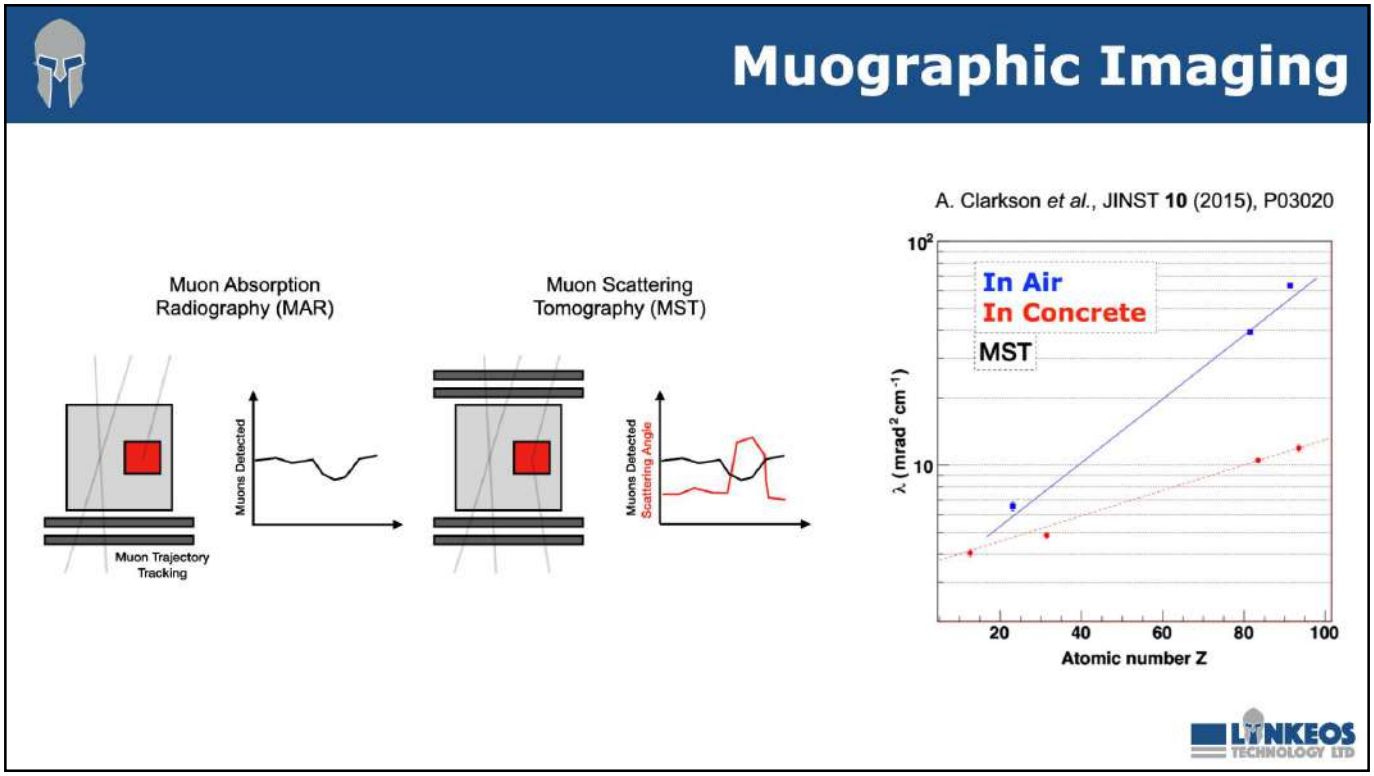
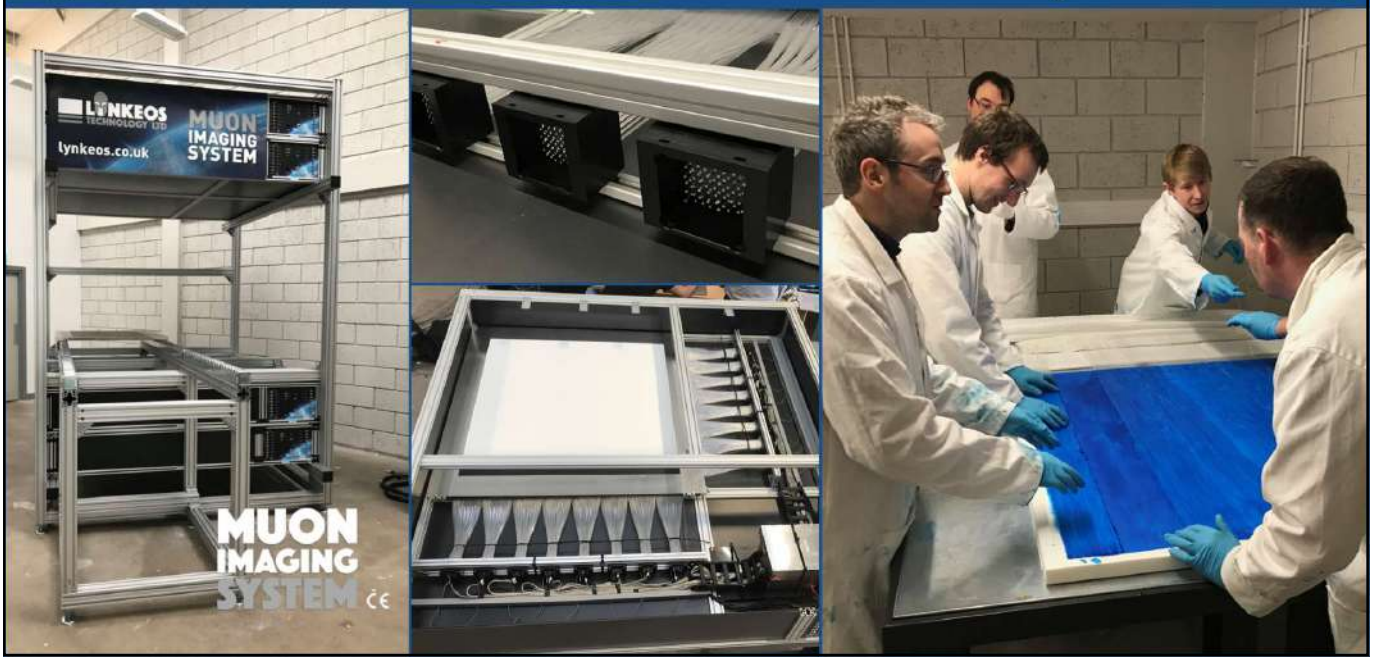

COSMIC-RAY MUOGRAPHY
ASTEROID MINING
VOLCANOES & GLACIERS
WIND TURBINE BASES
PYRAMIDS
DAMS
NUCLEAR REACTORS
OFFSHORE DECOMMISSIONING
HISTORIC BUILDINGS
NUCLEAR WASTE
SAFEGUARDS
CARGO SCANNING
BRIDGES
BLAST FURNACES & INDUSTRIAL OPERATIONS
SMART BUILDINGS
CARBON STORAGE MONITORING
SUBMARINE DECOMMISSIONING
CAVES & UNDERGROUND STRUCTURES
TUNNELS & PIPES
CO2
MINERAL EXPLORATION & PROSPECTING
LINKEOS TECHNOLOGY LTD


Muographic Imaging
Muon Absorption Radiography (MAR)
Muon Scattering Tomography (MST)
Muons Detected
Muon Trajectory Tracking
Muons Detected
Scattering Angle
A. Clarkson et al., JINST 10 (2015), P03020
In Air
In Concrete
MST
λ (mrad² cm⁻¹)
10²
10
20
40
60
80
100
Atomic number Z
LINKEOS TECHNOLOGY LTD

Lynkeos' Current MIS Technology

(sized for 500l Drums)



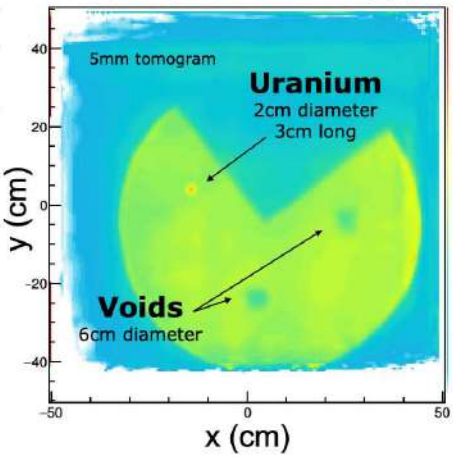
Case Studies

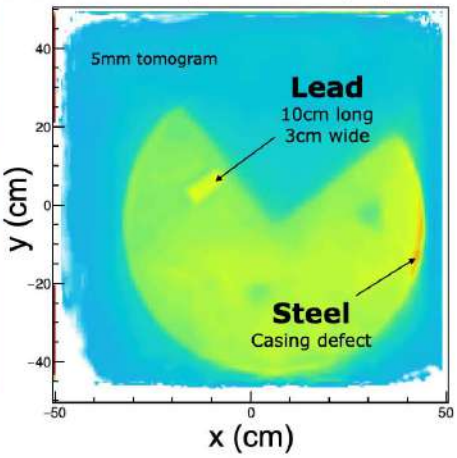
LINKEOS TECHNOLOGY LTD

Case Study #1:
500 Litre ILW Containers

Case Study #1:
500 Litre ILW Containers

*Mahon, D. et al., 2018, "First-of-a-kind muography for nuclear waste characterisation", Phil. Trans. R. Soc. A, **377**, 0048*





Supported by UKRI Innovate UK NDA

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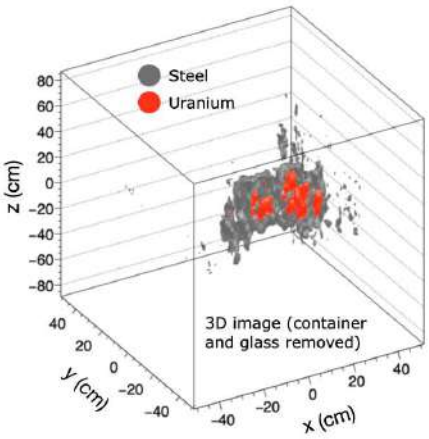
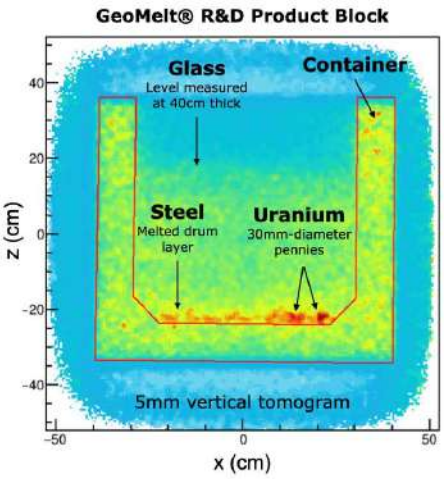
Case Study #2:
GeoMelt® In-Container Vitrification™

Steel drum

Uranium pennies





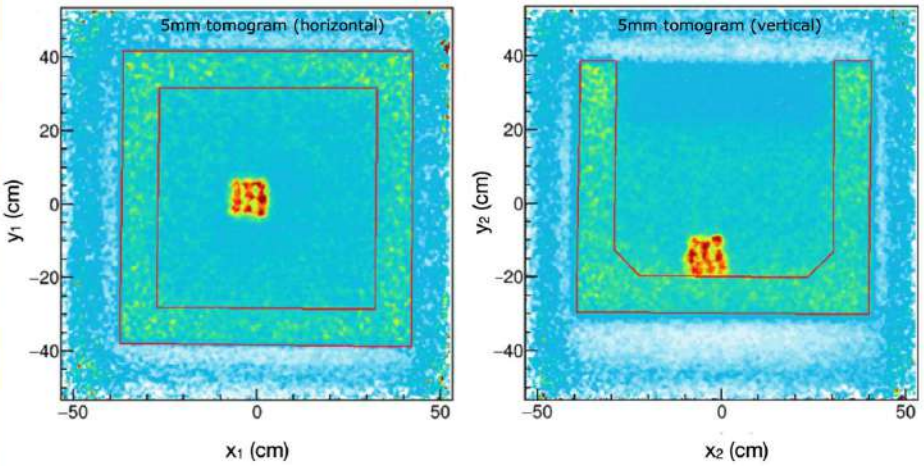
Imaging of R&D Product Blocks supported by NDA

LINKEOS TECHNOLOGY LTD

Case Study #2:
GeoMelt® In-Container Vitrification™

Steel skip

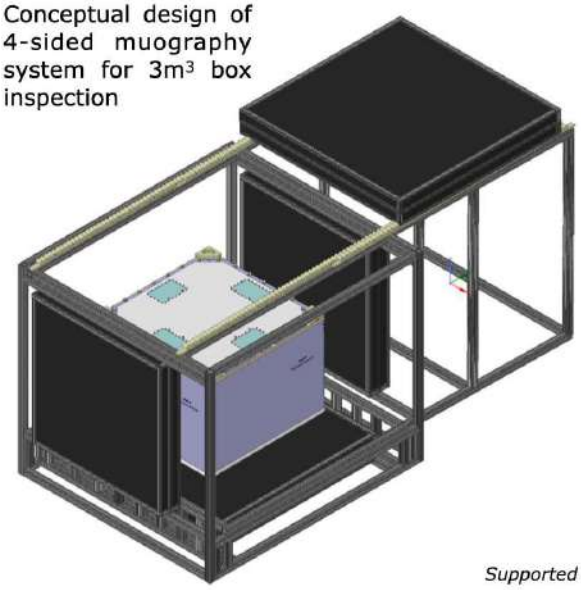
Uranium pennies

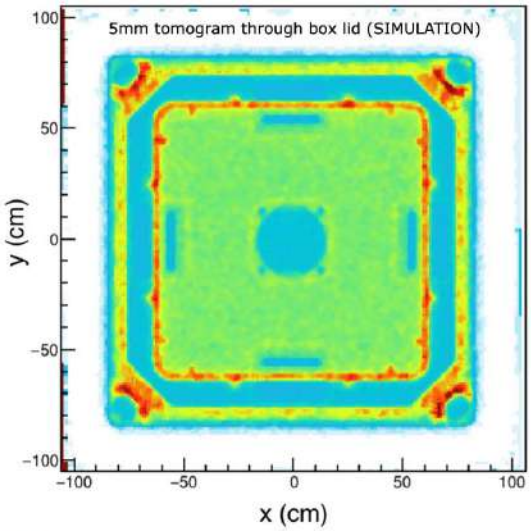


Imaging of R&D Product Blocks supported by

Case Study #3:
3m³ Box Condition Monitoring & Inspection

Conceptual design of 4-sided muography system for 3m³ box inspection





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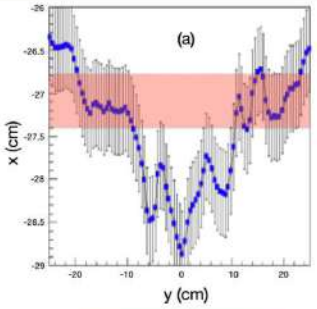
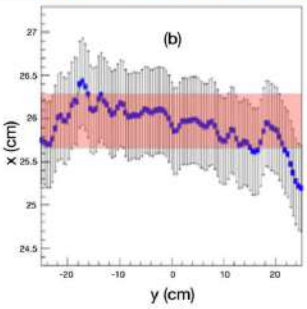
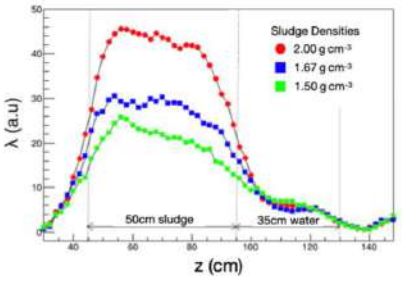
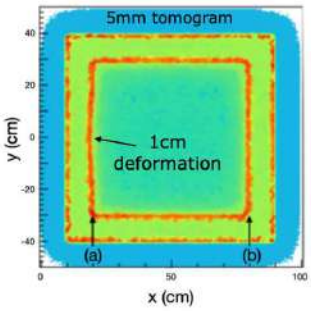
Case Study #3:
3m³ Box Condition Monitoring & Inspection



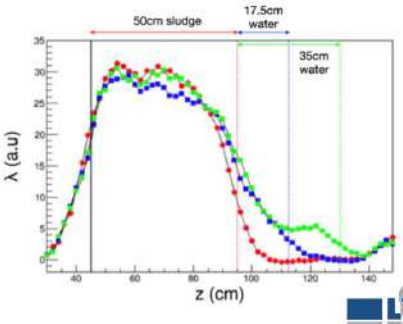






(left) automated container defect identification capable of several mm precision

(right) waste and water fill levels can be measured to less than 1cm accuracy using slope analysis. Independent of waste composition



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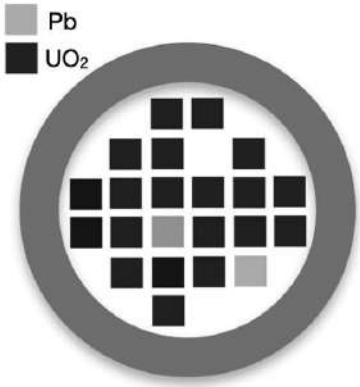
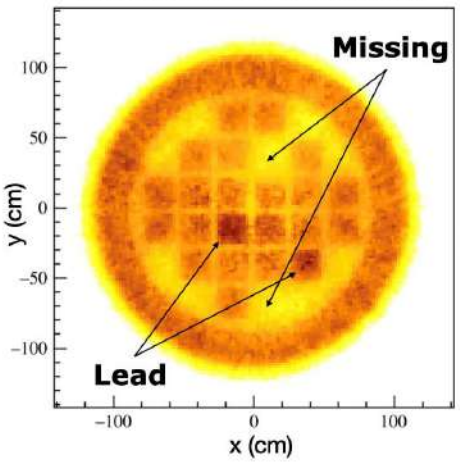
Case Study #4:
Spent Fuel Dry Storage Cask

Spent fuel dry storage cask



Equivalent to 1 day of imaging



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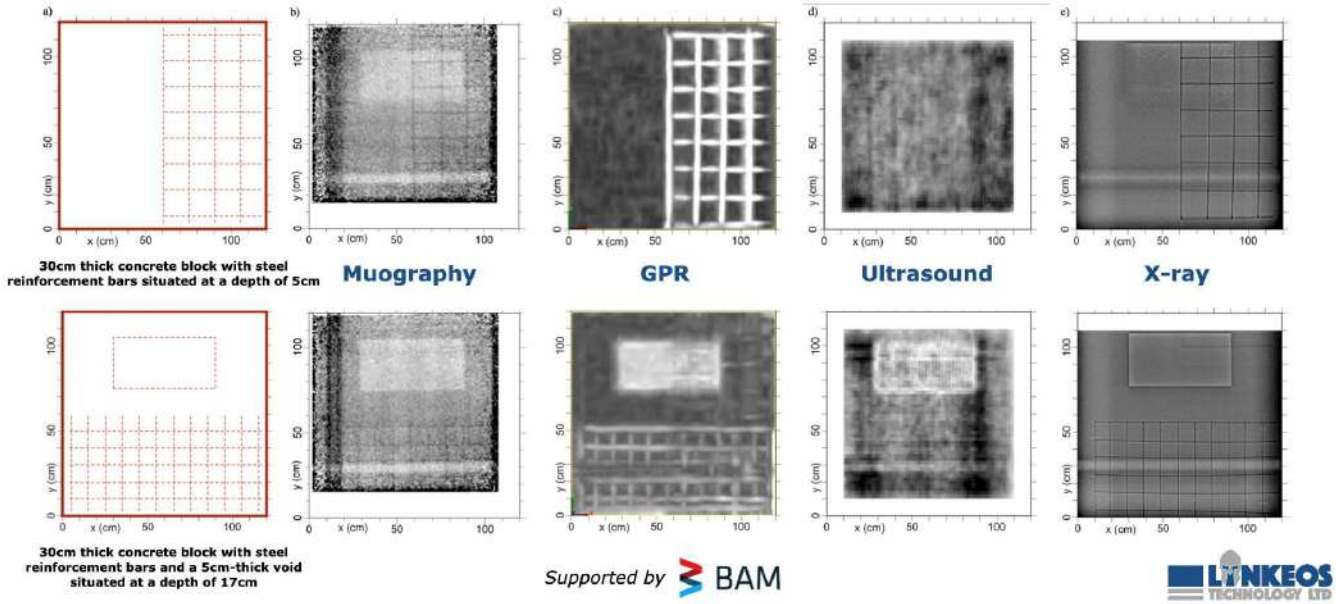
Case Study #5:
Reinforced Concrete NDT

Niederleithinger, E. et al., 2021, "Muon Tomography of the Interior of a Reinforced Concrete Block: First Experimental Proof of Concept", Journal of Nondestructive Evaluation, 40 (3) 1



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Dr David Mahon
david.mahon@glasgow.ac.uk
+44 (0) 7747 045 700
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Nonlinear Ultrasonic Inspection of Concrete Slabs Containing Embedded Steel Liners Subjected to Accelerated Corrosion

Markus Nilsson[1], Elina Huttunen-Saarivirta[2], Edgar Bohner[2], Miguel Ferreira[2]

[1]Division of Engineering Geology, Faculty of Engineering, Lund University, Lund, Sweden
[2]VTT Technical Research Centre of Finland Ltd, Espoo, Finland

E-mail address (corresponding author): markus.nilsson@tg.lth.se

The containment structure, which comprises a gas-tight steel liner embedded in concrete, serves as the outermost building element of a nuclear reactor, and acts as a safety barrier in the event of an accident. Unfortunately, corrosion of the liner has been reported occasionally, even to such an extent that the structure has not passed the leak tightness tests. One of the challenges in detecting corrosion in steel liners is that traditional non-destructive methods are not always effective. However, advanced techniques, such as nonlinear ultrasonic analysis, may be used to locate the areas of corrosion attack by identifying changes in the response of a concrete structure. For instance, corrosion products that form on steel accommodate greater volume than the metal itself causing swelling pressure and subsequently micro- and macro-cracking in the surrounding concrete. The concrete cracking, in turn, creates local elastic nonlinearity, distorting the acoustic waves and resulting in the generation of harmonics in the ultrasound response. Additionally, if the structure is excited by multiple frequency components, frequency-mixing and amplitude modulation will also occur in the collected data.

The present study used higher harmonic analysis and modulation spectroscopy to inspect concrete slabs containing embedded steel liners and an inlay, which represented the corrosion scenarios of foreign matter contribution and delamination gaps between the steel and the concrete. The slabs were exposed to wetting-drying cycles for the duration of up to 2 years, and additional acceleration was obtained by adding chlorides and/or using impressed current. In-situ electrochemical measurements were performed intermittently during the exposure. At the end of the exposure period, the concrete slabs were inspected non-destructively using nonlinear ultrasonic techniques. Eventually, the concrete cover was removed, and the liner specimens were photographed and characterized. Damage indices were defined as the ratio of the nonlinear response to linear response and normalized and summed to create a Total Damage Index (TDI). The results revealed that many of the slabs containing chlorides or accelerated by the use of impressed current had the highest measured TDI, indicating the highest levels of damage among the inspected samples. This is consistent with the results from electrochemical measurements and liner characterizations.

Keywords: liner corrosion, non-destructive testing, modulation, higher harmonics, corrosion rate

Nonlinear Ultrasonic Inspection of Concrete Slabs Containing Embedded Steel Liners Subjected to Accelerated Corrosion

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[1]Division of Engineering Geology, Faculty of Engineering, Lund University, Lund, Sweden
[2]VTT Technical Research Centre of Finland Ltd, Espoo, Finland

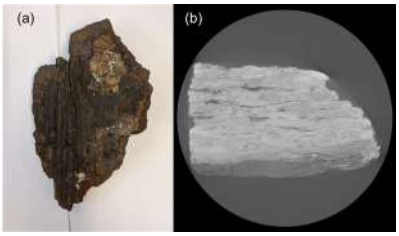
Agenda

- Motivation
- Samples and aging process
- Electrochemical measurements
- Ultrasonic measurements
- Results
- Conclusions

Motivation

- Liners embedded in concrete should not corrode severely due to the alkaline environment provided by the surrounding concrete.
- Corrosion occurring in concrete embedded containment liners is challenging to detect by conventional means.
- Nonlinear ultrasonic techniques have shown promise in detecting corrosion-induced damage in concrete.

Corrosion product from NPP Ringhals 3. Formed by the presence of embedded wood.



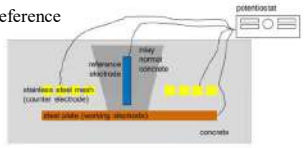
Samples

Sample name	Variable	Conditions
R	Reference	Normal concrete
RC	Reference with chlorides	Normal concrete, concrete inlay with added chlorides
PH	Concrete pH	Normal concrete, carbonated concrete inlay
PHI	Concrete pH, electrochemical acceleration	Normal concrete, carbonated concrete inlay, impressed current
PHCI	Concrete pH, added chlorides, electrochemical acceleration	Normal concrete, carbonated concrete inlay, impressed current, concrete inlay with added chlorides
WC	Embedded wood, chlorides	Chlorides added to a piece of wood embedded in normal concrete
D	Delamination in steel-concrete interface	Gap formed between steel and concrete, normal concrete.
DC	Delamination, chlorides	Delamination, normal concrete, concrete inlay with added chlorides

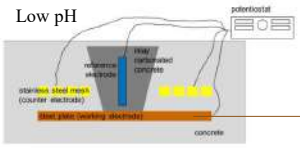
350x270x80 mm concrete slab

Samples

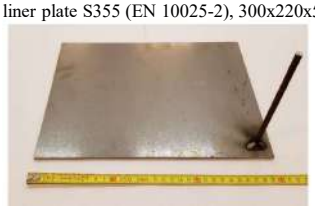
Reference



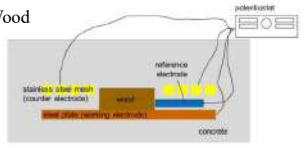
Low pH



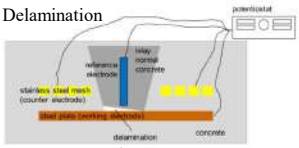
Steel liner plate S355 (EN 10025-2), 300x220x5 mm



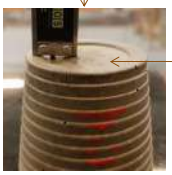
Wood



Delamination



Concrete mix design: C35/45, S3, w/c 0.46.
Low pH concrete (PH): carbonation treatment for 3 months.
Chloride content (C): 2.5% by cement mass



0.5 mm ‘delamination’

4

Aging process

- Stored in a constant climate of 20° C and 65% RH for the duration of 2 years.
- Periodical wetting-drying to accelerate corrosion.
- Certain samples were accelerated further by the use of impressed current.
- Electrochemical measurements performed intermittently during aging.
- Ultrasonic measurements performed at the end of the aging process.
- The concrete cover was mechanically removed after the ultrasonic measurements.

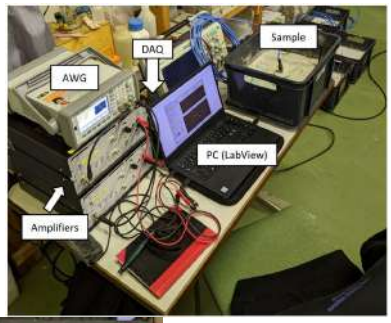
5

Electrochemical measurements

- Open Circuit Potential (OCP).
  - Indicates thermodynamic driving force for corrosion.
- Instantaneous corrosion rate estimates.
  - Linear Polarization Resistance (LPR).
  - Tafel measurements.

Ultrasonic measurements

- Investigated parameters:
  - Harmonic generation
    - $\frac{1}{A_1}$ & $\frac{A_2}{A_1^2}$ & $\frac{A_3}{A_1^3}$
  - Frequency-mixing and amplitude modulation
    - Frequency domain $\gamma = \frac{E_{sidebands}}{E_{probe}}$
    - Instantaneous modulation characteristics by Hilbert-Huang Transform (HHT)
- Excitation:
  - Probe: continuous sinusoid 36 kHz 35 Vpp
  - Impulse source: M4.5x15 mm Phillips button head screw on 370 mm cable tie.



Instantaneous modulation characteristics

- Amplitude- and frequency modulation occur simultaneously.
  - Cannot be separated in frequency domain.
- Analysis using Hilbert Transform (HT) can provide information about Instantaneous Amplitude (IA) and Frequency (IF).
  - Not suitable for multi-component signals.
- HHT uses Empirical Mode Decomposition (EMD) to extract Intrinsic Mode Functions (IMFs).
  - An IMF yields information regarding a single carrier frequency.

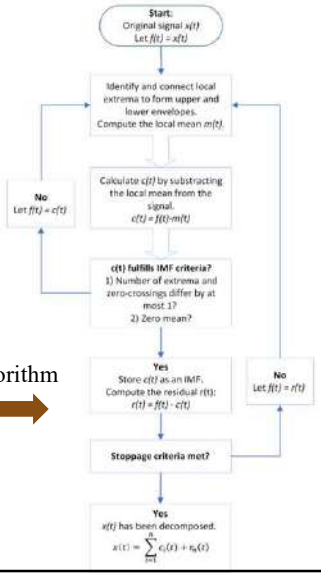
Damage indices:

$$DI_A = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}[IA(i) - \mu(IA)]^2}}{\mu(IA)}$$

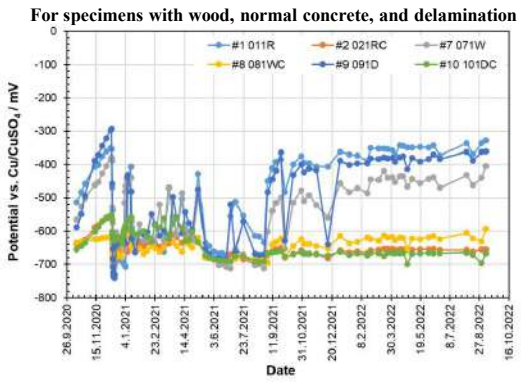
$$DI_F = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}[IF(i) - F_{probe}]^2}}{F_{probe}}$$

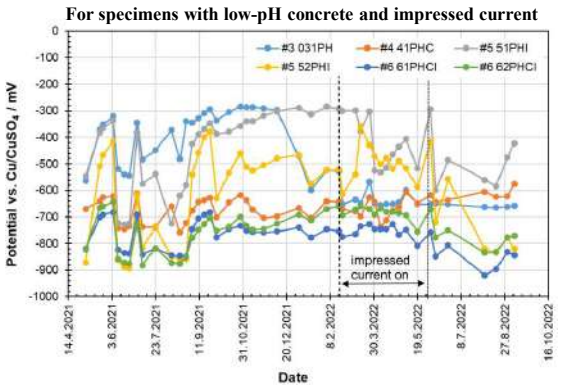
μ(IA) = average IA before impact

EMD algorithm



Results – OCP

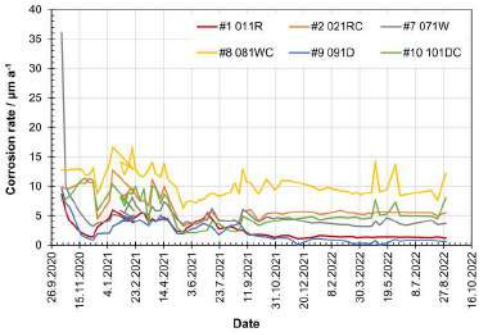




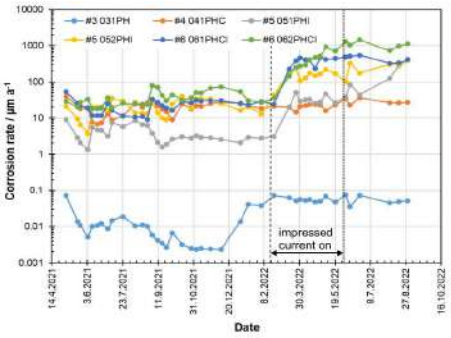
- Passive steel: -200 to 50 mV vs $Cu/CuSO_4$
- Corrosion due to carbonation: -200 to -500 mV $Cu/CuSO_4$
- Chloride-induced pitting corrosion: -400 to -700 mV vs $Cu/CuSO_4$

Results – Corrosion rate

For specimens with wood, normal concrete, and delamination



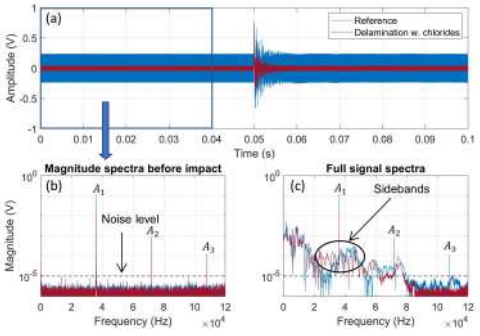
For specimens with low-pH concrete and impressed current

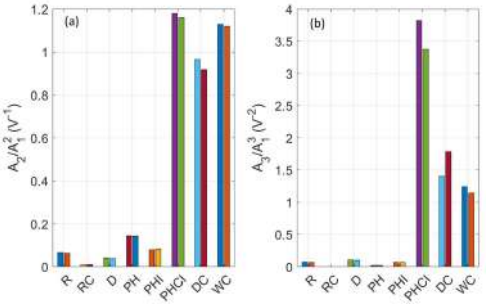


Low corrosion rate: **R, D, PH**
Medium corrosion rate: W, **WC**, **DC**, **RC**
High corrosion rate: PHC, **PHI**, **PHCI**

10

Results – Higher harmonics

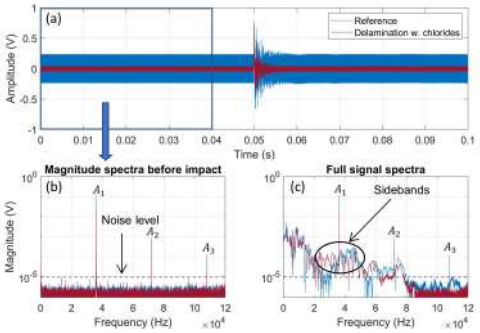


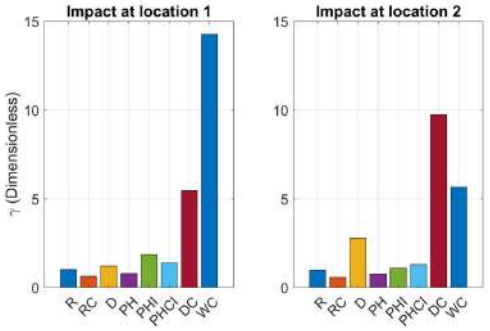


11

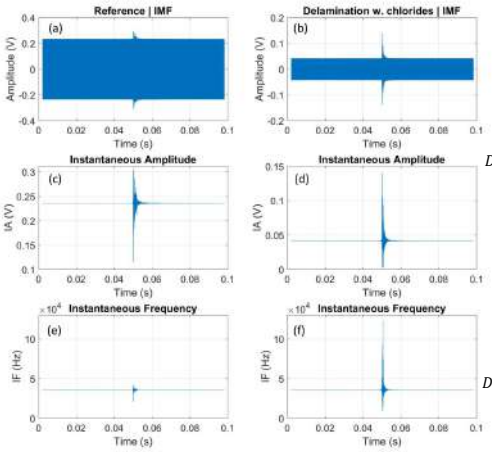
Modulation results – Frequency domain analysis

$$\gamma = \frac{E_{sideband}}{E_{probe}}$$





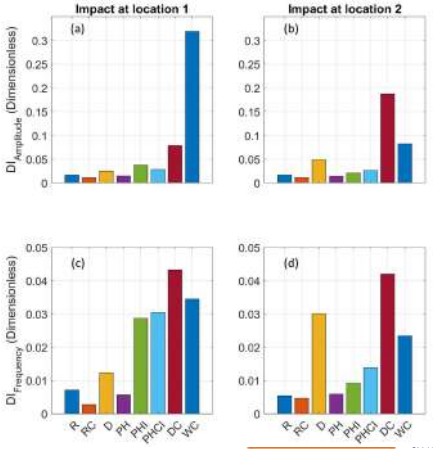
Modulation results – Instantaneous modulation



$$DI_A = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}[IA(i) - \mu(IA)]^2}}{\mu(IA)}$$

μ(IA) = mean IA before impact

$$DI_F = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}[IF(i) - F_{probe}]^2}}{F_{probe}}$$

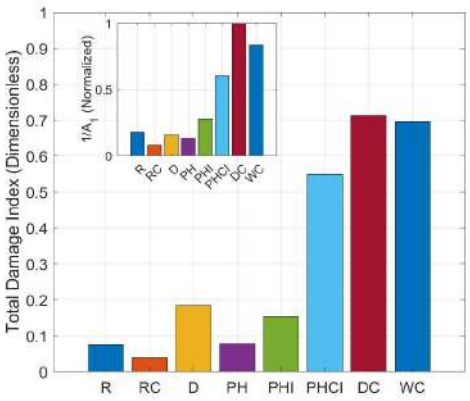


Results - Total Damage Index

- The Total Damage Index (TDI) is a combination of *N* normalized damage indices *DI*.

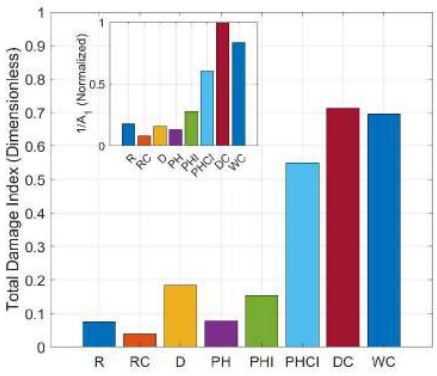
$$TDI = \frac{1}{N}\sum_{i=1}^{N} DI_i$$

- By combining several parameters into a single damage index, more than one phenomena is taken into account.



Corrosion characterization

Category	Maximum extent of corrosion, %	Specimens falling into the category	Example of steel plate surface after the test
No corrosion	0.1	R, D	
Minor corrosion	1	RC, DC	
Moderate corrosion	1-10	PH, WC	
Severe corrosion	>50	PHI, PHCI	



Conclusions

- OCP measurements and corrosion rate estimates indicated high corrosion risk for the specimens exhibiting strong signal distortion and acoustic attenuation.
- Specimens with minor and moderate corrosion (DC, WC) indicated similar corrosion potential and signal distortion as the specimen with the most severe corrosion (PHCI).
- Not all severely corroded specimens were identified using the presented methodology.

Thank you for your attention!

12. Automated Analysis of NDE Data incl. AI / ML (II)

The presentations in this session are listed in the table below.

Automated Analysis of NDE Data incl. AI / ML (II)	**Chair:** Leif Esp (EPRI)
Towards Deployment of AI-Assisted Ultrasonic Inspections in the Nuclear Power Industry	Thiago Seuaciuc-Osorio (EPRI) & Iikka Virkkunen (Trueflaw)
XAI for signal analysis of guided wave testing at pipe elbows	Toshihiro Yamamoto (JAPEIC) et al.
Evaluation of Assisted Data Analysis for Encoded Ultrasonic Examinations in Nuclear Power Plants	Richard Jacob & Jared Gillespie (PNNL)
Machine Learning Techniques for Detecting and Sentencing Surface Breaking Cracks using Ultrasonic Data	Channa Nageswaran & Xuening Zou (TWI)
Synthesizing Ultrasonic Data with Machine Learning	Terrill Massey (EPRI)

Towards Deployment of AI-Assisted Ultrasonic Inspections in the Nuclear Power Industry

Thiago Seuaciuc-Osorio[1], Iikka Virkkunen[2]

[1]EPRI, Charlotte, USA
[2]Trueflaw, Espoo, Finland

E-mail address (corresponding author): tsosorio@epri.com

Ultrasonic testing (UT) is the main volumetric inspection method employed in the nuclear power industry and form an essential part of the non-destructive evaluation (NDE) program of all plants. Many of the UT inspections performed in the field yield large volumes of data that need to be carefully reviewed by multiple qualified inspectors during an outage. Even though most of the data is benign, a detailed review of all data is needed, requiring inspectors to maintain high levels of focus for extended periods of time in an unfavourable environment.
To provide an aid to inspector in these analyses, EPRI and Trueflaw have developed machine learning (ML) tools that perform automated analysis of the data to flag suspicious regions for further review and screens out benign regions, thus greatly reducing the volume of data requiring human analysis.
We will discuss the value of such a tool and how it can benefit the industry in several ways, as well as present the numerous assessments performed to date that impart trust on it even under field conditions. Ultimately, we will showcase an example of a field inspection assisted by this tool which yielded the same outcome as traditional analysis even though the inspector reviewed only 2% of the data volume, and how qualification through performance demonstration is attainable following current practices.

Keywords: ultrasonic testing, machine learning, automated analysis, qualification.

Towards Deployment of AI-Assisted Ultrasonic Inspections in the Nuclear Power Industry

Thiago Seuaciuc-Osorio, EPRI
Sr. Technical Leader, Engineering

Iikka Virkkunen, Trueflaw
Managing Director

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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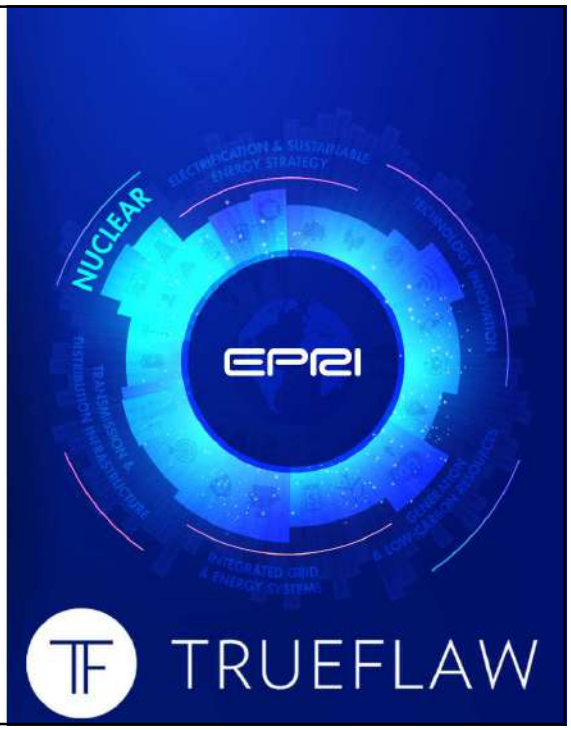

AI-Assisted Analysis of UT Inspections

- UT inspections are an important part of the scope of an NDE program
- Some inspections are challenging or have large volumes of data
- Machine learning tools can potentially **assist** in the analysis of the data
  - Increase reliability
  - Decrease analysis time
- *Assist* means AI flags regions for review: final decisions still rest with the qualified inspector.

***Goal:* Develop auto-analysis tools to assist in UT inspections**

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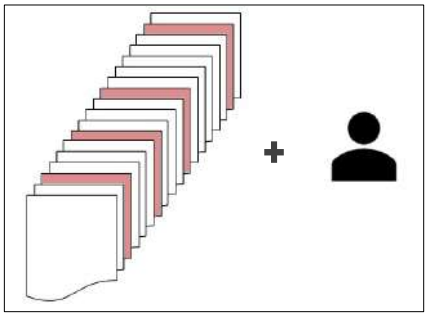
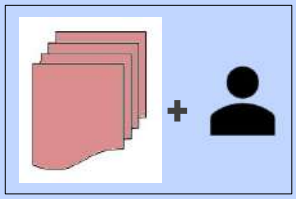
How Would AI Assist in UT Inspections?

- Current Inspection
  - Examiners distribute their energy across a high volume of (mostly benign) data



- AI Assisted Inspection
  - Examiners focus their energy on the regions that require more careful review, while AI takes care of the more monotonous portion



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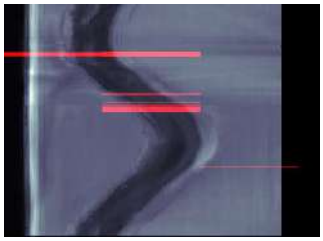
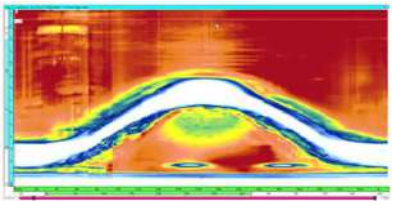
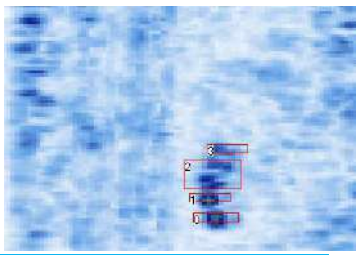
Deployment







1 UT data is saved in ML Box through local connection

2 Box automatically detects and processes UT data…

3 … and generates output for review

All data remains local; no SW needed

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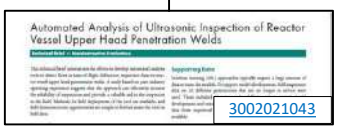
Timeline

OE study case shows promising results:
- Continue & improve
- Expand to DMW

2020 *Uncertain start*

Feasibility assessment:
- RVUH TOFD inspections

2021 *The promise*



3002021043

2022 *The breakthrough*

From lab to field:
- **First-of-a-kind field trial**
- Positive qualification outlook

NOTE: Models developed and trained from ground up based on raw NDE data.

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2022 Field Trial

EPRI

SUCCESS STORY

AI TOOL DEVELOPED BY EPRI SIGNIFICANTLY CUTS ANALYSIS TIME IN U.S. NUCLEAR PLANT FIELD TRIAL

Data analysis takes four hours compared to four days without artificial intelligence

A field trial at a U.S. nuclear power plant of an automated data analysis application being developed by EPRI has shown that the innovation offers not only substantial time savings but also a possible path to easing future staffing issues.

BACKGROUND: MILES OF DATA

During scheduled outages at nuclear plants, critical components are inspected for service-induced degradation. As part of the first-of-its-kind field trial at a U.S. plant in April 2022, ultrasonic inspection data from non-destructive evaluation (NDE) of 78 reactor pressure

EPRI staff performing AI-assisted analysis during the field trial. The orange box performs the analysis locally and produces the report for review.

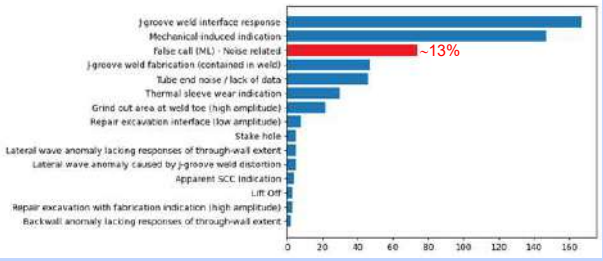
Success Story: 3002025510

AI-assisted analysis:
- Flagged **2%** of the volume for review (after on-site retraining)
- Flagged **all SCC** locations
- Yielded **same results** as the one from the qualified vendor

Amount of Data Requiring Review

Pre-AI		Post-AI	
4.4	miles	463	feet
7.0	km	141	meters

All values are approximate



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Qualification Prospects

- Looking at this as a “procedure” type:
  - Model should flag **all flawed regions** for review by inspector in “personnel” qual
  - Inspector has opportunity to detect all flaws
- Model was exposed to more than **5x** the amount of PDI data required for a traditional procedure qualification
  - Model accurately flagged flawed regions
    - Craze cracking
    - Axial, circ and off-axis oriented flaws
    - Small and large thru wall flaws
    - ID and OD surface connected

All observations point to AI being qualifiable when paired with human analyst

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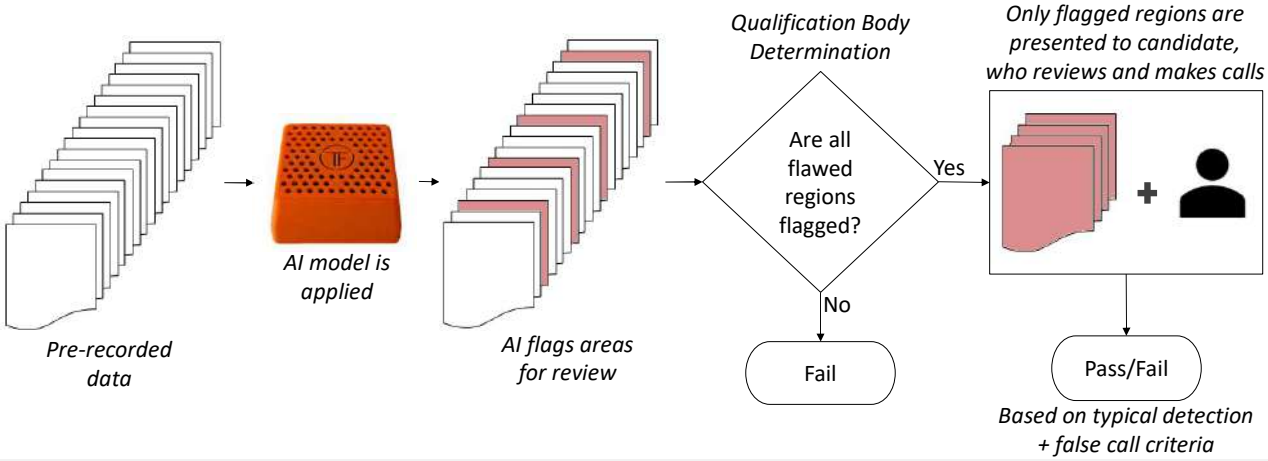
What initial qualification *may* look like

- Procedure would be updated to include a defined process for the AI evaluation
- AI algorithms for qualification would be developed and provided to the qualification body: model is **frozen** at this stage



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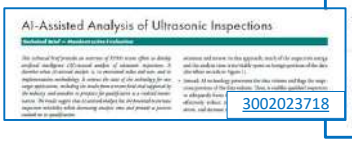
Timeline



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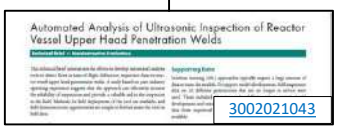
OE study case shows promising results:
- Continue & improve
- Expand to DMW

Improvements:
- Added field data (training)
- Indication identified

2020 *Uncertain start*

Feasibility assessment:
- RVUH TOFD inspections

2021 *The promise*



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2022 *The breakthrough*

From lab to field:
- **First-of-a-kind field trial**
- Positive qualification outlook

2023 *Confirmation*

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2023 Field Trial

- Another vendor, another site
- Model improved by added field data on training
  - Generalized well to previously unseen site conditions → *no need for site re-training*
- Additional model features
  - Pinpoints indication
  - Provides preliminary depth values
  - ➢ *Facilitates consistent data comparisons between sequential inspections*

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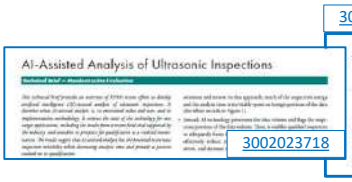
Timeline



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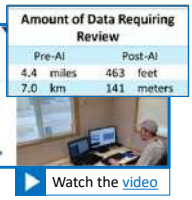
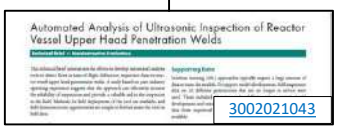


2020 *Uncertain start*

Feasibility assessment:
- RVUH TOFD inspections

2021 *The promise*

OE study case shows promising results:
- Continue & improve
- Expand to DMW



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2022 *The breakthrough*

From lab to field:
- **First-of-a-kind field trial**
- Positive qualification outlook

2023 *Confirmation*

Improvements:
- Added field data (training)
- Indication identified

2024

DMW Field Trial (Fall Outage)

NOTE: Utility staff, regulator site representatives, inspection vendors could all witness the field trials.

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DMW Application

Exhaustive data review

AI goes through *all channels* in detail…

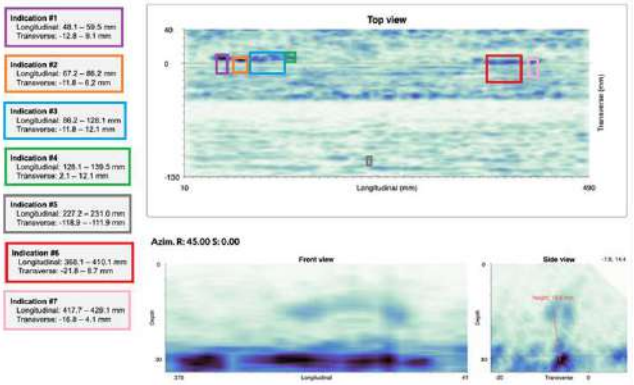
Detection

…*localizes* areas associated with flaws…

Consolidation

…and combines them into *indications*

C-Scan overview with Indication Table



- Model trained & validated on open samples
- Next steps
  - Evaluation against blind qualification data
  - Fine-tuning the reporting and workflow

AI highlights *indications* of interest for inspector review

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Envisioned Uses

Requires Qualification

- Credited as part of inspection as a required (secondary) review

Vendors can now develop procedures with AI-assisted analysis for qualification

Without Qualification

- To aid utility oversight
  - Utility staff data review
  - Facilitates data comparison
- To review previous outage data
  - Prioritize inspection order
  - Assess needed resources
  - Pre-job brief/prep

*Utilities can leverage these capabilities **NOW***

Inspection vendors are currently testing the AI box internally

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What's Next?

Additional Applications
- Core Shroud/Barrel UT
- Manual UT

Qualification Support
- Looking at qualification framework
- Driven by vendors

Deriving unanticipated value
- As we deploy the technology, new uses/values are identified
  - ➢Enables more efficient data comparison tools

Reliability Assessment
- (Human + AI) system as a whole
- Continue building **trust** in & **acceptance** of technology

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Conclusions

From an R&D perspective, the first AI-Assisted UT Analysis solution is deployment ready

Good qualification prospects

Building on the success factors so other applications can also leverage the benefits of the technology

Building trust in the technology with consistent performance and by exposing it to the industry through field trials

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XAI for signal analysis of guided wave testing at pipe elbows

Toshihiro Yamamoto[1], Takashi Furukawa[1] and Hideo Nishino[2]

[1]Japan Power Engineering and Inspection Corporation, Yokohama, Japan
[2]Tokushima University, Tokushima, Japan

E-mail address (corresponding author): yamamoto-toshihiro@japeic.or.jp

Abstract text (1/2 – 1 A4 page)

Guided wave testing can provide an efficient screening method for local wall thinning of piping owing to its long inspection range and its ability to inspect pipes with limited access (at height, buried, covered with insulation, etc.). Although the interpretation of echo signals to detect flaws is relatively simple in guided wave testing for straight pipes, geometric irregularities such as elbows, tees, and reducers make this interpretation much more difficult because these irregularities disturb the propagation of guided waves. On the other hand, local wall thinning such as liquid droplet impingement (LDI) erosion or flow-accelerated corrosion (FAC) often occurs around an elbow. Therefore, how to interpret echo signals is an important issue in applying guided wave testing to evaluation of local wall thinning of piping that includes an elbow.

In our past study, we conducted experiments of guided wave testing with the use of piping specimens that include an elbow and also their corresponding finite element method (FEM) simulations to investigate characteristics of echo signals due to a flaw at an elbow. As a result, we concluded that a flaw can be detected with high sensitivity in all parts of an elbow by guided wave testing using multiple frequencies and also that the position of a flaw may be estimated based on the frequency at which a strong flaw signal is obtained. However, a method to analyze echo signals remains an issue since echo signals obtained with multiple frequencies must be analyzed simultaneously.

This study investigates a signal analysis method that utilizes deep learning to evaluate local wall-thinning at an elbow based on echo signals in guided wave testing using multiple frequencies. To this end, we performed FEM simulations of guided wave testing to obtain training data for deep learning and considered the configuration of deep learning to analyze echo signals in guided wave testing. Moreover, we utilized Shapley additive explanations (SHAP), one of explanation techniques for machine learning, to provide reasoning for prediction results obtained by deep learning. Artificial Intelligence (AI) which can provide reasoning is called explainable AI (XAI).

Keywords: guided wave testing, pipe elbow, local wall thinning, deep learning, XAI

一般財団法人 発電設備技術検査協会

NDE in Nuclear 2023
27–29 June 2023
Cutlers' Hall
Sheffield, the United Kingdom

XAI for signal analysis of guided wave testing at pipe elbows

T. Yamamoto and T. Furukawa
Nondestructive Evaluation Center
Japan Power Engineering and Inspection Corporation

H. Nishino
Tokushima University

JAPEIC
JAPAN POWER ENGINEERING AND INSPECTION CORPORATION

Background

Guided wave testing can provide an efficient screening method for local wall thinning of pipes.

- Long range inspection (potentially more than 10 m)
- Ability to inspect pipes with limited access (covered with insulation, buried, etc.)

Problem in signal interpretation of guided wave testing

- Interpretation of echo signals is relatively simple for straight pipes.
- It becomes much more difficult when inspected piping includes an elbow because wave propagation becomes more complicated.

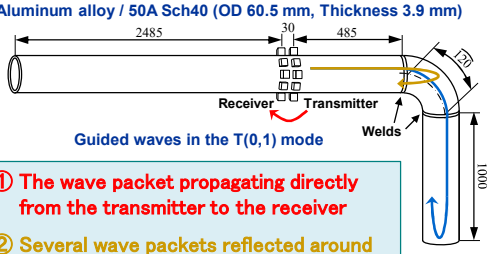
In actual application, local wall thinning frequently occurs around an elbow such as Liquid Droplet Impingement (**LDI**) or Flow Accelerated Corrosion (**FAC**).

Past study: Guided wave testing experiments

Laboratory experiments were conducted to apply guided wave testing to piping specimens that include an elbow.

Piping specimens

Aluminum alloy / 50A Sch40 (OD 60.5 mm, Thickness 3.9 mm)



Guided waves in the T(0,1) mode

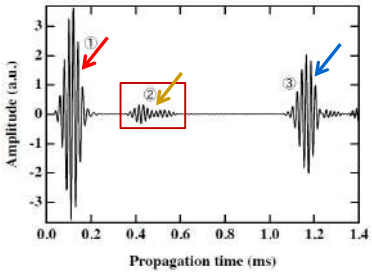
① The wave packet propagating directly from the transmitter to the receiver

② Several wave packets reflected around the elbow

③ The wave packet reflected by the lower end of the piping specimen

Received signals

Specimen without a flaw

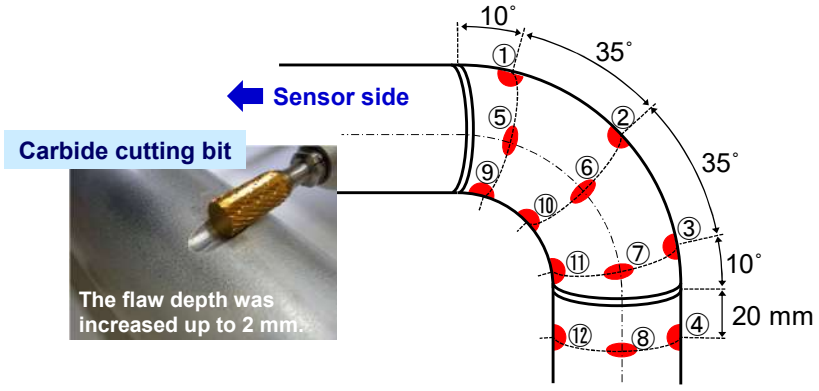


A signal variation due to a flaw at the elbow overlaps the signal ②.

T. Yamamoto, T. Furukawa and H. Nishino, "Frequency dependency of the defect sensitivity of guided wave testing for efficient defect detection at pipe elbows," Mater. Trans., 57 (3), pp. 397-403 (2016)

Past study: Flaw positions

12 piping specimens were prepared for **12 positions of a flaw**.

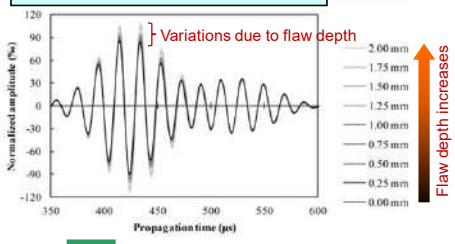


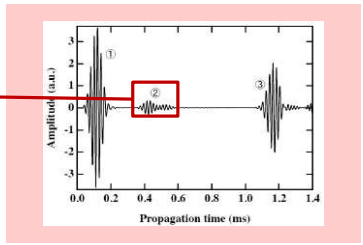
- Each piping specimen has a single artificial flaw at one of the 12 positions.
- The depth of each flaw was increased up to 2 mm.
- The echo signals were recorded for every 0.25 mm increase of the depth.

Past study: Signal variations due to flaw

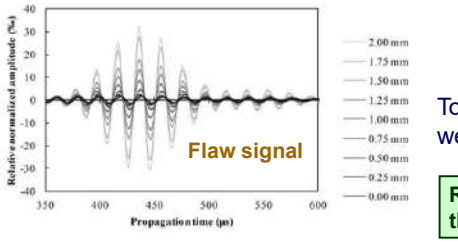
The signal variations due to the flaw depth are observed around the signal ②.

Frequency 50 kHz, Flaw position ①





Baseline subtraction



Baseline signals:
Received signals for a specimen without a flaw

To clarify the variations, the baseline signals were subtracted from all the received signals.

Received signals were normalized so that the amplitude of the signal ① becomes 1000.

Aim of this study

Knowledge obtained from our past study

- High flaw detectability is obtained throughout the elbow by guided wave testing using multiple frequencies.
- The flaw position can be estimated from the frequency at which a strong flaw signal is obtained.

Received signals obtained for multiple frequencies should be comprehensively analyzed.

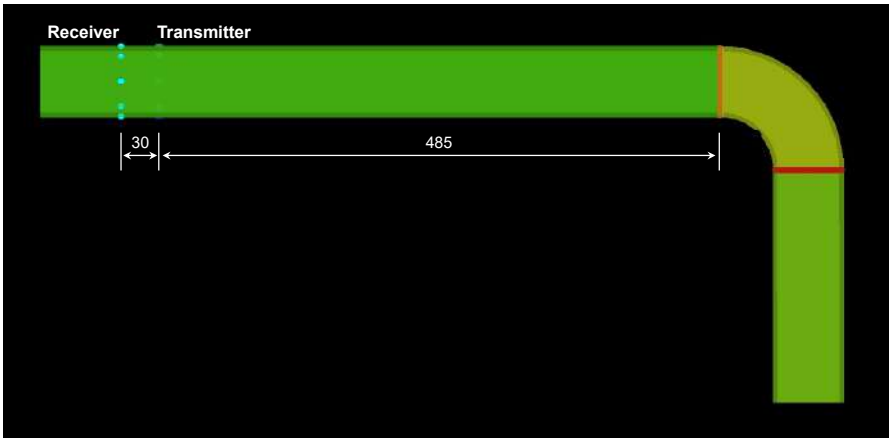
Deep learning is used to make the analysis more efficient and sophisticated.

In this study

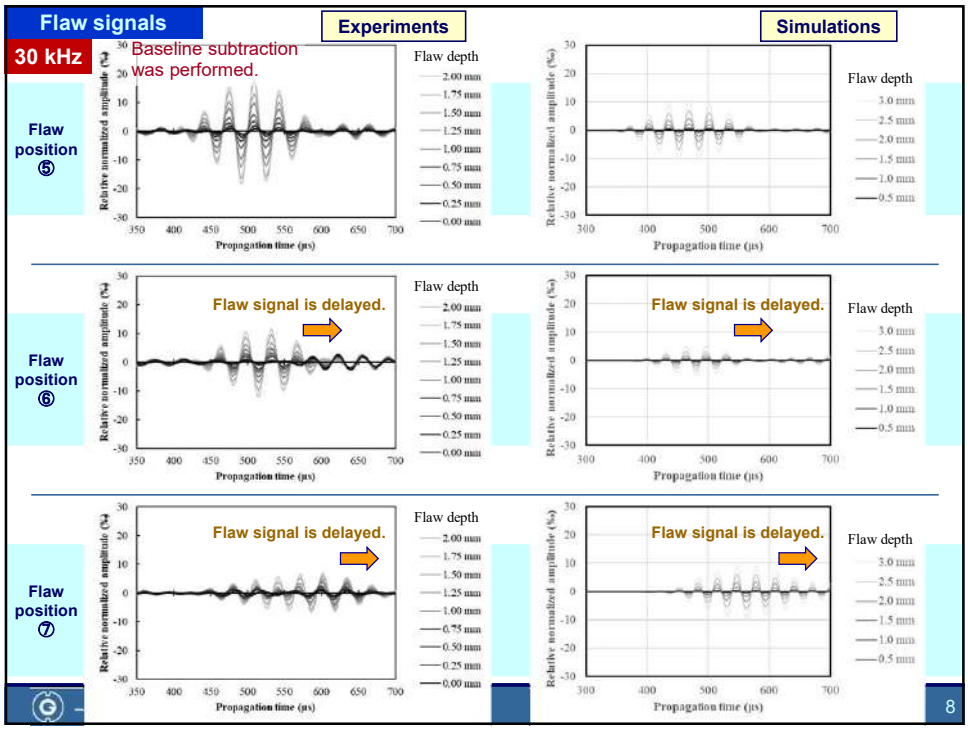
1. FEM simulation was conducted to prepare a number of training data.
2. The analysis of received signals was automated by deep learning.
3. The ability to provide reasoning for prediction results by deep learning was investigated by using SHAP.

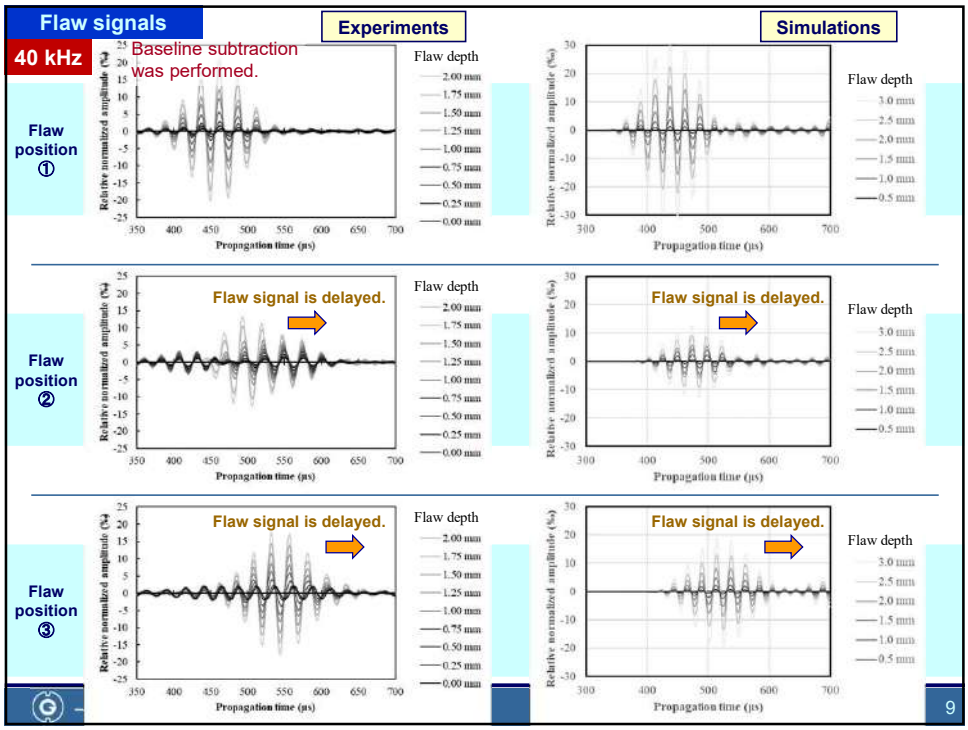
FEM simulation

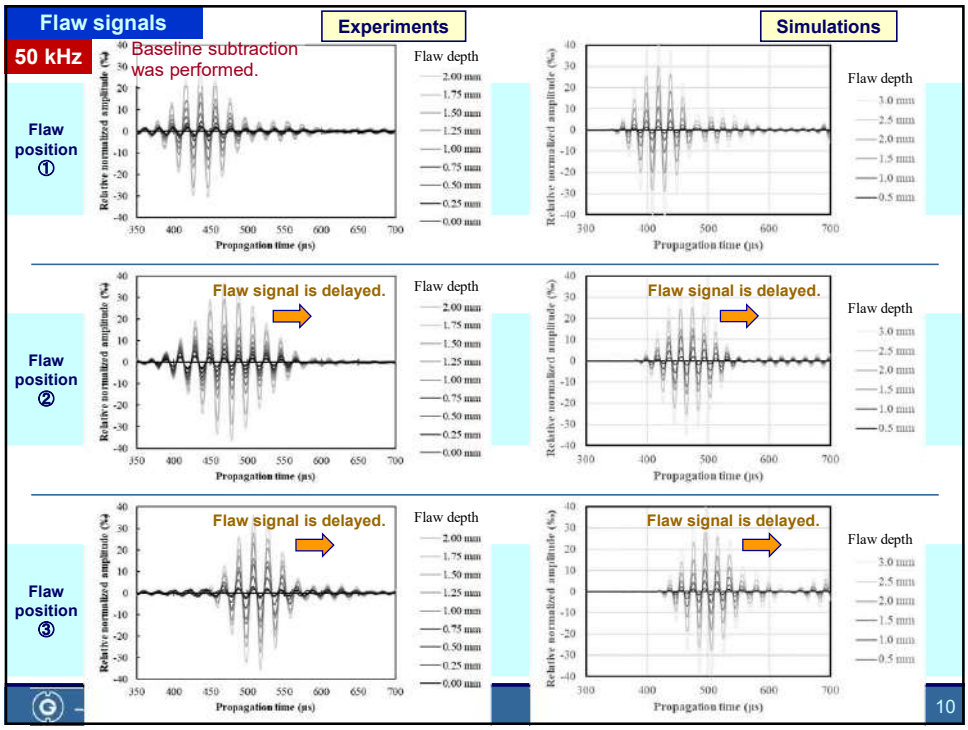
A shape model for FEM simulation was created to reproduce the past laboratory experiments (element size: 0.5 mm).



FEM simulation was performed with ComWAVE (ITOCHU Techno-Solutions Corporation).



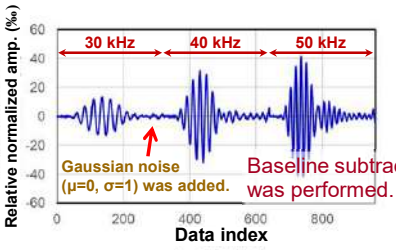

Flaw signals
Experiments
Simulations
40 kHz
Baseline subtraction was performed.
Flaw position ①
Flaw position ②
Flaw position ③
Flaw signal is delayed.
Flaw depth
Relative normalized amplitude (‰)
Propagation time (μs)
9


Flaw signals
Experiments
Simulations
50 kHz
Baseline subtraction was performed.
Flaw position ①
Flaw position ②
Flaw position ③
Flaw signal is delayed.
Flaw depth
Relative normalized amplitude (‰)
Propagation time (μs)
10

Function of deep learning system

Flaw signals of guided wave testing were used to make predictions by deep learning system.

Form of input data



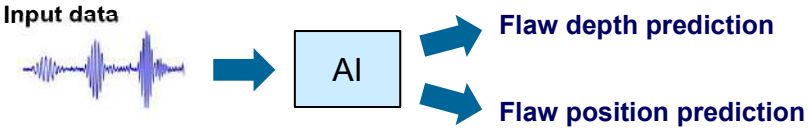
As the input data, the flaw signals obtained for three frequencies were connected for each combination of flaw position and depth.

noise

12 positions × 6 depths × 10 = 720

Training data: 460
Validation data: 116
Test data: 144

Function to be implemented



Specification of deep learning system

Used deep learning method

Libraries: TensorFlow + Keras (written in Python)

Category: Fully connected neural network

Intermediate layers: 4 layers (512 nodes for each)

Dropout: 20% for each intermediate layer

Mini-batch gradient descent: 32 in batch size

Loss function: Mean Square Error

Optimizer: RMSprop

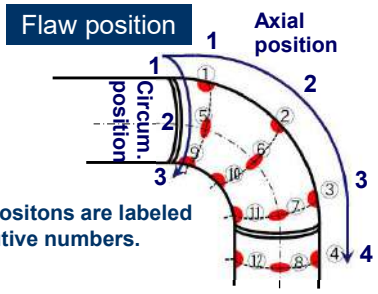
Early stopping: The error exceeds the interim minimum for 200 epochs in a raw

To obtain the prediction results as continuous values, prediction was performed to solve a

Regression problem*

*The other type is "classification problem".

Flaw position



Adjacent positons are labeled in consecutive numbers.

Explainable AI

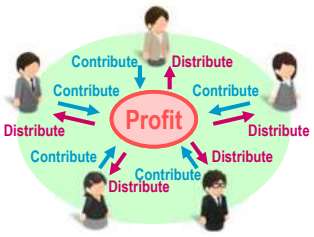
Explainable AI (XAI)

XAI can provide reasoning for prediction results obtained by an AI.

SHAP (SHapley Additive exPlanations)

SHAP is an explanation technique of machine learning using the notion of Shapley values in game theory.

Shapley values are used to fairly distribute profit among the players based on their contributions in a cooperative game.



In machine learning,

Players ⟶ ***Features of input data***

Profit ⟶ ***Prediction results***

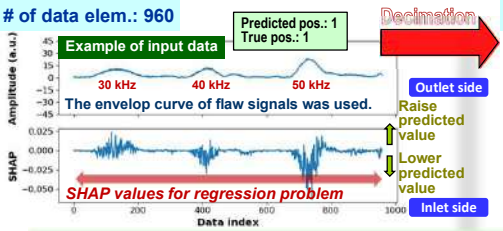
- **SHAP** has general versatility and can be applied to various machine learning techniques (including deep learning).
- **SHAP** has been implemented as a Python package and can be used in combination with scikit-learn or TensorFlow.

The prediction results for guided wave testing were analyzed by using SHAP.

Analysis of prediction results by SHAP

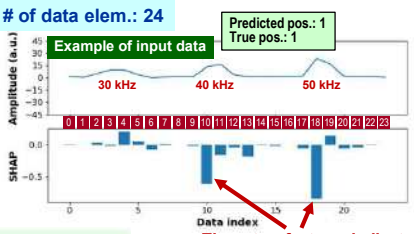
Prediction of axial position of flaw

# of data elem.: 960



Decimation

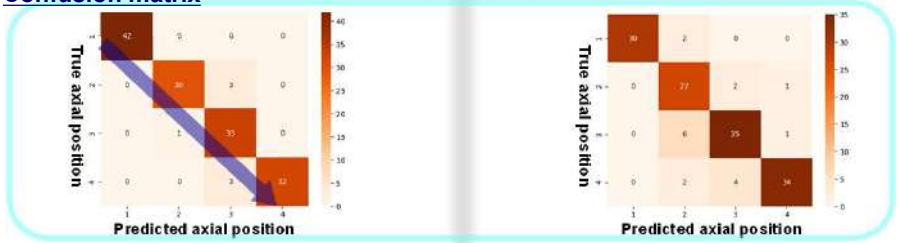
# of data elem.: 24



(predicted value) = (sum of SHAPs) + (mean of prediction values for all test data)

These two features indicate the flaw is nearer to the inlet of the elbow.

Confusion matrix



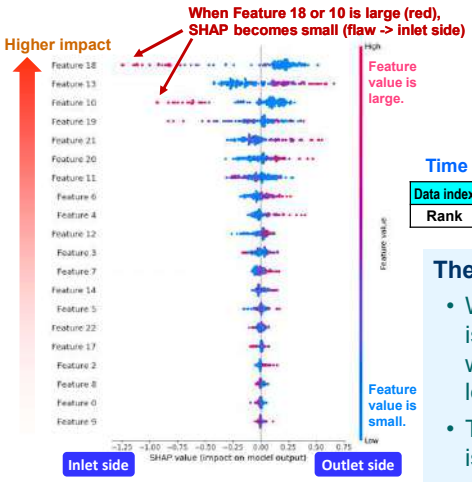
Decreasing data elements makes the analysis more understandable and does not necessarily decrease the accuracy.

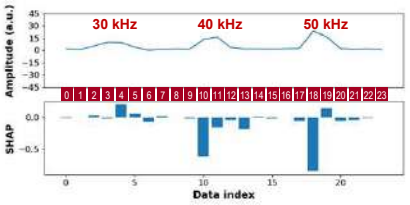
Global explanation (axial position)

SHAP can provide global explanation by using summary plot.

Prediction of axial position of flaw

SHAP—Summary plot





Time ➡

	30 kHz									40 kHz									50 kHz				
Data index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Rank				11	9	14	8	12			3	7	10	2	13				1	4	6	5	15	

The SHAP analysis results suggest

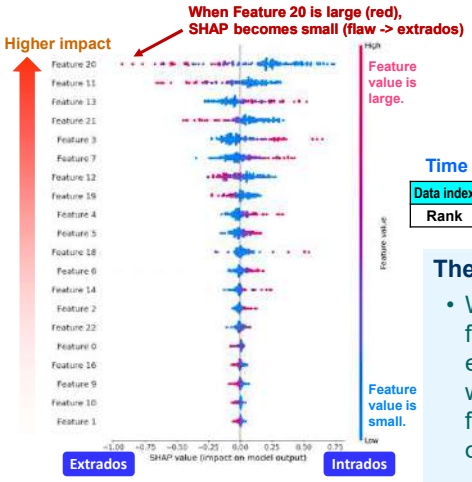
- When a flaw signal appears earlier, a flaw is located forward in the elbow;
  when a flaw signal appears later, a flaw is located backward in the elbow.
- The contribution of a flaw signal for 30 kHz is smaller.

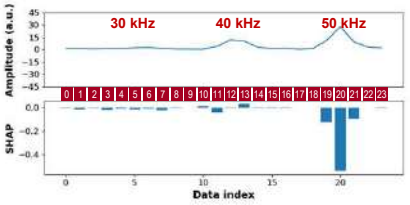
Global explanation (circum. position)

SHAP can provide global explanation by using summary plot.

Prediction of circumferential position of flaw

SHAP—Summary plot





Time ➡

	30 kHz									40 kHz									50 kHz				
Data index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Rank			14	5	9	10	12	6				2	7	3	13				11	8	1	4	15	

The SHAP analysis results suggest

- When a flaw signal has a large amplitude for 40 or 50 kHz, a flaw is located at the extrados of the elbow;
  when a flaw signal has a large amplitude for 30 kHz, a flaw is located at the intrados of the elbow.

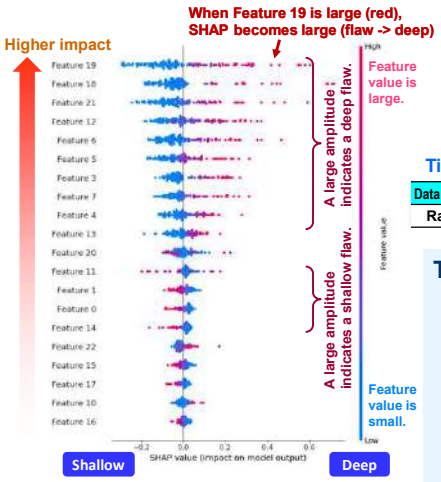
Global explanation (flaw depth)

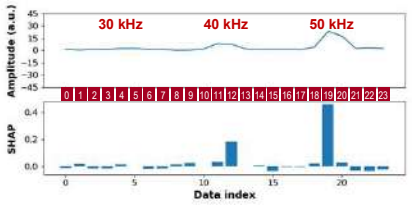
JAPEIC

SHAP can provide global explanation by using summary plot.

Prediction of flaw depth

SHAP—Summary plot





Time ➡

	30 kHz									40 kHz									50 kHz				
Data index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Rank	14	13		7	9	6	5	8				12	4	10	15				2	1	11	3		

The SHAP analysis results suggest

- Basically, when a flaw signal has a large amplitude, a flaw tends to be deep.
- However, there are some exceptions.

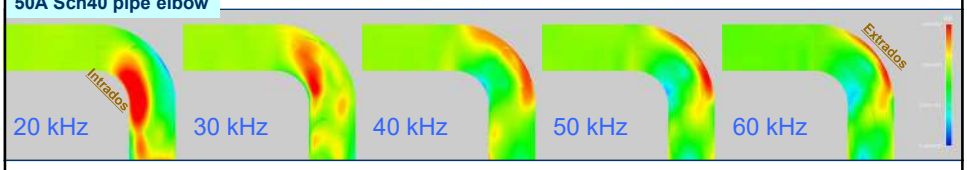
Known characteristics

JAPEIC

Past study:

Distributions of maximum magnitude of displacement obtained by FEM simulation

50A Sch40 pipe elbow



Lower frequencies

The maximum magnitude tends to be higher at the **intrados**.

Similarly,

The flaw sensitivity tends to be higher at the **intrados**.

Higher frequencies

The maximum magnitude tends to be higher at the **extrados**.

Similarly,

The flaw sensitivity tends to be higher at the **extrados**.

If you detect a flaw using 40 or 50 kHz, the flaw is supposed to be located at the extrados.
If you detect a flaw using 30 kHz, the flaw is supposed to be located at the intrados.

The SHAP analysis results basically support the observations made in our past study.

Summary

Prediction of flaw information for guided wave testing

- It was well implemented by deep learning as a regression problem.
- A neural network needs at least four layers for good prediction perhaps because signal analysis is rather complicated.

Explanation of prediction results

- SHAP can give the ability to provide reasoning for prediction results of deep learning models, which are often called “black box”.
- To make SHAP analysis results understandable, the number of data elements is preferred to be as small as possible.
- Moreover, because even 24 data elements make the analysis rather complicated, a well-organized analysis method is desired.

Future work

- Prediction from input data obtained in actual measurements based on training data obtained by FEM simulation

Evaluation of Assisted Data Analysis for Encoded Ultrasonic Examinations in Nuclear Power Plants

Richard E. Jacob[1], Jared Gillespie[1]

[1]Pacific Northwest National Laboratory, Richland, Washington, USA

E-mail address (corresponding author): Richard.jacob@pnnl.gov

Interest in automated or assisted data analysis is growing in the nuclear industry as the number of qualified inservice inspectors continues to decrease. Assisted analysis tools can help inspectors identify regions of interest for further evaluation and cut analysis time by reducing the amount of data to review. However, these benefits assume that the assisted analysis tools reliably identify all of the flaws, even if they capture some false calls as well. We have evaluated commercial off-the-shelf software packages designed to assist inspectors with data analysis. These software packages consist primarily of threshold-based algorithms and do not have machine learning algorithms. The objective of this work is to determine how well currently available software detects and sizes flaws compared to a human inspector. Fourteen circumferential flaws in five welded carbon steel and wrought stainless steel mockups were scanned with multiple line scans (i.e., translating the probe parallel to the weld). Eight of the flaws were electrical discharge machined notches and six were thermal fatigue cracks. Flaw through-wall depths ranged from 7% to 88%. Three phased-array probes were used in transmit-receive shear mode. The probe set comprised a 1 MHz matrix array, a 2 MHz matrix array, and a 4 MHz linear array.

Results show that the software was able to effectively detect all the intended flaws under conditions where the user optimized the threshold levels and where all line scans were considered. However, false calls were a significant problem. It was common for the software to flag indications from weld root, counterbore, and weld fabrication flaws in addition to other spurious signals. Altering the threshold level affected the detection rates, as lower thresholds caused lower false call rates but also lowered detection rates and vice versa. For example, with a threshold level of 25% full-screen-height, the detection rate was 91% but the false call probability was 97%. Conversely, for a threshold level 75%, the detection rate was only 39% while the false call probability dropped to 23%. In addition, considering only a subset of the line scans or just an individual line scan also decreased detection rates. The main challenge for amplitude thresholding is the software's ability to discriminate between noise and intended flaws. Currently, the high false call probability and variability that comes from user inputs such as threshold level make assisted data analysis impractical for inservice inspections. However, improvements in algorithms and the addition of machine learning tools suggest that assisted data analysis has strong potential for future applications.

Keywords: automated data analysis, assisted data analysis, ultrasonic inspections, encoded phased array ultrasound

Pacific Northwest NATIONAL LABORATORY

Evaluation of Assisted Data Analysis for Encoded Ultrasonic Examinations in Nuclear Power Plants

Richard E. Jacob and Jared Gillespie

Pacific Northwest National Laboratory
Richland, WA, USA
June 2023

This work was sponsored by the U.S. NRC
Carol Nove, NRC COR

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Motivation

- The number of qualified NDE inspectors in nuclear power plants is decreasing
- There is pressure for plant outages to be as short as possible
- As a result, there is a need to reduce the overall volume of NDE to be analyzed per outage
- An assisted or partially-automated approach can allow an inspector to analyze just a subset of data while confidently excluding data that does not require follow-up
- An assisted or automated approach should be able to pass performance demonstration requirements

2

Objective and Scope

- Evaluate the current capabilities of machine learning and assisted data analysis for NDE to provide a technical basis supporting the U.S. Nuclear Regulatory Commission in reviewing licensee submittals and evaluating proposed ASME Code actions
- Determine how assisted data analysis algorithms address flaw discrimination, detection, and characterization
  - Review literature to see what has been done
  - Assess current commercial options for usability and accuracy
  - Evaluate strengths, weaknesses, and capabilities of machine learning (ML) algorithms
  - Compare results to those of qualified inspectors
- This presentation will focus on commercially available rule-based software for assisted analysis

Assisted Data Analysis in NDE

- "Automated" and "assisted" are often used interchangeably in reference to NDE data analysis
- Automated analysis: not requiring direct human involvement
  - ML and "intelligent" approaches are heading in this direction, but they require further development
- Assisted analysis: used by analysts as a tool to expedite data analysis
  - Rule-based and threshold-based approaches are used to winnow down a data set to supplement (not eliminate) analyst involvement
- Various types of assisted NDE analysis can be performed
  - Data pre-processing
  - Defect detection
  - Defect characterization (position, depth, length, etc.)
  - Defect classification (flaw type)

The Path to Full Automation

- The automotive industry is a good example of the incremental steps between no automation to full automation
- Currently, UT data analysis for nuclear inservice inspections is at step 0
  - Field trials are being performed for an assisted analysis approach
- Rule-based assisted analysis would bring nuclear plant inspections to steps 1 or 2
  - This may mean reduced analyst involvement if the number of data sets requiring review is reduced
- Reaching full automation in nuclear plant inspections may not be feasible
  - Data requirements for training models
  - Costs for developing models or chasing down false positives
  - Potential risks to plant safety
  - Regulatory compliance

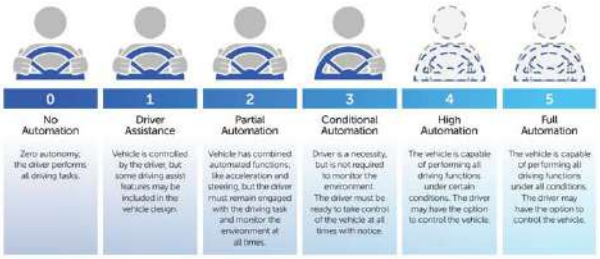


Image from U.S. Department of Transportation

Takeaways from Literature Review

- Most “automated analysis” described in the literature is actually assisted analysis
- Rule-based methods are easy to implement and can be used for simpler analysis but tend to be limited in scope
- ML is more prevalent for more sophisticated analyses
- Research in ML is growing rapidly, but relevant experimental data for training machine learning algorithms is extremely limited
- There are currently no standardized methods of quantifying performance and uncertainty of rule-based approaches

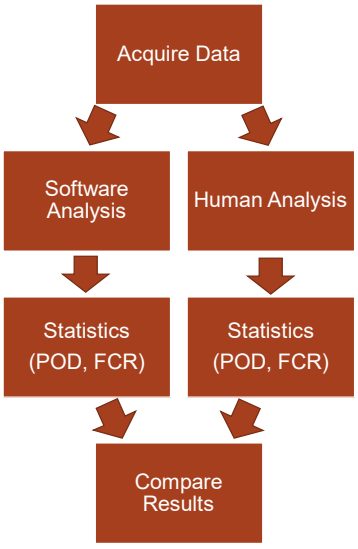
Commercially Available Software

- Our scope is to evaluate the assisted analysis capabilities of commercially available software
- Many data acquisition platforms have software for some level of assisted analysis
  - Most of the software take similar approaches to analysis
  - Proprietary methods can be difficult to evaluate because it is not clear what the algorithms are doing
- What types of capabilities are advertised?
  - Identify data issues like dropout and loss of couplant
  - Indicate areas of interest based on specific, user-selected criteria such as a weld profile
  - Generate a report showing potential flawed locations for analyst review

7

Experimental Approach

- Acquire an appropriate dataset to evaluate commercially available assisted data analysis software
  - Satisfy any software data requirements
  - Cover a range of different specimens, probes, and flaws
- Analyze the data using automated data analysis software
- Evaluate the results based on the documented flaw information
  - Label data as hit (true detection) or miss (false call)
  - Calculate probability of detection (POD) and false call rate (FCR)
- Compare results to those of a qualified ASNT Level III UT inspection



8

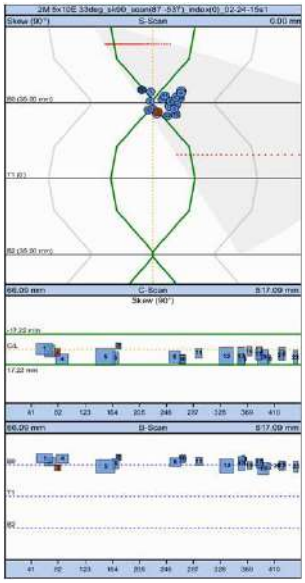
Data Acquisition

- Three Probes
  - Phased array probes in transmit-receive shear configuration
  - 1 MHz and 2 MHz matrix arrays and 4 MHz linear array
- Five mockups
  - 3 carbon steel (CS) pipe sections, 25 mm thick
  - 2 wrought stainless steel (WSS) mockups, 32 mm – 38 mm thick
    - ✓ One plate mockup
    - ✓ One pipe section mockup
- 14 Flaws, all circumferential
  - 6 Thermal fatigue cracks in the wrought mockups
  - 8 EDM notches
    - ✓ Two in each CS section
    - ✓ Two in the WSS pipe section
  - Through-wall depths ranging from 7% to 88%
- Encoded data were collected using an OmniScan MX2
  - Line-scan acquisition (probe motion parallel to the weld)

9

Analysis Software

- The assisted analysis software had specifications on specimen material, specimen thickness, range of probe frequencies, wave mode, and scan resolution
- We evaluated performance within the software specifications and outside the specifications
- The reported detections were primarily based on amplitude and location
  - User provides an amplitude threshold
  - User enters a weld profile and part geometry
- The software reported flaw metrics including: signal intensity, position, length, and location relative to the ID surface

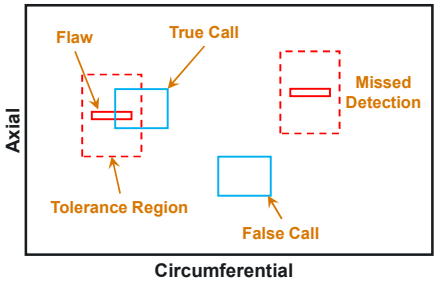


Screenshot showing all the indications identified by the software in a single line scan

10

Grading Criteria

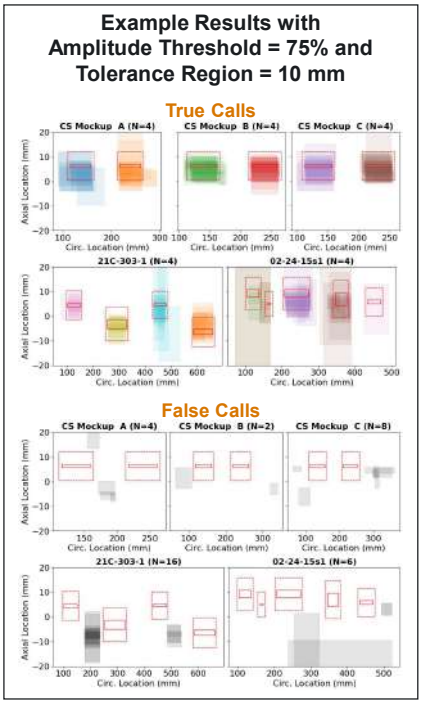
- Flaw true-states were taken from the specimens' documentation
- Circumferential and axial tolerance regions were used to define the grading units
- A true call was recorded when the reported flaw intersected a tolerance region
- A false call was recorded when the reported flaw did not intersect a tolerance region
- A missed detection was recorded when no reported flaw intersected the tolerance region
- Grading criteria were implemented as per "Results of Blind Testing for the Program to Assess the Reliability of Emerging Nondestructive Techniques" NUREG/CR-7235 (2017)



11

Analyzing Results

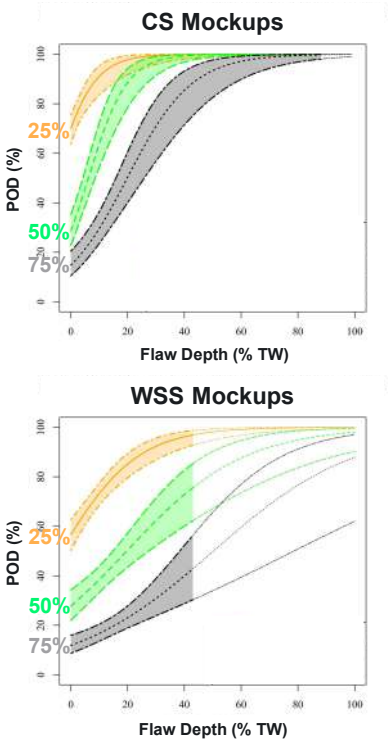
- Each true call was correlated with the corresponding flaw
- We adjusted the threshold parameter and the tolerance region
- Adjusting the threshold required a balance between including too many false calls and excluding too many true calls
- Adjusting the tolerance regions required a balance between accepting false calls as true calls and vice versa
  - A 10 mm tolerance showed best results



12

Probability of Detection

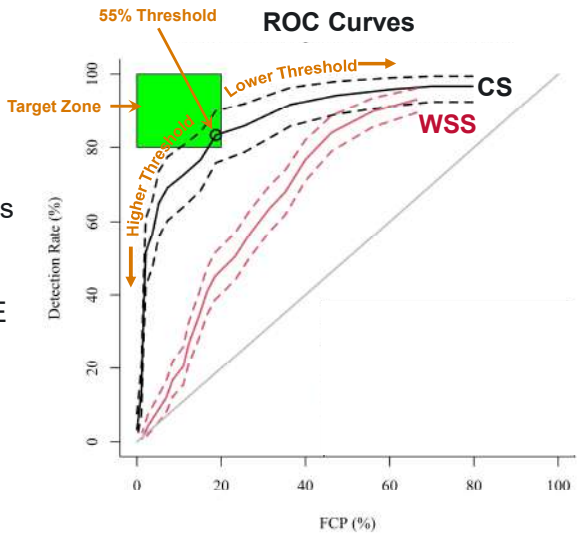
- The amplitude threshold has a large impact on POD and FCP
- Initially, amplitude thresholds of 25%, 50%, and 75% were considered
- POD curves for the CS and WSS specimens show that the POD increases with decreasing amplitude threshold
  - Lower thresholds are less discriminating, so more indications are reported
  - More reported indications also means more false calls
- Selecting the amplitude threshold is arbitrary and requires some trial-and-error to optimize results



13

Receiver Operating Characteristic (ROC) Curves

- Detection rate and false call probability were calculated for threshold levels from 20% to 100% in 5% increments
- ROC curves were calculated
- Separating CS and WSS specimens shows the performance difference between materials
  - 55% threshold level was found to be the optimal threshold in this case
- Would this rule-based method pass an ASME Section XI, Appendix VIII performance demonstration test?
  - MAYBE for CS, and only with carefully optimized settings



14

Takeaways from Rule-based Method

- Flaws are readily detected using rule-based methods
  - High detection rates can be achieved
  - Rule-based methods are good at finding indications but poor at discriminating between true flaws and other signals
- Rule-based methods can return many false calls
  - Most false calls were associated with component geometry, such as weld root and counterbore
  - The amplitude threshold has a large impact
  - Too many false calls will not help an analyst save time
- The threshold and other parameters need to be carefully adjusted to optimize performance
  - Performance is dependent on material type and may depend on other factors such as probe frequency, flaw type, flaw location, flaw size, etc.
- Rule-based methods may be well suited for CS exams
  - Are there enough CS exams in the nuclear industry to warrant investment in such tools?
- Discriminating between geometry, noise, and actual flaws is difficult
  - Rule-based methods cannot make complex decisions
  - Learning-based methods are likely needed for flaw discrimination

15

Ongoing Work

- Compare results across different software platforms
- Compare assisted analysis results to those of an ASNT Level III UT inspection
- Determine limitations of rule-based assisted analysis tools
  - Material types?
  - Inspection methods (phased array, full matrix capture, conventional UT)?
  - Flaw types?
- Compare rule-based tools to machine learning approaches

16

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Machine Learning Techniques for Detecting and Sentencing Surface Breaking Cracks using Ultrasonic Data

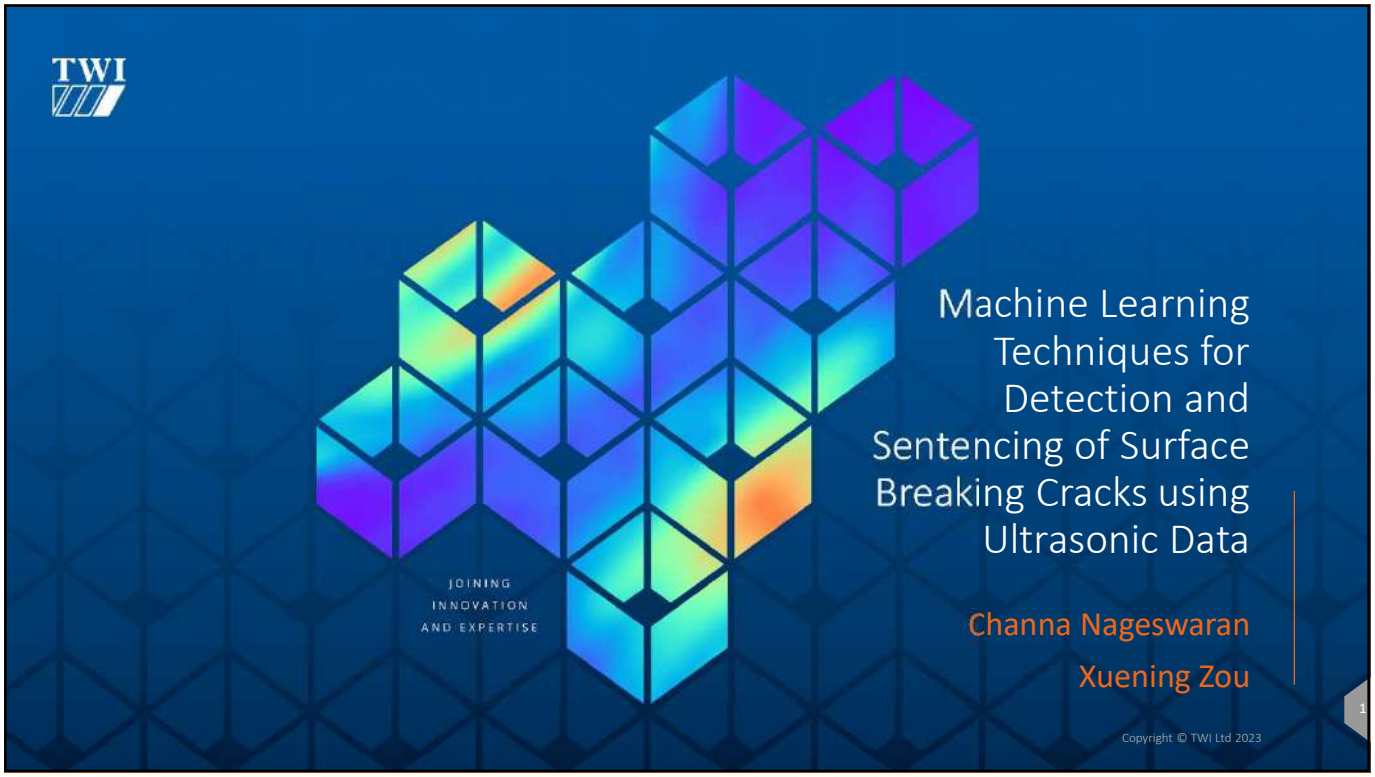
Channa Nageswaran and Xuening Zou

TWI Ltd, Great Abington, Cambridgeshire, UK

E-mail address (corresponding author): channa.nageswaran@twi.co.uk

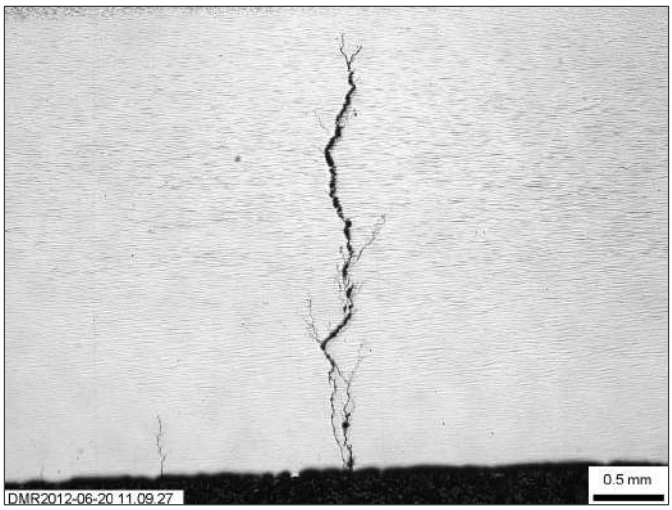
Surface breaking cracks such as stress corrosion cracks and thermal fatigue cracking occur in nuclear power plants. They are straightforward to detect if the surfaces on which they are initiated can be inspected using methods such as visual and dye penetrant testing. However, it may not be possible to access the affected surfaces such as the insides of pipes and vessels. In such scenarios, ultrasonic testing can be a viable approach and has been shown to not only be effective in detecting the cracking, but also characterise and size their extent within the component. Modern ultrasonic techniques generate large amounts of data that can take a long time for data interpreters to analyse, which has cost implications for industry as well as quality issues surrounding personnel training, competence and fatigue. Modern machine learning (ML) techniques based on neural networks offer an avenue to help process large amounts of ultrasonic data rapidly. This talk will present and discuss a case study to explore and understand the capabilities and limitations of ML techniques for ultrasonic inspection, including strategies to validate and qualify them as a component of ultrasonic inspection systems and procedures, following guidance in ENIQ RP 13.

Keywords: Cracks, Machine Learning, Ultrasonic, ENIQ.



Content

- Industrial scenario
  - Stress corrosion cracking
  - Thermal fatigue cracking
- Ultrasonic inspection techniques
  - Full matrix capture (FMC) data
- Machine learning (ML) techniques
  - Neural networks
- Goal
  - Aid/automate detection & sentencing
- System validation and qualification
  - ENIQ RP 13



Source: TWI Members Report 1091/2017

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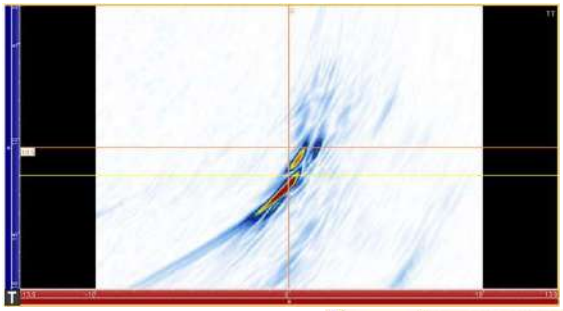
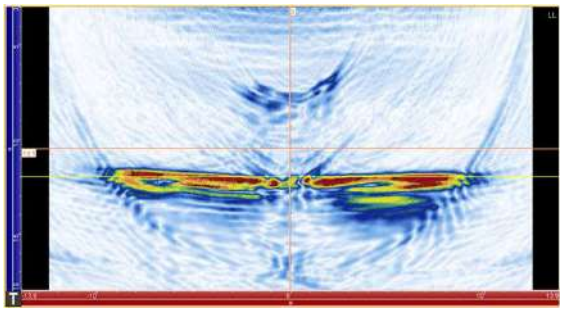
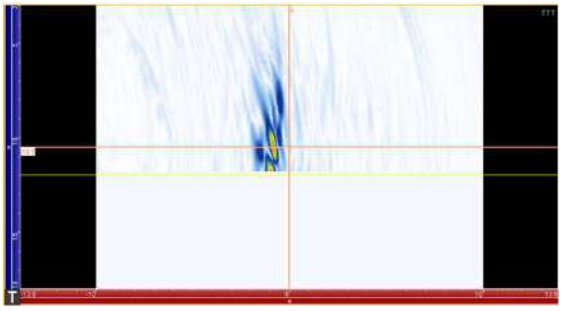
2

Ultrasonic imaging techniques







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Challenges

- Data
  - Statistical and ML (particularly deep neural network models) require large datasets
  - Training complex models can lead to ‘fitting’ issues, especially with limited data
- Dimensionality
  - Measurements in ultrasonic inspection involve many dimensions
    - Time-series resolution/duration, image size/resolution, probe/flaw position/orientation
  - Current approaches use amplitude thresholds, time-of-flight, spectral features
- Features
  - Different flaws/types – SCC clusters for example – are complex for an ML system
  - Hence, feature engineering is necessary, but difficult for ultrasonic inspection

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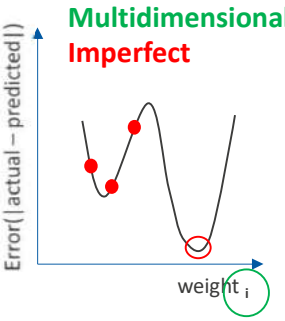
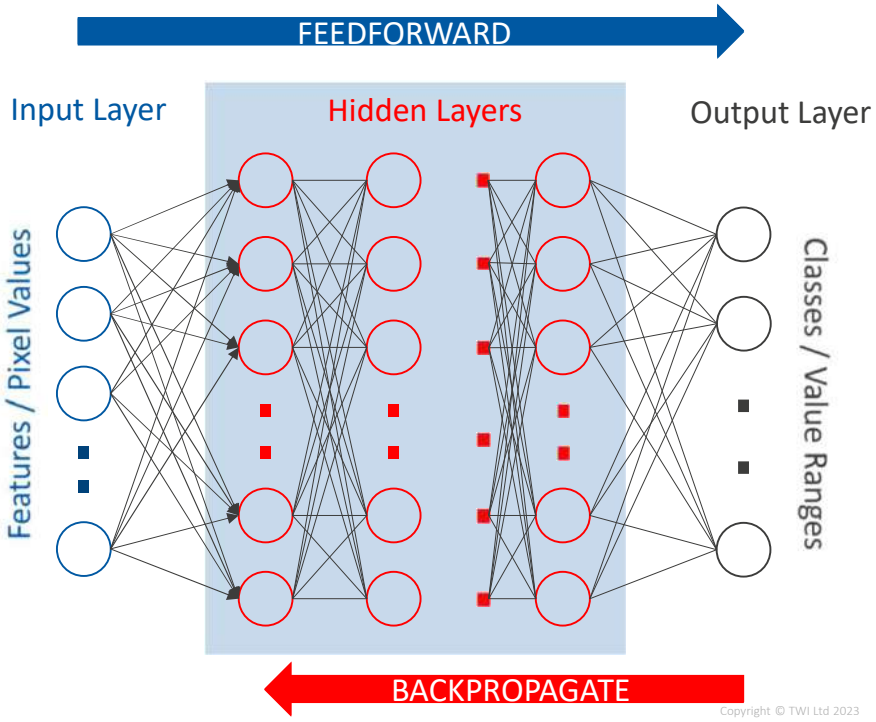
Neural Networks





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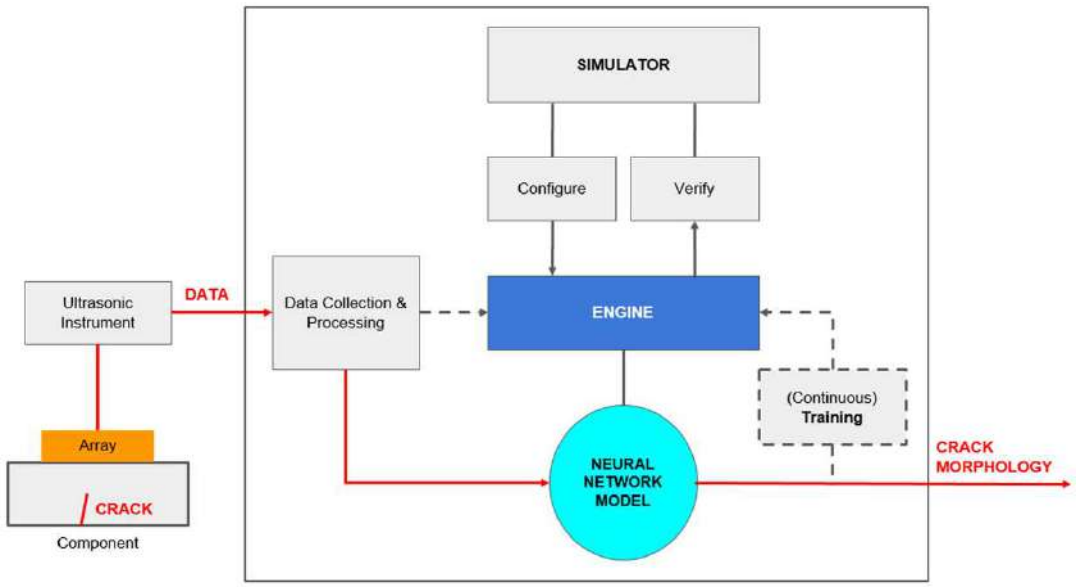
System architecture



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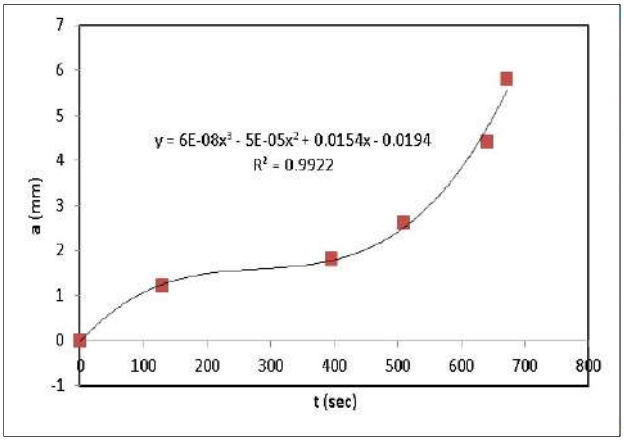
Case study: Artificial Neural Networks (ANNs) for fatigue cracks

- **State** = trained parameter values
  - Fundamental – **it is the state that is qualified**
- A 'toy' imaging technique – snooker
  - Aids conditioning for neural networks
  - Provides feature engineering
  - AI for UT Webinar Recording – YouTube
  - Preprint
- ANN model for illustration:
  - Neurons per layer = 30
  - Number of layers = 3
  - Activation = **sigmoidal**
  - Model function = **through-wall size**
  - Trained parameters = 34192
- Monitoring fatigue crack growth
  - Relevant to many industries



Source: Measuring the growth rate of a fatigue crack - YouTube

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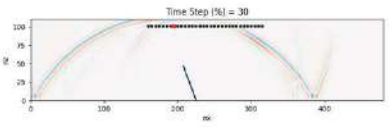
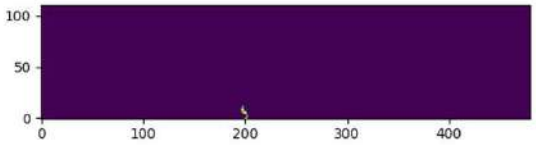
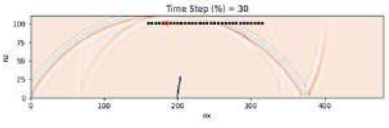
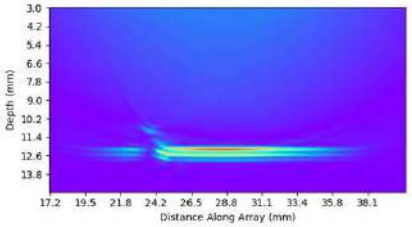
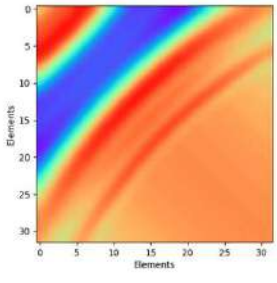
Configuring using simulation

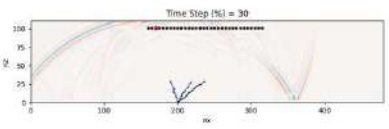












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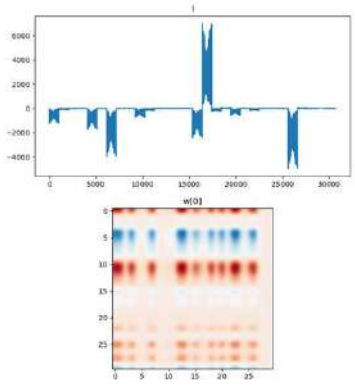
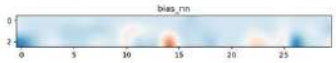
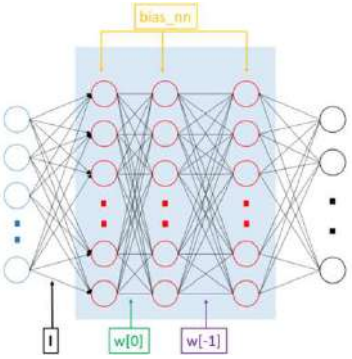
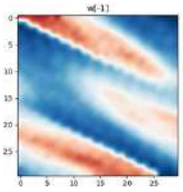
Visualising state transitions

Training: 5000 models
Verification: 585 models
Changing through-wall height, tilt, offset
Experiment: <50 samples



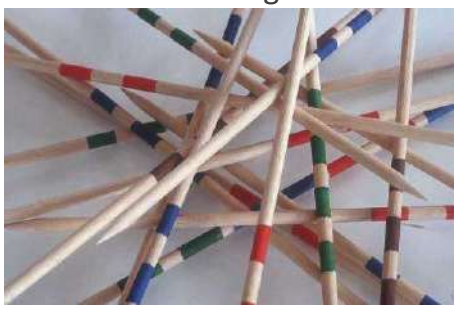






Experiment

Continuous training …??!!!



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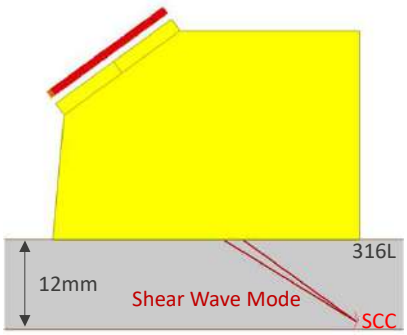
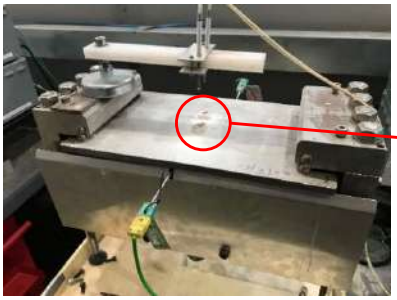
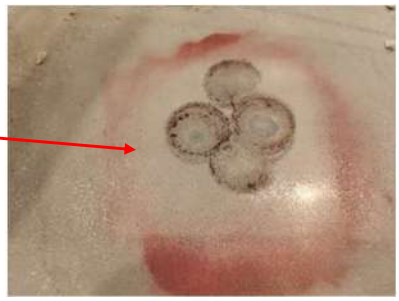
Case study: Convolutional Neural Networks (CNNs) for SCC



Parameter	Range	Step	Number
TWE (mm)	0.5 to 3.5	0.2	15
Offset (mm)	-10 to 10	1	20
Non-cracked	Below threshold		50
Total number of models = 15 x 20 + 50 = **350**			





Parameter	Plate 1	Plate 2	Plate 3
Number of critical cracks	3	8	4
Critical crack samples	50	160	70
Non-critical crack samples	30	90	60
Total	80	250	130
Total number of samples = 80 + 250 + 130 = **460**			

SIMULATION ⟷ EXPERIMENT

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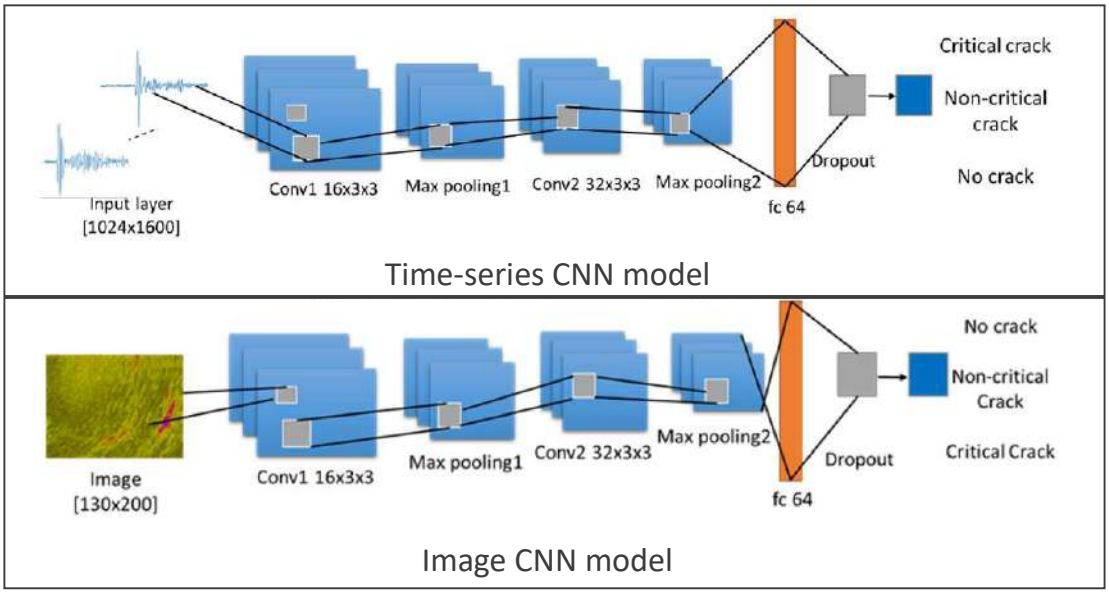
Standard CNN setup for time-series and images



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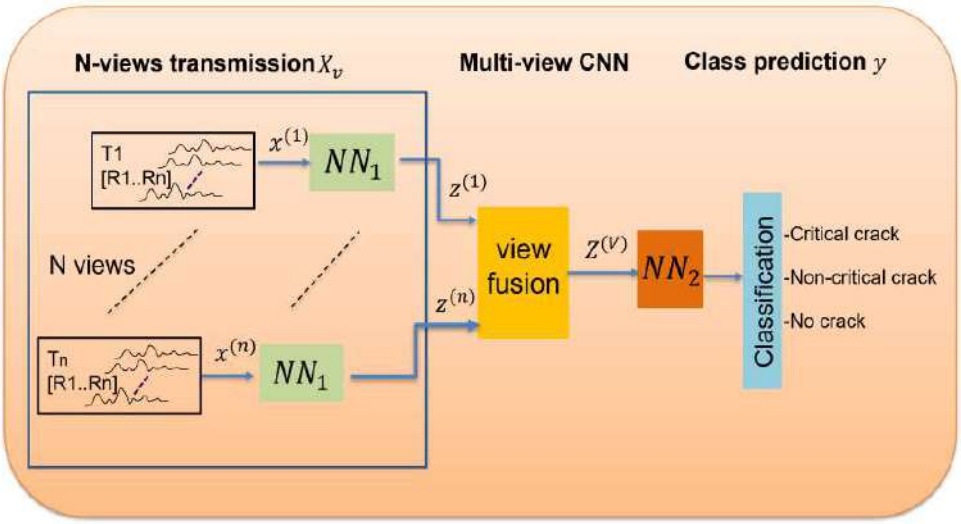
Multi-view CNN

- Reduced training parameters
- Concepts based on pair-wise coherence (neuroscience)
- Sped up using parallel computing
- Increased scope to interpret the ML system by checking the NN outputs



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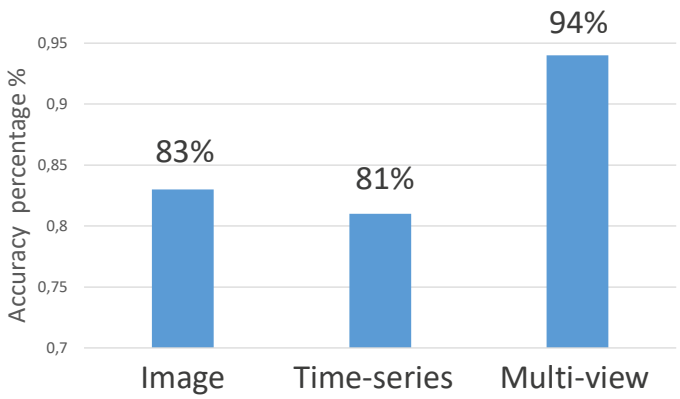
Performance



Type	Image CNN model	Time-series CNN model	Multi-view CNN model (stride=1)
Trained parameters	3 million	323 million	12 million

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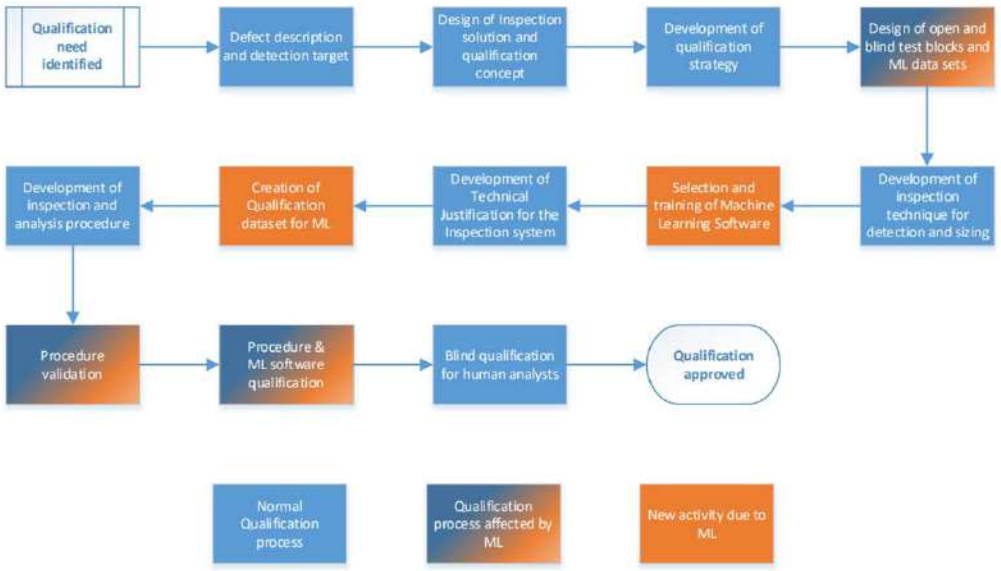
Qualification of the ML system



Source: ENIQ RP13 Issue 1

Validation Team (VT) with Data

Model Development Team (MDT)

Machine Guardian (MG)

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Concluding remarks

- Evidence indicates detection, classifying severity and sizing is possible;
- Some level of dimensionality reduction and feature engineering is necessary to process the rich FMC dataset – otherwise it is heavy for ML;
- Once ML model is built it can be deployed on edge devices, but continuous training is anticipated, hence reasonable computing requirements required;
- Case studies were done using limited number of samples aided by simulation - robustness of the models in field implementation is unknown;
- Are there better neural network architectures for ultrasonic inspection?

- **Prize?**
  - **An <u>autonomous</u> automated inspection system!**

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Channa Nageswaran
EngD, CEng FIMechE, PAUT Level 3
Technology Consultant (UT, AI)

Non-destructive Inspection Services

channa.nageswaran@twi.co.uk

Synthesizing Ultrasonic Data with Machine Learning

Terrill Massey[1], Mark Dennis[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): tmassey@epri.com

The objective of this research is to investigate the creation of synthetic ultrasonic testing (UT) data using emerging developments in artificial intelligence (AI) deep learning tools such as autoencoders (AE), variational AEs (VAEs), and generative adversarial networks (GANs). During this research, a synthetic UT data generator will be proposed. This tool will use a trained and optimized deep learning model to produce synthetic UT data in real time.

The innovation in this research is realized in the method used to generate synthetic UT data. Currently, the only methods that have been used in our industry to generate UT data are from physics-based modeling and simulation software. This research attempts to use existing UT data to generate synthetic UT data using advancements in AI and deep learning.

The value in this research is realized in the proposed UT synthetic data generator. Each time the proposed generator would be called, a new, unique set of data could be produced. This could potentially provide an endless supply of synthetic UT data that could be implemented into NDE training and realistic UT simulations that could support industry applications. The results of this research could save the NDE industry a significant amount of resources that have been traditionally dedicated to UT data collection and mockup fabrication.

Keywords: Non-Destructive Evaluation, Artificial Intelligence, Deep Learning, Ultrasonic Testing, Data Processing

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Synthesizing Ultrasonic Data with Machine Learning

Terrill Massey, EPRI
Technical Leader, Plant Support / NDE Program

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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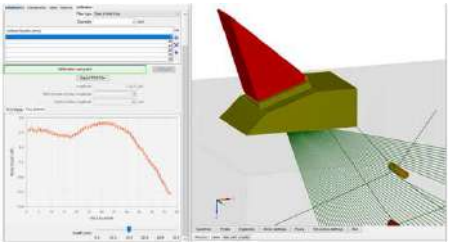
Research Problem Statement

- UT data is paramount for activities such as NDE training(i.e. Data analysis, Hands-On-Practice with the EPRI UT Simulator).
- Currently in industry, there are only two methods to generate UT data:
  - Collect data on a physical sample with an encoding setup.
  - Create simulated data via simulation and modeling tools (i.e. CIVA).
- Collecting data on a physical sample may be costly and time consuming to fabricate and prepare. Also, there may be limited access to the physical sample.
- Creating simulated data via simulation and modeling tools is also time consuming due to limiting factors in computing performance. Also, simulated data may not appear fully realistic.



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Research Objective and Scope

- The objective of this project is to investigate the creation of synthetic ultrasonic testing (UT) data using recent developments in artificial intelligence (AI) deep learning tools such as Generative Adversarial Networks (GANs).
  - This project focuses on the generation of 1-dimensional UT data referred to as A-scans.
  - This project utilizes GANs for generation of synthetic a-scans.
- Value of using AI to Synthesize UT data is shown through:
  - An endless supply of synthetic UT data for NDE training and studies.
  - Realtime creation of synthetic UT data. This will be faster than collecting real UT-data and using simulation software for simulated UT data.
  - Synthetic UT data will contain realistic features (i.e. real noise, material interactions, etc.)
- While outside the scope of this initial effort, this approach is not limited to ultrasonic data

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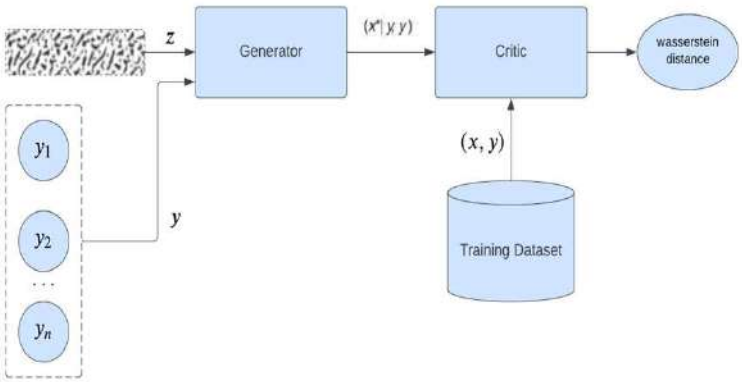
CWGAN AI Model and Validation Explanation



Model Performance was Characterized by:

- **Mean and Standard Deviation** : The mean and std. deviation of the real data was compared to the mean and std. deviation of the synthesized data.

- **Normalized Average Power Spectrum Difference (Normalized Average PSD):** Used to compare the difference between the real A-scans and synthesized A-scans in the frequency domain.

The following classes were used for A-scan generation in the CWGAN:

- **Class 1:** SS with probe frequencies less than 1.5 MHz
- **Class 2:** SS with probe frequencies between 1.5 MHz and 3.0 MHz
- **Class 3:** CS with probe frequencies of 2.25 MHz and 5.0 MHz.

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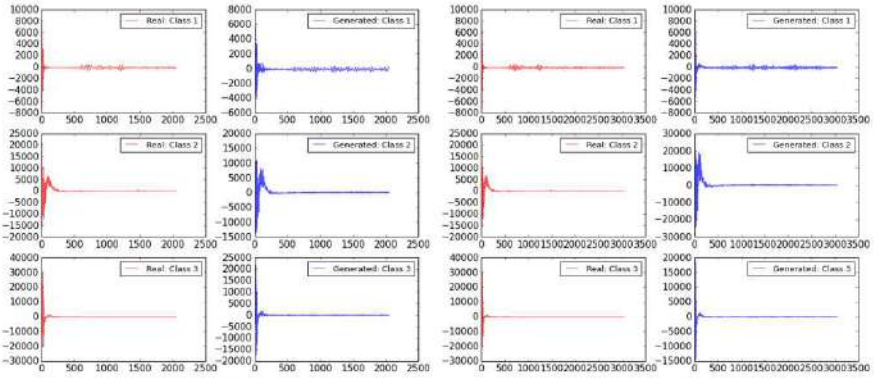
WGAN and CWGAN Test Cases and Validation

- WGAN and CWGAN models with various configurations were tested and compared.

Model name	A-scan Length
WGAN - 2048	2048
WGAN - 3050	3050
WGAN - 3968 - 1	3968
WGAN - 2048 - 2	2048
WGAN - 3050 - 2	3050
WGAN - 2048 - 3	2048
WGAN - 3050 - 3	3050
CWGAN - 2048	2048
CWGAN - 3050	3050

- Example of Standard Deviation and Mean of the real A-scans compared to the generated A-scans.



(b) Model CWGAN - 2048 (b) Model CWGAN - 3050

Mean generated vs mean real A-scans for different classes.

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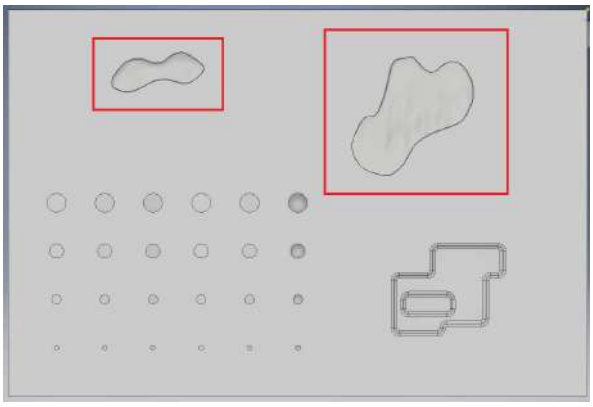
Corrosion Block A-scan Generation

- Acquired several A-scans from a 0.75in (19.1mm) thick aluminum plate with two simulated corrosion defects using a 10MHz/0.375in(9.5mm) diameter transducer in contact.
- Trained and updated the AI models to produce synthetic responses (see next slides for examples of signals from corrosion):
  - Train the CWGAN architecture on UT data collected on a corrosion block.
  - The CWGAN model is trained for synthesizing two classes of A-scans from the corrosion block data – corrosion and backwall.



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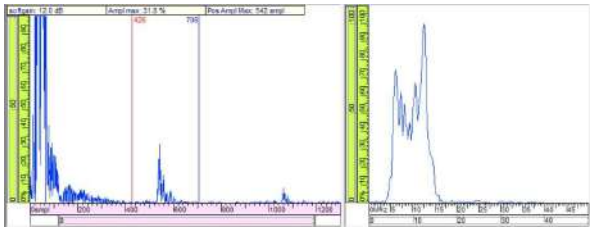
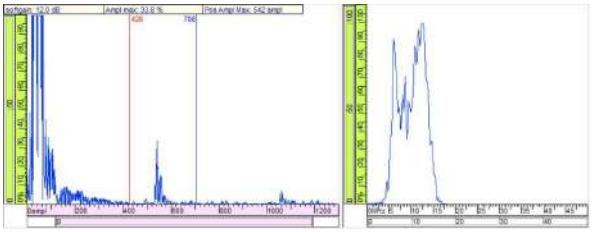
Corrosion A-scan Example 1





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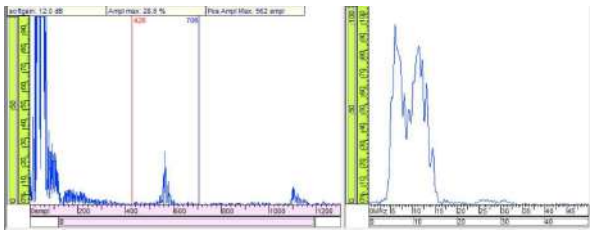
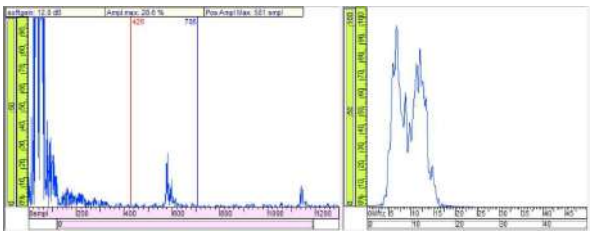
Corrosion A-scan Example 2





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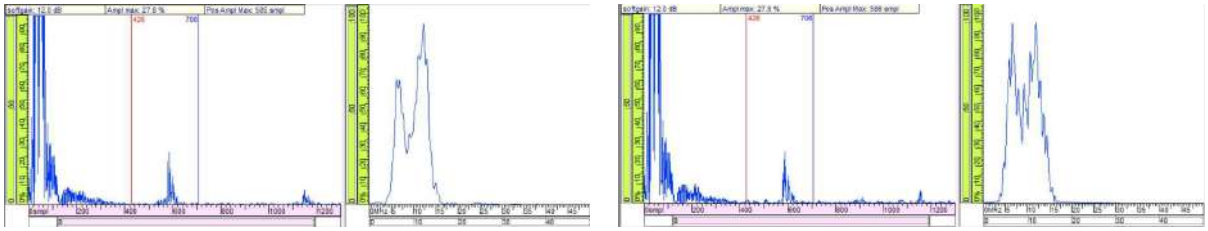
Corrosion A-scan Example 3



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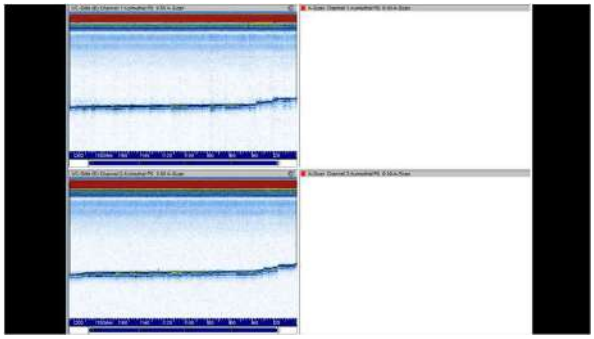
Summary

- A study was performed on machine learning techniques capable of synthesizing UT datasets.
- The WGAN and CWGAN implemented in this study were able to generate realistic looking A-scans with a non significant amplitude difference with real A-scans.
  - Note that for the corrosion A-scan study, an experienced ultrasonic level III technician was asked to distinguish between A-scans generated by the AI model and real A-scans collected on the physical corrosion block. The technician was unsuccessful in doing so and stated that both sets of A-scans looked similar.
- Another corrosion block has been fabricated and will be used for additional training and validation data.
- The final project deliverable will be available in Q4-2023 or Q1-2024



One Corrosion Dataset is Real, the other is Generated by the CWGAN AI Model.

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EPRI

13. NDE Reliability & Qualification (I)

The presentations in this session are listed in the table below.

NDE Reliability & Qualification (I)	**Chair:** Jeff Weed (CANDU Owners Group)
Baffle to Former Bolts Inspection in Spain: Procedure & Ultrasonic Data Analysts Qualification	Ignacio Real (Iberdrola) & Jose Ramon Gadea (Tecnatom)
Round Robin Tests for WWER Heat Exchange Tubes	Michal Benak, Roman Krajčovič (VUJE) et al.
ENIQ Inspection Qualification for the UK Civil Nuclear New Build	Chris Curtis (IVC)
ENIQ based Inspection Qualification of novel techniques (FMC case study)	Miles Weston (TWI) & Stavros Avramidis (IVC)
Update of CEX-120 Methodology for Qualification of Non-Destructive Testing used in the In-Service Inspections of Spanish Nuclear Power Plants	Ignacio Real Rubio (Iberdrola) & Francisco Javier Campaña Martín (Tecnatom)

Baffle to Former Bolts Inspection in Spain: Procedure & Ultrasonic Data Analysts Qualification Process

Ignacio Real[1], Jose Ramon Gadea[2]

[1]Iberdrola Energia Sostenible, Madrid, 28033, Spain
[2]Tecnatom, San Sebastian de los Reyes (Madrid), 28703, Spain

E-mail address (corresponding author): jireal@iberdrola.es

Baffle to Former Bolts (BFB) are part of the Westinghouse design, PWR reactor vessel internals. They are required, according to ASME, to undergo a visual inspection every ten years regarding to structural integrity. Any nuclear power plant that wants to increase its operational life beyond the design defined 40 years life expectation, needs to develop an Aging Management Program. This Program requires BFB to be inspected by ultrasonic, looking for cracks inside the bolt.

Procedures to be used on these UT inspections need to be qualified according to EPRI Materials Reliability Program (MRP) and Nuclear Regulatory Body requirements. The Spanish case required the procedure to be qualified under CEX-120, Spanish Qualification Methodology (an ENIQ type one). Additionally, to the inspection procedure qualification, it is required to qualify the analysis personnel using a blind test type examination procedure.

In the present work, inspection procedure and personnel qualification work will be described, including sample manufacturing, UT data generation, exam development, etc.

Keywords: personnel qualification, blind test, NDE, phased array UT, BFB, RPV internals

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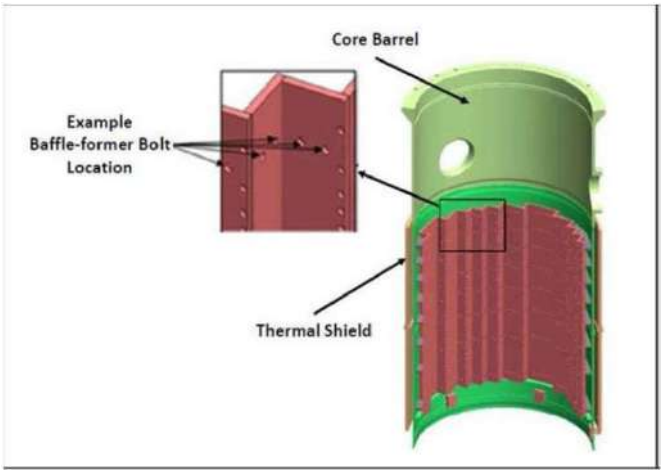

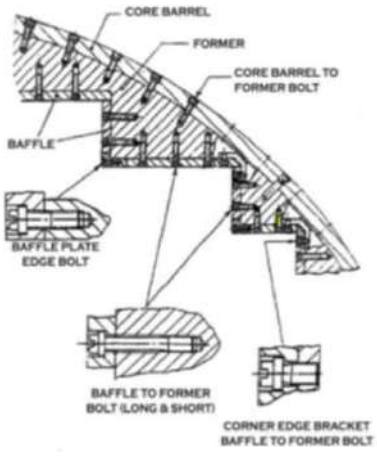

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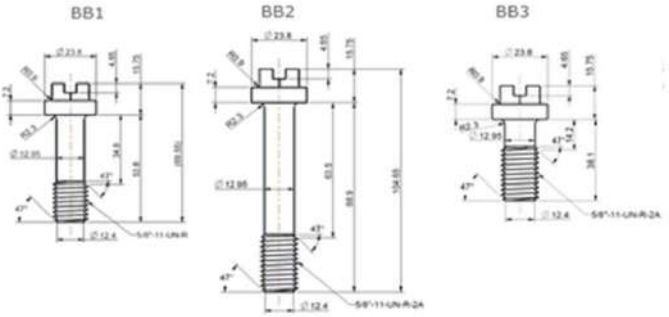

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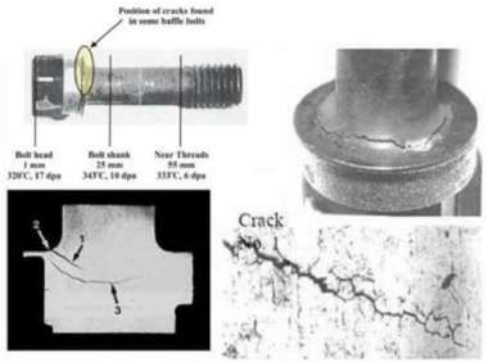

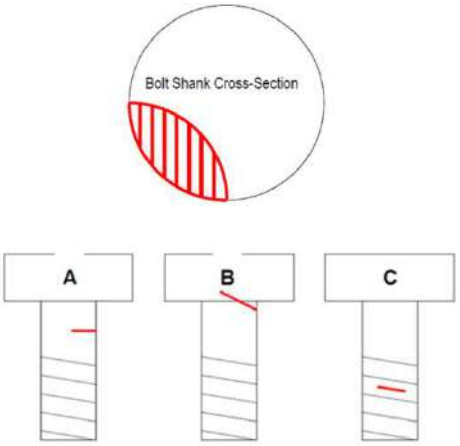

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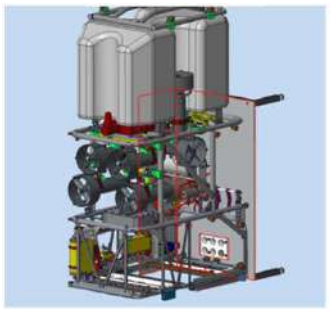

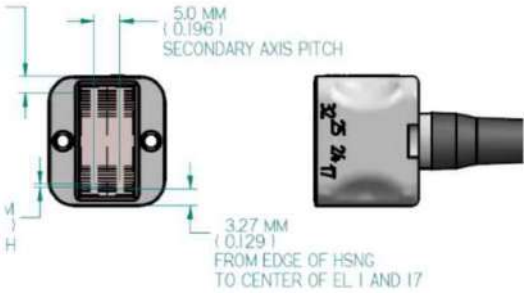

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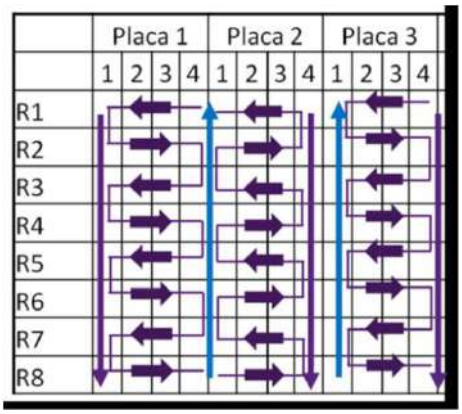

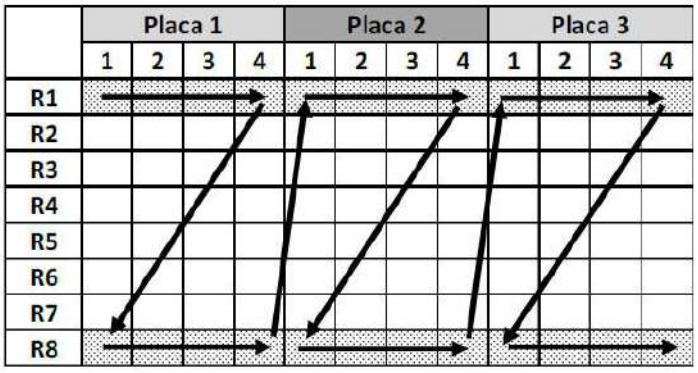

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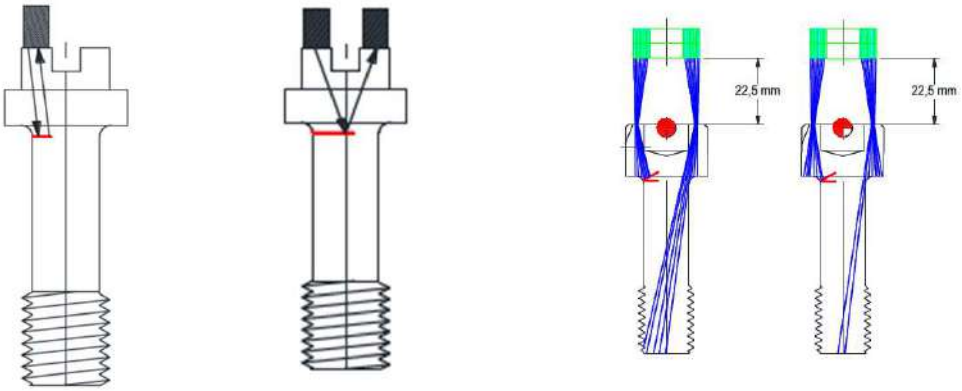

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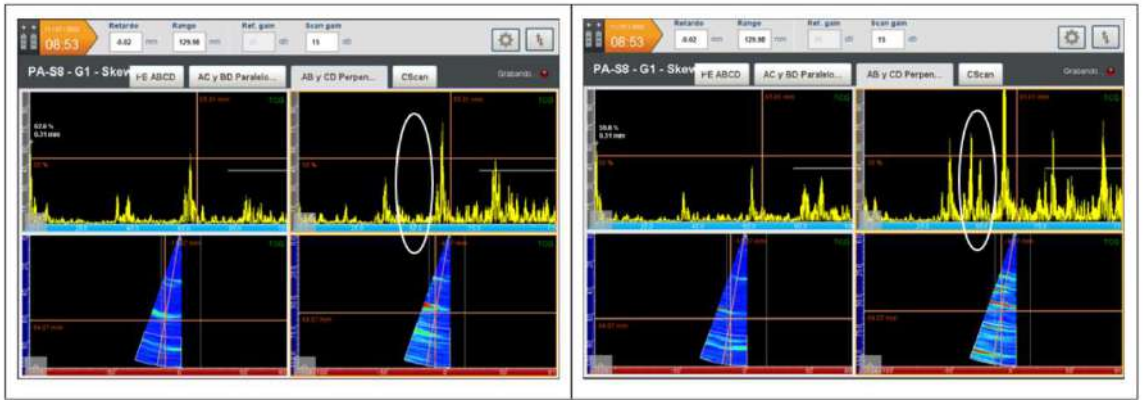

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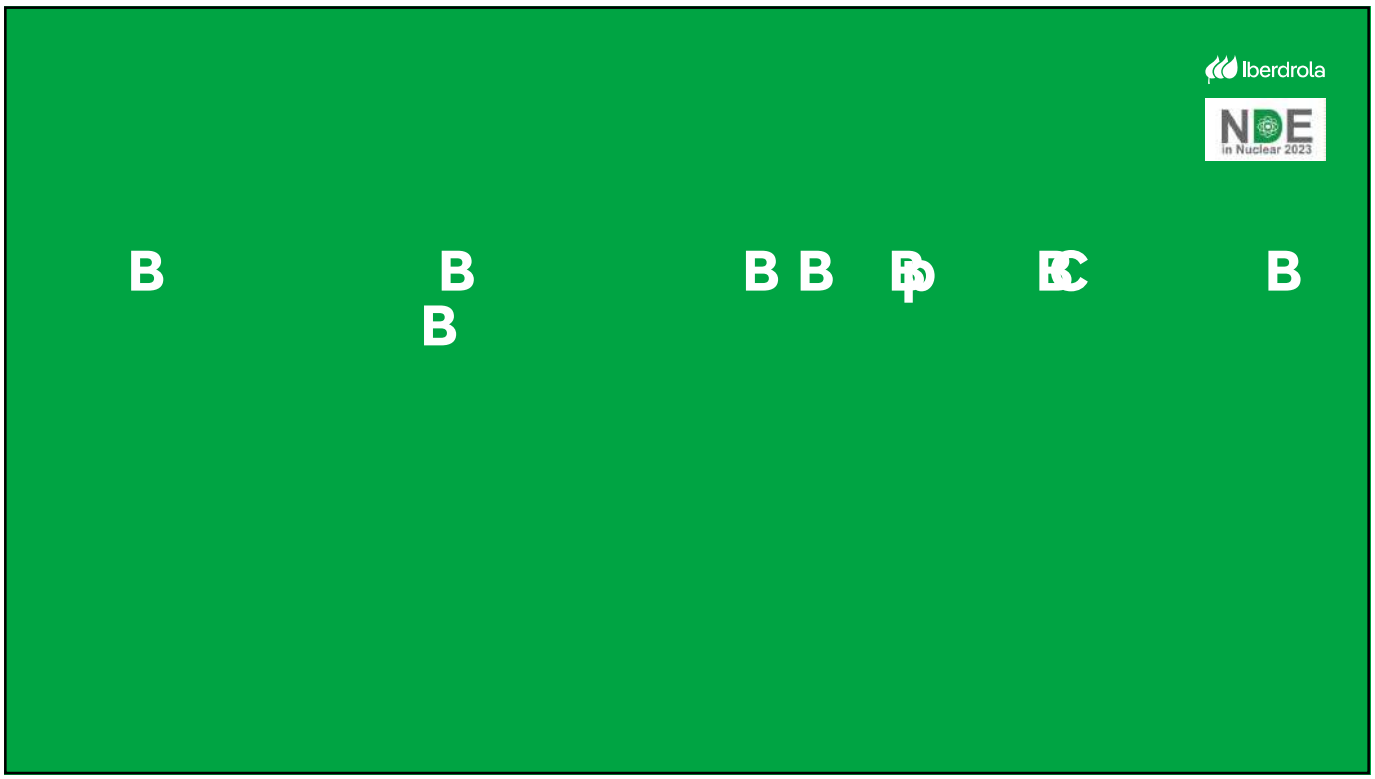

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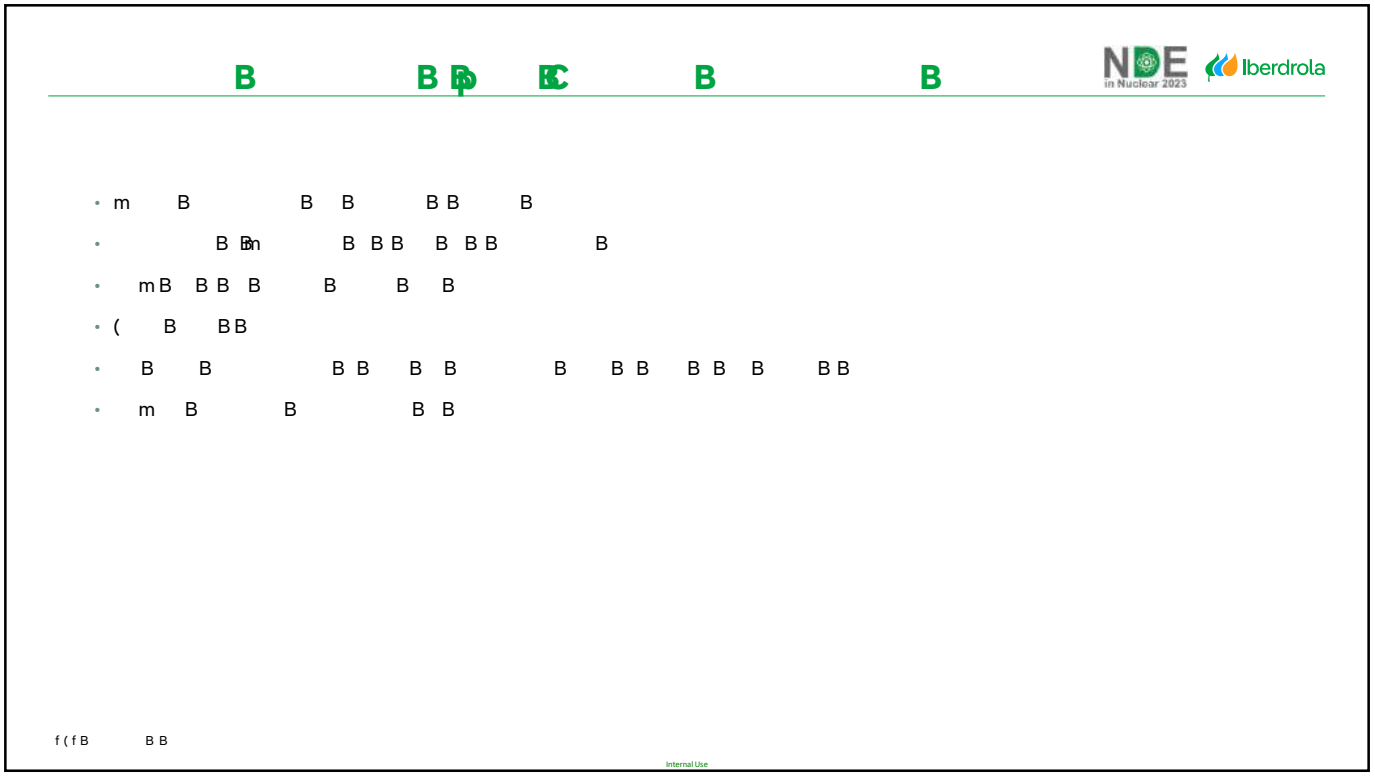

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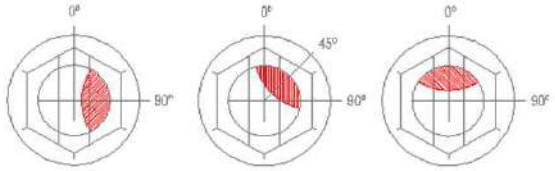

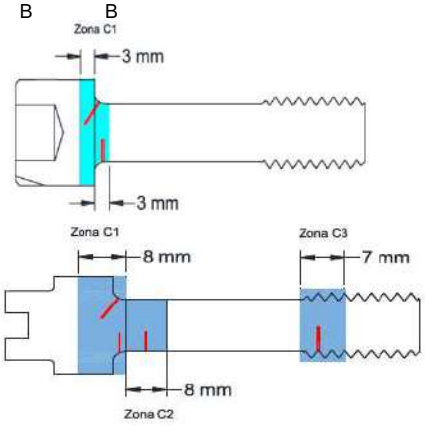

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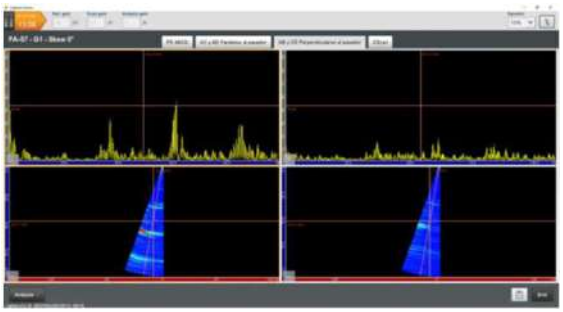

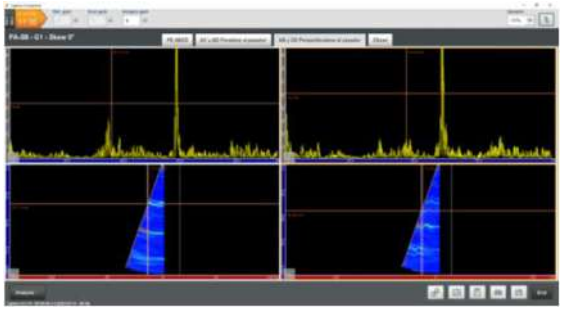

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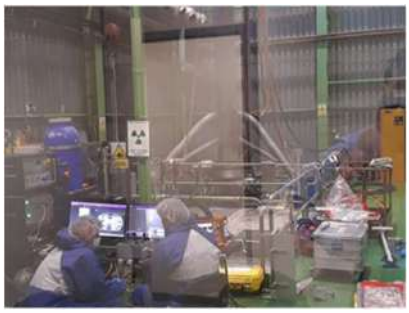

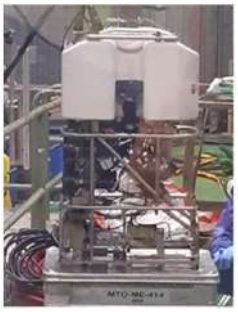

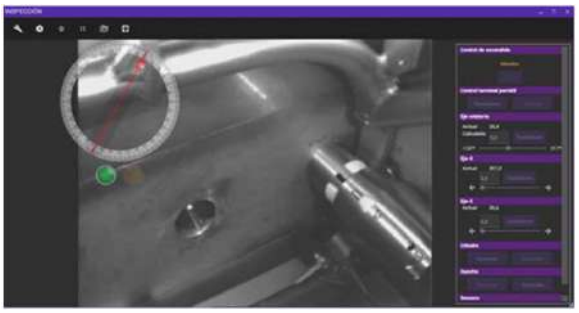

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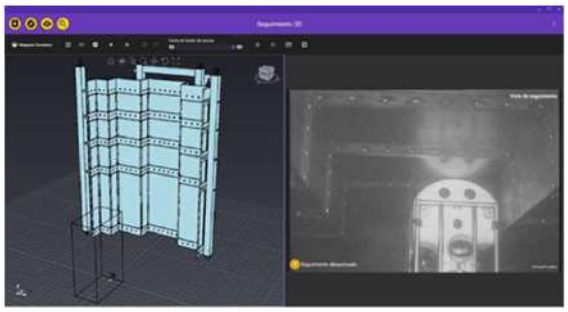

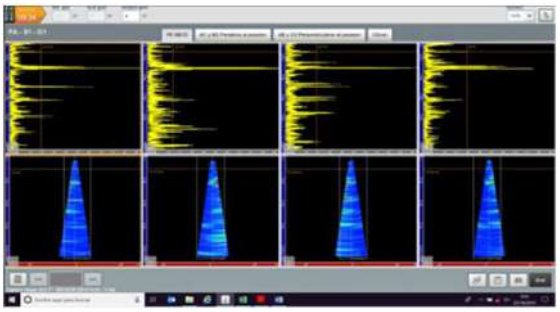

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Round Robin Tests for WWER Heat Exchange Tubes

Roman Krajčovič[1], Michal Benák[2], Radim Kopřiva[3], Szabolcs Szávai[4], Csaba Takacs[5]

[1]VUJE, a.s., Okružná 5, 918 64 Trnava, Slovak Republic
[2] VUJE, a.s., Okružná 5, 918 64 Trnava, Slovak Republic
[3]ÚJV Řež, a. s., Hlavní 130, Řež 250 68, Husinec, Czech Republic
[4]Bay Zoltan Nonprofit Ltd. for Applied Research, Kondorfa utca 1, H-1116 Budapest, Hungary
[5]Bay Zoltan Nonprofit Ltd. for Applied Research, Kondorfa utca 1, H-1116 Budapest, Hungary

E-mail address (corresponding author): michal.benak@vuje.sk

One of the most affected components from the point of view of long-time operation of VVER reactors are heat exchanging tubes of steam generators. With the nominal tube wall thickness of 1,4 only and significant consequences of many factors, such as; increasing power output, the long-time operation, secondary water chemistry and, in many cases, mechanical impact due to dissimilar welds (DN1100) repair, steam generator tubing represents one of the most critical component significantly limiting overall lifetime of many units.
New forms of degradations came into being in many of VVER unites, many of them specific for some units only. Therefore, there is a wide accepted need for applying new inspection techniques. As such, these techniques are now on the market, being partially used in some units.
Pulled-out tubes from Jaslovske Bohunice units 1 and 2, with real defects, well documented from the point of view of historical eddy current results and results from last inspection, carefully stored and treated, provide the great opportunity for experimental verification of these new, state-of-the art inspection ET techniques (e.g. Bobbin, MRPC, X-Probe, etc.).

Keywords: Round robin test, WWER, steam generator, heat exchange tubes, eddy current testing.

ENIQ Inspection Qualification for the UK Nuclear Newbuild

Christopher Curtis, CEng MInstNDT

Jacobs Inspection Validation Centre, Warrington, UK

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E-mail address (corresponding author): chris.curtis@jacobs.com

Jacobs Inspection Validation Centre have been acting as the Type 1 Qualification Body for the independent qualification of High Integrity Component manufacturing inspections for the UK EPR. This presentation details the process undertaken to independently assess the manufacturing inspections deployed on High Integrity Components in line with UK regulatory expectations. It starts by defining the requirements for qualification in the UK set by the regulator, then proceeds to the process undertaken, issues that had to be overcome, and the confidence achieved. The presentation then details how this will then be taken forward to pre and in-service inspection qualification and also other new build opportunities in the UK.

Keywords: ENIQ, Inspection Qualification, NDT, NDE, Ultrasonic, New Build, EPR, UK, Nuclear

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ENIQ Inspection Qualification for UK Civil Nuclear New Build

Chris Curtis
The Inspection Validation Centre

IVC Inspection Validation Centre

The Inspection Validation Centre (IVC)

IVC Inspection Validation Centre

- UKAS Accredited to ISO 17020
- Independent third-party Inspection Qualification Body
- Part of the Jacobs organisation
- Convened by the UKAEA in 1987 for Sizewell B.
- A founding member of the European Network for Inspection and Qualification (ENIQ)
- Provides Independent Inspection Qualification to:
  - Sizewell B – In-Service Inspections
  - Hinkley Point C – Manufacturing Inspections and Pre-Service Inspections

Image Credit – Jacobs IVC

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UK Civil Nuclear New Build Programme

In Manufacture

- UK EPR
  - Hinkley Point C
  - Sizewell C

Proposed

- SMRs
- Wylfa, Anglesey
- Bradwell B, Essex

Image Credit - https://www.sizewellc.com/proposals/

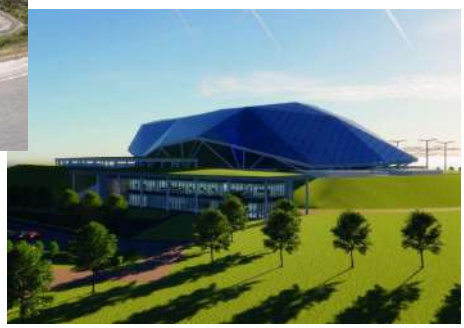

Image Credit - https://www.rolls-royce-smr.com/about-us/our-vision

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Inspection Qualification

What is Inspection Qualification?

A formal process to provide confidence that the inspection system can meet its objectives

The UK approach to Qualification was derived in the 80's and 90's for the manufacture of Sizewell B.

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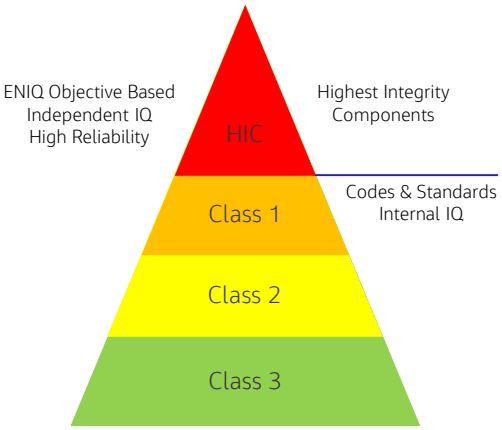
Inspection Qualification Requirements in the UK

- The licensing and operation of civil nuclear plant is regulated by the Office for Nuclear Regulation (ONR).
- The ONR's Safety Assessment Principles (SAPs) set out the requirements for qualification of NDE.
- The level of qualification depends on the safety classification of the component being inspected.
- High-Integrity Components (HIC) require the highest level of qualification, including the use of a fully independent third-party Qualification Body.
- Applied at Manufacture, Pre-Service (PSI) and during the lifecycle of the reactor (ISI)



Credit: Russ Booler – ONR Presentation – NDT of Highest Reliability Components

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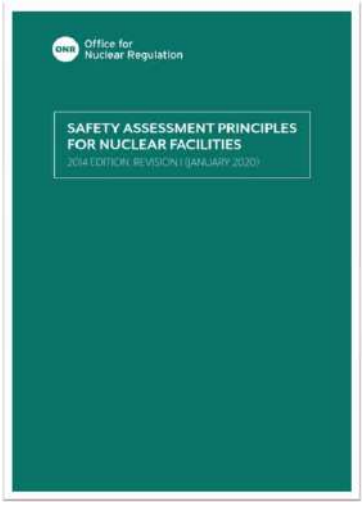
ONR SAPs EMC

Engineering principles: integrity of metal components and structures: general	Defects	EMC.5
It should be demonstrated that components and structures important to safety are both free from significant defects and are tolerant of defects.		
Engineering principles: integrity of metal components and structures: general	Defects	EMC.6
During manufacture and throughout the full lifetime of the facility, there should be means to establish the existence of defects of concern.		
Engineering principles: integrity of metal components and structures: manufacturing, pre- and in-service examination and testing	Redundancy and diversity	EMC.29
Methods of examination of components and structures should be sufficiently redundant and diverse.		
Engineering principles: integrity of metal components and structures: manufacturing, pre- and in-service examination and testing	Qualification	EMC.30
Personnel, equipment and procedures should be qualified to an extent consistent with the overall safety case and the contribution of examination to structural integrity aspects of the safety case.		



https://www.onr.org.uk/saps/

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Inspection Qualification Requirements in the UK

- Objective Based
  - Defects to be Detected
  - Performance Requirements
    - Highly Reliable
      - Redundancy & Diversity
      - Quality Assurance
- ENIQ Methodology
  - Justified via Technical Justification (ENIQ RP2)
    - Identification of Essential Parameters
    - Physical Reasoning
    - Modelling
    - Practical Tests
- Separate Procedure and Personnel Trials

https://snetp.eu/eniq-reports/

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Hinkley Point C - Manufacturing Inspections

- The UK EPR primary circuit components are mainly being manufactured by Framatome in France and the final inspections of the welds are subject to End-of-Manufacturing IQ
- Manual and Automated Ultrasonic Inspections of the RPV, Steam Generator, Pressuriser and Primary Circuit Pipework
- Target Defects
  - Lack-of-Fusion
  - Cracking
- Inspection Zone
  - Weld + HAZ
- Grouping of Components for Qualification

Image Credit - https://www.world-nuclear-news.org/Articles/First-reactor-vessel-for-Hinkley-Point-C-completed

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Inspection Qualification Applied

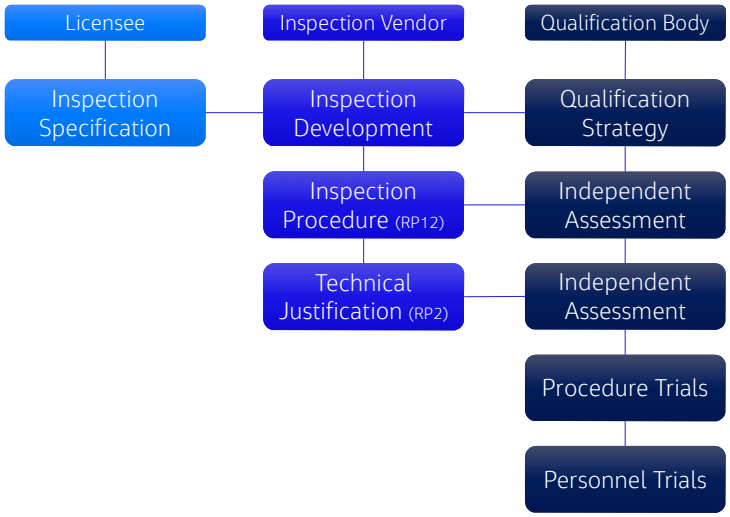

Image Credit – Jacobs IVC

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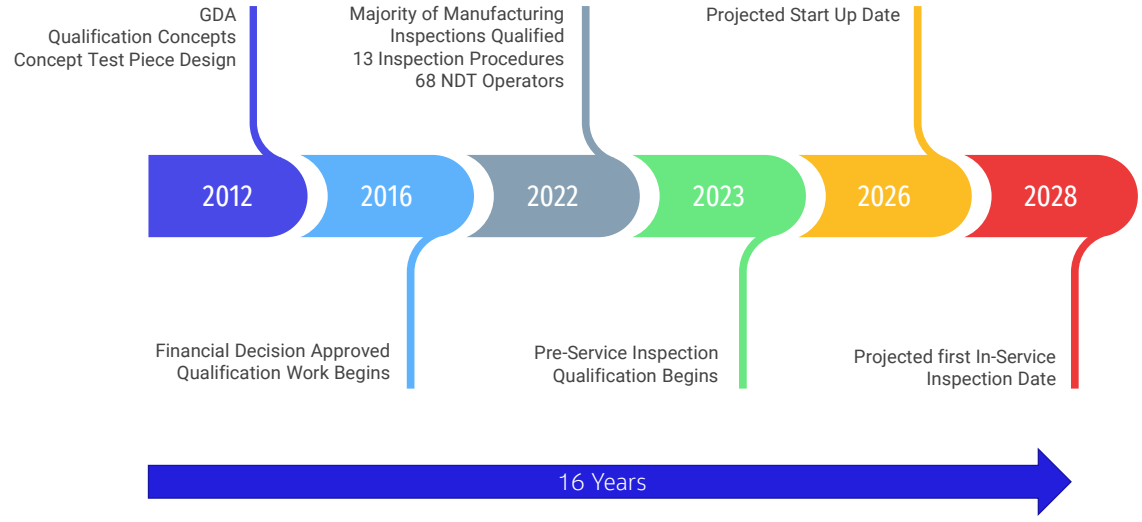
Hinkley Point C Qualification Timeline



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Future Qualification for HPC and SZC

- HPC Pre-Service Inspection
  - Applied once the reactor is built before operation
  - Baseline inspection
  - Focused at serviced induced defects (cracking at component surfaces)
- HPC In-Service Inspection
  - Periodic over a 10-year cycle
  - Applied at refuelling outages (every 18 months)
- Sizewell C
  - End-of-Manufacturing
  - Pre-Service Inspection
  - In-Service Inspection

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Thank You for Your Time

Chris Curtis
IVC Technical Manager
chris.curtis@jacobs.com

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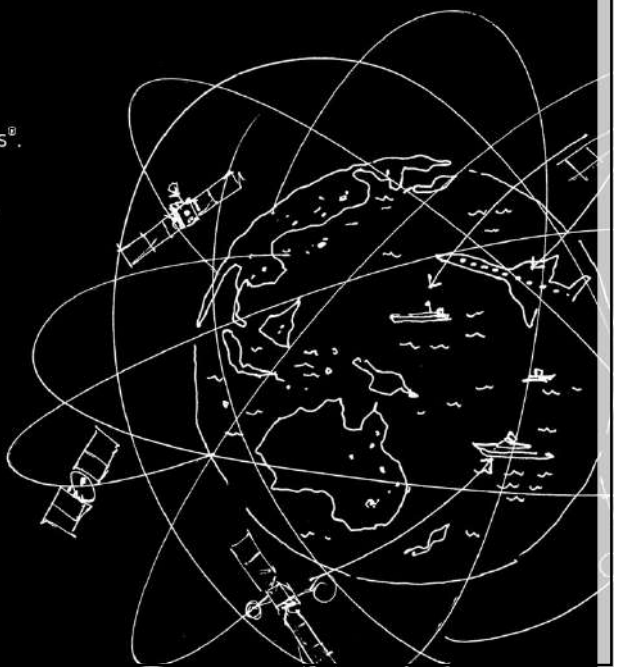

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ENIQ based Inspection Qualification of novel techniques (FMC case study)

Stavros Avramidis[1], Miles Weston[2]

[1]Inspection Validation Centre (IVC), Jacobs, Warrington, UK
[2]TWI, Harbourside Business Park, Port Talbot, UK
[3]EDF Energy, Bristol, UK
…

E-mail address (corresponding author): Stavros.avramidis@jacobs.com, Miles.Weston@twi.co.uk

Inspection Qualification in the UK Nuclear Energy Sector is undertaken by organisations acting as Inspection Qualification Bodies (IQB) according to the European Network for Inspection Qualification (ENIQ). ENIQ qualifications, depending on the qualification level and qualification approach selected, involve document assessment and practical trials of procedure and personnel. The documents assessed will include as a minimum an Inspection Procedure (IP) and a Technical Justification (TJ) and the practical trials may be blind or open using representative test pieces with realistic defects. ENIQ recommended practices guide the qualification activities and the content of the documents involved.

This presentation aims to assist Inspection Vendors and Qualification Bodies when planning to qualify novel inspection techniques through ENIQ. It investigates the areas that require additional attention, development and effort from the standpoint of the Inspection Vendor as well as from the standpoint of ENIQ and the Qualification Body.

A case study is presented on the development and qualification of an FMC inspection procedure offering improved sizing accuracy for in-service inspection of a complex geometry structure within the nuclear energy sector.

Keywords: Inspection Qualification, FMC, ATFM, Ultrasonic Techniques… (max. 5).

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IVC Inspection Validation Centre

ENIQ based Inspection Qualification of novel techniques (FMC case study)

Miles Weston - TWI, Harbourside Business Park, Port Talbot, UK

Stavros Avramidis - Inspection Validation Centre (IVC), Jacobs, Warrington, UK

Introduction

IVC Inspection Validation Centre

- Inspection Qualification
- Introduction and General Remarks
- Inspection Qualification for Novel Techniques – Challenges
- Technical Justification
- ENIQ – Standards

FMC Case Study

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Inspection Qualification – Introduction and General Remarks

Inspection Qualification in the UK Nuclear Energy Sector

- Is undertaken by organisations acting as Inspection Qualification Bodies (IQB)
- According to recommended practices from the European Network for Inspection Qualification (ENIQ)
- Typically involves document assessment (IP and TJ) and open or blind practical trials of procedure and personnel
- Test Pieces used in Qualification Trials are typically of representative geometry and include induced representative defects

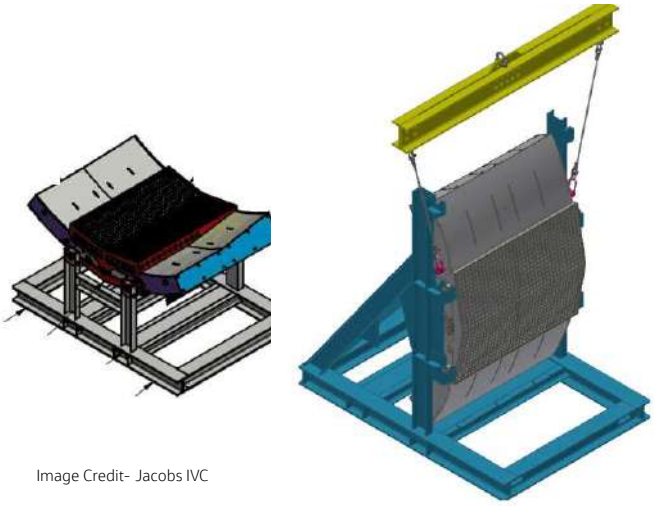

Image Credit- Jacobs IVC

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Inspection Qualification for Novel Techniques - Challenges

- Lack of theoretical evidence.
- Lack of historical experimental evidence.
- No previously identified essential inspection parameters.
- Data processing with complex algorithms introduces uncertainties not existing with other techniques.
- Lack of relevant standards for the specific technique.
- Lack of IQB familiarisation with the technique.

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Technical Justification (TJ)

Its role is to justify why the inspection is likely to work reliably.

- Identification of the essential parameters of the inspection is key for all inspection techniques (TJ Section 4).
- For novel techniques there is less standardized information, and more effort is required to identify essential parameters (i.e. pixel resolution, surface mapping algorithm).
- TJ Section 5 – Physical Reasoning
  - Benefits and drawbacks of the proposed technique and what is the justification for using it (reference industry good practice and relevant literature).
  - Justification around the physical principles that govern the technique and its effectiveness (defect interaction, interaction with material, transmit and receive paths).
  - Justify algorithms and calculations used.

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Technical Justification (TJ)

- TJ Section 6 – Modelling
  - Why is the modelling performed relevant and representative?
  - Is the simulation model used for this technique verified and do the experimental results agree?
- TJ Sections 7&8 – Experimental Results and Parametric studies
  - Lack of past relevant studies would require new experimental data to be collected. This is the case for most qualifications.
- TJ Section 9 – Equipment, Data Analysis, Personnel Requirements
  - Description of the data processing involved (if any) for generation of data for analysis
  - Assurance that the algorithms involved will remain unchanged post-qualification and implementation of version control methods for the software and setup files involved.
  - The IQB would require justification for any changes to software or setup files.
  - Personnel should be adequately trained.

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Standards and ENIQ

- In conventional techniques standards are used to dictate as a minimum well established calibration methods for sensitivity and equipment checks.
- In the absence of recognized standards for novel techniques, the calibration methods have to be justified more thoroughly.
- ENIQ RP2 gives examples of the common essential parameters for some conventional NDE techniques (Pulse Echo UT, PA UT, Eddy Current) to be included in the TJ. Novel techniques will have some different essential and influential parameters than conventional techniques and these have to be carefully defined and justified.
- Bespoke and optimized inspections should be encouraged instead of generic fully code-based inspections.

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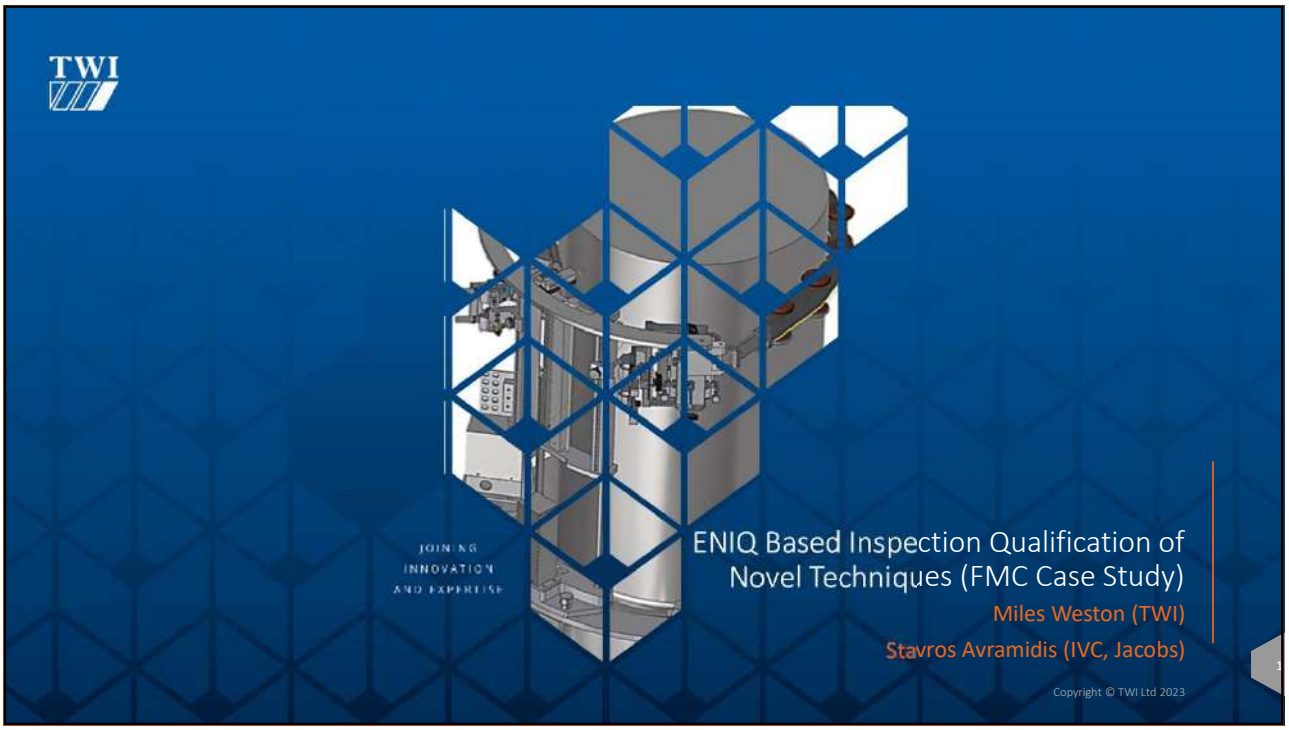

Case Study - Qualification of FMC System and Procedure for ISI of Nuclear Plant

- TWI in collaboration with EDF has developed an automated FMC system and procedure for inspection of thick section austenitic steel complex geometry plant structure.
- Primary objective was to improve sizing accuracy of SCC relative to current in-service inspection, with a target accuracy of ±2mm.
- TWI providing concept through to site deployment
  - R&D
  - System development
  - Procedure development
  - Technical justification
  - Operator training package development
  - In-service inspection.

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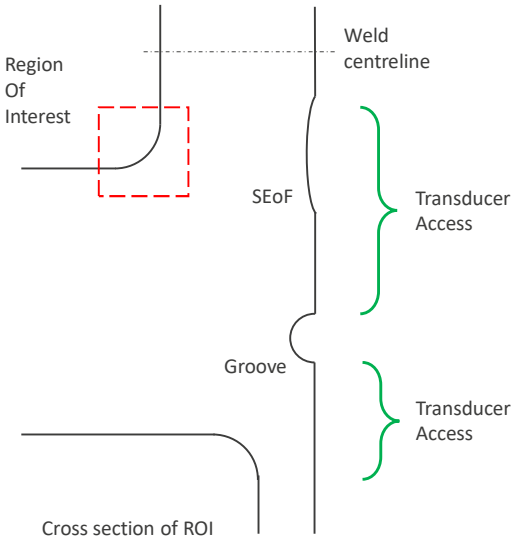
Component geometry



CAD render

Not to scale

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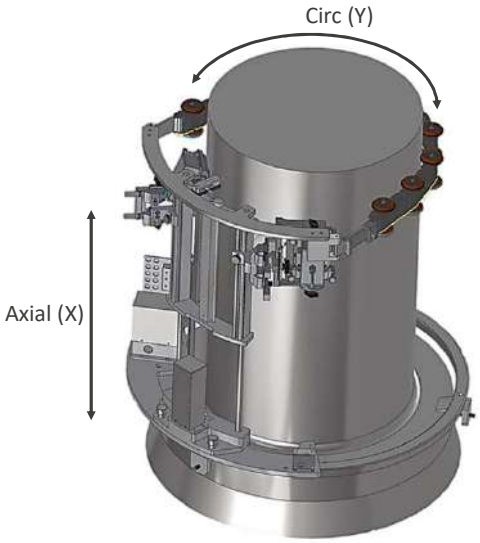
Setup - general

- Automated 2 axis (X, Y) scanner & controller



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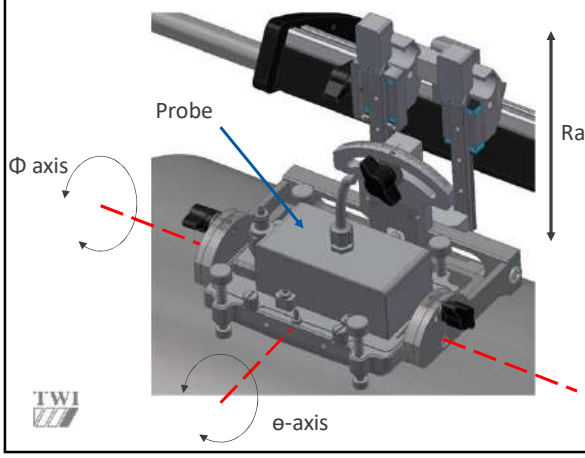
Setup - general

- Automated 2 axis (X, Y) scanner & controller
- 3 axis (lockable) toolpost



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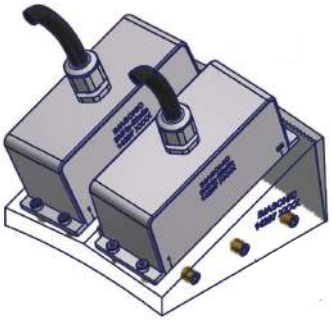
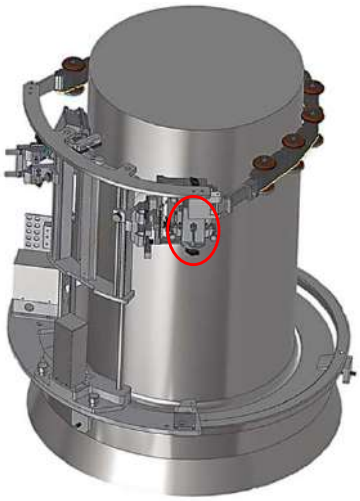
Setup - general

- Automated 2 axis (X, Y) scanner & controller
- 3 axis (lockable) toolpost
- 3x transducers: conformable membranes & DLA probe
  - 15° L-wave conformable probe
  - 35° L-wave conformable probe
  - 60 ° DLA





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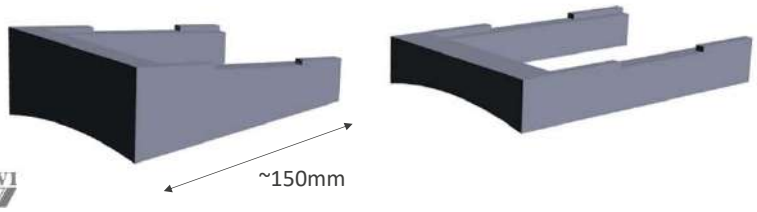
Setup - general

- Automated 2 axis (X, Y) scanner & controller
- 3 axis (lockable) toolpost
- 3x transducers: conformable membranes & DLA probe
  - 15° L-wave conformable probe
  - 35° L-wave conformable probe
  - 60 ° DLA
- Conformable membrane jigs (wedge angle calibration)



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Setup - general

- Automated 2 axis (X, Y) scanner & controller
- 3 axis (lockable) toolpost
- 3x transducers: conformable membranes & DLA probe
  - 15° L-wave conformable probe
  - 35° L-wave conformable probe
  - 60 ° DLA
- Conformable membrane jigs (wedge angle calibration)
- Crystal FMC acquisition, analysis and reporting software

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Setup - general

- Automated 2 axis (X, Y) scanner & controller
- 3 axis (lockable) toolpost
- 3x transducers: conformable membranes & DLA probe
  - 15° L-wave conformable probe
  - 35° L-wave conformable probe
  - 60 ° DLA
- Conformable membrane jigs (wedge angle calibration)
- Crystal FMC acquisition, analysis and reporting software
- Pulser-receiver: PeakNDT LTPA

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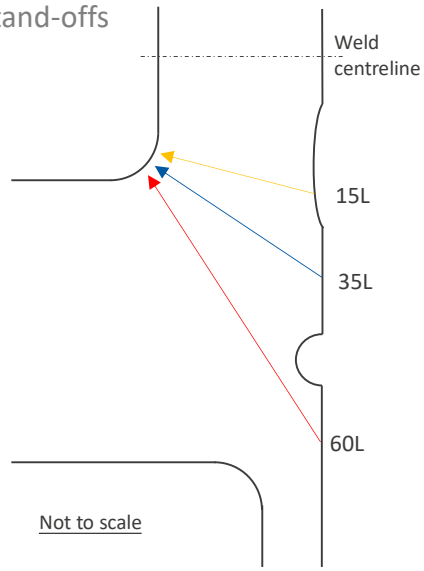
Setup - general

- A total of 3 stand-offs



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Challenges of the Technical Justification (TJ)

Some of the essential parameters and other factors requiring control within defined tolerances, justified in the TJ

- Use of conformable membrane water box + ATFM in presence of SEoF
  - Limit to the SEoF which sound can propagate through and achieve reliable sizing
  - Use of angled wedge water box
  - Maintaining acceptable transducer tilt/skew angle relative to component surface
- Achieving sufficient sensitivity for all flaw orientations given surface access restrictions

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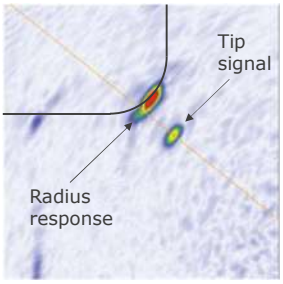
Technical challenges

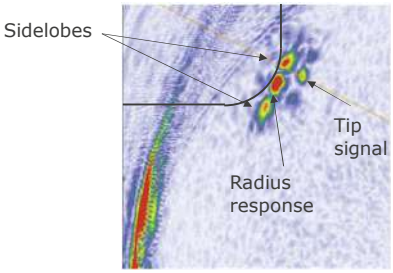
Limit to the SEoF which sound can propagate through and achieve reliable sizing.

- Increasing SEoF increases sidelobe amplitude relative to main beam
- Maximum SEoF established
- Pre-scan and post-scan sidelobe level checks to monitor data quality

No sidelobes visible



Presence of sidelobes



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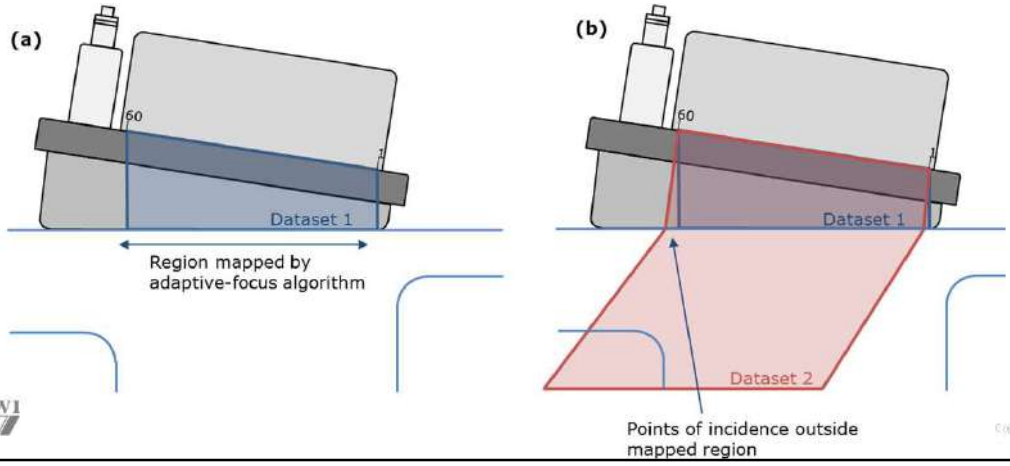
Technical challenges

Use of angled wedge water box

- Wedge angle influences useable number of elements (aperture size)



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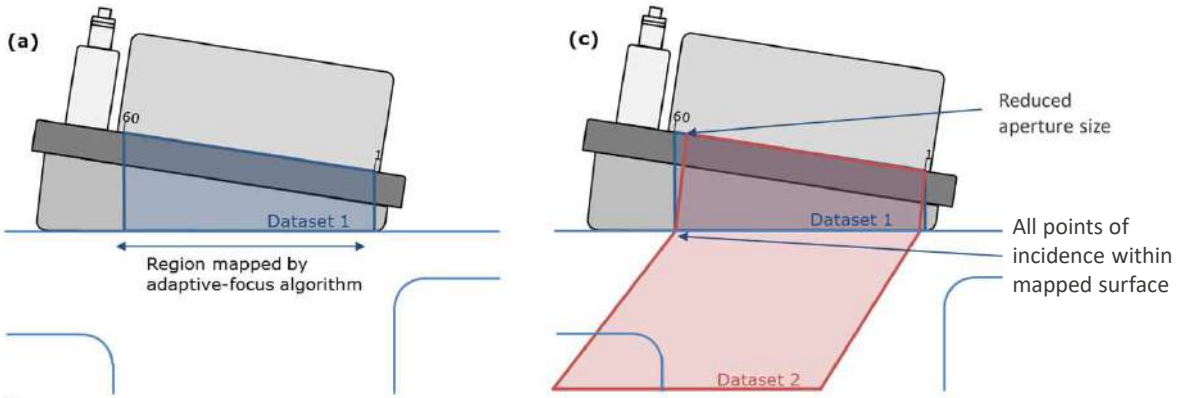
Technical challenges

Use of angled wedge water box

- Wedge angle influences useable number of elements (aperture size)



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Challenges of the Technical Justification (TJ)

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  - **Maintaining acceptable transducer tilt/skew angle relative to component surface**
- Achieving sufficient sensitivity for all flaw orientations given surface access restrictions

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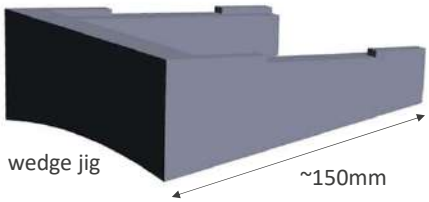
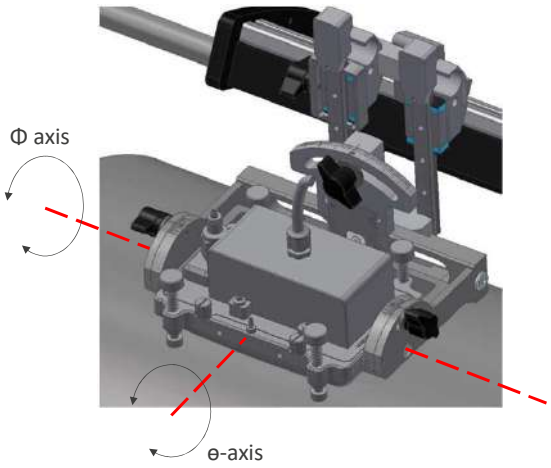
Technical challenges

Maintaining acceptable transducer tilt/skew angle relative to component surface

- Water boxes wedges suspended above component using scanner – no legs to hold wedge on component surface as poor performance over SEoF.
- Jigs used to present transducers to component to set wedge angle and minimise transducer skew.
- Transducer toolpost axis (Φ, ɵ) locked before jig removed.





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- **Achieving sufficient sensitivity for all flaw orientations given surface access restrictions**

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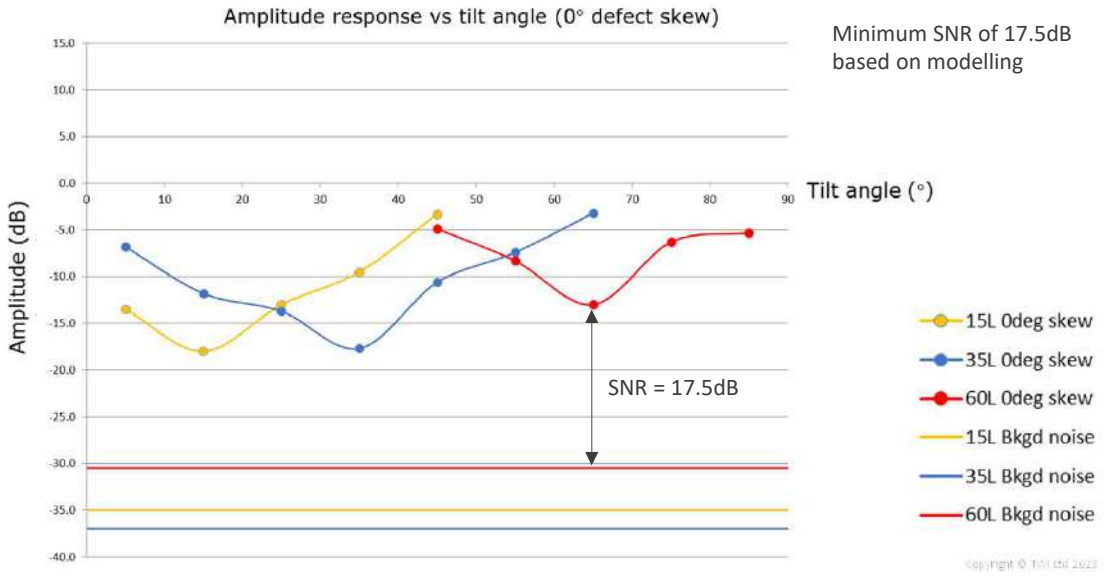
Achieving sufficient sensitivity for all flaw orientations given surface access restrictions



Minimum SNR of 17.5dB based on modelling

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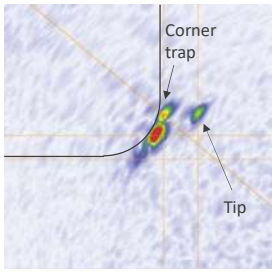
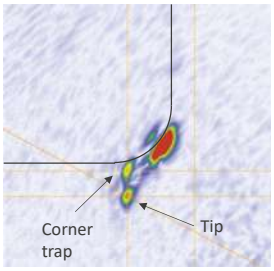
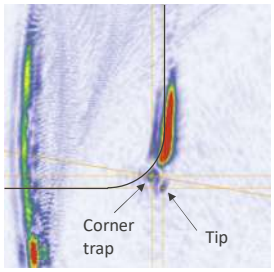
Results from Mockup containing EDM slots



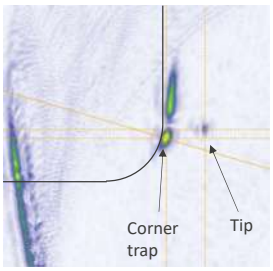
Notch 1



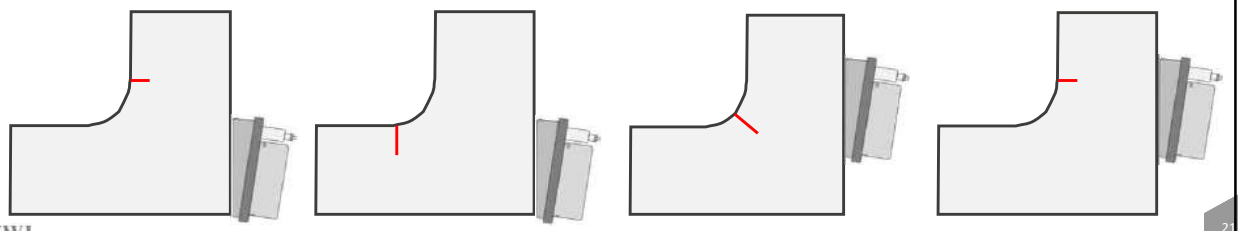
Notch 2



Notch 3



Notch 4



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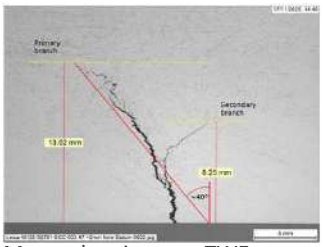
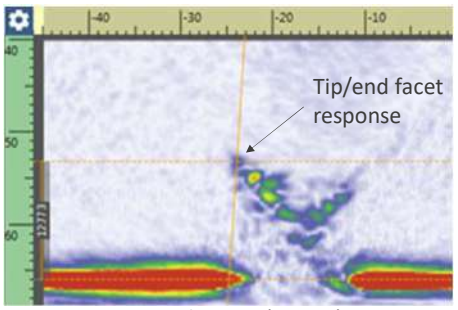
Results from lab induced SCC sample

- SCC grown within a lab environment
- SCC characteristics from macro:
  - Two main branches
  - Max TWE: 13.0mm
  - Primary branch tilt angle: 40°
- FMC inspection system measured TWE:
  - 12.8mm
  - Yields 0.2mm undersizing relative to max TWE from sectioning



Macro showing max TWE



FMC cross sectional image (B-scan)

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Questions

Miles Weston
NDT Consultant, **TWI Ltd**
miles.weston@twi.co.uk

Stavros Avramidis
Senior NDT Validation Consultant, **IVC (Jacobs)**
stavros.avramidis@Jacobs.com

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Update of CEX-120 Methodology – Spanish ENIQ Type Methodology for Qualification of Non-Destructive Testing used in the In-Service Inspections of Nuclear Power Plants

Ignacio Real Rubio, Iberdrola
Francisco Javier Campaña Martín, Tecnatom

The first issue of the European Methodology for Qualification of Non-Destructive Testing (NDT) was initiated by Action Group 8 on support for codes and standards for the Inspection of Steel Components Programme (PISC III) and finalised by ENIQ (European Network for Inspection and Qualification). It was published as ENIQ Report no. 1 in 1995. Since then, the European Methodology for Qualification of Non-Destructive Testing has been revised three times. The second, third and fourth issues were published in 1997, 2007 and 2019 respectively.

ENIQ Methodology for Qualification of NDT consists of a group of documents (one Methodology Document and some Recommended Practices, among others) which give general guidelines on how inspection qualification of NDT should be carried out. The ENIQ Methodology has been adapted to the characteristics of the Spanish Nuclear Plants by means of the CEX-120 Methodology.

In other words, CEX-120 Methodology is based on ENIQ Methodology. Currently, it has one Main Document and seven Technical Documents which adapt the most important aspects of the ENIQ documents to the Spanish NPP framework.

The revision 1 of CEX-120 Methodology was initially published in 2003 and has been in effect to this day. Nowadays, it is being updated with the last revision of ENIQ Methodology Document as well as twelve Recommended Practices to include the most recent available information about Qualification of NDT systems.

This work will present the evolution on the Spanish Methodology and the way ENIQ Methodology has been adapted to Spanish fleet.

E-mail address (corresponding author): fjcampana@tecnatom.es / jireal@iberdrola.es

Keywords: Qualification Methodology

Internal Use

Update of CEX-120 Methodology for Qualification of Non-Destructive Testing used in the In-Service Inspections of Spanish Nuclear Power Plants

NDE in Nuclear 2023 Conference
Sheffield, 28th June 2023

Confidential

Content

1. Spanish Nuclear Sector Background
2. Spanish Methodology: CEX 120
3. ENIQ Methodology & Recommended Practices Review Process
4. Spanish Methodology Update
5. Future Work: Spanish Regulator Review & Approval
6. Summary & Conclusions

1 Spanish Nuclear Sector Background

Spanish Nuclear Sites

Spanish Nuclear Power Pants

NPP	Gross Power (MWe)	Reactor Type	OEM	First Conexión Date
Almaraz 1	1.049	PWR. 3 loops	Westinghouse	1981
Almaraz 2	1.044	PWR. 3 loops	Westinghouse	1983
Ascó 1	1.032	PWR. 3 loops	Westinghouse	1983
Ascó 2	1.027	PWR. 3 loops	Westinghouse	1985
Cofrentes	1.092	BWR-6	GE	1984
Vandellós II	1.087	PWR. 3 loops	Westinghouse	1987
Trillo	1.066	PWR. 3 loops	Siemens KWU	1988

- Nuclear PP represent 7 % of installed capacity but generated 20 % of Spanish electricity in 2022

Spanish ISI Programs Requirements

- Spanish nuclear power plants, in-service inspection programs scope is defined according to ASME XI
  - Trillo has also some additional requirements from KTA 3211.4
  - Steam Generator Tubes are also included according to Spanish Regulator Requirement
- NDT personnel is, preferably, qualified according to EN ISO 9712
- Pressure barrier inspection procedures are qualified according to CEX-120 Methodology (ENIQ type)

2

Spanish Methodology: CEX-120

Spanish Methodology: CEX-120

- CEX-120 Methodology is based on ENIQ Methodology
  - It has one Main Document and seven Technical Documents.
  - It adapts the most important aspects of the ENIQ documents to the Spanish NPP framework.
  - Revision 2 of CEX-120 Methodology was approved by CSN (Spanish Nuclear Regulator) in April 2003 and has been in effect since then.

Spanish Methodology: CEX-120

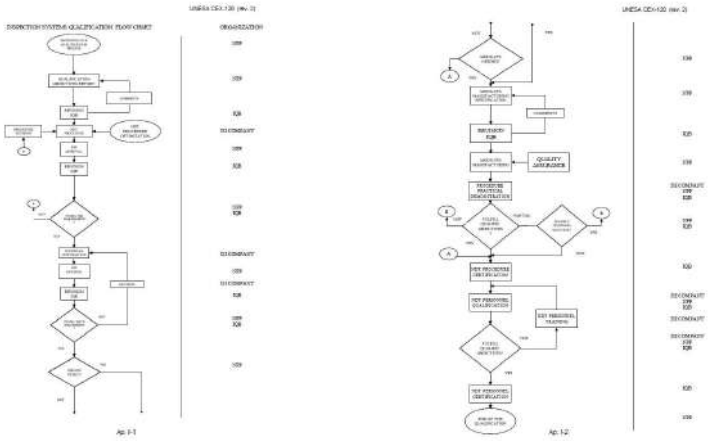
- CEX-120 Methodology documents:
  - 1 Main Document: **Methodology** for Qualification of Non-Destructive Testing used in the In-Service Inspections of Nuclear Power Plants
  - 7 Technical Documents
    - CEX-120.1 Guidelines for the definition of **Qualification Objectives** of In-Service Inspection Systems.
    - CEX-120.2 Guidelines for the definition of **Influence and Essential Parameters** of Inspection.
    - CEX-120.3 Guidelines for **Technical Justification** Preparation.
    - CEX-120.4 Guidelines for the **Specification of Mock-ups** of the Qualification Process.
    - CEX-120.5 Guidelines for the preparation and execution of **Practical Trials**.
    - CEX-120.6 Guidelines for the preparation of the **Qualification Final Report**.
    - CEX-120.7 Guidelines for the **Organization and Management of the Qualification Process**.

Spanish Methodology: CEX-120 Summary (I)

- **Methodology** for Qualification of Non-Destructive Testing used in the In-Service Inspections of Nuclear Power Plants:
  - Based on European Methodology for Qualification (2nd issue); ENIQ Report Nº 2 (1997).
  - **Scope Areas:** Class 1 Piping welds (Wrought austenitic, ferritic, Dissimilar metal; Overlay); Vessel (Clad/Base Metal Interface Region; Nozzle Inside Radius Section, Reactor Vessel Welds Other than Clad/Base Metal Interface; Nozzle-to-Vessel Weld); Bolts and Steam Generator Tubes.
  - **Inspection Methods:** Ultrasonic / Eddy Current Test.
  - Three types of defects: Specific (detected in an Area), Postulated (potential or based on Operative Experience) & undetermined.
  - Required Level for Qualification:
    - Specific defect: Open trail + Technical Justification (TJ) for Procedure / Blind Trial for Personnel.
    - Postulated defect: TJ (sometimes may be necessary open trial).
    - Undetermined defect: Simplified TJ.

Spanish Methodology: CEX-120 Summary (II)

- **Methodology** for Qualification of Non-Destructive Testing used in the In-Service Inspections of Nuclear Power Plants Flow Chart:



Spanish Methodology: CEX-120 Summary (III)

- Guidelines for the definition of **Qualification Objectives** of In-Service Inspection Systems (CEX-120.1):
  - Based on European Methodology for Qualification (2nd issue); ENIQ Report Nº 2 (1997).
  - Information related to:
    - **Description of the component/area** (Diameter, Thickness, Surface conditions);
    - **Type of defect** (Degradation mechanism);
    - Analysis of the **size** of defects
    - Define influential for component/area and defects.
  - Define **Inspection Objectives** for Qualification:
    - Method of Inspection, Probability of Detection,
    - False calls and depth/length of defects and their error of measurement.
    - Some data are supported by Section XI of ASME Code.
  - Describe the content of the inspection procedure to be qualified.

Spanish Methodology: CEX-120 Summary (IV)

- Guidelines for the definition of **Influence and Essential Parameters** of Inspection (CEX-120.2):
  - Based on European Methodology for Qualification (2nd issue); ENIQ Report Nº 2 (1997) and ENIQ RP 1; Report Nº 6: Influential/Essential Parameters (1998)
  - Define influential and essential parameter concepts.
  - Define groups for influential and essential parameters and Classify essential ones.
- Guidelines for **Technical Justification** Preparation (CEX-120.3):
  - Based on European Methodology for Qualification (2nd issue); ENIQ Report Nº 2 (1997); ENIQ RP 2; Report Nº 4: "Recommended contents for a Technical Justification" (1998) and ENIQ RP 3; Report Nº 5: "Strategy document for Technical Justification" (1998).
  - Define the TJ concept, different application for TJ and the content of TJ

Spanish Methodology: CEX-120 Summary (V)

- Guidelines for the **Specification of Mock-ups** of the Qualification Process (CEX-120.4):
  - Based on European Methodology for Qualification (2nd issue); ENIQ Report Nº 2 (1997) and ENIQ RP 5; Report Nº 14: Guidelines for the Design of Test Pieces and Conduct of Test Piece Trials, (1999).
  - Define technical criteria for the Specification of mock-ups for Qualification purpose:
    - Type of mock-ups: open/blind.
    - Specification: defects specification (number, population, tolerance…), fabrication mock-up specification.
- Guidelines for the preparation and execution of **Practical Trials**) (CEX-120.5):
  - Based on same ENIQ's documents than CEX-120.4.
  - Define the requirements for the preparation and execution of demonstrations trials for the Qualification of Inspection Systems.

Spanish Methodology: CEX-120 Summary (& VI)

- Guidelines for the preparation of the **Qualification Final Report** (CEX-120.6):
  - Based on European Methodology for Qualification (2nd issue); ENIQ Report Nº 2 (1997) and ENIQ RP 4; Report Nº 13: Recommended Contents for the qualification dossier, (1999).
  - Define the content of Final Report for the Qualification.
- Guidelines for the **Organization and Management** of the Qualification Process (CEX-120.7):
  - Based on same ENIQ's documents than CEX-120.6.
  - Define the management and organization process of Qualification.

3

ENIQ Methodology & Recommended Practices Review Process

ENIQ Methodology & Recommended Practices Review Process (I)

- From 2003, ENIQ's reports have been updated/reviewed, or even, replaced…

Original Reference		New Reference
European Methodology for Qualification (second issue); ENIQ Report Nº 2 (1997)		European Methodology for Qualification of Non-Destructive Testing (issue 4); ENIQ Report No. 61 (2019)
ENIQ RP 1; Report Nº 6: Influential/Essential Parameters (1998)		ENIQ RP 2; ENIQ Report Nº 54: Strategy and Recommended contents for Technical Justifications (issue 3) (2018)
ENIQ RP 2; Report Nº 4: "Recommended contents for a Technical Justification" (1998)	Turns into	
ENIQ RP 3; Report Nº 5: "Strategy document for Technical Justification" (1998)		
ENIQ RP 5; Report Nº 14: Guidelines for the Design of Test Pieces and Conduct of Test Piece Trials, (1999)		ENIQ RP 5; ENIQ Report Nº 56: Guidelines for the Desing of Test Pieces and Conduct of Test Pieces Trails (issue 3) (2018).
ENIQ RP 4; Report Nº 13: Recommended Contents for the qualification dossier, (1999).		ENIQ RP 4; ENIQ Report Nº 55: Recommended Contents for the qualification dossier (issue 2) (2018).

ENIQ Methodology & Recommended Practices Review Process (& II)

- … and some of them have appeared in this period:
  - ENIQ RP 6: The Use of **Modelling** in Inspection Qualification (Issue 3). ENIQ Report Nº 57 (2018).
  - ENIQ RP 7: Recommended General Requirements for a **Body Operating Qualification** of Non-Destructive Test (issue 2). ENIQ Report Nº 58 (2018).
  - ENIQ RP 10: **Personnel Qualification** (Issue 2). ENIQ Report Nº 60 (2018).
  - ENIQ RP 12: Strategy and Recommended Contents for **Inspection Procedures** (Issue 1). ENIQ Report Nº 63 (2019).
  - ENIQ RP 13: Qualification of Non-Destructive Testing Systems that Make Use of **Machine Learning** (Issue 1). ENIQ Report No. 65 (2021).
- All these changes have made necessary to update the Spanish Methodology with the last revision of ENIQ Methodology Document as well as Recommended Practices to include the most recent available information about Qualification of NDT systems.

4

Spanish Methodology Update

Spanish Methodology Update (I)

- The review process has consisted of the following phases:
  - Identify the current issue of ENIQ Reports needed to updated CEX-120 documents.
    - Understand the document and consider the Spanish fleet.
  - Modify CEX-120, and CEX-120.1 documents according to European Methodology for Qualification of Non-Destructive Testing (issue 4); ENIQ Report No. 61.
    - In this case, it was also necessary to consider ASME Section XI.
  - Modify CEX-120.2 and CEX-120.3 documents according to ENIQ RP 2; ENIQ Report Nº 54: Strategy and Recommended contents for Technical Justifications (issue 3).
  - Modify CEX-120.4 and CEX-120.5 documents according to ENIQ RP 5; Report Nº 56: Guidelines for Design Test Pieces and Conduct of Test Pieces Trials (issue 3).
  - Modify CEX-120.6 document according to ENIQ RP 4; Report Nº 55: Recommended Contents for the Qualification Dossier (issue 2).
  - Modify CEX-120.7 document according to ENIQ RP 7; Report Nº 61: Recommended General Requirements for a Body Operating Qualification of NDT (issue 2).

Spanish Methodology Update (II)

- Create 4 new documents:
  - CEX-120-8 Guidelines for the use of models in Inspection Qualification according with ENIQ RP 6.
  - CEX-120-9 Personnel Qualification according with ENIQ RP 10.
  - CEX-120-10 Strategy and Recommended Contents for Inspection Procedures according with ENIQ RP 12.
  - CEX-120-11 Qualification of Non-Destructive Testing Systems that Make Use of Machine Learning according with ENIQ RP 13.

Spanish Methodology Update (III)

- The review process described in the previous slides, generated the following major modifications:
  - **Methodology** for Qualification of Non-Destructive Testing used in the In-Service Inspections of Nuclear Power Plants (CEX-120):
    - Formal review (It is a compendium of all CEX-120.X documents).
    - Scope: new point for components which have a new technique or those components in which al the parties involved in qualification process decide to qualify the technique.
    - For specific flaw: it was issued a Certification of Qualification for those analysts who passed the mandatory blind trial.
    - Certification of Qualification validity has been modified: **5 years** (no limit in previous revision, it there were no technical modifications).
  - Guidelines for the preparation of the **Qualification Final Report** (CEX-120.6) & Guidelines for the Organization and **Management of the Qualification Process** (CEX-120.7):
    - Only formal review.

Spanish Methodology Update (IV)

- Guidelines for the definition of **Qualification Objectives** of In-Service Inspection Systems (CEX-120.1)
  - Appendix 2: Acceptance Criteria of Supplements of Appendix VIII of Section XI of ASME Code have been updated.
  - Appendix 3: Figures for defects characterization (Article IWA-3000 of Section XI of ASME Code) have been updated.
  - Important to note: documents generated with the Objectives of In-Service Inspection were updated, as a part of a previous project (2018/2021), with the influential/essential parameters for defects according to new Acceptance Criteria of IWB-351X of Section XI of ASME Code).
- Guidelines for the definition of Influence and Essential Parameters of Inspection (CEX-120.2)
  - Recommendation of RP 2: definition of influential/essential parameter have been extended in order to harmonized both concepts with RP.
  - Recommendation of RP 2: new Appendix included in CEX-120.2 to have an example guide of influential parameter for phased-array technique.

Spanish Methodology Update (V)

- Guidelines for **Technical Justification** making (CEX-120.3)
  - If a **new defect** appears, with other degradation mechanism or new type of flaw, a comparison with a **different technique** could be used in order to qualified the applied technique.
  - Recommendation of RP 2: tables for the information (for Ultrasonic Test and Eddy Current Test) which should be included in the Section which describe the inspection system.
- Guidelines for the Specification of **Mock-ups** of the Qualification Process (CEX-120.4):
  - Recommendation of RP 5: Experience has shown that maximizing the number of test pieces and defects can lead to technical issues in demonstrations for defect detection. Sparse and irregularly distributed defects will provide a more challenging and **realistic inspection** situations.
- Guidelines for the preparation and execution of **Practical Trials** (CEX-120.5)
  - Recommendation of RP 5: This rationale may also be used to assess the capability of similar inspections applied to a group of similar components and from this assessment, to identify the worst-case component, thus reducing the number of test pieces from one per component type in a group to one or two to describe the entire group.

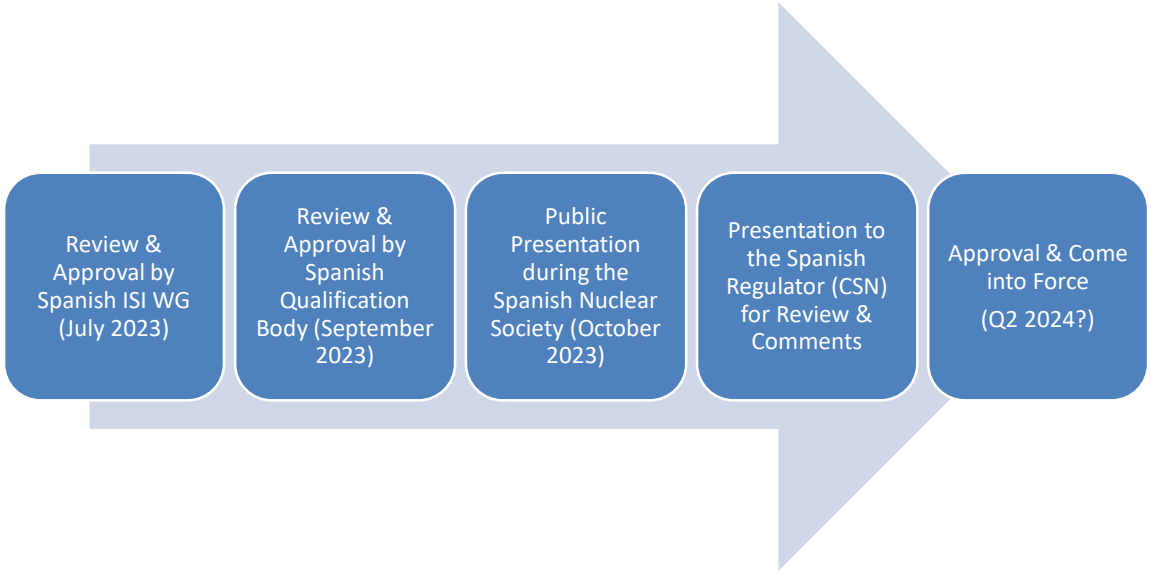
Spanish Methodology Update (& VI)

- The review process described in the previous Section, generated the following new documents:
  - Guidelines for the use of **Modelling** in Inspection Qualification (CEX-120.8):
    - This document provide a guidance on how to use modelling to develop inspection techniques and how to use the modeling results in the JT, both for their development and evaluation.
  - Guidelines for **Personnel Qualification** (CEX-120.9)
    - This document provide a guidance for those involved in the qualification of inspection personnel to ensure that those carrying out an inspection are appropriately trained, experienced and examined to ensure the inspection is applied correctly and effectively.
  - Guidelines for Strategy and Recommended Contents for Inspection Procedures (CEX-120.10)
    - This document provide a guidance with the recommended content of a Inspection Procedure.
  - Guidelines for Qualification of Non-Destructive Testing Systems that Make Use of **Machine Learning** (CEX-120.11):
    - This document provide a guidance on the specific considerations related to the use of ML in the qualification process.

5

Future Work: Spanish Regulator Review & Approval

Future Work: Spanish Regulator Review & Approval



6

Summary & Conclusions

Summary and Conclusions

- CEX-120 is the Spanish Methodology for Qualification of Non-Destructive Testing used in the In-Service Inspections of Nuclear Power Plants
  - It is compound by one Main Document and seven Technical Documents all of them issued in 2003.
  - CEX-120 adapt the most important aspects of the ENIQ documents to the Spanish NPP framework.
  - It has other references, such as, Section XI of ASME Code.
- It was necessary to updated the Documents due to ENIQ Methodology Document for Qualification of Non-Destructive Testing and Recommended Practices has been updated (or appear some new ones or other have been replaced).
  - Furthermore, other references (ASME XI) have had relevant modifications that should be included too.

Summary and Conclusions

- An updating process has been defined:
  - Look for the current issue of ENIQ Reports that we want to use in order to updated CEX-120 documents.
    - Understand this document and extract the relevant information for the Spanish Nuclear fleet.
  - Review other sources of information (references) such as ASME XI with the same goal
- As a result of this process:
  - The Main Document, CEX-120 has been updated, and the seven Technical Document has been updated too.
  - Four new Technical Document has been created.
- Spanish Methodology for Qualification of Non-Destructive Testing used in the In-Service Inspections of Nuclear Power Plants is currently in the state of the art.

¡Gracias! Thank you!

¿Preguntas? Questions?

14. Advanced Manufacturing and NDE

The presentations in this session are listed in the table below.

Advanced Manufacturing and NDE	**Chair:** Ignacio Real Rubio (Iberdrola)
Exploratory Ultrasonic Testing (UT) Nondestructive Evaluation (NDE) Applied to Dissimilar Metal Components	George Connolly (EPRI) et al.
Real-Time Phased Array Ultrasonic Weld Pool Monitoring During Multi-Pass Weld Deposition	Nina E. Sweeney, David Lines (Univ. of Strathclyde) et al.
Non-destructive testing of Additive Manufactured (AM) components for the nuclear industry as well as other applications of AM	Ola Johansson (Ringhals AB) & Jorge Benítez (SQC)
In-Process Ultrasonic Inspection During Fusion Welding	Charles N. MacLeod, David Lines (Univ. of Strathclyde) et al.
Proposal of mechanical benchmarks for image-based simulation (IBSim) workflows in high-value manufacturing	Llion M. Evans et al. (Swansea Univ.)

Advanced Ultrasonics and Additive Manufacturing in Support of Low Carbon Energy Generation

George Connolly[1], Mark Dennis[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): gconnolly@epri.com

In the support of the EPRI Low Carbon Resources Initiative (LCRI), this research addresses the application of modern and advanced ultrasonic NDE techniques to additively-manufactured (AM) components. We present UT results, from both conventional UT and Total Focusing Method (TFM), and observations therefrom upon various series of AM coupons and reference standards designed in-house at EPRI and printed using laser powder bed fusion (LPBF). The UT results are correlated against RT results and microstructural characterisation. A procedure to estimate UT sensitivity to various reflectors is presented, where the applicability and strength of TFM is demonstrated.

In this research, we also comment upon UT performance in application to a pair of pipe sections. The pipe sections varied in grade of the nickel alloy material. Zero-degree UT, angle-beam UT, and time-of-flight diffraction were all applied to the pipe outside diameter, revealing the presence of significant defects of cracking and porosity within certain parts of the pipes. Small pieces were cut from each pipe and optical metallography strongly corroborated the UT results. Destructive testing was also applied to the removed pieces.

Keywords: Additive Manufacturing, Directed energy deposition, Dissimilar metal component, Phased Array, Ultrasonic testing

Exploratory Ultrasonic Testing (UT) Nondestructive Evaluation (NDE) Applied to Dissimilar Metal Components

Wednesday 28 June 2023

George Connolly, EPRI, Inc.
John Shingledecker, EPRI, Inc.
Anand Kulkarni, Siemens
Jeff Crandall, CCAT, Inc.
Bruce Greer, EPRI, Inc.
Stephen Tate, EPRI, Inc.

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Outline

- Two case studies:
  - AM test artifact for UT designed at EPRI, Inc.
    - Volumetric UT results
    - FMC/TFM application
    - Work carried out in conjunction with the Siemens Charlotte Advanced Technology Collaboration Hub (CATCH) for Additive Manufacturing [1]
  - Pair of dissimilar metal pipes with carbon steel cladding a Nickel-based alloy
    - Material selection made in support of ongoing EPRI research [2]
    - Intended to demonstrate NDE techniques and capabilities upon novel fabrication methods
    - Work carried out in collaboration with the Connecticut Center for Advanced Technology, Inc.
- Summary

EXTERNAL PARTNER:
CONNECTICUT CENTER FOR ADVANCED TECHNOLOGY, INC.

EXTERNAL PARTNER: SIEMENS CORPORATION
Charlotte Advanced Technology Collaboration Hub

[1] DiPasquale, C. *Siemens Opens New Technology Hub in Charlotte, NC to Accelerate Industrialization of Additive Manufacturing* url: https://new.siemens.com/us/en/company/press/press-releases/usa/siemens-opens-new-technology-hub-additive-manufacturing.html **2022**
[2] *ICME and In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-Based Powder Bed Additive Manufacturing Processes for Nuclear Structural Applications*. EPRI, Palo Alto, CA. **2020** 3002018273

Project funded by the Department of Energy of the U. S. Government under Award Number DE-FE0031808

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AM Test Artifact for UT

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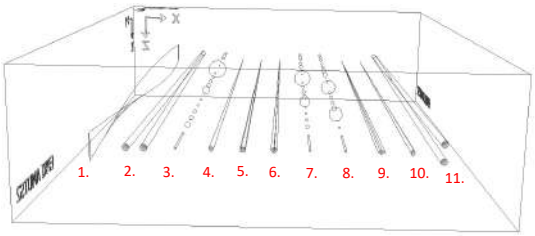
AM Test Artifact for UT

Arrangement of Internal Features

- Test artifact designed at EPRI intended for UT
  - Flat outer surface
  - In third iteration of design
- Internal artifact features:
  - Difficult or impossible to produce with conventional manufacturing:
    - Embedded spheres
    - Tapering SDH
    - Rotating slots
  - "Continuous" variants of discrete features in demo blocks
- Build by EOS M400-1 of Alloy 718 at the Siemens CATCH
- Exterior dimensions: (140×36×115)mm
- Heat post-treatment; held at 2050°F for 1h



ID	Name	Description
1.	Rotating slot	6.4mm tall; rotates 180°
2.	Horizontal SDH pair	Ø1.5mm diameter; maximum separation 4mm
3.	Embedded spheres and surface-connected SDH	42 spheres of Ø0.075mm to Ø1.500mm in Ø0.041mm intervals; surface-connected SDH are Ø0.4mm and 15mm in depth
7.	Embedded spheres and surface-connected SDH	
8.	Embedded spheres and surface-connected SDH	
4.	Tapering SDH	Ø1mm diameter; 125mm long
5.	Tapering square hole	1mm side; 125mm long
6.	Tapering diamond hole	1mm side; 125mm long
9.	Tapering wide rhombus	1mm side; internal angles of 30° and 60°; 125mm long
10.	Tapering tall rhombus	1mm side; internal angles of 60° and 30°; 125mm long
11.	Vertical SDH pair	Ø1.5mm diameter; maximum separation 4mm

EPRI "VTFM" demo block (**2011**) [5]

EPRI "SRI" demo block (**2017**) [6]

[5] Nondestructive Evaluation: Study of the Enhancements to the Total Focusing Method. EPRI, Palo Alto, CA: **2012**. 1025233.
[6] Laroche, N., Bourguignon, S., Carcreff, E., Idier, J., Duclos, A. *Fast inverse approach for the deconvolution of ultrasonic TFM images using a spatially varying PSF in NDT* in: Proc. IEEE Int. Ultrason. Sym. **2019**

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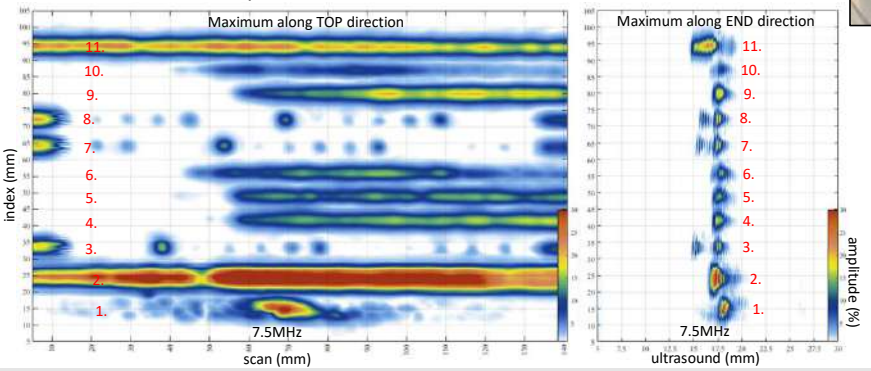
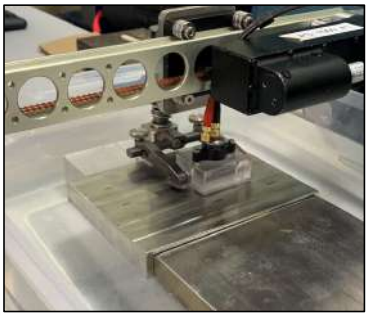
AM Test Artifact for UT

Selected Conventional UT Scan Results

- Scanned in immersion from top and bottom using Ø0.375in. conventional UT probes
  - Instrument: Zetec DYNARAY Lite
  - Four frequencies: [2.25, 3.50, 5.00, 7.50]MHz
- Observations:
  - Variation in surface coupling evident
  - SDH pairs difficult to distinguish
- Limit in detection computed as a function of feature dimension or orientation





CAD animation

Conventional UT volumetric reconstruction

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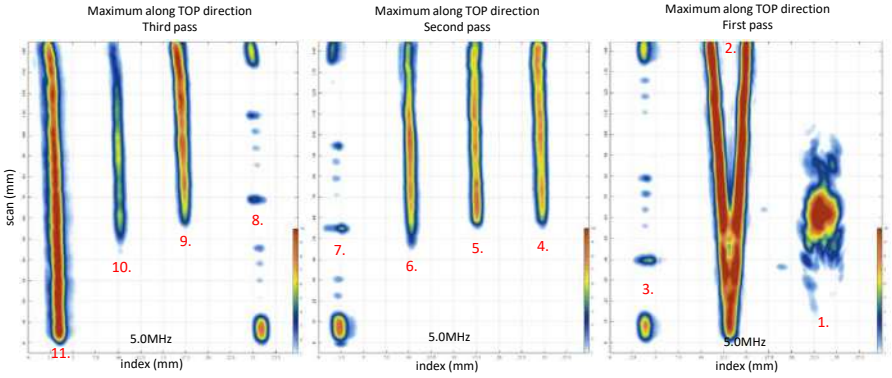
AM Test Artifact for UT

Selected FMC/TFM Scan Results

- Scanned in immersion from top and bottom using LPA probes
  - Instrument: Zetec Topaz64
  - Two frequencies: [5, 10]MHz; probe characteristics in table
- Observations:
  - SDH pairs are strongly distinguishable
  - Aperture is 8mm wider than the region of interest; must consider ultrasonic directivity
- Limit in detection computed as a function of feature dimension or orientation



Attribute	5MHz probe	10MHz probe
Pitch	0.6mm	0.3mm
Elevation	10.0mm	10.0mm
Active aperture size	38.4mm	19.2mm
Active aperture element count	64	64

FMC/TFM volumetric reconstruction

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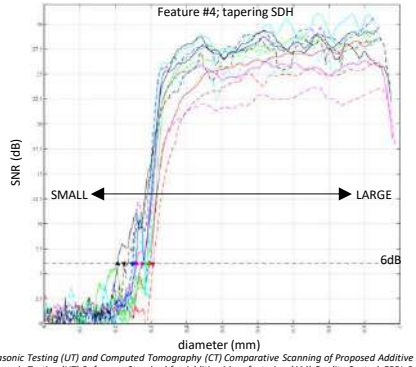
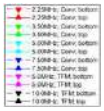
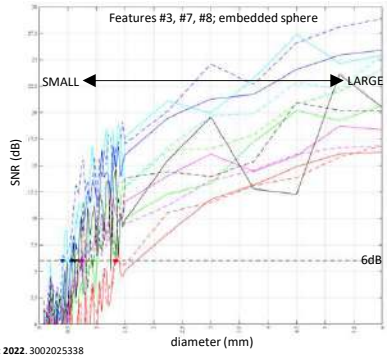
AM Test Artifact for UT

Example processed results

- Relatively constant SNR (depending on background noise) then sharp drop
  - Limit of detection in the range Ø0.20mm to Ø0.31mm
  - Higher frequencies perform better for conventional UT and FMC/TFM
  - FMC/TFM generally outperforms conventional UT
- Other tapering features behave similarly
  - Diamond and tall rhombus detectible at slightly smaller dimensions
  - Square and wide rhombus detectible at comparable dimensions
- Three rows of spheres aggregated and processed
  - Limit of detection in the range Ø0.42mm to Ø1.35mm; much greater variation
  - Higher frequencies perform better for conventional UT and FMC/TFM
  - Best SNR given by conventional UT at higher frequencies
- General observations:
  - Results not significantly affected by scan face [7,8]
  - Modest improvement in results after surface machining [7]







[7] *Ultrasonic Testing (UT) and Computed Tomography (CT) Comparative Scanning of Proposed Additive Manufacturing Reference Standard.* EPRI, Palo Alto, CA: **2022**. 3002025338
[8] *Ultrasonic Testing (UT) Reference Standard for Additive Manufacturing (AM) Quality Control.* EPRI, Palo Alto, CA: **2022**. 3002025339

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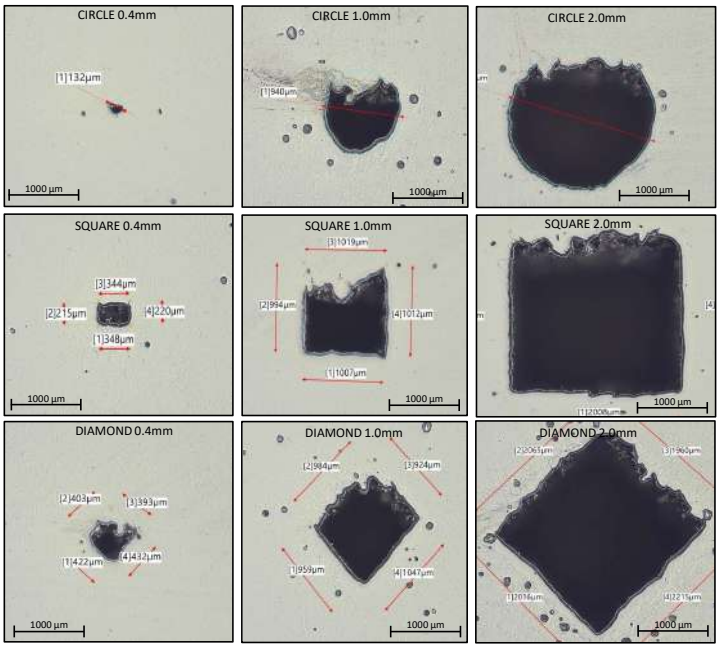
UT and VT comparison

Feature Visibility and Feature Distortion

- A smaller block built to accompany the AM test artifact by the same instrument and same build parameters
  - Pits of varying dimension match the shapes and size range of the five tapering features of the AM test artifact
  - Image processing measures as-built feature dimension and area for quantitative analysis; compared against nominal or expected values [8]
- VT observations:
  - Evident feature distortion becoming more severe as shape dimension decreases
  - Limits of detection depend on shape
  - Detection limit in the range 0.30mm to 0.40mm
  - Comparative limits of detection in table for certain shapes (UT and VT) shown in table [8] (***WIP***)

Feature	VT	Conventional UT 5MHz	Conventional UT 7.5MHz	FMC/TFM 5MHz	FMC/TFM 10MHz
Circle	0.40	0.29	0.27	0.20	0.25
Square	0.40	0.26	0.20	0.18	0.20
Diamond	0.40	0.25	0.23	0.16	0.26

build direction



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Dissimilar Metal Pipes

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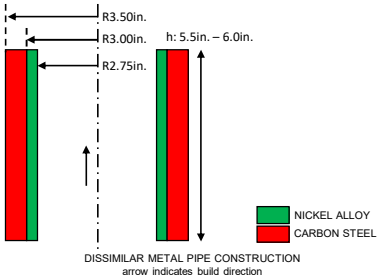
Dissimilar Metal Pipes

Pipe Structure and Composition

- Intended to demonstrate NDE techniques and capabilities upon novel fabrication methods
- Pair of pipes built by CCAT, Inc. under contract to EPRI, Inc.
  - Overall dimensions: 178mm (OD); 139mm-158m (height)
  - Instrument: DMG Mori LaserTec 65-3D, selected for its high deposition rate
  - Tool path programming for appropriate motion of deposition nozzle for both materials with minimal contamination
    - 100k lines of code
    - 170 deposition layers; 0.86mm layer thickness
  - Build time per pipe ≈27h due to time taken to clear feed lines when switching material
  - No applied heating post-treatment



- Applied UT techniques:
  - 0° conventional UT at 2MHz and 4MHz
  - Matrix array probe at 5MHz
  - DMA at 2MHz
  - ToFD at 3.5MHz and 5.0MHz
  - Looking both directions along axis (except 0° scan)
  - Positional encoding axially and circumferentially

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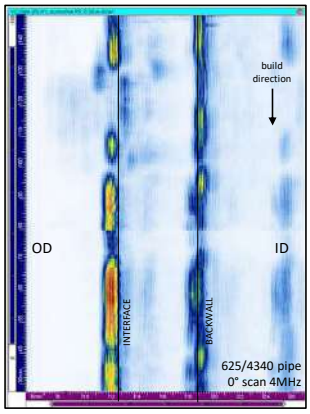
Dissimilar Metal Pipes

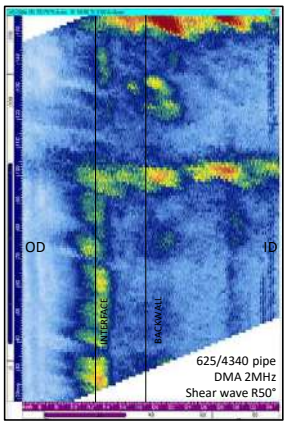
Ultrasonic Results Comparison and Summary: 625/4340

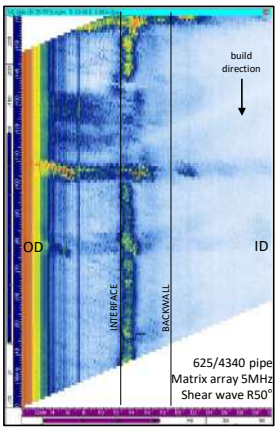
- Difference in sound speeds not accounted in the image reconstructions
- General observations:
  - Strong response from the dissimilar metal interface at most locations
  - Backwall not seen in angle beam scans
  - Apparent cluster is seen at “gap” in interface response
  - There exists a noticeable feature extending perpendicularly from the OD

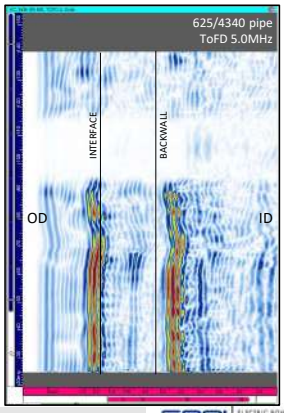
Volumetric Reconstruction: 0° scan at 4MHz

Volumetric Reconstruction: R50T at 2MHz









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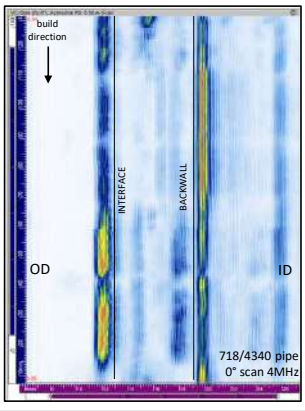
Dissimilar Metal Pipes

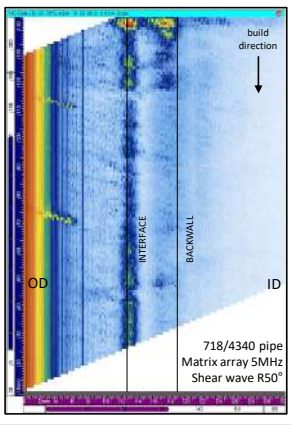
Ultrasonic Results Comparison and Summary: 718/4340

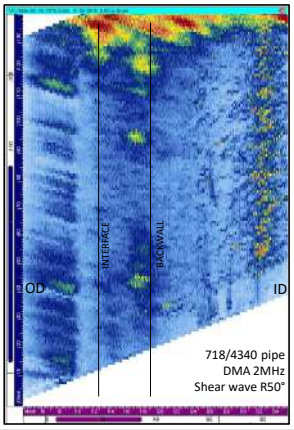
- Difference in sound speeds not accounted in the image reconstructions
- General observations:
  - Strong response from the dissimilar metal interface; some “gaps”
  - Relative strength of interface and backwall varies strongly
  - Backwall not seen in angle beam scans

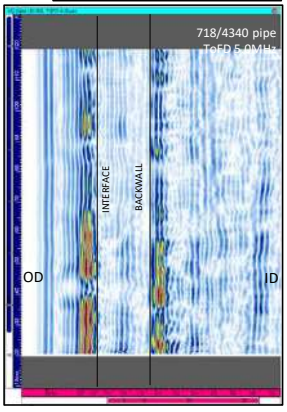
Volumetric Reconstruction: 0° scan at 4MHz

Volumetric Reconstruction: R50T at 2MHz









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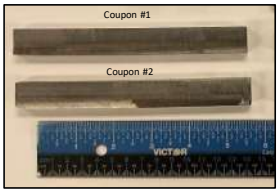
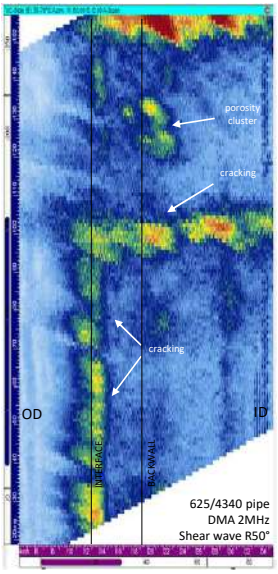
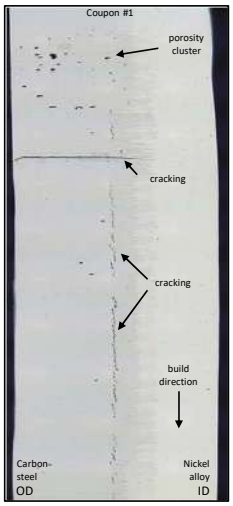
Dissimilar Metal Pipes

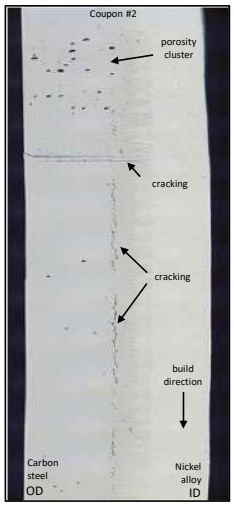
Qualitative Results Comparison and Summary: 625/4340

- Two longitudinal coupons cut from each pipe for optical metallography at 20×
  - Coupons measure ≈(158×13×6)mm each
- General observations [9]:
  - Good qualitative agreement with UT results
  - Persistent cracking confirmed near interface; arrangement of cracks matches that indicated by UT
  - Cracking and porosity clusters visible in metallography
  - Both materials have distributions of small circular features thought to be porosities









[9] *Program for Technology Innovation: Exploratory Ultrasonic Testing (UT) Nondestructive Evaluation (NDE) applied to Dissimilar Metal Components.* EPRI, Palo Alto, CA: **2022**. 3002025424

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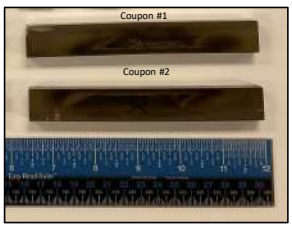
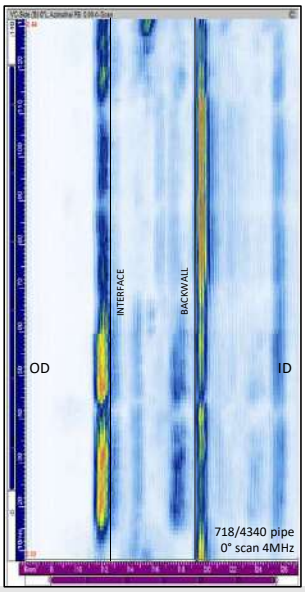
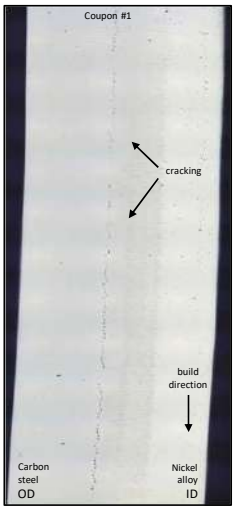
Dissimilar Metal Pipes

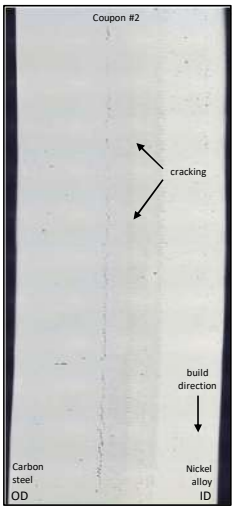
Qualitative Results Comparison and Summary: 718/4340

- Two longitudinal coupons cut from each pipe for optical metallography at 20×
  - Coupons measure ≈(139×13×6)mm each
- General observations [9]:
  - Good qualitative agreement with UT results
  - Persistent cracking confirmed near interface; arrangement of cracks matches that indicated by UT
  - Both materials have distributions of small circular features thought to be porosities









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Summary

- Case studies of exploratory NDE UT application to AM parts
  - Including the use of FMC/TFM showing strength of superior ultrasonic focusing
  - Optical metallographic results support UT observations
  - Test artifact may prove useful as part of a library of artifacts for quantifying UT capabilities
    - Demonstrates viability of test standards involving UT
    - Greater understanding and insight into quality deviation characteristics

- EPRI contacts for further information of ongoing AMM research in nuclear power:
  - John Shingledecker jshingledecker@epri.com
    - AM Demonstrations to Develop Alternative Supply Chain Routes for Common Piping System Product Forms
  - Marc Albert malbert@epri.com
    - Additive Manufacturing Roadmap for the Nuclear Power Industry [10]
  - David Gandy davgandy@epri.com
    - Candidate ALWR and lwSMR primary system components and roadmap [11]
  - Marc Tannenbaum mtannenbaum@epri.com
    - Review of AM to support acquisition of spare and replacement components
  - Stephen Tate state@epri.com
    - Lead for directed energy deposition research

[10] *Advanced Nuclear Technology: Additive Manufacturing Roadmap for the Nuclear Power Industry—Metal Alloy AM Technologies.* EPRI, Palo Alto, CA: **2020**. 3002018276.
[11] *Advanced Manufacturing Methods: Candidate ALWR and lwSMR Primary System Components and Roadmap.* EPRI, Palo Alto, CA: **2021**. 3002021059

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Real-Time Phased Array Ultrasonic Weld Pool Monitoring During Multi-Pass Weld Deposition

Nina E. Sweeney[1,2]*, Charles N. MacLeod[1], Simon Parke[2], David Lines[1], Charalampos Loukas[1], Momchil Vasilev[1], Stephen G. Pierce[1]

[1] *Centre for Ultrasonic Engineering (CUE), Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow G1 1XQ, UK*

[2]*Peak NDT Ltd, Jubilee Business Park, 1 Enterprise Way, Derby DE21 4BB, UK*

*Corresponding author's email: nina.sweeney@strath.ac.uk

Technical Presentation Abstract

Track: Advanced manufacturing and NDE

Many industrial sectors such as nuclear and defence, employ ultrasonic Non-Destructive Evaluation (NDE) as a means of ensuring the integrity of welded components at the point of manufacture and throughout their service life. In recent years, there have been increasing industrial and economic drivers to reduce manufacturing costs, particularly as the nuclear sector is being called upon to play a significant role in the delivery of a low-carbon energy future. The development and deployment of innovative in-process inspection and monitoring techniques in one way in which the NDE sector can support the achievement of this aim. Real-time inspection and monitoring of welding processes can help to reduce fabrication costs by detecting defects as they occur, allowing more efficient and cost effective repair.

In this body of work, phased array ultrasonic testing is used to interrogate the molten weld pool in real-time during deposition of multi-pass gas tungsten arc welds. The received ultrasonic signals contain sufficient information to isolate the molten weld pool and monitor key physical transitions occurring within the welding process, namely the melting and solidification of the weldment. Furthermore, it is also found that this technique is capable of discerning weld quality in real-time with significant signal changes occurring when defects such as Lack of Root Penetration (LORP) are present. It is believed that with suitable modification to the deployment strategy to allow for concurrent inspection, the received signals are of sufficient quality to form the basis of a closed-loop weld control system in the future.

Keywords: Weld pool monitoring, Phased Array, Multi-Pass Welding, Non Destructive Evaluation

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Real-Time Phased Array Ultrasonic Weld Pool Monitoring During Multi-Pass Weld Deposition

NDE in Nuclear 2023

Nina E. Sweeney[1,2]*, Charles N. MacLeod[1], David Lines[1], Simon Parke[2], Stephen G. Pierce[1], Charalampos Loukas[1], Momchil Vasilev[1]

[1]University of Strathclyde, Glasgow, UK;

[2]Peak NDT Ltd., Derby, UK

*nina.sweeney@strath.ac.uk

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OUTLINE

- Industrial Motivations & Aims
- Technical Background and Associated Challenges
- Real Time Ultrasonic Weld Pool Monitoring
  - Bridging root weld to isolate the molten weld pool
  - Full length root weld replicating standard welding practice
  - Root weld with induced Lack of Root Penetration
  - Hot pass weld to isolate molten weld pool in upper layers
- Conclusions & Future Work

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INDUSTRIAL MOTIVATION

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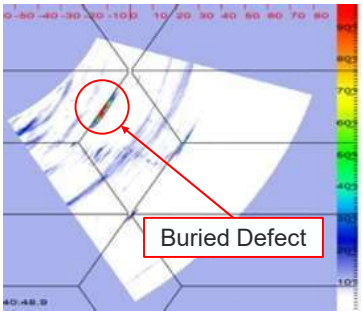
- Ultrasonic Non Destructive Testing (NDT) ensures safety of welded components both before and during service
- Multi-pass welding is common in high-integrity welding
- Traditional inspection occurs after deposition of all passes, leaving defects introduced in early weld runs buried until final inspection
- In-process ultrasonic inspection and monitoring offers:
  - Real-time volumetric weld measurement
  - Early detection of defects
  - Reduced rework time & costs

Phased Array Inspection of Completed Weld



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AIMS & OBJECTIVES

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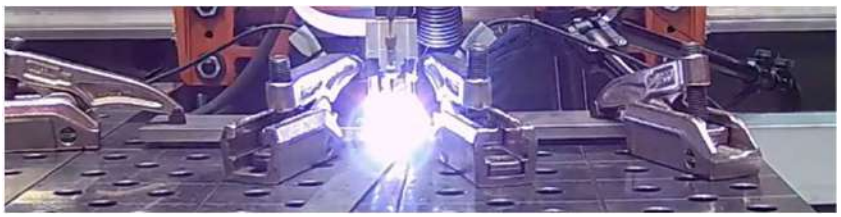
- Real-time, in-line ultrasonic inspection and monitoring of molten weld pool offers:
  - Immediate detection of common weld defects
  - Volumetric inspection unlike common optical and laser systems
  - Opportunity for closed-loop control to reduce defect occurrence
- **High-integrity welds, right first time, every time**
- **Objective: Real-time imaging of the molten weld pool**



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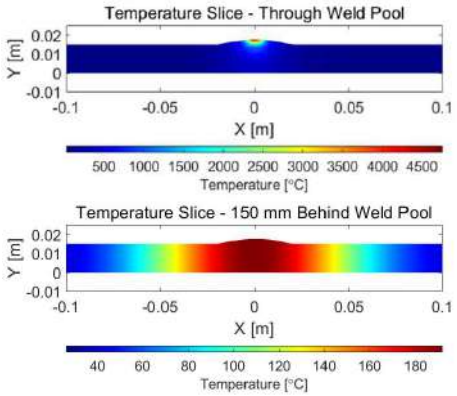
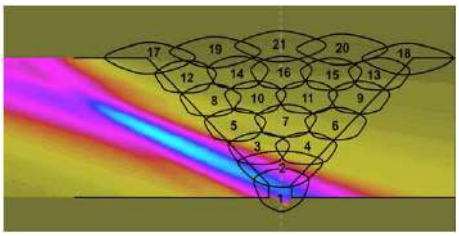
ASSOCIATED CHALLENGES

- Changes in thermal gradients present during fusion welding processes cause complex ultrasonic beam refraction, energy loss and time shifts due to varying sound velocities
- Experimentally validated COMSOL models of GTAW process allows prediction of bulk thermal gradients experienced during welding
- Thermal gradients are most extreme in the plane directly below the weld torch





- Fixed characteristics of single elements make them ineffective for inspection of individual weld passes
- Phased arrays allow for accurate beam-steering and focussing
- Acoustic energy can be concentrated on the intended molten weld pool

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EXPERIMENTAL HARDWARE SETUP

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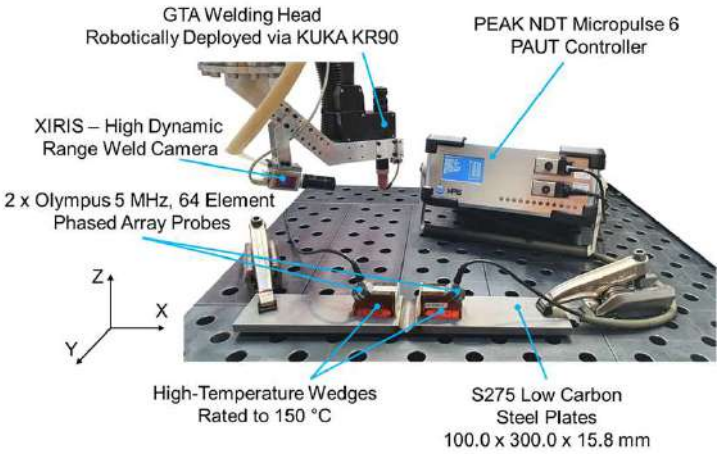

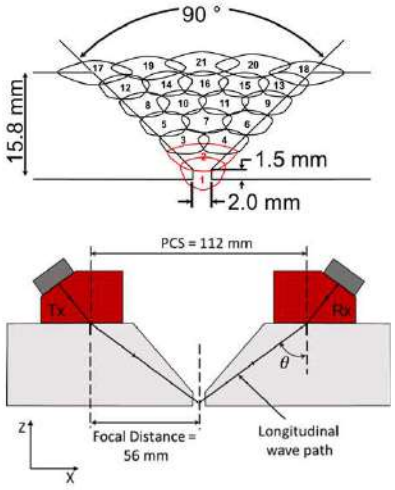

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REAL TIME WELD POOL MONITORING

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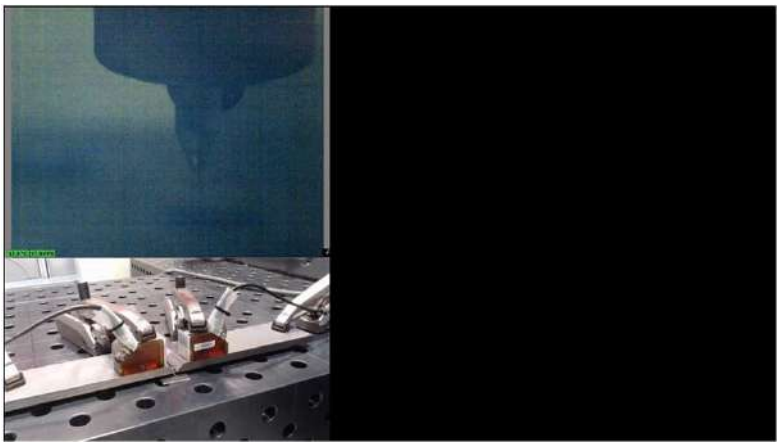
- Bridging root weld to isolate the molten weld pool
- 75° pitch-catch beam, focused at mid-point of root



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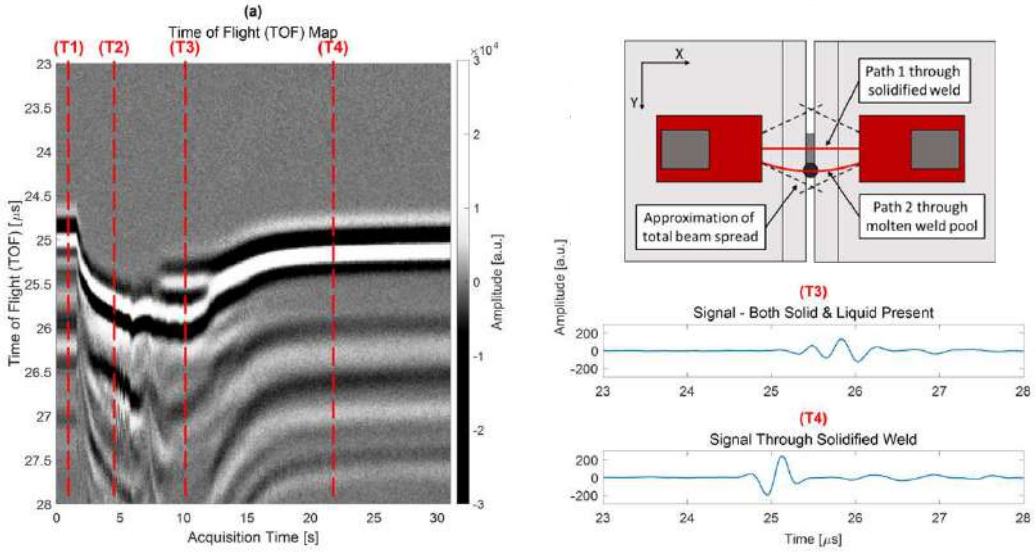

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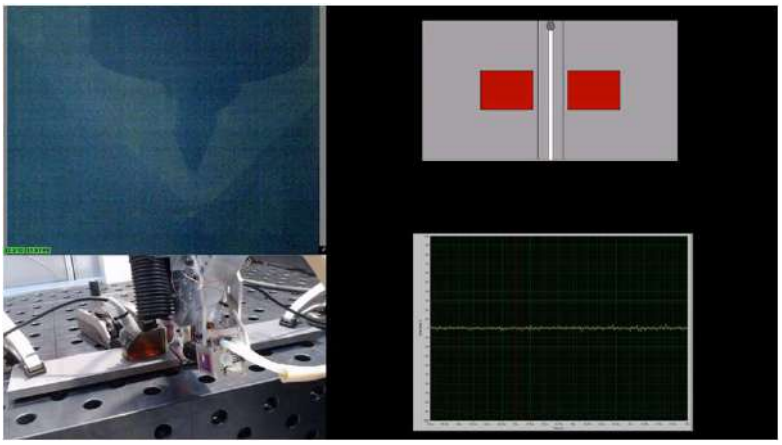

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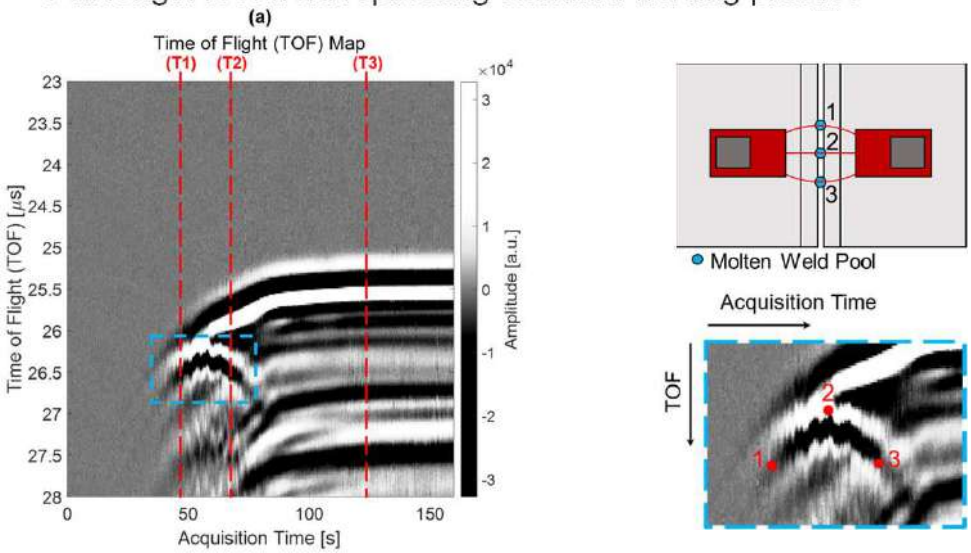

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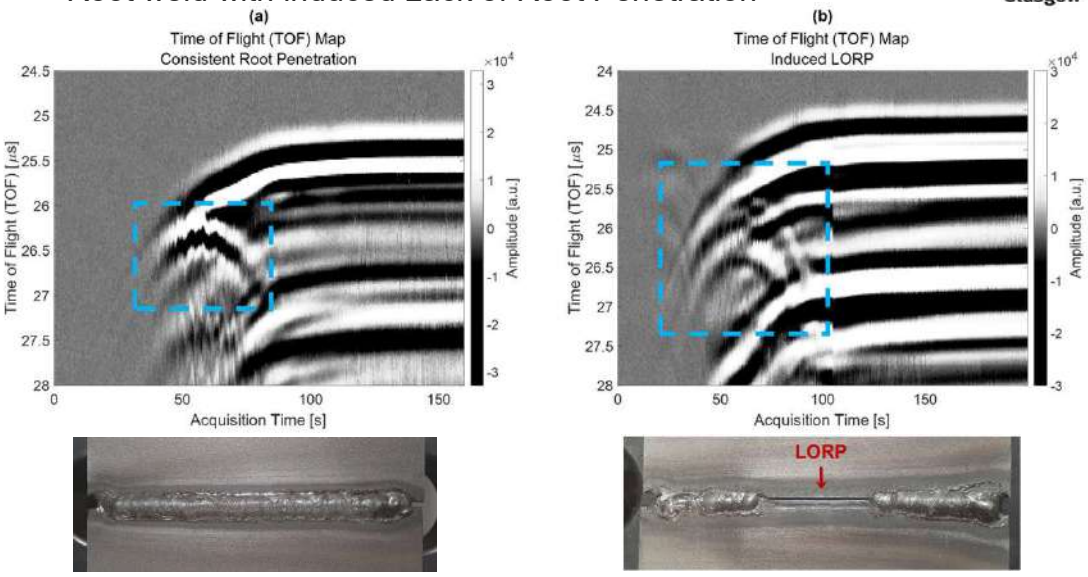

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REAL TIME WELD POOL MONITORING

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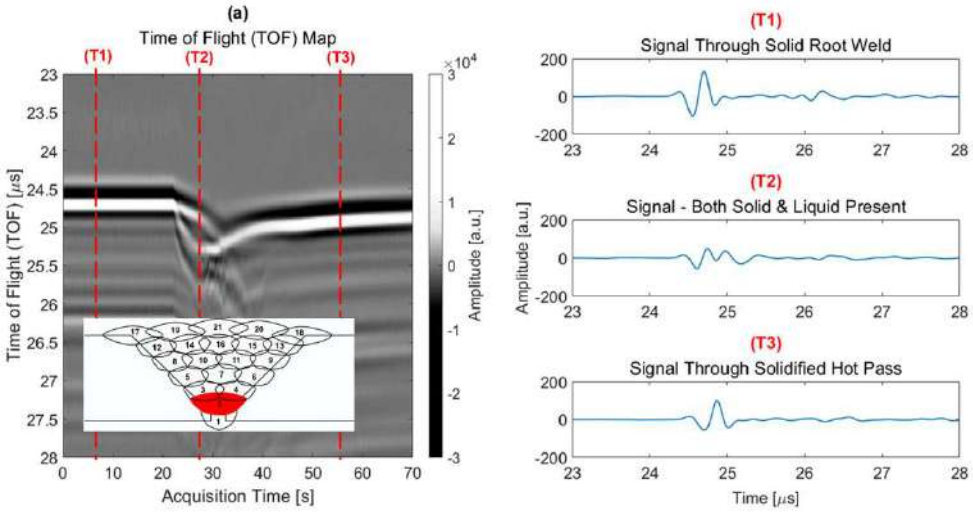
- Hot pass weld to isolate molten weld pool in upper layers



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CONCLUSIONS & FUTURE WORK

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- In-process phased array monitoring and control offers significant technical and commercial benefits to future manufacturing
- Focussed phased array pitch-catch inspection has been successfully implemented to monitor in real-time robotically deployed GTAW welds
- 3 key received signal changes have been identified and attributed to physical stages within the welding process

Future Work

- Quantitative Analysis
- Incorporating Dry-Coupling
- Automated Defect Detection
- Closed Loop Control

13

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Abstract

Non-destructive testing of Additive Manufactured (AM) components for the nuclear industry as well as other applications of AM

Ola Johansson[1], Jorge Benítez[2]

[1]Ringhals NPP, Varberg, Sweden
[2]SQC Swedish Qualification Centre (SQC), Stockholm, Sweden
…

E-mail address (corresponding author): jorge.benitez@sqc.se, ola.johansson@vattenfall.com

Title of Presentation: ***Non-destructive testing of Additive Manufactured (AM) components for the nuclear industry as well as other applications of AM***

Additive Manufacturing (AM) refers to the creation of objects by "adding" material. Therefore, 3D printing is a form of additive manufacturing. When an object is created by adding material one layer at the time.

During the last decades, the development of new type of 3D-printers and new materials have been quickly developed and became cheaper. The AM has lot of benefits that make it use very attractive even for the nuclear industry. Among these benefits are:

- Design complexity: Possibility to manufacture components with complex geometries
- Minimal machining
- Reduction of lead time
- Components can be manufacture on-site when they are necessary to replace

However, at the moment, there are not any accepted codes for AM for the nuclear industry. It means the requirement of the specific qualification of the process of manufacturing for each type of components from the point of view of Material integrity and Non-Destructive-Examination (NDE).

Ringhals NPP has manufactured two (2) AM test pieces to perform a feasibility study regarding NDE. This presentation describes the trials performed on two (2) test blocks manufactured by Ringhals to perform a feasibility study of the AM material´s proprieties from the NDE point of view. The presentation also gives a glimpse of other application of the AM, i.e. the use of the AM technology to manufacture defects for test blocks to be used during the qualification of the NDT techniques.

Keywords: Ringhals NPP, SQC, Additive Manufactured (AM), NDE.

Non-destructive testing of Additive Manufactured (AM) components for the nuclear industry as well as other applications of AM

Ola Johansson – Ringhals AB
Jorge Benitez – SQC

NDE in Nuclear, Sheffield, 2023
26-29 June 2023

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Content:

- Introduction of AM for nuclear industry
- Feasibility Study of AM material´s properties
- Other Applications using AM

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Introduction of AM for nuclear use

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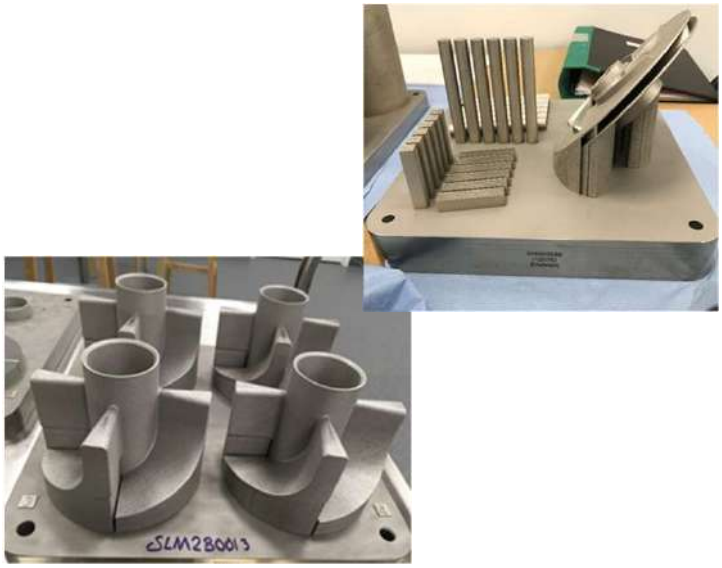
Why do BA-nuclear look at PM/AM?

- Economical crunch – "2-cent/kWh" – need to be economical relevant to stay on the grid! Compare to "The Nuclear Promise" in the US!
- Ageing plants means new challenges, i.e. moving outside our comfort zone, and possibly obsolescence, i.e. inability to sustain spare part, in-house or delivery at acceptable cost and time!
- A number of manufacturers already present AM and/or PM as a "preferred method of choice" from their perspective, at the same time the regulatory guidance points at "proven technology"
- Need to make strategic choices of what and whom to rely upon, and whom to turn to when in need for technical expertise as well as spare part deliveries!
- Avoid "nuclear specifics" where not needed or forced on us!
- Need to understand manufacturability, ageing and degradation of components (including on-line inspection methods and repairs) and extended maintenance to include that knowledge



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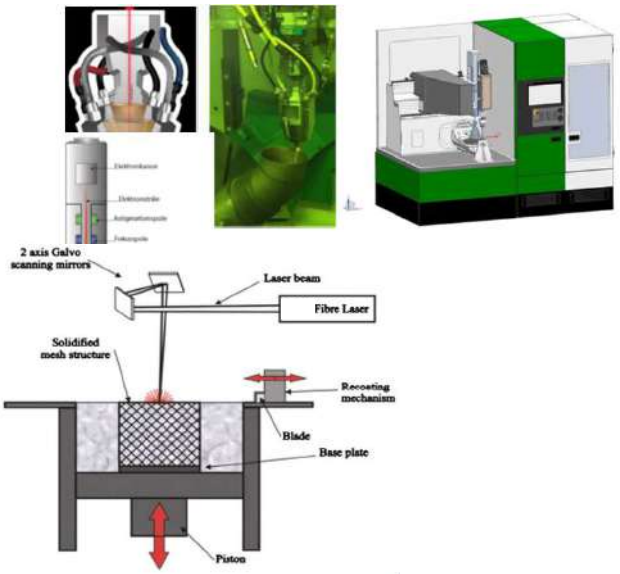
Additive Manufacturing - Metal

Methods of choice:

- **D**irect **E**nergy **D**eposition (**DED**)
  also known as
  Beam **M**etal **D**eposition (**BMD**)
- **E**lectron **B**eam **M**elting (**EBM**)
- **L**aser **P**owder **B**ed **F**usion (**L-PBF**)
  also known as
  Selective **L**aser **M**elting (**SLM**)



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Advantages with AM

Compared to conventional manufacturing AM/PM allow for a number of advantages:

- Control of microstructure – i.e. improved structural integrity & ISI
- Obsolescence – reverse engineering (no. manufacturer or tooling exists)
- Minimize number of Welds – less ISI
- Embedded sensors (e.g., temperature …) at fabrication
- Possibility to Manufacture parts with complex geometries and/or property gradients
- Improved Supply Chains
- Minimizing the amount of material and waste needed for the part (improved circularity)
- ….
- Virtual Warehouse - On-demand manufacturing
  - Time saving process
  - Cost efficient - producing low number of units

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Feasibility study of AM material´s proprieties

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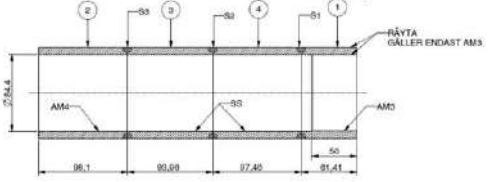
RAB manufacturing of AM Components for NDT feasibility study

- Ringhals has manufactured 2 test pieces to perform a feasibility study regarding NDT:
  - Pipes that have been welded together
  - T-nozzle
- The pipe test sample consists of 4 segments: 2 AM (1 of those HIP) and 2 forged SS-316
- The T-nozzle have a complex geometry, and some support structures that have been removed.



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Feasibility study of AM material´s proprieties of Pipe SS-316 - AM

- The investigation of the piece of pipe was carried out in two parts:
  - DEKRA performed a trial with a qualified procedure used for testing pipes and components on the primary systems, to verify that the UT-technique also works on an AM component
  - SQC investigated using different NDT techniques to check if there are any differences of the material proprieties (SS and AM) that make impact from the NDT point of view. This comparison was achieved by:
    - ✓ comparing signal to noise ratio UT techniques such as phased array (PAUT) and time of flight diffraction (TOFD),
    - ✓ comparing sound velocity in the material for longitudinal waves and transversal waves,
    - ✓ comparing the material attenuation
    - ✓ comparing signal to noise ratio with ET,
    - ✓ comparing the electrical material conductivity of the SS and AM using ET.

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Measurement of Noise Level - Pipe

- The amplitude of the noise level was measured as an average over the full axial and circumferential volume for each area (1-4) of the test specimen. This measurement (with PAUT, TOFD and ET) will give information if there are any deviation in material properties between SS and AM.
- The example, below shows the principle of measuring the noise level with UT/PAUT

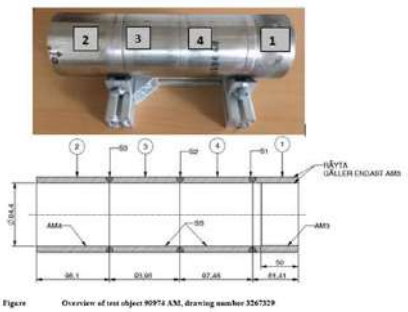

Figure Overview of test object 90974 AM, drawing number 3267329

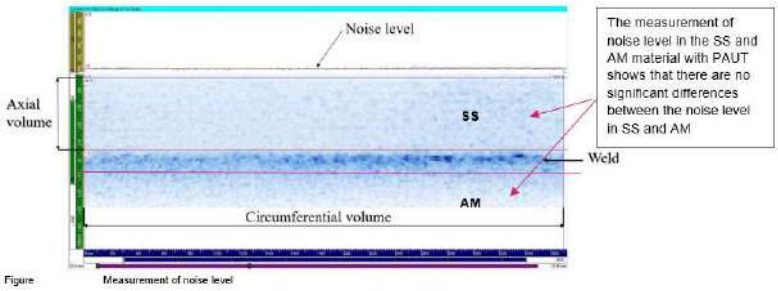

Figure Measurement of noise level

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Material attenuation - Pipe

- The attenuation was measured as deviation in amplitude between the first and second bottom echo (BE).
- The attenuation was measured in a specific point every 90° in the middle of each area (1-4) of the test specimen,

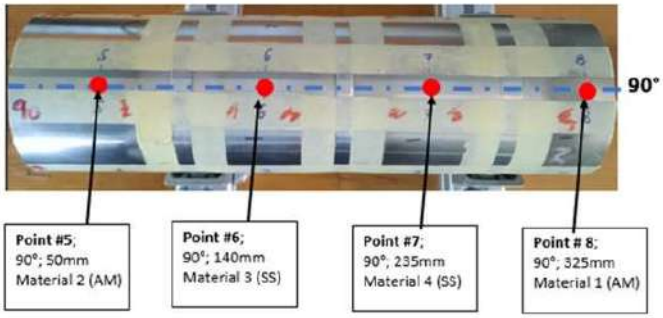

Figure Overview of measurement points of test specimen

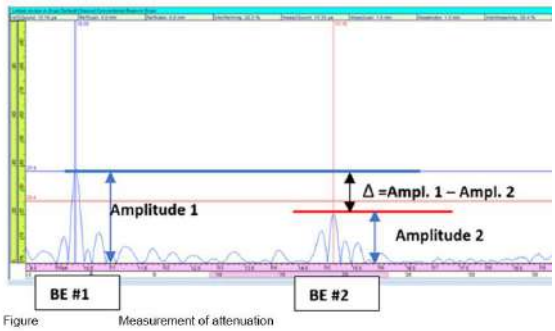

Figure Measurement of attenuation

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Noise level and attenuation comparison - Pipe

- There are no significant differences between the AM and SS and all individual measurements are within acceptable limits for SS.

Table Results of noise level and attenuation measurements

	Measurement of Noise level						ET Noise level	
	TOFD (FSH%)	PAUT Long (FSH%)	PAUT Trans (FSH%)	PAUT Long throug the weld,(FSH%)	PAUT Trans throug the weld, (FSH%)	Measurement Attenuation (dB)	ET D/P (V)	ET ABS (V)
Material 1 (AM)	10.3	5.3	5.9	15.1	14.9	-4.5	0.1	0.5
Material 2 (AM)	11.8	5.3	8.6	17.9	13.2	-5.6	0.05	0.4
Material 3 (SS)	11.8	4.6	6.6	15.1	13.8	-4.8	0.15	0.3
Material 4 (SS)	10.3	5.3	6.6	14.9	14.5	-5.0	0.15	0.3
Max deviation between AM vs SS	1.5	0.7	2	3	1.3	0.8	0.1	0.2
Max deviation between AM vs AM	1.5	0	2.7	2.8	1.7	1.1	0.05	0.1
Max deviation between SS vs SS	1.5	0.7	0	0.2	0.7	0	0	0
Relative deviation between AM vs SS	0	0.7	0.7	0.2	0.4	0.3	0.05	0.1

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Summary of Results - Pipe

- The measurement of noise level in the AM and SS materials with, TOFD and PAUT shows that there are not significant differences between the noise level in the SS and the AM materials
- The measurement of sound velocity has not been possible to perform due to it has been impossible to measure the wall thickness of the material with required accuracy
- The measurement of the attenuation of the material shows that there are not significant differences between the noise level in the SS and the AM materials
- The electrical conductivity in the SS and AM material is similar which means that the SS and AM material has similar chemical composition
- The measurement of noise level with ET show no significant differences between the noise level in the SS and the AM materials

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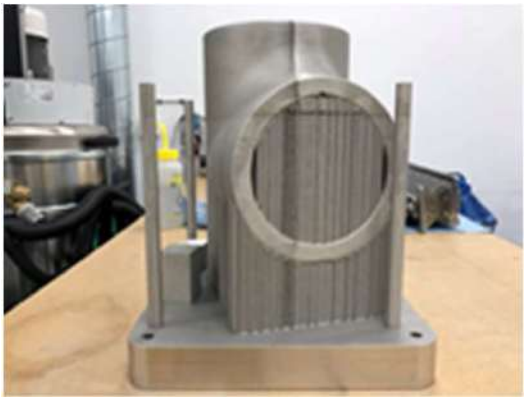
Trials on the 3D printed T-nozzle



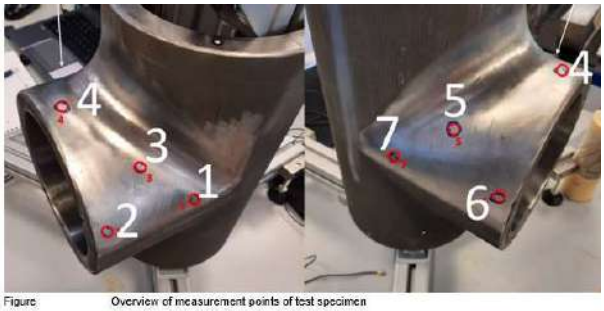


Figure Overview of measurement points of test specimen

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Feasibility study of AM material´s proprieties of T-nozzle

- The goals of the investigation of T-nozzle were to check if the material composition and characteristics have any negative impact on NDT, depending on the printing direction and complex geometries.
- During the trials, the following measurement were performed:
  - General noise level with ET and TOFD
  - Measurement of attenuation
  - Measurement of conductivity
  - Measurement of travel time with longitudinal waves
  - Thickness measurement

Remark:
Due to complexity of the geometry around the curved part of the nozzle the measurements were made as reasonable possible without damaging the equipment used. For TOFD only “back” (i.e. 0-90° of test object were investigated)

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Measurement of Noise Level - T-nozzle

- Due to the geometry of the test specimen the noise level measurements were limited to ET and TOFD.

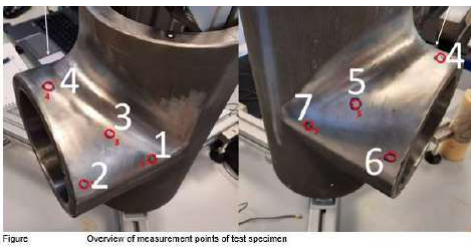

Figure Overview of measurement points of test specimen

Table - Noise level measurement

Avg. Noise level E0134, (ET driver/pickup) (V)	Avg. Noise level ET #4583, (ET absolute probe) (V)	Avg. Noise level TOFD (%FSH)
0,2	0,2	6

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Attenuation, sound velocity(ΔT), thickness and conductivity measurement - T-nozzle

- Thickness, attenuation, travel time (ΔT) and conductivity were measured in specific points marked on the test specimen.

Table Measurement of attenuation, sound velocity(ΔT), conductivity and thickness

Measure point	Thickness (mm)	Attenuation (dB)	Travel time (µs)	Phase angle deviation (°)
1	18,3	5,8	6,24	0
2	17,9	5,6	6,16	1
3	18,1	7,3	6,16	4
4	18,5	4,8	6,32	2
5	18,3	5,6	6,20	3
6	18,2	6,2	6,20	2
7	18,4	6,2	6,32	0

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Summary of Results - T-nozzle

- All the measurements are giving information that this test specimen will not affect ET, UT and TOFD technique.
- Measurements in all points indicates that there is no major deviation in material characteristics and all measurements are within acceptable tolerances.
- Geometries of the test specimen are complicating NDT inspection in the curved part.

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Conclusions of the feasibility study:

- The feasibility study of the pipe SS-AM shows that;
  - SS and AM has similar material proprieties
  - It is possible to inspect using NDT techniques
- The feasibility study of T-nozzle shows that:
  - machining areas (curved) do not make any negative impact regarding UT, TOFD and ET inspections techniques.
  - the printing direction and more complexed geometries does not affect the techniques.
  - In order to perform a check of the material proprieties from the NDT point of view is required customized probes and manipulators

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Other Applications using AM

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Other Applications

- RAB is looking for the possibility to use AM technology to manufacture defects and whole test piece with defects
- The goal in the first phase is to see how thin a defect can be created during the AM process.
- The technology is based on using a laser and metal powder to build layer by layer and where you don't want to create a solid bond between each layer, you turn off the laser and in this way you could theoretically create a cavity (i.e. a defect with a specified form)
- The test pieces will then be tested with different methods CT, VT, ET and cut into pieces and examined in a Microscope
- The first trials in this area have been done with very good results

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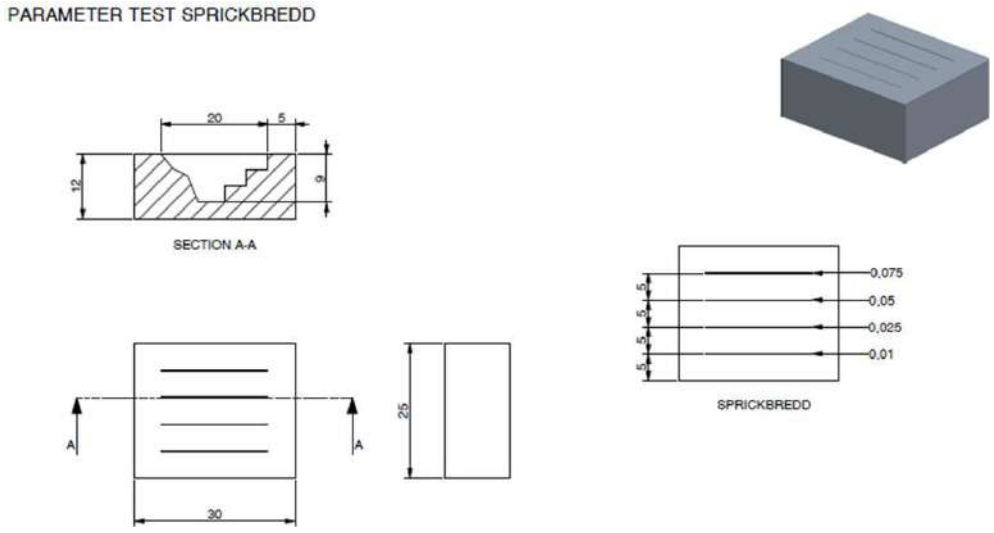
First Phase – 3D-printed small test-pieces with defects



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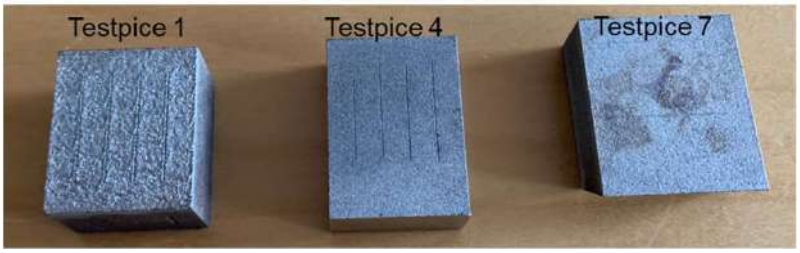
Actual 3D-printed small test-piece with defects

- Printed in different directions:
  - Laying down (Testpice 1)
  - Standing (Testpice 4)
  - In an angle (Testpice 7)



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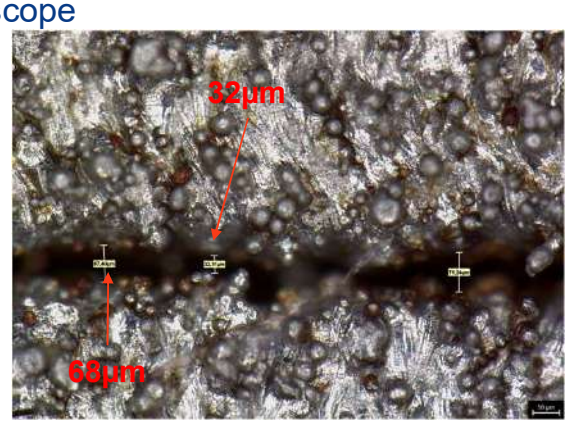
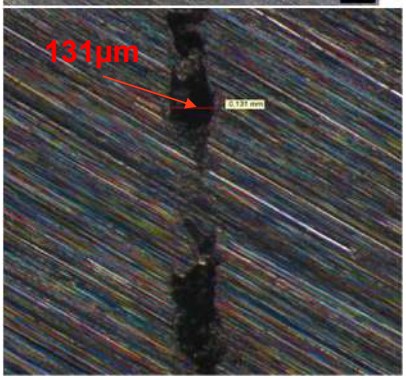
Investigation under a Microscope

The pieces have been cut and examined under a microscope





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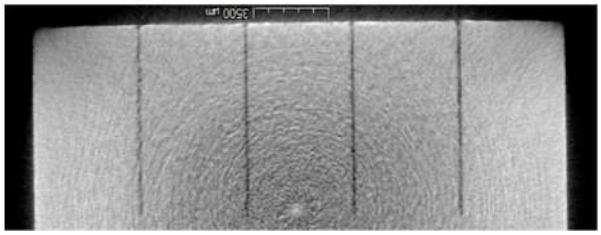
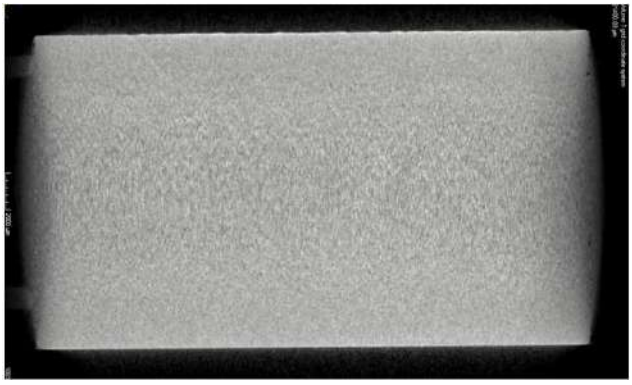
CT – Computed tomografi

The pices has been scanned with a slice of 10µm





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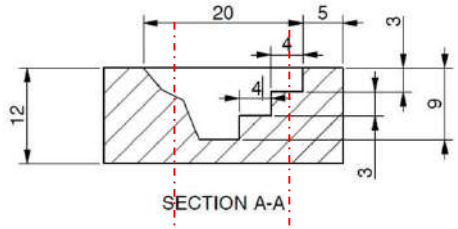
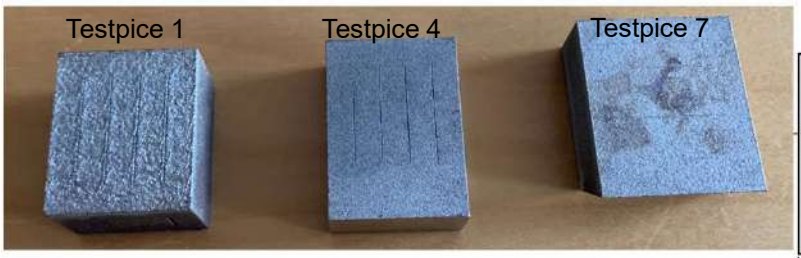
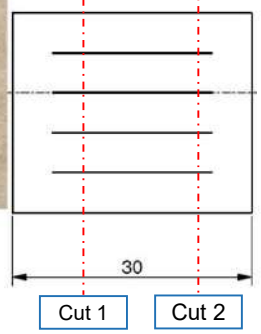
Metalurgical evaulation







Crack 4 - 0,075 mm
Crack 3 - 0,05 mm
Crack 2 - 0,025
Crack 1 - 0,01

Cut 1 Cut 2

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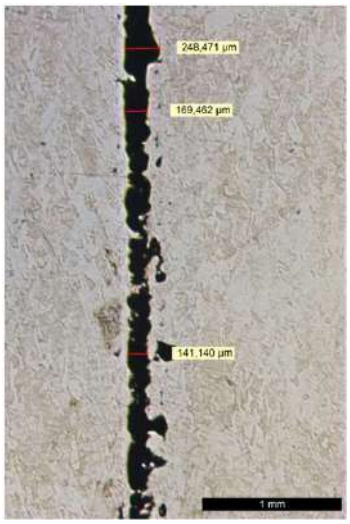
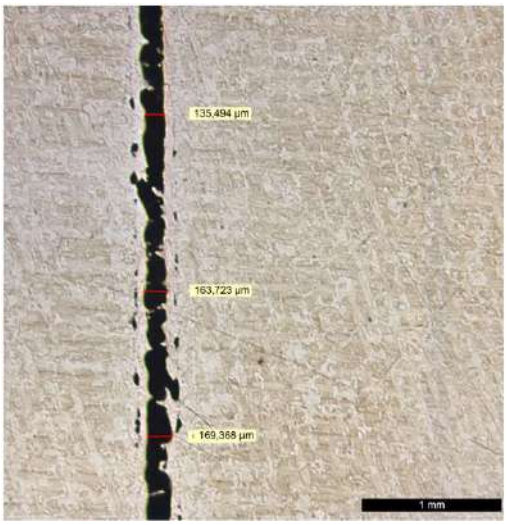
Metalurgical evaulation

Cut 1, Crack 4 (0,075 mm), 25x magnification

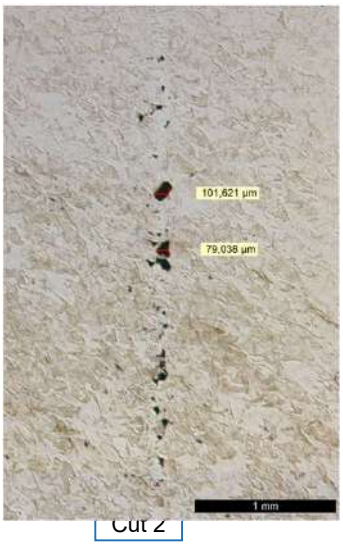
Testpice nr 1



Testpice nr 4



Testpice nr 7



Cut 2

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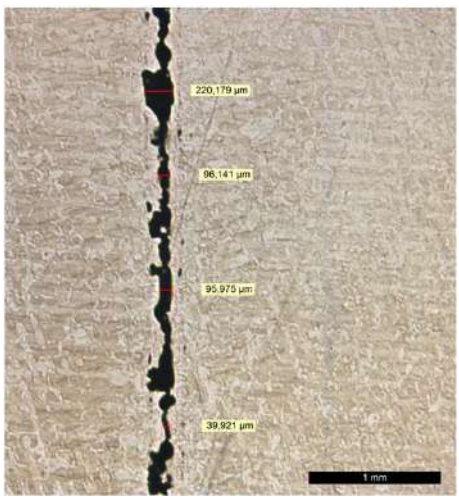
Metalurgical evaulation

Cut 2, Crack 1 (0,01 mm), 25x magnification

Testpice nr 4



Testpice nr 7

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Conclusion of possibility of printing defect with AM

- The result of the investigation shows that printing direction has a relevance for printing defects.
- It is possible to print with small width.
- The best result from the printing are in a standing orientation.

29

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Further investigation

- Manufacture larger pieces that can be tested with UT, ET, etc
- Manufacture embedded defects
- Manufacture defects with skew and tilt
- Investigate the possibility of manufacturing a full-scale test block with both weld and base material defects using AM technology.

30

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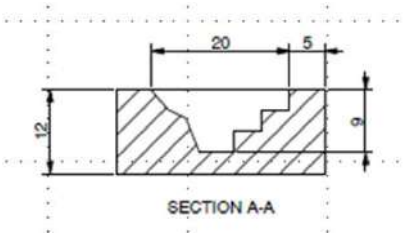
Further investigation

- 6 testpices in the same direction as testpice nr 4 and width 0.01 mm
  - Print with same setup of AM-printer
  - Testing other AM-setup to try to improve the crack width
  - Testing to print defect with skew and tilt



31

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Overall Conclusions

- Ringhals is in the process to adopt AM as one of the way to manufacture components to be used for replacement of component in Ringhals units
- A feasibility study of the AM material proprieties shows that there are not any differences from the NDT point of view of component manufactured traditional way (Subtractive manufacturing) versus AM
- The AM open a new field of use: the manufacturing of defects for test blocks to be used during the qualification of the NDT techniques

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In-Process Ultrasonic Inspection During Fusion Welding

C. N MacLeod[1], D. Lines[1], R. Vithanage[1], M. Vasilev[1], C. Loukas[1], N. Sweeney[1], E. Foster[1], E. Mohseni[1], Y. Javadi[1], G. Dobie[1], S.G. Pierce[1], A. Gahagan[1], N.King[1], P. Applequist[1], A. Burnett[2], C. Murray[2], R. Whitmore[2], P. Robinson[2], B. Holt[3], M. Symington[3], J. Allan[3], G. Little[3], M. Smart[4], D.L Ayres[4], J. Leatherland[4],

[1]Centre of Ultrasonic Engineering (CUE), Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow G1 1XQ, UK

[2]Cavendish Nuclear, Babcock Technology Centre, Unit 100A, Bristol Business Park, Stoke Gifford
BS16 1EJ

[3] Altrad Babcock, Porterfield Rd, Renfrew PA4 8DJ

[4] Nuclear Advanced Manufacturing Research Centre (NAMRC), University of Sheffield, Advanced Manufacturing Park, Brunel Way, Catcliffe, Rotherham S60 5WG

Abstract

Traditionally, the welding and inspection of welds are distinctly separate manufacturing processes, which limits productivity and throughput along with increasing re-work if defects are detected post-build. The Advanced Welding Equipment System Inspection and Monitoring (AWESIM) project introduces ultrasonic phased array inspection directly during welding to allow detection of imperfections and flaws as they occur, thus reducing rework, repair and delivering high-quality welds right, first time.

High-temperature dry-coupled Phased Array Ultrasonic Testing (PAUT) is introduced directly during Gas Tungsten Inert Welding (GTAW) deposition. A novel high-temperature automated weld inspection roller probe alongside new imaging algorithms compensate for the effect of negative process parameters such as temperature gradients, partially-filled grooves and Electromagnetic Noise Interference (EMI) to enable in-process inspection.

Results of this work are presented on sub-scale plate and pipe demonstrators with both intentionally controlled and unintentional defects. The SNR and sensitivity of the imaging and inspection system is measured, evaluated and quantified offering impact benefits such as reduced rework, schedule slippage and cost.

In-Process Ultrasonic Inspection During Fusion Welding

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1: Centre of Ultrasonic Engineering (CUE), Department of Electronic & Electrical Engineering, University of Strathclyde, Glasgow 2: Cavendish Nuclear, Babcock Technology Centre, Unit 100A, Bristol Business Park, Stoke Gifford
3: Doosan Babcock, Porterfield Rd, Renfrew 4: Nuclear Advanced Manufacturing Research Centre (NAMRC), University of Sheffield, Rotherham

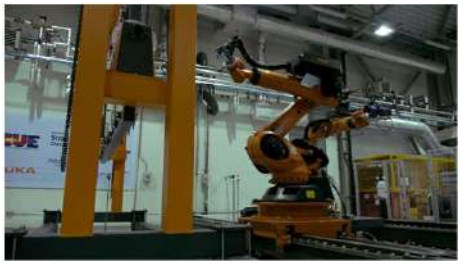
Sensor Enabled Automation

- Flexible manufacturing enhancement of high value assets and components
  - Increased Throughput – Faster Builds
  - Safety and Lifetime Enhancements – Quality Builds
  - Reduced Costs – Cheaper Builds

Measurement & Sensors

Automation & Robotics

Inspection Technologies



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Sensor Enabled Automation Robotics & Control Hub

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UK RESEARCH CENTRE IN NDE

University of Strathclyde Engineering

Inspection for new metal AM processes and materials – (applications in remanufacture & repair)

Inspection for Additive Manufacture

Inspection for High Value Manufacture

Autonomous inspection to reduce cycle time for aircraft production (A32x, 737 series)

Asset Inspection & Decommissioning

Autonomous inspection for hazardous/ limited access environments

Inspection for Materials Joining (welding)

In-process inspection for welding and material joining

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In-Process Ultrasonic Weld Inspection

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- Quality of weld measured at point of deposition
- ***Defects detected when they occur***
- ***Reduced rework when compared to completed fully-filled welds***
- ***Increased Schedule Certainty***
- Increased Throughput
- Reduced Production Time
- Increased safety and lifetime benefits
- Opportunity for Process Control

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In-Process Inspection Challenges

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Coupling – Traditional Liquid Coupling will invariably introduce defects

Electromagnetic Interference

Signal to Noise Challenges

Probe Deployment

High-Temperatures experienced in close proximity to weld

Speed of sound varying due to temperature change in material

Partially-Filled Groove Reflections

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In-Process Wave Propagation - Temperature

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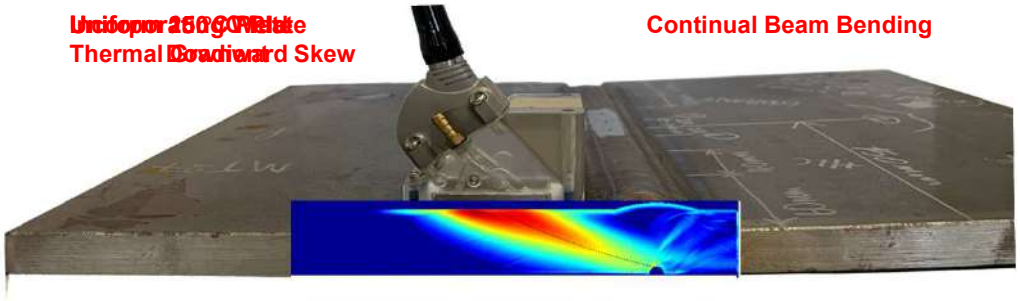
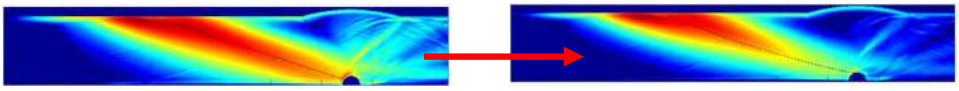
Thermal Gradient Forward Skew

Continual Beam Bending



- Non-uniform thermal gradients present during in-process fusion weld inspection result in complex wave beam refraction, energy reduction and time shifts from weldment defects/reflectors present.



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In-Process Inspection – Partially Filled Grooves

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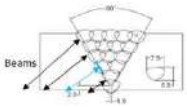
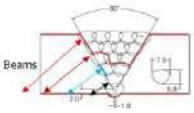


Standard Complete Weld and Correctly Reports LOF Defects (Blue)



Defect During Welding: Need to detect LOF Defects (Blue), whilst rejecting False-Positive (Red)

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In-Process Inspection – Partially Filled Grooves

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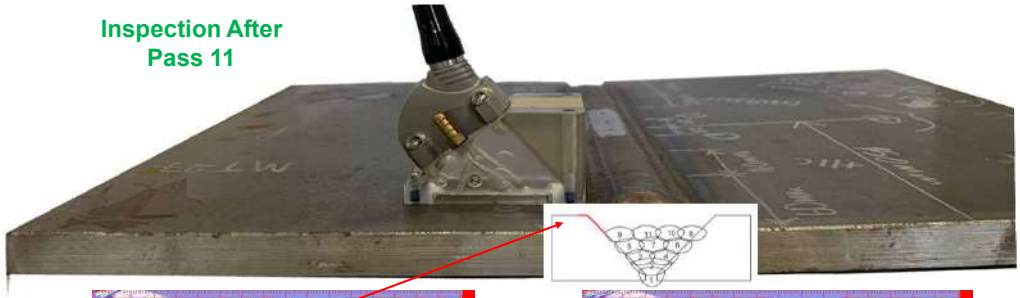
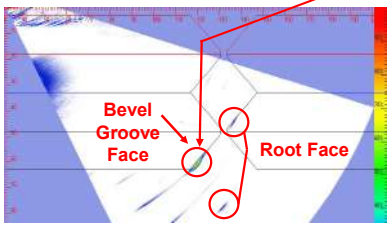
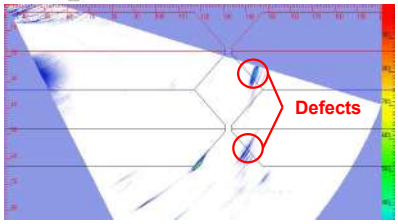
Inspection After Pass 11





Position 1 - Un-Defected Zone



Position 2 - Defective Zone

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In-Process Inspection – Partially Filled Grooves

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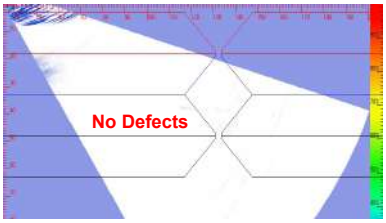
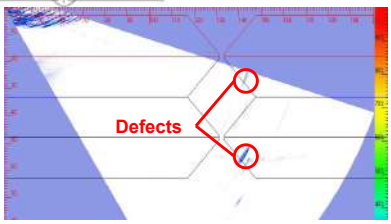
Inspection After Pass 21



Position 1 - Un-Defected Zone



Position 2 - Defective Zone

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AWESIM

SEARCH Sensor Enabled Automation Robotics & Control Hub

University of Strathclyde Engineering

- **AWESIM (Advanced Welding Equipment System for Inspection and Monitoring)**

AWESIM

Automated Welding Equipment System Inspection Monitoring

- AWESIM builds upon the in-process inspection activities of an EPSRC Prosperity Partnership and builds on the collaboration on the SIMPLE project with the Nuclear AMRC at University of Sheffield.

babcock DOOSAN PEAK NDT UNIVERSITY of STRATHCLYDE ADVANCED NUCLEAR RESEARCH CENTRE

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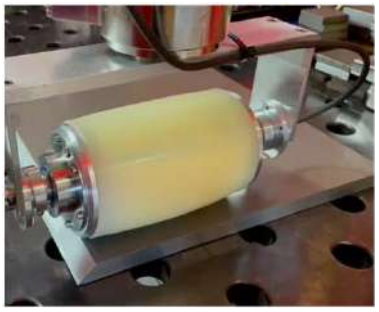
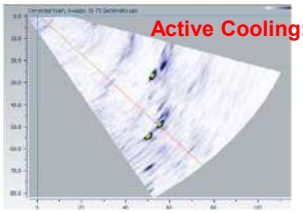
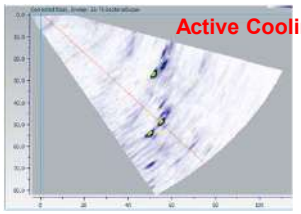
Roller Probe – Dry-Coupled, High-Temperature Inspection



- High-Temperature (350 degC) inspection
- Reduced Liquid Couplant – *Dry Coupling*
- High-Temperature Compliant Tyre
- 55º Shear Wave Inspection
- 64 Elements, 5 MHz, 0.5 mm Probe
- Inter-pass multi-layer inspection
- Integrated Surface Temperature Measurement



Active Cooling: Off



Active Cooling: On

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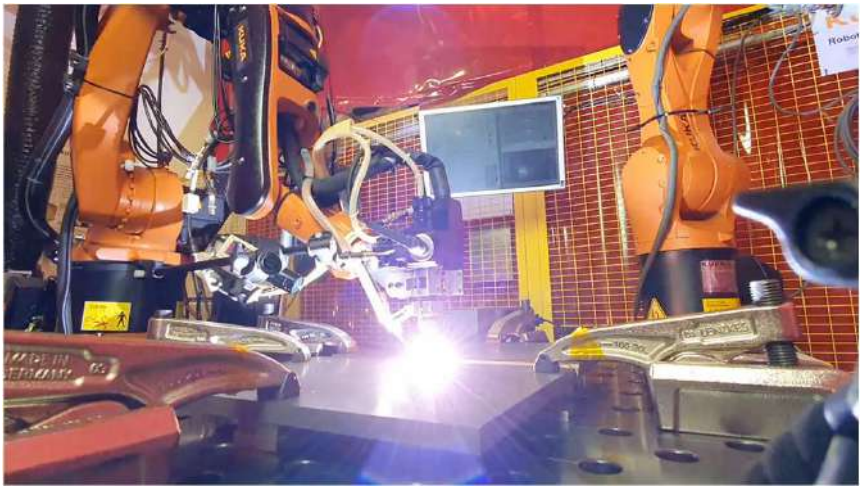
In-Process Inspection – Live Arc Trials



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In-Process Inspection – Thermal Compensation

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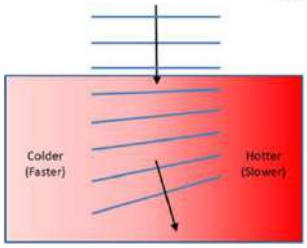
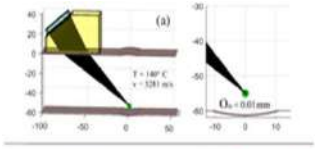
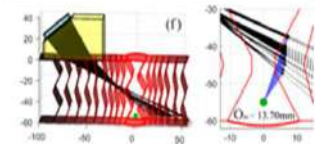
- Non-uniform thermal gradients present during in-process fusion weld inspection result in complex wave beam refraction, energy reduction and time shifts from weldment defects/reflectors present.
- *Ray Tracing Compensation – Enhanced Focusing*
- *Automated Compensation based on known geometry*



In the presence of a temperature gradient, the beam will tend to bend toward the heat



Cold Focused



Thermal Gradient Un-Focused

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In-Process Inspection – Thermal Compensation

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Thermal Compensation Verification Test

- 15 mm Pseudo Weld
- 2x 2.0 mm Diameter SDH
- 8 Thermocouples on mirror side of weld centre

- Step 1: Cold Inspection with PAUT Roller Probe
- Step 2: Autogenous Weld for Thermal Input
- Step 3: Inspection with PAUT Roller Probe with Thermal Gradient

- Thermocouple Logging Throughout
- PAUT Images Analysed

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In-Process Inspection – Thermal Compensation

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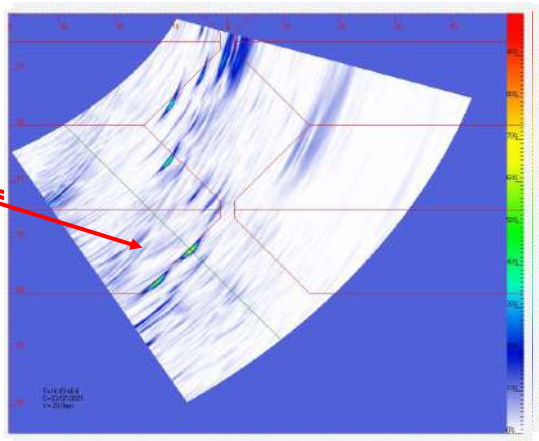

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In-Process Inspection – Region of Interest

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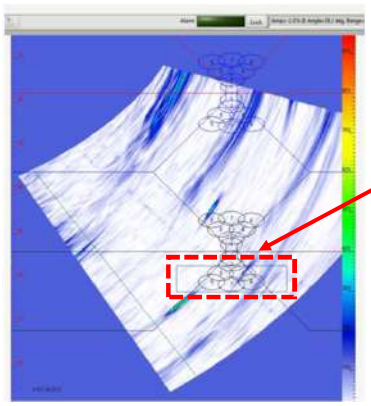
- Monitors echoes within adaptive Region of Interest (ROI) and sets Alarm if over a user-defined threshold
- Calibrated via Staircase Sample or real-time Laser Profiler data input



Region of Interest (ROI) Window

Dynamically adapts to varying filled groove

Staircase Sample

Laser Profiler

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In-Process Inspection – Region of Interest

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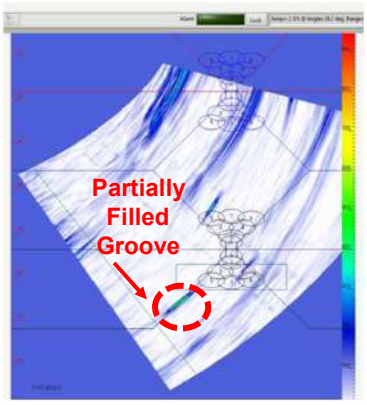
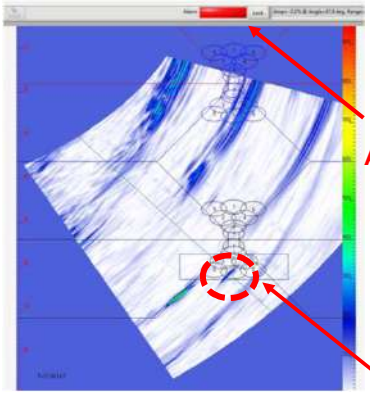
- Monitors echoes within adaptive Region of Interest (ROI) and sets Alarm if over a user-defined threshold

After Pass 7 - No defect 18mm thick 90° V-Groove



After Pass 7 - Tungsten Tube (1.0 mm ID 30 mm long) (Pass 7) 18mm thick 90° V-Groove



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In-Process Inspection – Noise Suppression

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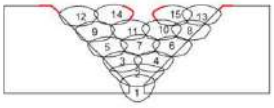
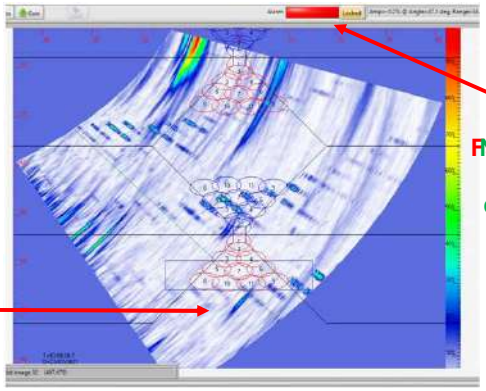
- Electromagnetic Interference and Noise from Robot Servo Drives appears in filtered PAUT frequency window (*3.75 – 7. 5 MHz*)
- Non-Linear Noise Suppression Strategy developed – patent pending

Inspection after Pass 15



Reflection From Bevel & Pass 15



False Triggers Alarm as no defect in ROI

Adaptive Filtering

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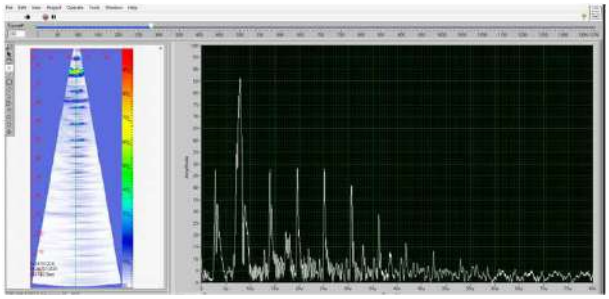
In-Process Inspection – Automated Thickness Variation Compensation

- Requirement to compensate for variation in pipe wall thickness
- Current 16 mm Nominal Thickness Pipes vary between 15.5 and 17.5 mm thickness
- Due to multiple PAUT skips, this error gives defect position error of multiple millimetres
- Automated 0° ultrasonic thickness mapping with resultant compensation



Thickness Map of Pipe Coupon 3

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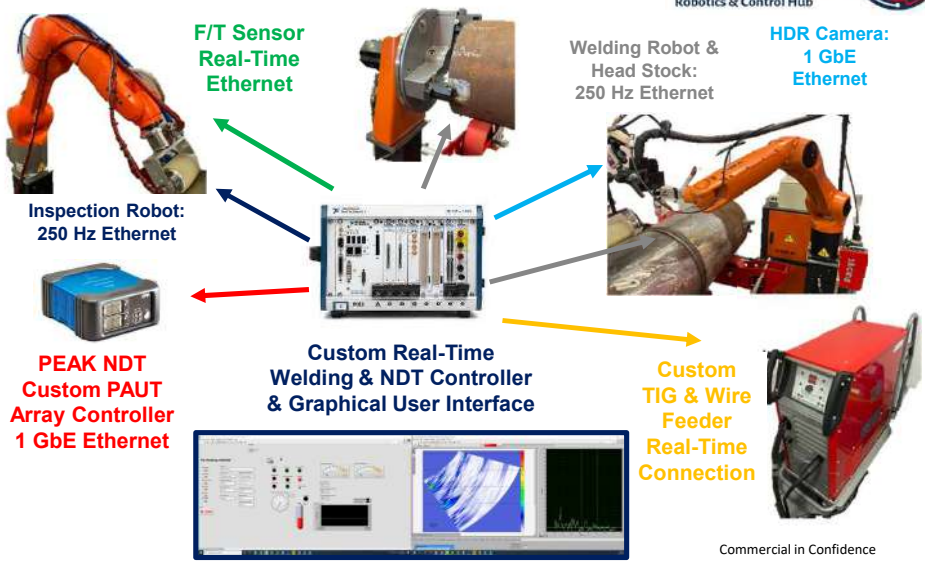
System Configuration



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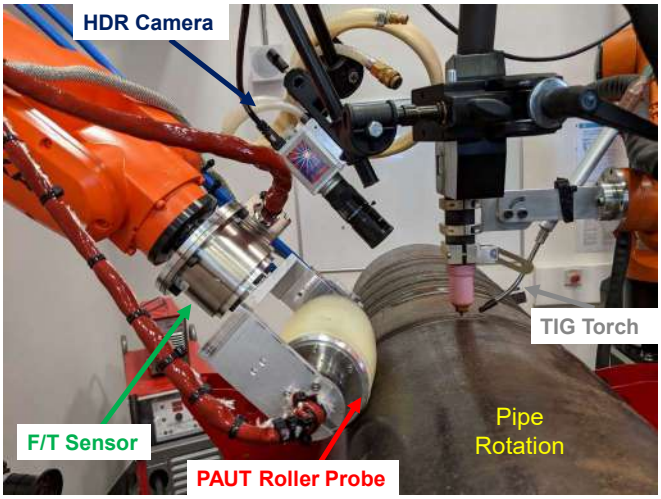
System Configuration



- Welding torch at 12 o'clock (1G) position.
- Roller probe is approximately 100 mm behind weld torch

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Artificial Reflectors

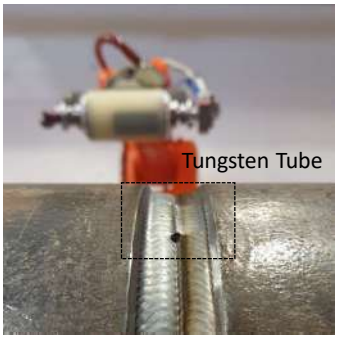
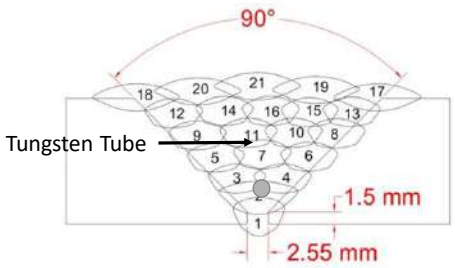


Image: Tungsten tube covered by pass 8 and 9

- Artificial Defect Embedded
- Objective: Simulate point defects/porosity
- Tungsten Tube: ID = 1.0 mm, OD = 2.9mm and L=30mm
- Secured within a groove created on pass 7



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In-Process Phased Array Ultrasonic Weld Inspection

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- *World First: In-Process PAUT Inspection ≈ 100 mm behind Arc*

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In-Process Phased Array Ultrasonic Images

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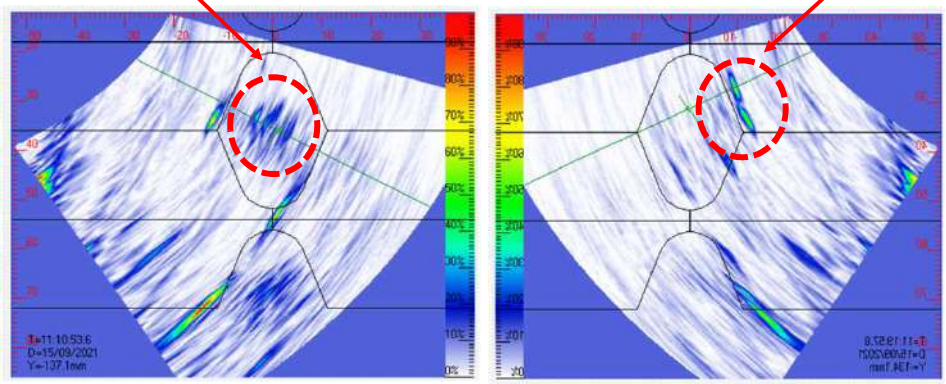
- Defect 3: Porosity
- *Defect 7: Lack of Sidewall Fusion*



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In-Process Phased Array Ultrasonic Images

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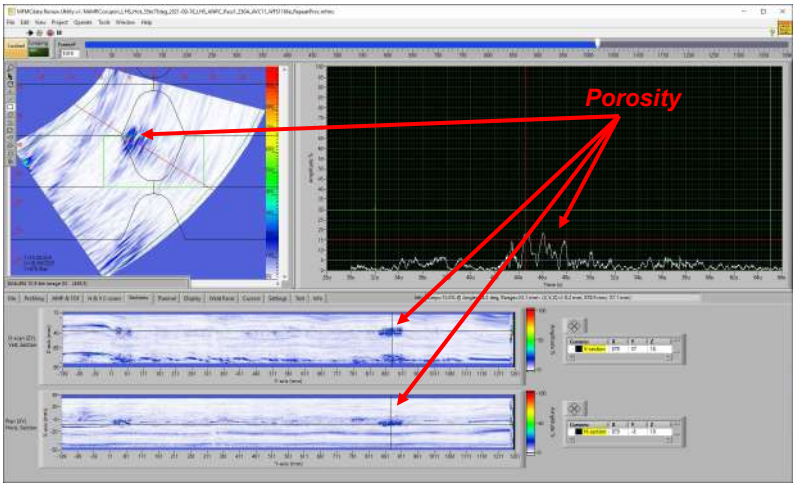
University of Strathclyde Engineering

- B-scan, D-scan and Transverse plane views
- Interactive cursors between all displays



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Summary & Conclusion

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University of Strathclyde Engineering

1. Dry-coupled high-temperature in-process ultrasonic weld inspection directly at the point of manufacture
2. Compensation for geometric distortion and beam de-focusing due to the elevated temperatures and thermal gradients of the welding process.
3. Compensation for the false-positive echoes from the bevelled edges of the partially-filled weld groove present during in-process inspection
4. In-process inspection demonstrated on flat and circumferential welds
5. In-Process Weld Inspection offers ***significant commercial*** benefits:
   - Confidence in final build
   - Reduced re-work
   - Improved schedule certainty
6. In-Process Weld Inspection offers ***significant technical*** benefits:
   - Inspection at temperature with no liquid coupling
   - Reduced heating and cooling cycles on components (*Sustainability Benefits)*

Commercial in Confidence

Proposal of mechanical benchmarks for image-based simulation workflows in high-value manufacturing

Ll.M. Evans[1,2], R. Lewis[1], A. Cornell-Thorne[1], E. Sözümert[1], W. Bielajewa[1]

[1]Faculty of Science and Engineering, Swansea University, Swansea, UK
[2]United Kingdom Atomic Energy Authority, Culham Science Centre, Abingdon, Oxfordshire, UK

E-mail address (corresponding author): llion.evans@swansea.ac.uk

The current state-of-the-art in using micro-X-ray CT (µXCT) for NDT/NDE is to perform analyses such as quantifying flaws, characterising porosity and measuring tolerance deviations. Typically, these analyses pass or fail parts by comparing results against threshold criteria, e.g., maximum allowable defect/deviation size. This does not quantify the impact on performance, e.g., small defects in a critical location may have a greater impact than a large one located elsewhere.

'Image-based simulation' (IBSim) is used to convert µXCT images directly into engineering models able to quantify the 'effect of the defect' under virtual 'in-service' conditions [1]. The IBSim technique's origins are in biomechanics and it is increasingly being used for characterisation of advanced materials and manufacturing, e.g., composite materials and additive manufacturing, within high-value manufacturing (HVM) sectors. Despite this, it is still underutilised and not yet considered a mature technology. A recent review identified that for IBSim to become more widely accepted, particularly in heavily regulated sectors like nuclear and aerospace, there needs to be verification processes focused on internationally recognised and industrially relevant benchmarks [2].

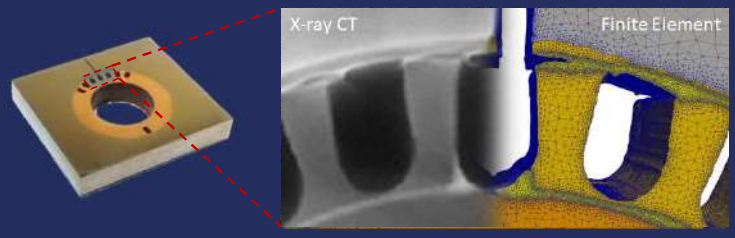
This work proposes a mechanical benchmark based on an international tensile testing standard for metallic materials (BS EN ISO 6892-1:2016). Three 'identical' batches of ten Ti-6Al-4V, Grade 5, samples were fabricated according to the standard with the inclusion of controlled defects of varying sizes. The samples were physically tested with measurements taken using a conventional strain gauge and with digital image correlation (DIC). Before physical testing occurred, the exact same samples were digitised via µXCT and converted into finite element meshes. Thus, direct comparison of physical experimental and virtual simulation results is possible for verification, validation and uncertainty quantification (VVUQ) of IBSim workflows.

Results will be presented from a workflow which used CT Pro (Nikon Metrology NV) for image reconstruction, image segmentation and meshing used Simpleware (Synopsys Inc.), finite element analysis used Code_Aster (EDF S.A.) and data analysis with ParaView (Kitware Inc.). A study into which workflow parameters impact the accuracy of the IBSim approach will also be presented. Experimental and simulation data from each stage of the workflow will be made publicly available in due course such that other users and developers of IBSim workflows may benchmark their own approaches.

References:
[1] https://doi.org/10.1016/j.fusengdes.2015.04.048
[2] https://doi.org/10.1007/s11831-022-09836-2

Keywords: X-ray CT; component qualification; manufacturing; simulation

Proposal of mechanical benchmarks for image-based simulation (IBSim) workflows in high-value manufacturing



NDE in Nuclear 2023, 27-29 June 2023, Sheffield, UK

Llion M. Evans[1,2], R. Lewis[1], A. Cornell-Thorne[1], E. Sözümert[1], W. Bielajewa[1]

[1]Zienkiewicz Institute, Faculty of Science and Engineering, Swansea University, UK
[2]UK Atomic Energy Authority, UK

Swansea University Prifysgol Abertawe | Faculty of Science and Engineering Cyfadran Gwyddoniaeth a Pheirianneg

Outline

- What is IBSim?
- Why are benchmarks needed?
- What is being proposed and current status

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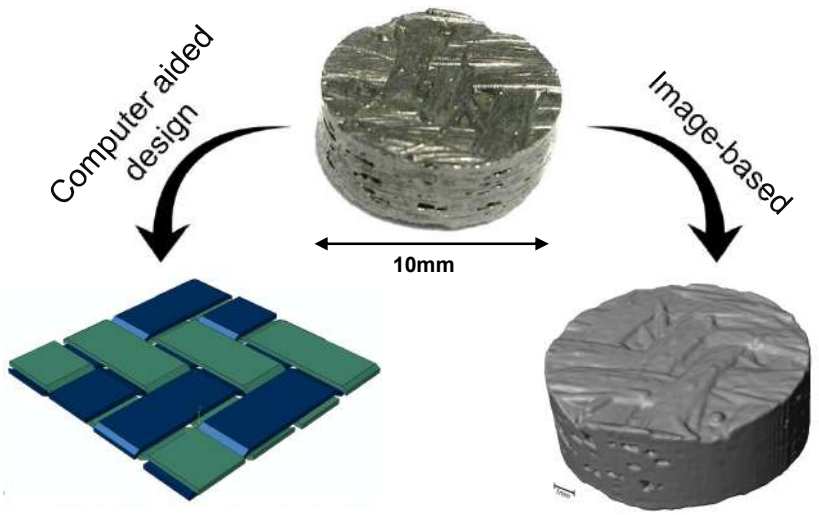
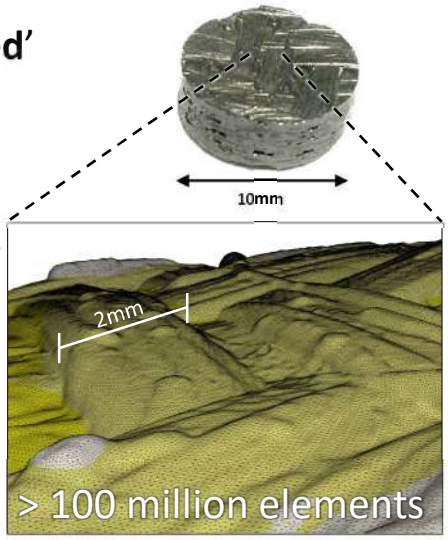
Design/Image based simulation



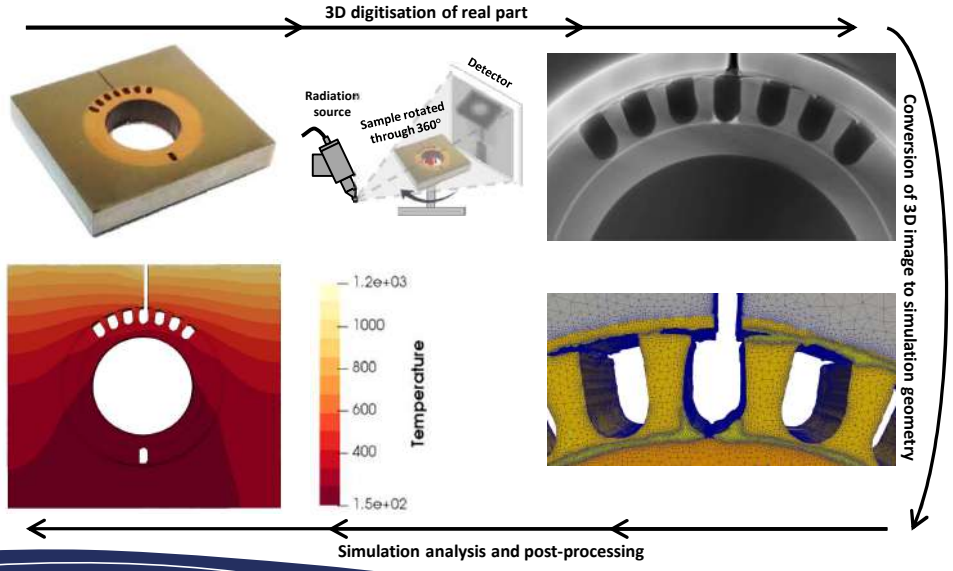
Benefits of IBSim

Simulate '**as manufactured**' instead of '**as designed**'.

- **Real** components at microscale.
- Complex architectures.
- Include fabrication defects
  - flaws, cracks, porosity
- Model actual test specimen
  - **virtual qualification**



Overview of IBSim workflow



3D and volumetric imaging techniques

Laser scanning

Ultrasound

Photogrammetry

3D and volumetric imaging techniques

CT

MRI

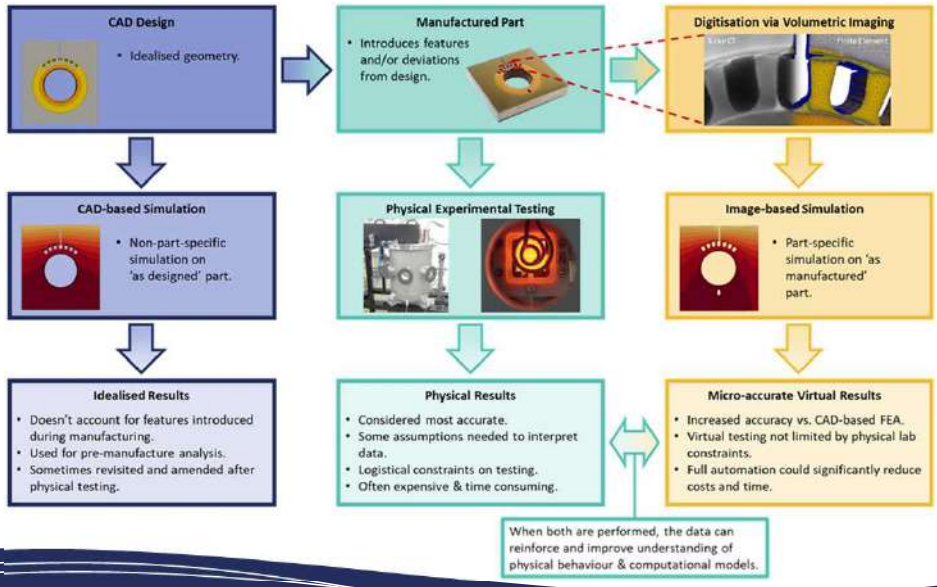
Micro-CT,
Nano-CT
*Research team at Swansea typically use micro-CT

FIB-SEM

Serial sectioning

Confocal microscopy

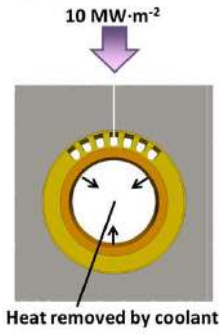
Bridging physical and virtual analyses

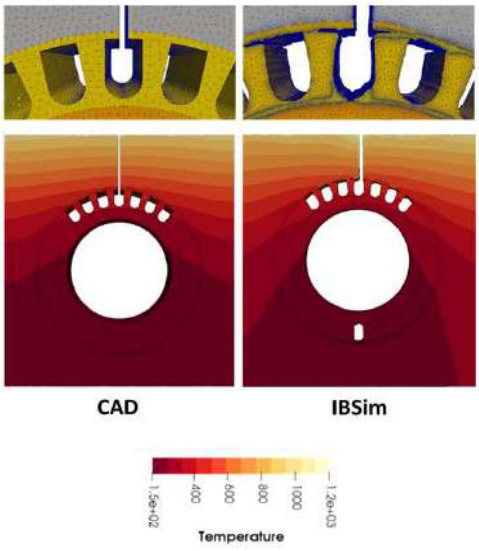


Effect of the defect

Performance impact due to feature:

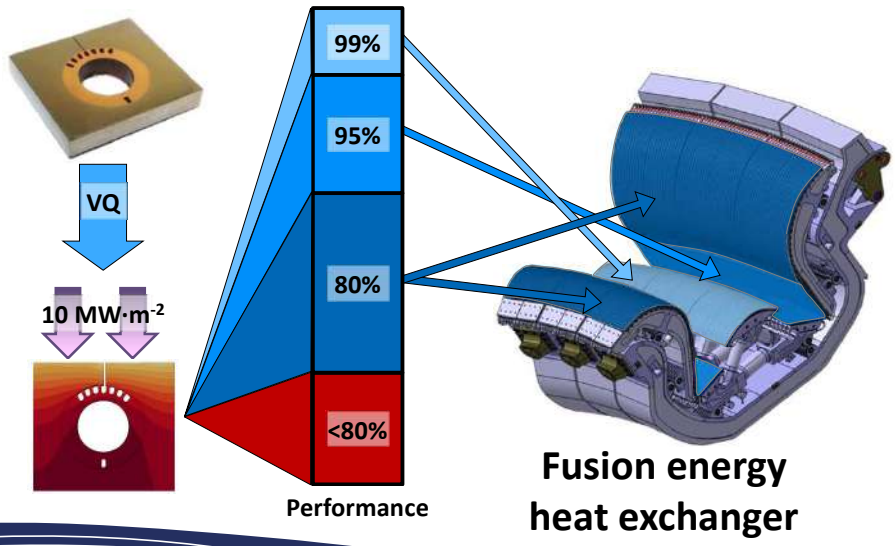
- Location
- Size
- Shape





Ll.M. Evans et al., "Comparison of X-ray and neutron tomographic imaging to qualify manufacturing of a fusion divertor tungsten monoblock",
Fus. Eng. Des., Vol. 134, pp. 97-108, 2018.
https://doi.org/10.1016/j.fusengdes.2018.06.017

Potential for in-service optimisation



Outline

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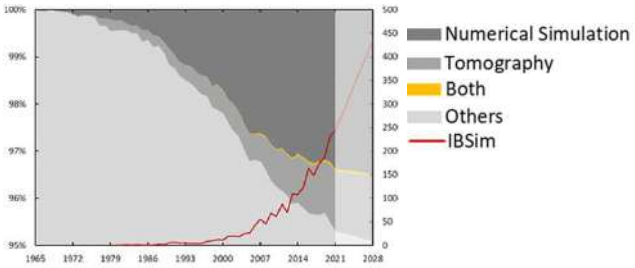
Current status of IBSim in HVM

Ll.M. Evans et al., "A Review of Image-Based Simulation applications in High-Value Manufacturing", *Arch Computat Methods Eng*, Vol. 30, pp. 1495–1552 (2023). https://doi.org/10.1007/s11831-022-09836-2

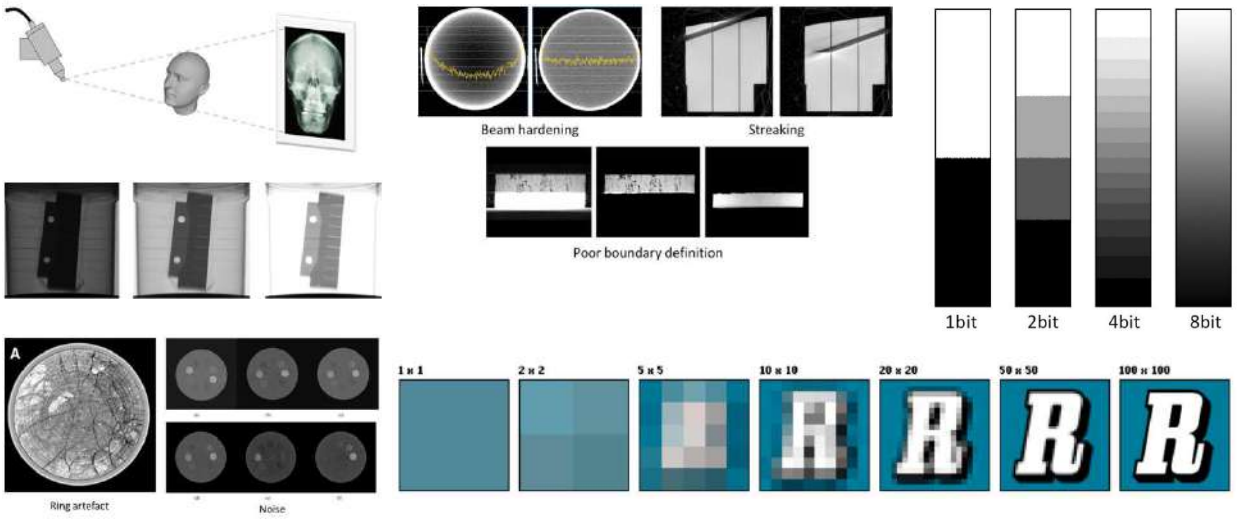
- 1st review for non-medical IBSim
- > 350 papers reviewed
- Applications
  - Material characterisation
  - Manufacturing processes
  - Component scale
- Sectors
  - Aerospace
  - Energy
  - Personalisation



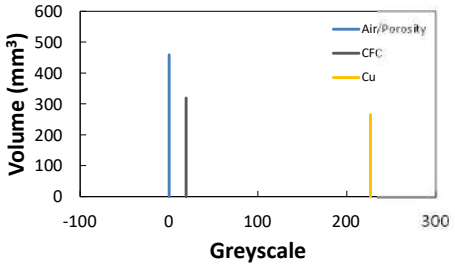
International standards exist (or in development) for:

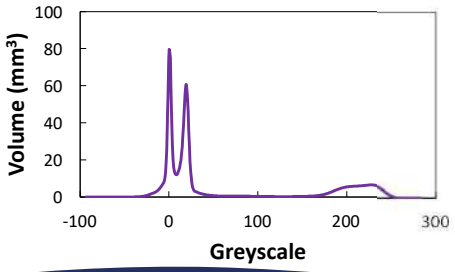
- Simulation (FEA/CFD)
- XCT
- Physical testing
- ~~IBSim~~

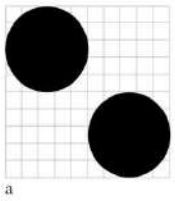
Impact on IBSim accuracy: Imaging & Reconstruction

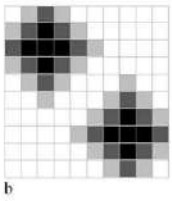


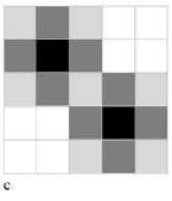
Impact on IBSim accuracy: Segmentation & Meshing

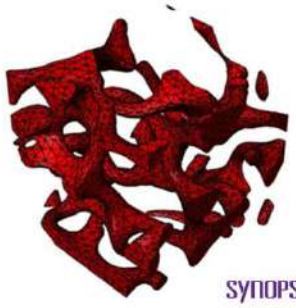












SYNOPSYS

IBSim benchmarks

Create benchmark tests and data for workflow verification.

- Three data sets for cross-comparison:
  - Experimental
  - Design-based (CAD)
  - IBSim
- Select well established laboratory tests that have associated international standards (e.g. ISO, ASTM).
- Include controlled defects within samples.

Make data at all stages publicly available:

- Sample design & manufacture specifications
- Experimental raw and processed data
- X-ray radiographs
- CT reconstruction
- Image segmentation
- Meshed geometry
- FEA analysis

Outline

- What is IBSim?
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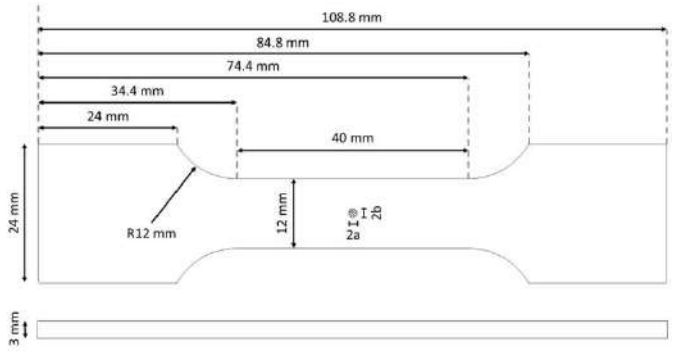
Mechanical - tensile testing

- BS EN ISO 6892-1:2016
- Initial focus on Ti-6Al-4V, Grade 5
- Defect machined by EDM
- 3 ‘identical’ batches of 10 samples

Sample type	a (mm)	b (mm)
1	0.00	0.00
2	0.50	0.50
3	0.75	0.75
4	1.00	1.00
5	0.50	0.75
6	0.50	1.00
7	0.75	0.50
8	0.75	1.00
9	1.00	0.50
10	1.00	0.75



*2a and 2b refer to the radii of an elliptic hole machined through the centre of the test sample.

Physical results

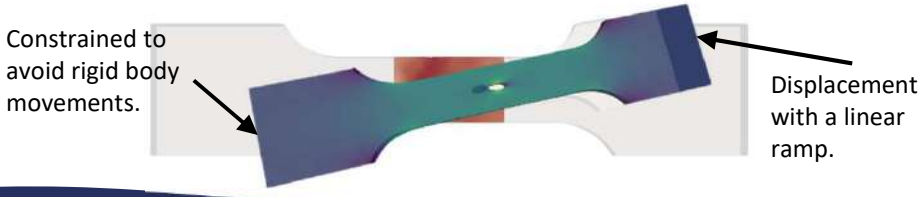
Emulating the physical setup

Experimental Setup:

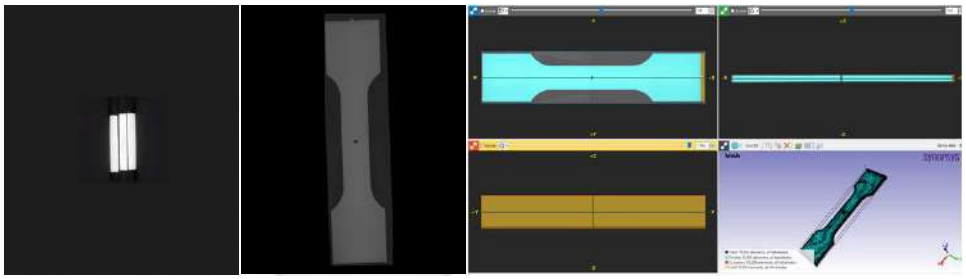
- BS EN ISO 6892-1
- Displacement controlled.
- Rate: 0.0042 min^{-1} (up to 2%)
- Two camera DIC (1Hz)
- Resolution: 2448x2050 pixels
- Working distance: 300mm
- Pixel size: 13.8-16.3µm

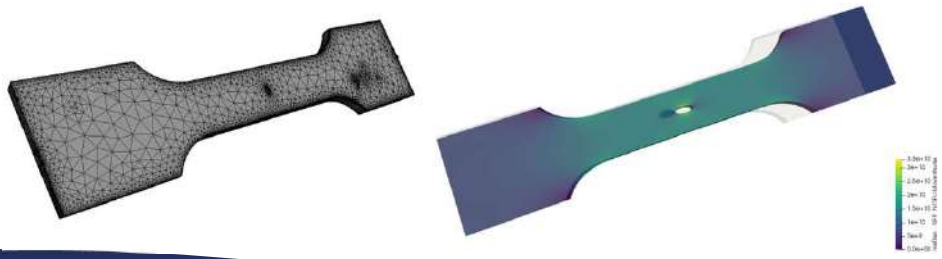
Simulation Setup:

- Linear elastic to yield point
- Isotropic Von Mises Plasticity
- Large strain formulation based on J. C. Simo C. Miehe
- Experimental data as input
- Adaptive stepping

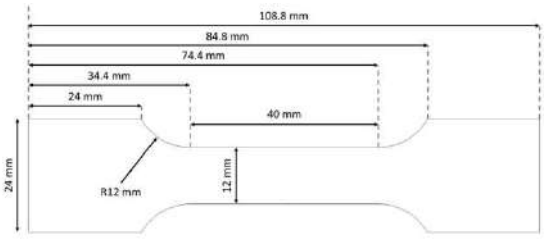


Building the virtual laboratory

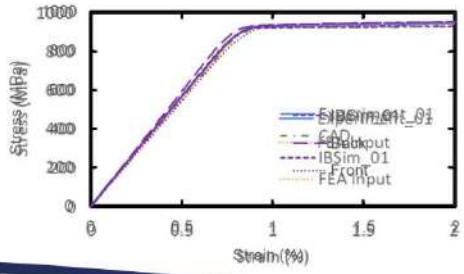




1D validation



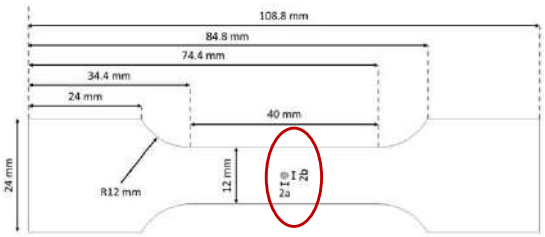
Sample type	a (mm)	b (mm)
1	0.00	0.00
2	0.50	0.50
3	0.75	0.75
4	1.00	1.00
5	0.50	0.75
6	0.50	1.00
7	0.75	0.50
8	0.75	1.00
9	1.00	0.50
10	1.00	0.75



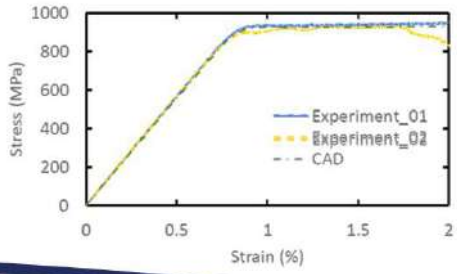
Simulation validation:

- Agrees well with experimental data.
- No void.
- Expected, because this data used as input.

1D validation



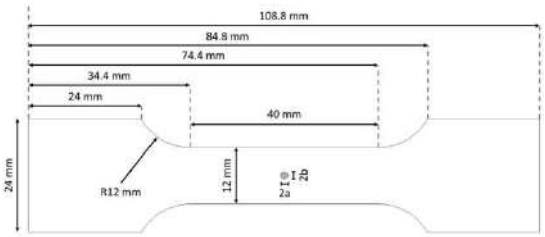
Sample type	a (mm)	b (mm)
1	0.00	0.00
2	0.50	0.50
3	0.75	0.75
4	1.00	1.00
5	0.50	0.75
6	0.50	1.00
7	0.75	0.50
8	0.75	1.00
9	1.00	0.50
10	1.00	0.75



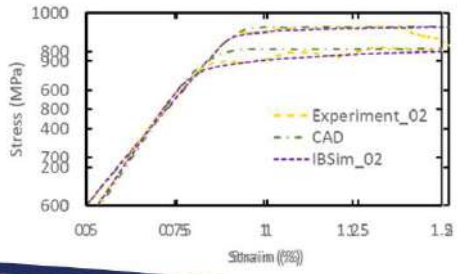
Controlled defect impact:

- Mechanical softening.
- Earlier onset of UTS.
- CAD simulation cannot account for unexpected.
- Follows 'ideal' behaviour.

1D validation



Sample type	a (mm)	b (mm)
1	0.00	0.00
2	0.50	0.50
3	0.75	0.75
4	1.00	1.00
5	0.50	0.75
6	0.50	1.00
7	0.75	0.50
8	0.75	1.00
9	1.00	0.50
10	1.00	0.75

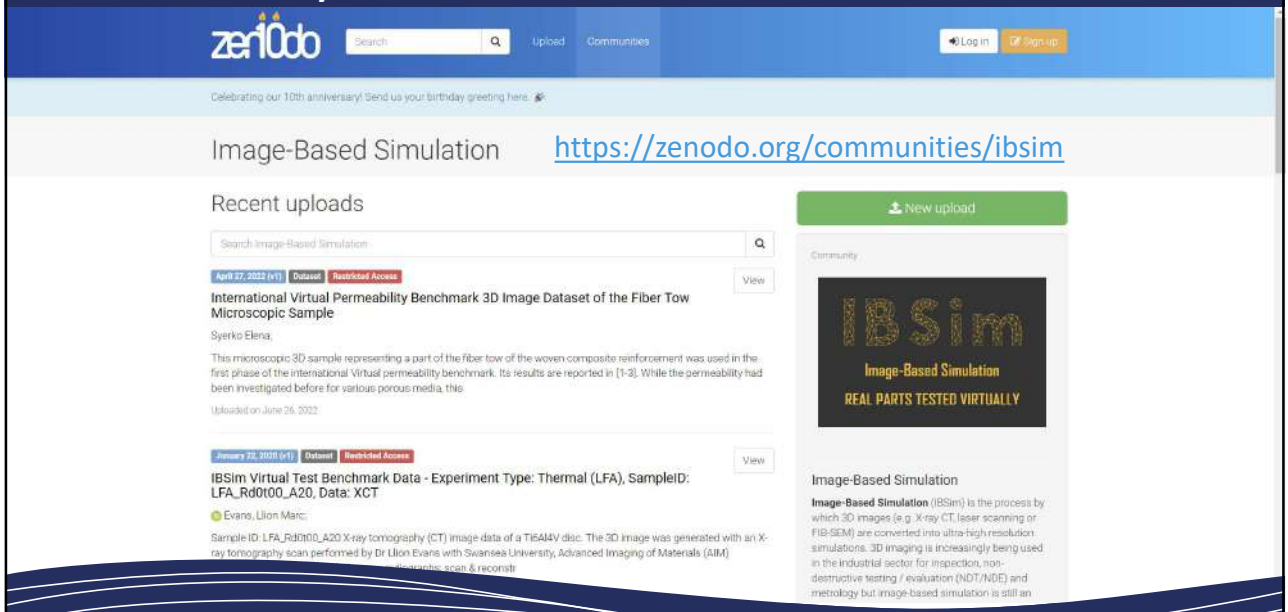


IBSim performance:

- Inherently accounts for impact of 'defect'.
- Diverges after yield because not included in model.

2D Validation

Data availability



Annual IBSim event

Acknowledgements

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Dr Llion Marc Evans | EPSRC Research Fellow | llion.evans@swansea.ac.uk
A211, Engineering Central, College of Engineering, Bay Campus
Swansea University Bay Campus, Swansea SA1 8EN, UK

@LlionEvans
www.researchgate.net/profile/Llion_Evans
www.linkedin.com/in/llionevans

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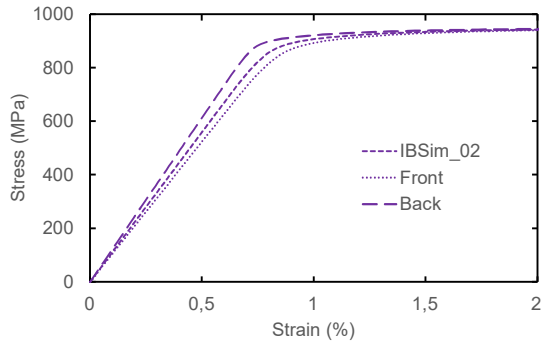
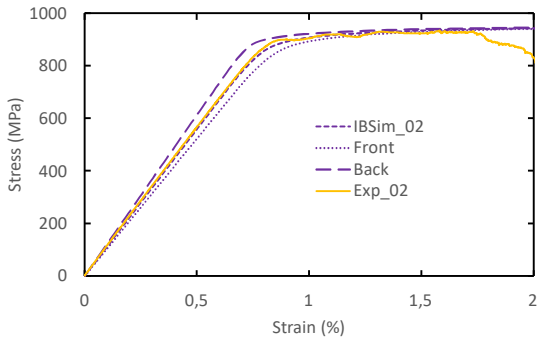
Additional slides



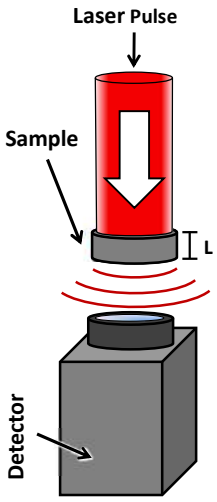


IBSim benchmarks: Thermal – laser flash analysis

- ASTM E1461 / ASTM E2585
- Initial focus on Ti-6Al-4V, Grade 5
- Layers joined by diffusion bonding to have internal 'defect'

	Diameter (mm)	Thickness (mm)	Recess d (mm)	Recess t (mm)	Recess V (mm^3)
	12.6	2.5	N/A	N/A	N/A
	12.6	1.25 x 2	N/A	N/A	N/A
	12.6	1.25 x 2	8.0	0.2	10.05
	12.6	1.25 x 2	8.0	0.8	40.21
	12.6	1.25 x 2	6.0	0.2	5.65
	12.6	1.25 x 2	6.0	0.8	22.62
	12.6	1.25 x 2	4.0	0.2	2.51
	12.6	1.25 x 2	4.0	0.8	10.05

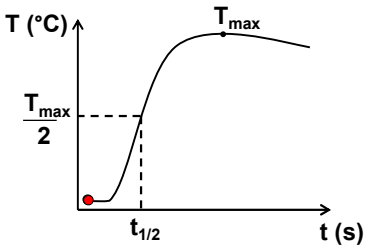
Case study: Virtual material characterisation

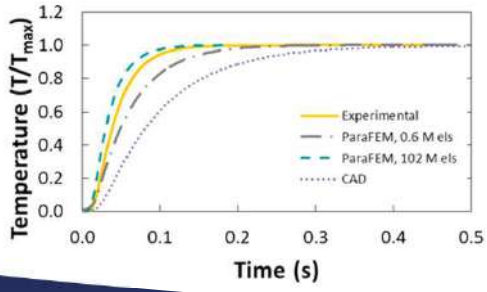


$\kappa = (0.1388 \cdot L^2) / t_{1/2}$

$K = \rho \cdot c_p \cdot \kappa$

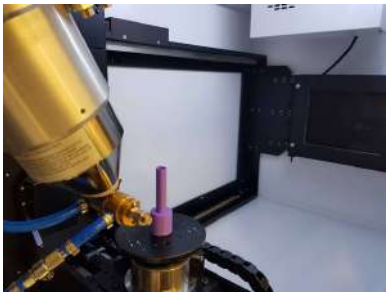
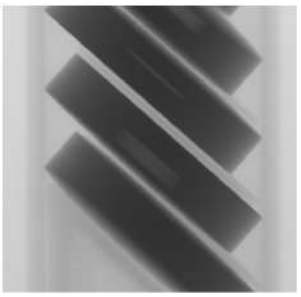
κ = thermal diffusivity
K = thermal conductivity
ρ = density
c_p = specific heat capacity

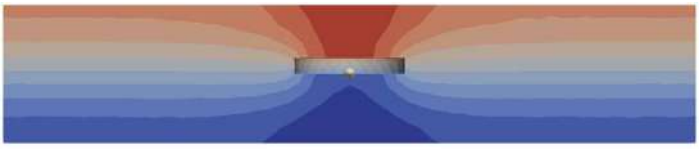




IBSim benchmarks: Thermal – laser flash analysis

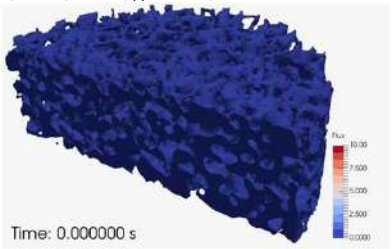
IBSim benchmarks: Thermal – laser flash analysis

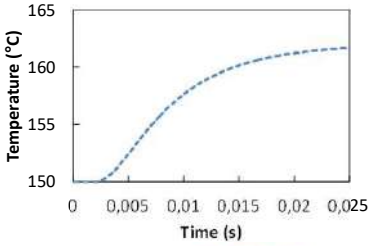





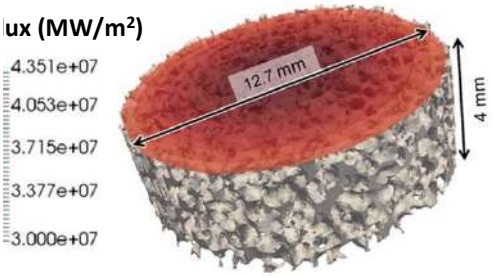
IBSim benchmarks: Thermal – laser flash analysis

Ll.M. Evans, L. Margetts, P.D Lee, C.A.M. Butler, E. Surrey, "Image based in silico characterisation of the effective thermal properties of a graphite foam", *Carbon*, vol. 143, pp. 542-558, 2019.



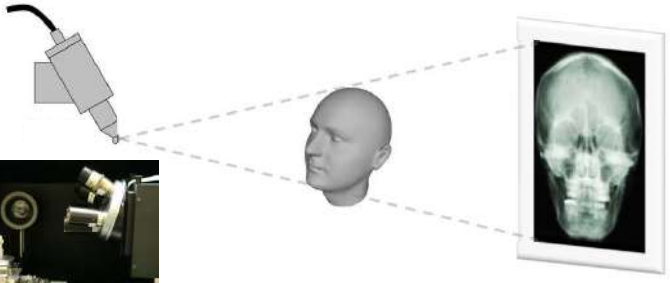


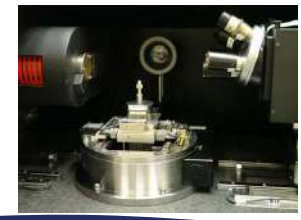
	K_{in} (W/m•K)	$K_{effective}$ (W/m•K)
$IBFEM_{xz}$	978	151
$IBFEM_{yz}$	978	162
$IBFEM_{xy}$	978	164



Beam magnification

- Moving sample closer to source increases magnification.
  - Can move detector further; source & detector are often fixed.
- Want to fill field of view to maximise resolution.
- Can scan 'region of interest' but introduces artefacts.

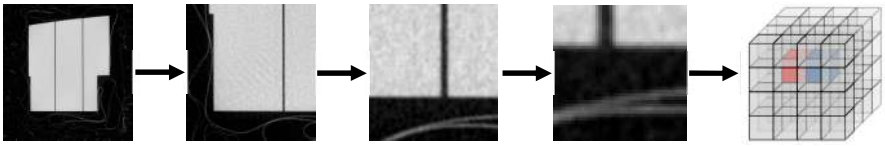




- Alternatively, use optics

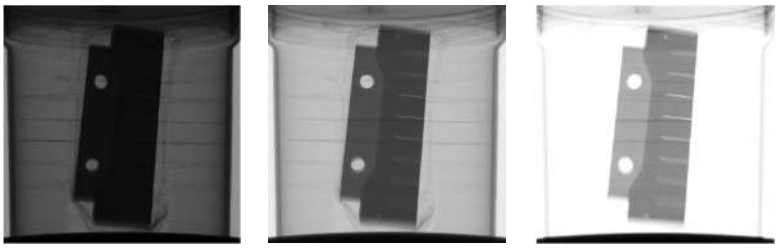
Resolution vs Accuracy

- Maximum system resolution is fixed by the X-ray source 'spot size' and detector pixel widths.
- The scan resolution is given by the relative separation of the source, sample and detector which define the voxel width.
  - i.e. the smaller the sample, the closer it can be placed next to the source to maximise resolution up to the system max.
- However, typically 5-10 voxels are required to resolve a feature.
- In practice noise/artefacts increase the number of voxels required.
- Thus, there can be an order of magnitude of difference between the scan resolution and accuracy.



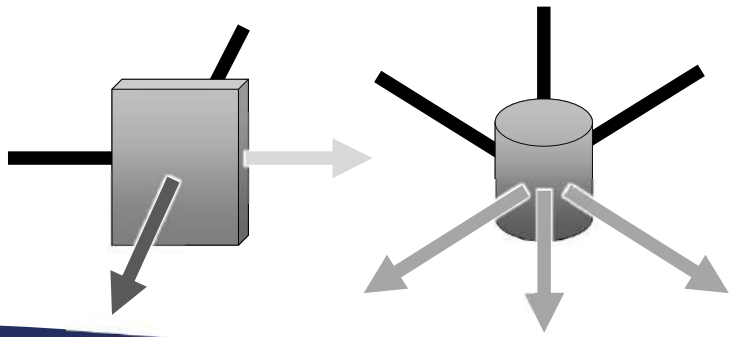
Considerations - Exposure

- The main aim when setting up a CT scan is to maximise contrast between the lowest attenuating region (normally air) and the highest attenuating region.
  - However, it must be ensured that no part of the image is under or over exposed i.e. too little or too much signal.
- Exposure is controlled by varying the X-ray source's voltage and current or by changing the exposure time of the detector.



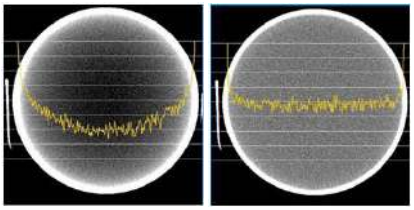
Considerations - Geometry

- The sample geometry has direct influence over X-ray attenuation paths. X-ray source energies are 'tuned' during set up. Samples with high aspect ratios will have high and low levels of attenuation in orthogonal directions, thus a mid-level energy must be chosen which compromises contrast. The ideal sample is cylindrical.

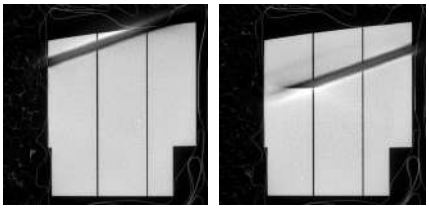


Considerations - Materials

- Likewise a very high contrast in attenuation due to material interfaces can introduce undesired effects.



Beam hardening

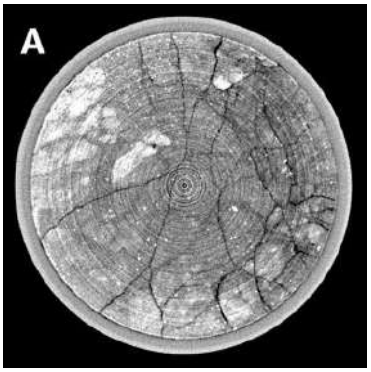


Streaking

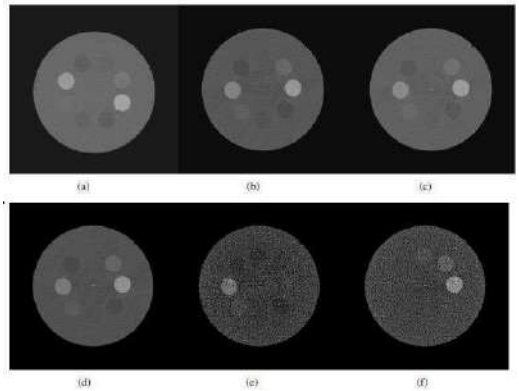
Poor boundary definition

Considerations - Equipment

- Systematic and random issues are often introduced by the scanner.



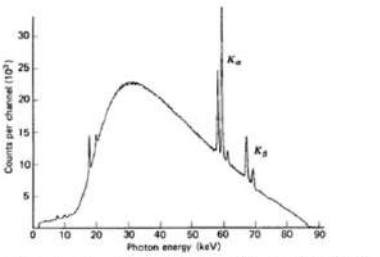
Ring artefact



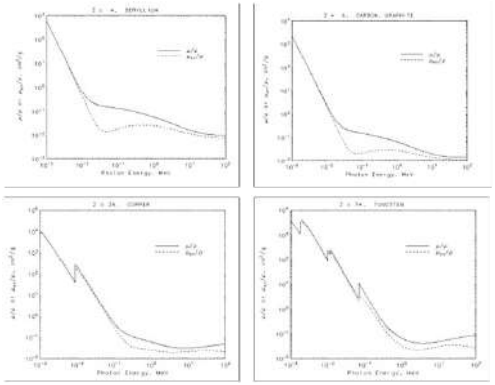
Noise

Considerations - Material identification

- It is not possible to use greyscale to give absolute values for attenuation. However, with the use of calibration samples, 'phantoms', these can be estimated using by comparison.
- Although attenuation is an indicator of density it is not directly correlated due to a mixture of attenuation mechanisms.



The spectrum from a tungsten target x-ray tube operated at 87 kVp.



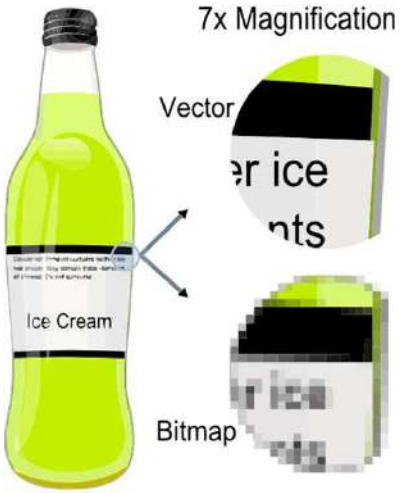
Considerations – Digital images

SYNOPSYS®

A digital image is a numerical representation of a two dimensional image. There are two image types: **vector type** or **raster type**.

Vector images (e.g. *.svg) use geometrical primitives (e.g. lines and curves) to create an image based on mathematical expressions. This image type is not supported by Simpleware.

Raster images have a finite set of digital values (pixels). Pixels are the smallest individual element in an image, holding quantised values that represent the intensity of a given colour at any specific point.



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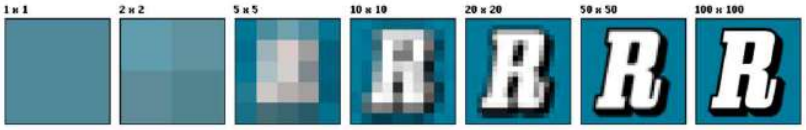
http://en.wikipedia.org/wiki/Vector_image

Considerations - Image (pixel) resolution

SYNOPSYS®

- The term resolution is often used for a pixel count in raster images.
- Traditionally defined with a two positive integer numbers:
  - Number of pixels across (width).
  - Number of pixels down (height).
  - Example: 7680 by 4320.
- Can also be defined by a number of 'megapixels'.
  - Example: An image that is 2048 pixels in width and 1536 pixels in height has a total of 2048×1536 = 3,145,728 pixels or 3.1 megapixels.
  - Typically used to define the resolution of digital cameras.



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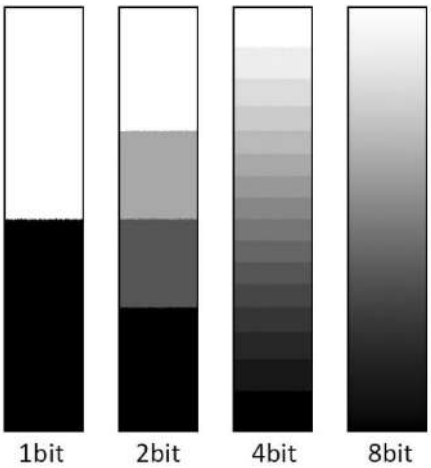
Considerations - Greyscale image

SYNOPSYS®

- Greyscale images are digital images with a single intensity value (or grey level).
- Number of grey levels depends on the bit-depth of the image.
- Calculated as 2 to the power of the bit depth value:
  - Example an 8-bit image can have 2^8 or 256 grey levels.
- 'Binary' images are 1-bit.
- Generally, the intensity value 0 is assigned the colour black and the maximum grey level value (e.g. 255 in an 8-bit image) is white.



Greyscale images digitised at varying bit-depths

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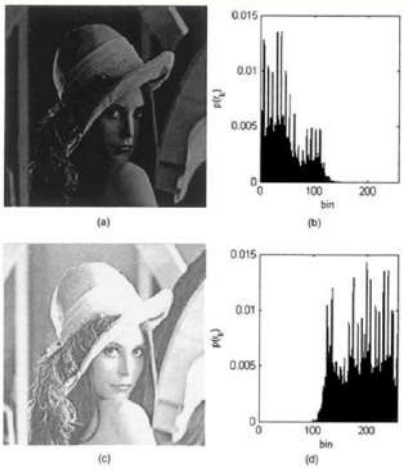
Considerations - Greyscale distribution

SYNOPSYS®

- Acts as a graphical representation of the intensity distribution in a digital image.
- Plots the number of pixels (y-axis) for each intensity value (x-axis).
- The left side of the x-axis represents the darker areas, and the right side represents the lighter areas.
- Used to determine whether image detail has been lost due to blown-out highlights or blacked-out shadows.
- Generally, the contrast of an image can be improved by 'spreading out' the most frequent intensity values (i.e. equalization).



Examples of dark (a) and bright (c) images.
Examples of dark (b) and bright (d) histograms.

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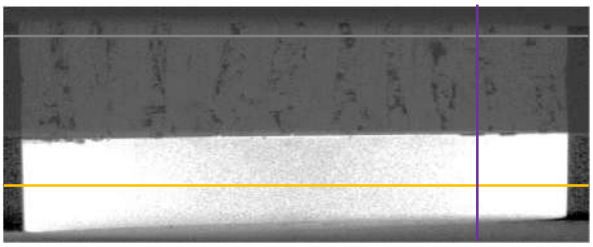
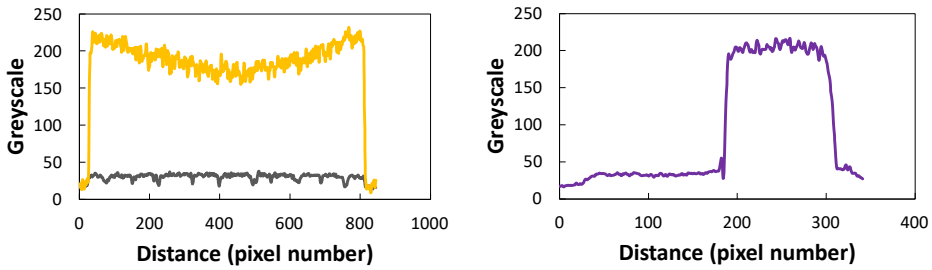
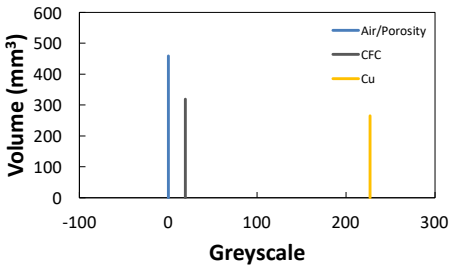
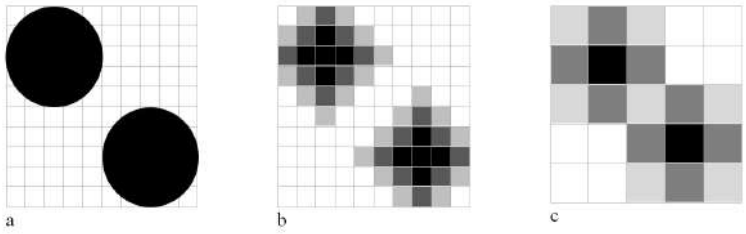
Considerations - 'Real' samples





Considerations - Defining interfaces

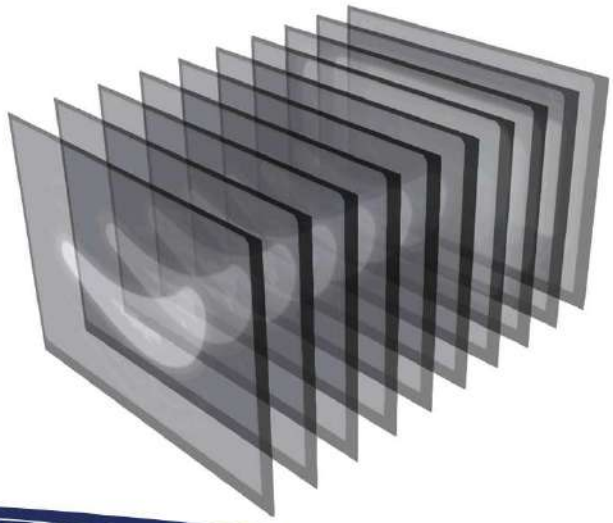




Volume image to mesh

Image-Based Simulation

- Import Volume Image Data
- Form Voxel Grid
- Segment Regions of Interest
- Extracted Segmented Voxels
- Create Volume / SurfaceMesh
- Simulation



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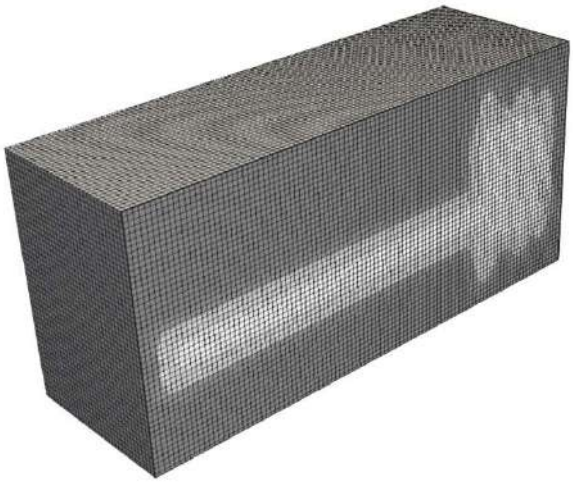

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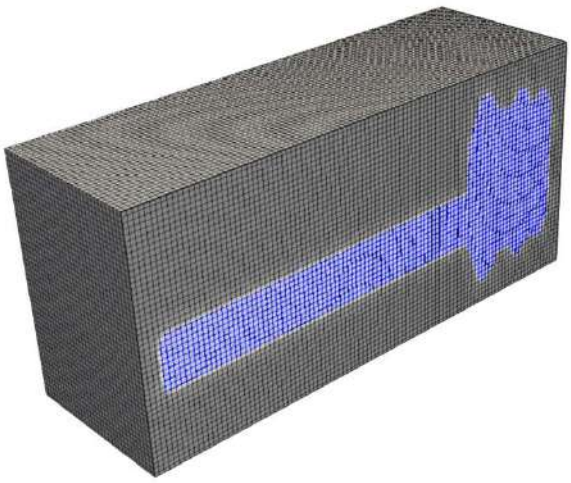

Volume image to mesh

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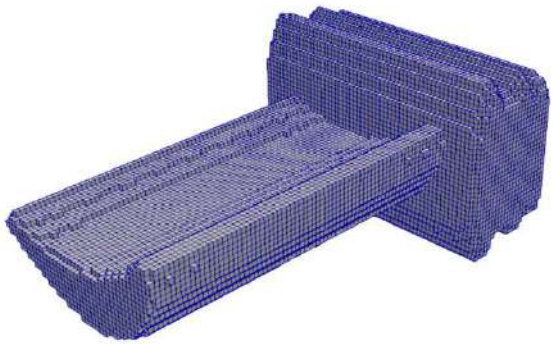
- **Extracted Segmented Voxels**
- Create Volume / SurfaceMesh
- Simulation



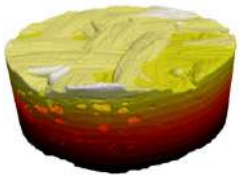
Volume image to mesh

Image-Based Simulation

- Import Volume Image Data
- Form Voxel Grid
- Segment Regions of Interest
- Extracted Segmented Voxels
- **Create Volume / SurfaceMesh**
- Simulation

Considerations

- Resolution
- Local refinement
- Smoothing
- Challenges not in standard FEA/CFD
- High resolution simulations



125 million elements

Meshing considerations - resolution

SYNOPSYS

Surface triangles:

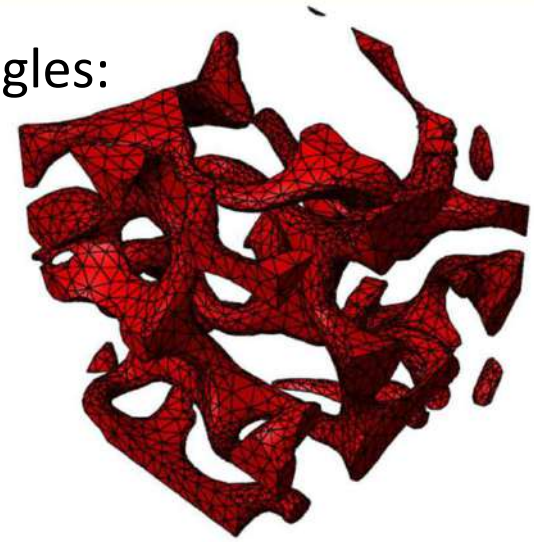
108,292

41,142

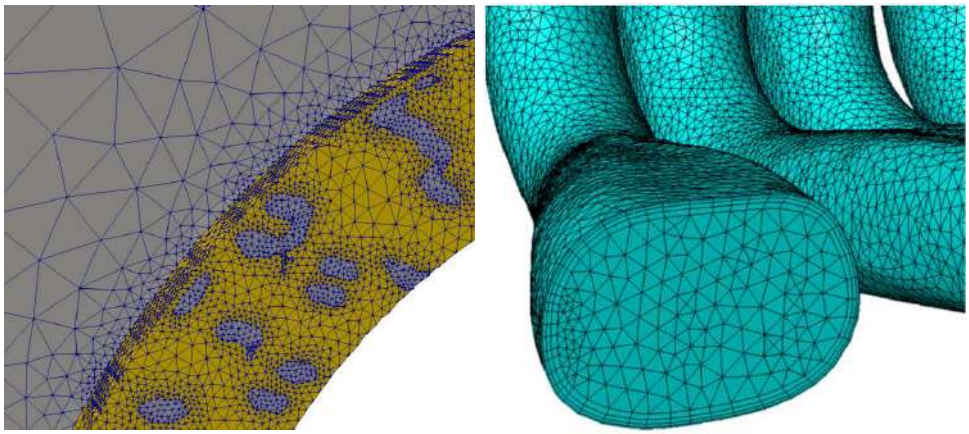
25,048

14,612

10,198

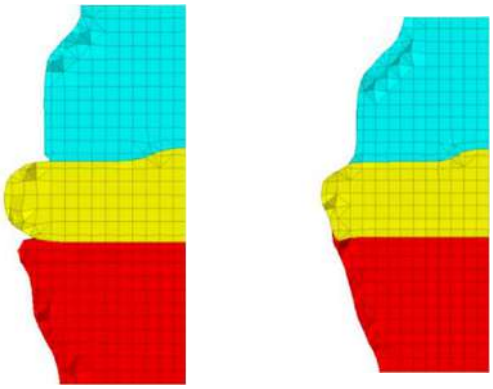


Meshing considerations - local refinement



Meshing considerations - smoothing

SYNOPSYS®

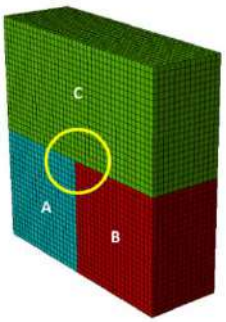


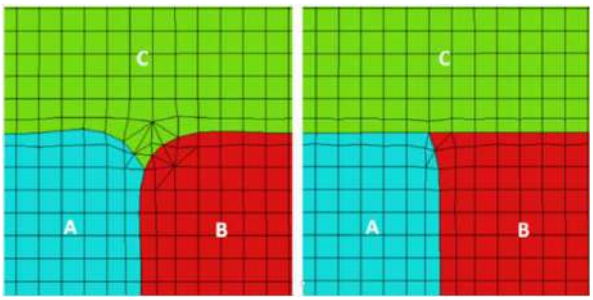
Smoothing **without** the background

Smoothing **with** the background

Meshing considerations - smoothing

SYNOPSYS®





B -> A -> C C -> A -> B

Importance of smoothing order (linked to mask hierarchy)

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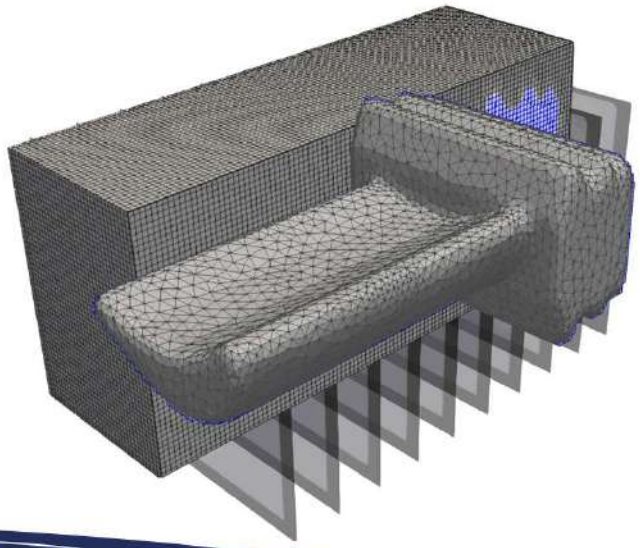

15. NDE Reliability & Qualification (II)

The presentations in this session are listed in the table below.

NDE Reliability & Qualification (II)	**Chair:** Chris Curtis (Jacobs-IVC)
Challenges of Mechanized NDE at Ringhals 4 Pressurizer 2022/2023	T.Hallqvist (Dekra), O.Johansson (Ringhals NPP), P.Alzen (SQC)
Virtual round robins – new insight into NDE reliability	Iikka Virkkunen & Tuomas Koskinen (Aalto Univ.)
Qualification of Eddy Current Inspection of WWER Steam Generator Threaded Holes	Roman Krajčovič (VUJE) et al.
HPC End-of-Manufacturing Inspections Qualification	Mikaël Debroise (Framatome) & Thomas Bloodworth (Bloodworth Consulting)
Non-destructive testing of components used in MARIA research reactor	Marcin Kowal et al. (NCBJ)

Abstract

Challenges of Mechanized NDE at Ringhals 4 Pressurizer 2022/2023

T.Hallqvist[1], O.Johansson[2], P.Alzen[3]

[1]DEKRA Industrial, Stockholm, Sweden
[2]Ringhals NPP, Varberg, Sweden
[3]Swedish Qualification Centre, Stockholm, Sweden
…

E-mail address (corresponding author): ted.hallqvist@dekra.com

Presentation of NDE Qualification work involving the unscheduled inspection of Ringhals 4 Pressurizer during 2022/23.
On the 29th of August 2022, Reactor 4 at Ringhals Nuclear Power Plant suffered an incident causing the electric heater elements in the Pressurizer to overheat during an outage testing sequence. This incident initiated an extensive NDE inspection campaign of the Pressurizer to ensure structural integrity of the vessel and all its internal parts affected by the overheating.

The purpose of the NDE campaign were to verify that the internal surface of the Pressurizer, the J-groove welds for the heating elements and wall penetrations are free from defects, cracks and also copper residue from the spattering of the partly melted cartridge elements that would cause surface contamination inside the pressurizer vessel.

The Accredited Testing Laboratory DEKRA Industrial was contacted for support and development of multiple mechanized manipulators (robotics) as well as NDE techniques for inspection of the internal surfaces, J-groove welds and wall penetrations was started. The challenge was to develop specialized Eddy Current-transducers (ET) for detection of both crack-like defects but also detection of copper contamination on internal surfaces, cameras for Visual Testing (VT) and technique for application of Mechanized Red Dye Penetrant Testing (PT) in a very limited time frame of less than four months from start to finalized Factory Acceptance Test. All the techniques above were required to be qualified by SQC according to the ENIQ Qualification scheme.

This presentation describes the close and pragmatic collaboration between the Utility, the Accredited Testing Laboratory and the Qualification Body. Focus in this article is the technical experiences from Ringhals NPP, the challenges and short time frame for technical development at DEKRA Industrial and the qualification approach by Swedish Qualification Centre, SQC.

Keywords: Ringhals NPP, Eddy Current, Red Dye Penetrant, Pressurizer, PWR, Sweden (max. 5).

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Challenges of Mechanized NDE Ringhals 4 Pressurizer

SWEDEN / 2022-2023

Ola Johansson
Vattenfall

Peter Alzén
SQC

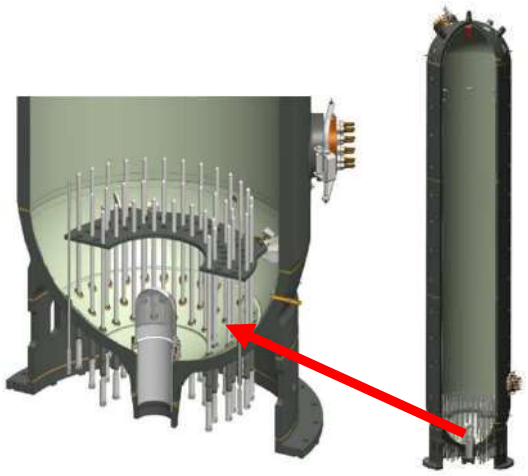
Jonathan Findin
DEKRA

Philip Sandersjöö
DEKRA

DEKRA VATTENFALL SQC

R4 Pressurizer – Design

- Ringhals 4 – 3 Loop Westinghouse design NPP
- The pressurizer regulates the pressure in primary circuit
- PRZ contains 67 heaters & spray nozzles



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R4 Pressurizer – Chain of Events

- During a routine test sequence, in the end of the outage some of the heaters were incorrectly energized
- This resulted in a breach of the heater sheath with melted copper spilling out, and/or being sputtered on the lower plenum, surge line cover and other heaters

R4 Pressurizer – Affected Heaters

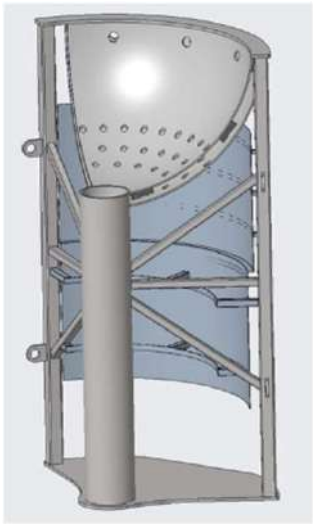
<u>3 Distinct Types:</u>

- 19 heaters which have been energized <u>and</u> failed structurally
- 9 heaters which have been energized but <u>show no visual mechanical failure</u>
- 37 heaters which were not energized in the incident, and thus possibly are reusable/possible to refurbish

Main Focus Areas in Project

- Several steps in program to return to service:
  - Removal of heaters
  - Clean up/recovery of system(s)
  - Structural integrity analysis of RCPB and heaters
  - In Service Inspection – NDE of all affected areas
  - Re-welding of refurbished heaters and plugs

Mockup

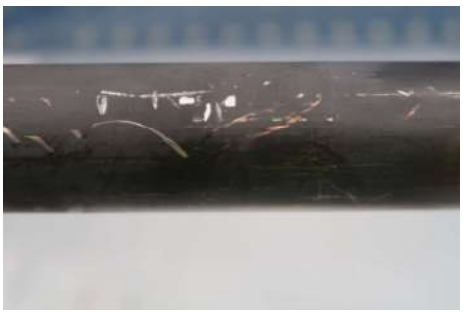


NDE Challenge – Timeframe and Technique

<u>Timeframe</u>
- First contact with DEKRA & SQC 6th of September
- Perform inspection in the end of December

<u>Qualified NDE</u>
- Requirement to have qualified system for crack detection with ET, VT and PT of the Bottom of the PRZ.

<u>Non Qualified NDE</u>
- A system to detect copper residuals in the heater penetration and on the heaters.



Qualification Requirement

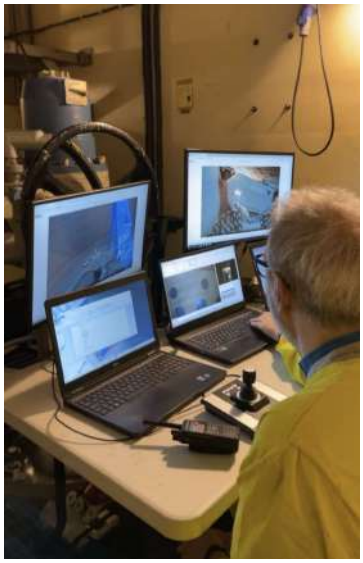
<u>Swedish Qualification System according to ENIQ:</u>
- Procedure
- Manipulator
- Personnel

<u>Ringhals Requirements</u>:
- 3 NDE Techniques combined in 1 manipulator + personnel

<u>NDE Techniques:</u>
- 2 Technichal data sheets based on PT and VT genereal procedures
- 1 procedure for EC based on TJ from previously qualified techniques

<u>Manipulator:</u>
- Demonstration for each of the 3 NDE techniques

<u>Personnel:</u>
- Demonstration/TJ required for EC



Qualification Challanges

- Sudden start – Short time frame
- Based on existing, qualified NDE-techniques
- Use of existing test blocks for manipulator demonstration
- Personnel demonstration online via video
- Many documents to be tied together

DEKRA Manipulator During Qualification of "Svanen"

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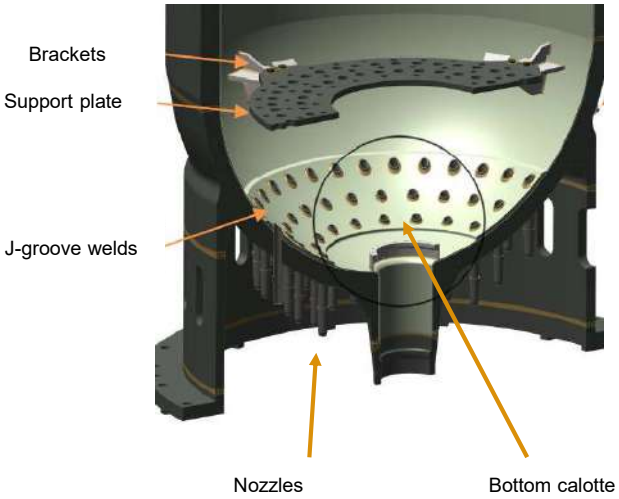
DEKRA Industrial AB – NDE Scope

Qualified part of NDE (Bottom)

- Support plate
- J-groove welds
- Inner surface of bottom calotte

Non qualified part of NDE (Outside)

- Nozzles
- Active Work Shop: Testing of heaters



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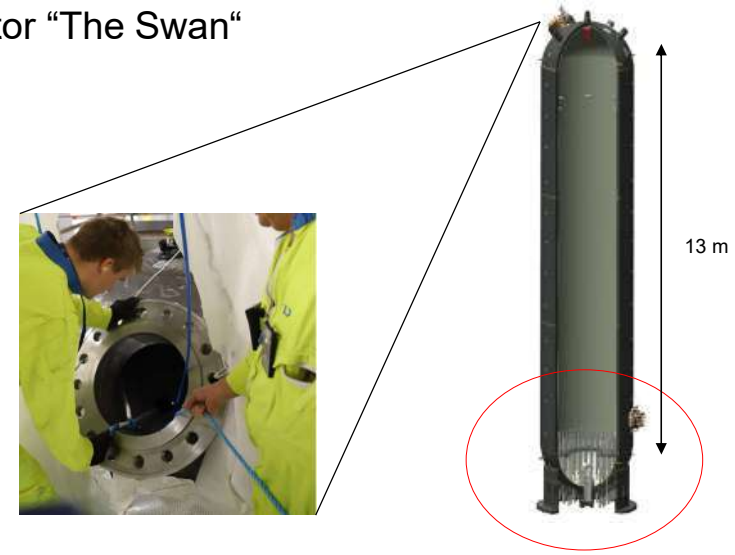
Internal Inspection – Manipulator “The Swan“

- Internal Inspection
- Ø500mm Manhole
- High Contamination
- All-in-one Manipulator System

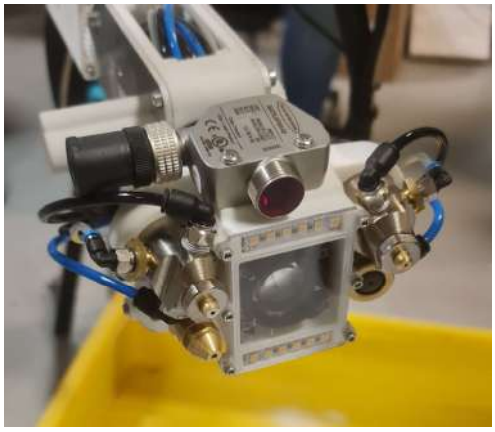


Manipulator Design – DEKRA “The Swan“

Manipulator docked onto support plate

Internal Inspection – Manipulator “The Swan“

- Laser Distance Measurement Sensor
- In-House Designed Nozzles
- Full HD Inspection Camera
- Multiple Surveillance Cameras
- Multiple Pan- Tilt- Zoom Cameras



Internal Inspection – Manipulator “The Swan“

- Laser Distance Measurement Sensor
- In-House Designed Nozzles
- Full HD Inspection Camera
- Multiple Surveillance Cameras
- Multiple Pan- Tilt- Zoom Cameras

Internal Inspection – NDE of Bottom Calotte and J-groove welds

VT of Cladding

EC of Cladding

Red Dye Penetrant J-groove welds

Nozzle Inspection – Manipulator Design “Vör“

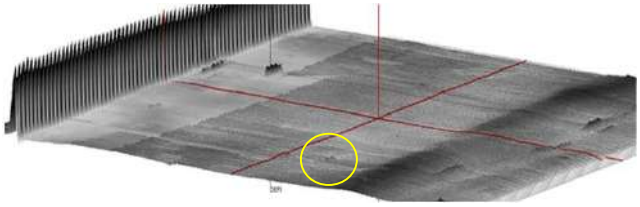
- From outside
- 2 axis movement
- 67 nozzles in 36 hours
- Two units scanning simultaneously

Pressurizer – Underside-up view

Nozzle Inspection – NDE Results

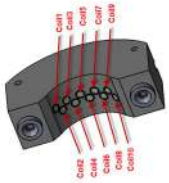
- Detection of copper residues and crack like indications
- Eddy Current & Visual inspection
- Double manipulators & control systems to speed up the test sequence
- Verification of relevant indiciations with visual inspection
- Dual probes (Absolute + DP) & Fiber optics VT

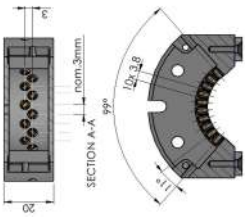
DEKRA Design Probes with absolute and XR type core



Heater Inspection – Manipulator “EIR“

- Active workshop
- 2 axis movement
- Pre programmed scan sequence
- SHRC (Super High Resolution Camera)
- DEKRA Design ET-Array – Coverage 100





Heater Inspection – Manipulator “EIR“

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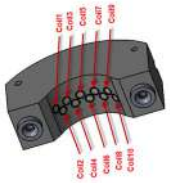
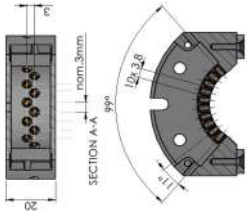
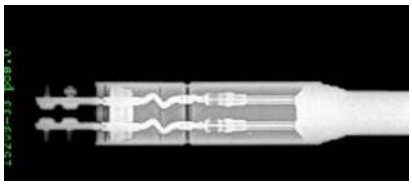


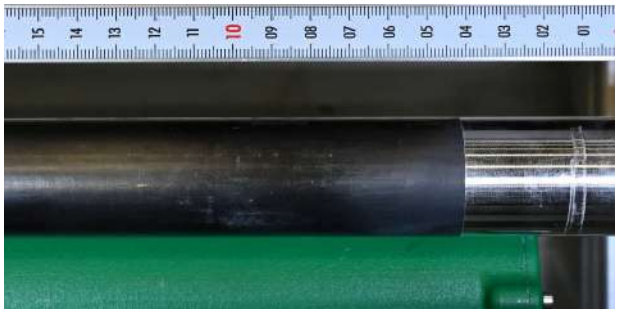


NDE of Refurbished Heaters

<u>Detection of copper residues and crack like indications</u>

- Eddy Current
- Visual Inspection
- Digital RT
- PT
- Moulding Technique (AVT)
- XRF





Summary of NDE Scope

What has been accomplished from the 3rd of September until the restart 7th April?

EC and VT
(Nozzle Inspection)

EC, VT + (Digital RT, PT, AVT, XRF)
(Heaters Inspection)

EC, VT, PT, XRF
(Internal Inspection)

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Summary Full Extent of Project

- 37 heaters cleaned, verified and re-installed
- Cleaning Internal and ISI of surface of PRZ, Surge line and Penetrations
- 184 days from start of project until re-delivery of plant to operating dept.
- 100 k working hours spent in the project
- 350 individuals involved
- Project library of about 550 documents
- R4 returned to control room on March 3rd
- Grid re-connection on March 31st, full power on April 7th
- Future In Service Inspection of nozzles in August -23
- Full extent In Service Inspection of Pressurizer bottom -24

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DEKRA VATTENFALL SQC

20230304 10:03:17
R4 40-315 PRZ Renhetsinspektion inför återmontage_
THANK YOU!

Virtual round robins – new insight into NDE reliability

Iikka Virkkunen[1], Tuomas Koskinen

[1]Aalto University, P.O.Box 14200, 00076 AALTO

E-mail address (corresponding author): Iikka.virkkunen@aalto.fi

Round-robin exercises have traditionally been laborious to arrange in non- destructive testing (NDT). The exercises have involved manufacturing of costly big mock-ups and then distributing them around the world to facilitate testing by numerous laboratories. This has limited both the number of such round robins and their scope. Often the round robins have contained small number of flaws and the representativeness of these flaws has been limited. Nevertheless, the few round robins that have been completed have yielded significant additional understanding on the capability of the used NDT methods and procedures. Recently, the increased use of automated inspections together with the development of virtual flaws (independently by Trueflaw and EPRI) has enabled a new type of round robin, where instead of moving samples around the world, the round robin is focused on the data analysis and only pre-acquired data files are distributed.

In 2019–2020, first of a kind virtual round robin (VRR) was completed. The round-robin allowed for the first time to compare inspection performance from teams around the world with statistically significant number of flaws and with ultrasonic data representative for nuclear dissimilar metal weld inspection. In 2021–2022, the second virtual round robin was completed. This improved on the first round robin and, in particular increased the richness of the data distributed and put more emphasis on the difficult to find cracks. Both of these studies resulted in important new insight into NDE reliability for nuclear applications. Both round robins were completed in connection to the international project “PIONIC” and attracted participants around the world.

This presentation reviews the round robin results and discusses the insight gained from these studies. In particular, the evaluation of POD and value of adding numerous channels to the data is discussed.

Keywords: round robin, virtual flaws, NDE reliability

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VTT

Virtual round robins
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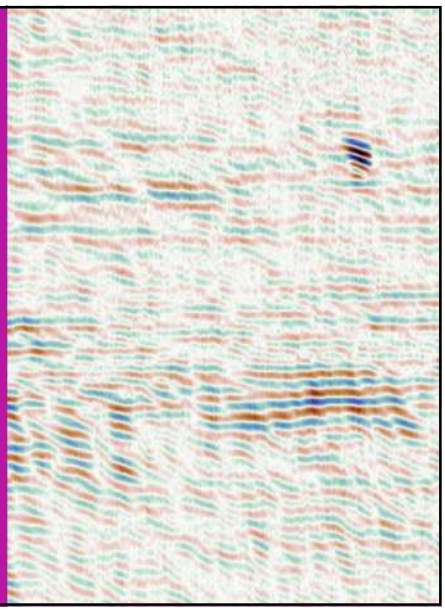


The problem

Reliability evaluation needs flaws and mock-ups

Mock-ups are expensive

Flaws are expensive

Reliability is hard

Virtual round robin

First-of-a-kind Virtual round robin performed

In connection with the international PIONIC program
(USA, Japan,Switzerland, Sweden, Korea)

In a virtual round robin

- *Data is gathered once*
- *Data is augmented with virtual flaws for better flaw distribution*
- *Data is distributed to participants digitally*
- *Results are collected and evaluated as in a normal virtual round robin*

Why go virtual

Benefits

- *Costly sample transportation and management avoided*
- *All teams can do evaluation in parallel*
- *Virtual flaws greatly reduce sample cost and improve data quality*
- *Effort focused on the important data evaluation phase*
- *Results are highly comparable since everyone evaluates the same data*

Limitations

- *Data gathering is excluded from the scope*
- *Procedure is necessarily limited by the gathered data*

Two virtual round robins completed

2019 VRR1

- *First-of-a-kind Virtual round robin*
- *Reduced data to invite wide participation*
- *Focus on POD*
- *12 detection results, 7 length sizing, 5 depth sizing*

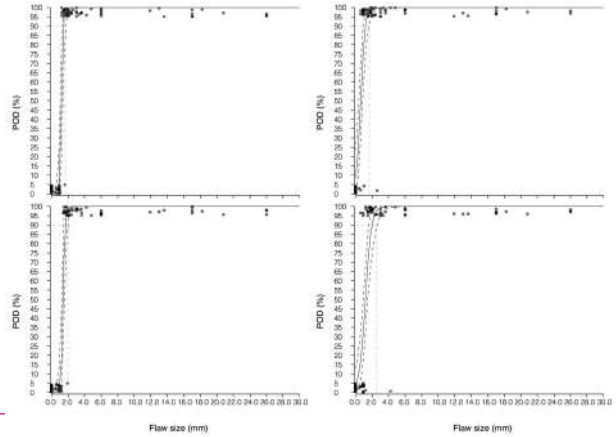
2022 VRR2

- *More comprehensive and representative data*
- *More representative sizing results*
- *Smaller participation due to bigger burden and more difficult data*
- *5 result sets, 3 with sizing results*

VRR 1: POD results show big variation

ID	Set identifier	Standard $a_{90/95}$	Modified $a_{90/95}$	False calls (count)	False call (%)	PFP 95 (%)
A	cd9b7ef8		**1.7**	11	5 %	8 %
B	7f76f387	3.5	1.7	21	9 %	13 %
C	b5b069aa	1.4	2.0	8	4 %	6 %
D	c3c55eff	3.2	2.6	13	6 %	9 %
E	7f1850e8	2.9	2.9	8	4 %	6 %
F	5bb2d9c0	5.9	2.9	11	5 %	8 %
G	9ca46cc3	4.1	3.8	9	4 %	7 %
H	b609241d		4.7	5	2 %	5 %
I	31316ac4	3.5	4.7	4	2 %	4 %
J	c06442e1	5.6	5.3	7	3 %	6 %
K	45e0cda8	24.5	5.6	10	5 %	8 %
L	27bda941	7.1	**7.1**	3	1 %	3 %

POD curves – the best



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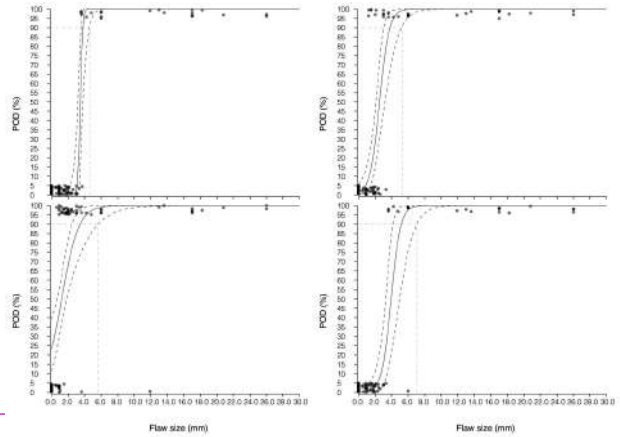
POD curves – the worst



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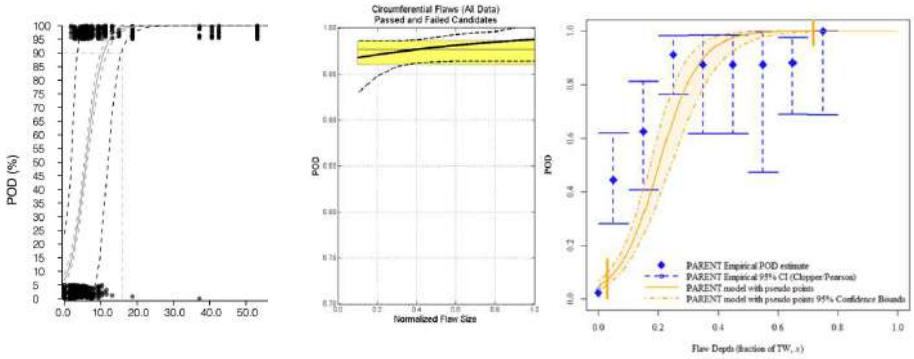
Comparison with previous results



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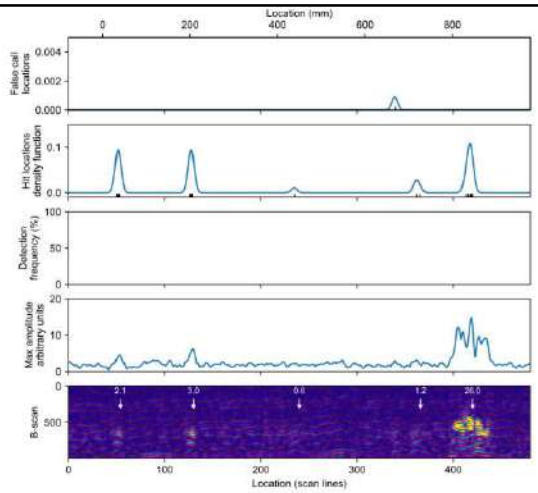
MRP-262/2017, Figure 6-7 *Parent slide set*

Typical results



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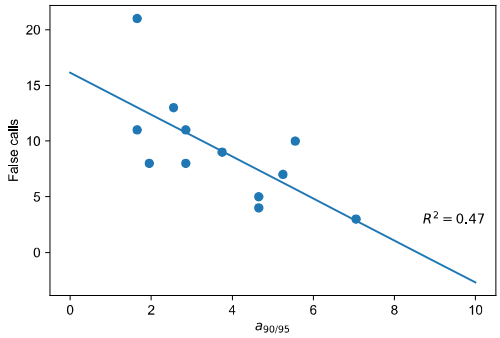
Poor correlation with false call rate

Poor correlation with false call rate



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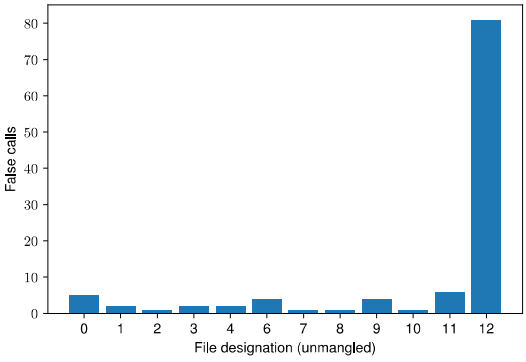
Most false calls on clean file



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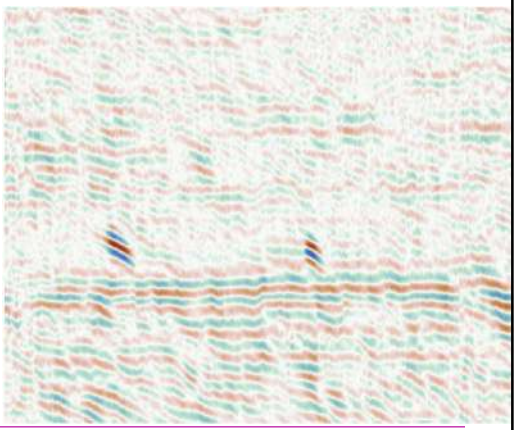
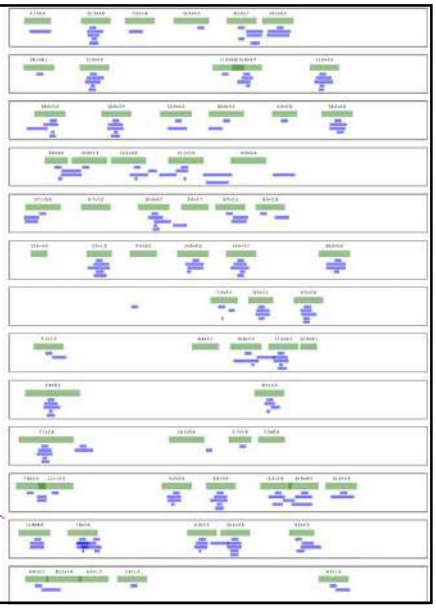
VRR 2

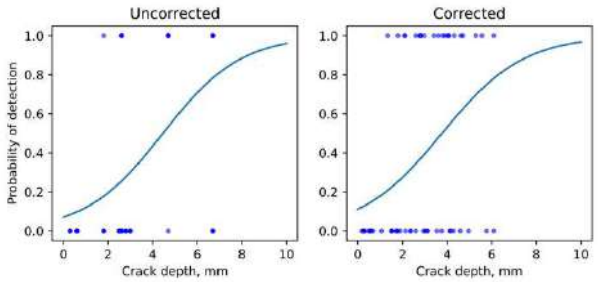
More realistic data
More realistic flaws
More small flaws
Improved virtual flaws



Small result set wide differences



Poor correlation with effective flaw size



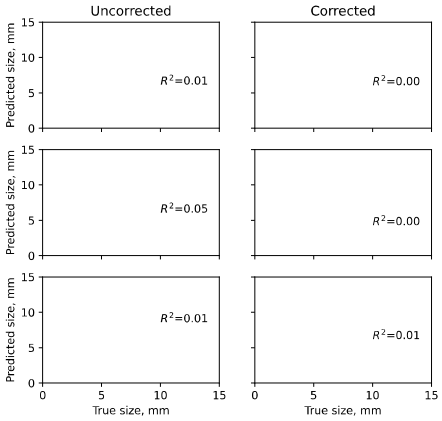
Cracks only visible in ”peripheral” channels are often missed

Sizing results are bad

Comprehensive data

Difficult flaws

High variation in sizing results



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One more thing…

During project, AI reached maturity

Machine learning (ML) and Artificial Intelligence (AI) had reached a level needed for use in NDE

CNN's were able to make sense of raw data not unlike NDE data

Virtual flaws enabled generation of training data sets

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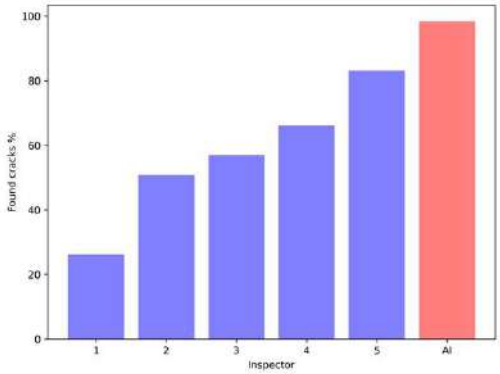
If AI had been used in the VRR2

… it would have been the best submission



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Conclusions

- **Virtual round robins provide important new tool to study NDE reliability**
- **Virtual flaws allow POD evaluation, where previously impossible**
- **VRR highlighted issues with DMW inspection and sizing that would have been difficult to detect otherwise**
- **Early results indicate that AI can address the issues arising from large data sets**

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Qualification of WWER Steam Generator Threaded Holes Eddy Current Inspection

Roman Krajčovič[1], Peter Hudcovič[2] Ladislav Carbol[3], Marian Štefanka[4]

[1]VUJE, a.s., Okružná 5, 918 64 Trnava, Slovak Republic
[2] VUJE, a.s., Okružná 5, 918 64 Trnava, Slovak Republic
[3]ČEZ, a.s. Duhová 2/1444. 140 53 Praha 4. Czech Republic
[4]SE, a.s. Mlynské nivy 47, 821 09 Bratislava 2, Slovak Republic

E-mail address (corresponding author): roman.krajcovic@vuje.sk

Automated eddy current inspections of WWER steam generator collector threaded holes, as one of the key components of primary circuit is being carried out as a standard operation during outages in NPPs.
The purpose of the inspection is to determine the condition of the threaded holes with the aim of verifying the further operability of the component.
The eddy current method is practically the only method in the relatively inaccessible space of threaded holes that enables quick and reliable detection of defects having in mind, first, the requirements for sizing and growths of detected cracks in between two inspections.
The goal of inspection is to detect specific imperfections such as corrosion cracks spreading from the inner surface of the threaded hole. The secondary objective of the inspection is the detection of damage to the internal surface, such as mechanical damage to the thread or sub-threaded part and the bottom.
The programs, scopes, criteria and periodicity of these inspections are determined by the operator's internal operating regulations.
The system performance demonstration must be performed before first inspection. The qualification process is performed fully in accordance with ENIQ rules and recommendations.

Keywords: eddy current inspection, WWER, steam generator, threaded holes, virtual mock-up.

Qualifying the End-of-Manufacture Inspections of the High-Integrity Components for Hinkley Point C

Mikaël Debroise[1], Thomas Booodworth[2]

[1]Framatome, 71380 St Marcel, France
[2]Bloodworth Consulting Limited, Wigan, UK

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E-mail address (corresponding author): mikael.debroise@framatome.com

High-Integrity Components of the Hinkley Point C nuclear power station are manufactured at Framatome's St Marcel factory. The inspection of the welds used to fabricate the components is required to meet a specification defined by the customer. The specification sets out the required detection capability, the required accuracy for measurement of defect location and length and the required capability for characterization of any indication. It is a requirement that the inspections used to make the final "end-of-manufacture" inspections be qualified according to an ENIQ-type approach; to determine whether or not they meet the specifications.

A diverse range of ultrasonic techniques has been implemented for the end-of-manufacture inspections. In most cases, automated phased-array pulse-echo inspections replace the manual ultrasonic testing that has been done in the past. In addition, ultrasonic ToFD examinations of the full weld thickness are made. An LLT-tandem examination provides an examination optimized for certain target defects identified by the specification.

An important part of the Qualification process is the Technical Justification, in which we explain the reasoning for the design of the techniques being deployed and why we believe that the inspection is (or is not) capable of meeting the many requirements. The Technical Justification relies in part on inspection simulations using mathematical models and on data collected in practical tests of the inspection techniques on test specimens and mock-ups containing intentional defects.

The Inspection Procedure that defines how the inspection techniques are deployed for each group of similar welds is tested in a "blind" trial by an Independent Qualification Body. Once the Procedure qualification is achieved, each of the operators assigned to make the inspections in the factory has to submit to Personnel Qualification before they can be permitted to perform that inspection on the actual components.

The experience of the Qualification process, spanning several years, is described. The history of the project is described; from inspection specifications to successful delivery of components, inspected with Qualified inspections.

Keywords: Ultrasonic testing, inspection qualification, technical justification, phased-array.

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HPC End-of-Manufacturing Inspections Qualification

Mikaël DEBROISE
NDT Engineer

NDE in Nuclear – Sheffield, June 2023

Content

1. Introduction/Framatome presentation

2. HPC Inspection Qualification program

3. Qualified RPV EoM inspection

FRAMATOME Activities

Engineering & Design Authority: Development, design and licensing of nuclear steam supply systems (NSSS) and associated services, including worldwide Technical Centers.

Projects and Components Manufacturing: Design and manufacturing of heavy and mobile components for nuclear islands. Management and execution of nuclear reactor new build projects, and component replacement projects.

Instrumentation & Control: Design and manufacturing of automation and instrumentation technologies for the safe, sustainable and economic operation of nuclear power plants.

Fuel: Development, design, licensing and fabrication of fuel assemblies and core components for all types of light water reactors (PWR, BWR, VVER) as well as for research reactors. Development of zirconium alloy components.

Installed Base: Products and services to maintain, modernize and extend the service life of facilities in operations; commission new facilities and support to decommissioning & dismantling activities.

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Worldwide presence

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Framatome in Burgundy:

Saint-Marcel

Saint-Marcel Plant
Manufacturing of the nuclear reactor primary coolant system components

Burgundy Calculations Center
Mechanical calculations and innovation

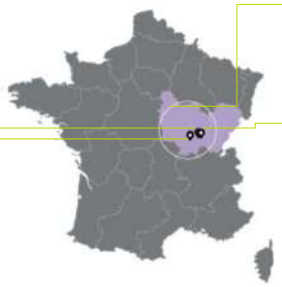
Laboratory (Technical Center France)
Mechanical tests and metallography tests

Inspection Academy
School for quality inspectors for the nuclear industry

Le Creusot

Le Creusot Plant
Forging, casting and machining of the nuclear reactor primary coolant system components

Technical Center France
Research and development to increase the reliability and safety of nuclear power plants



Montbard

Montbard Plant
Tube production for the steam generators

Chalon-sur-Saône

Installed Base (Chalon-Sully)
Nuclear services: installation, repair, maintenance and components replacement

INTERCONTRÔLE
In-service inspections, technical assistance and non-destructive testing

NETEC
NDT Research and Development facilities

CETIC
Framatome-EDF training and qualification center

3 270 employees (Feb. 2023)

600 recruitments planned in 2023

*without CETIC

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Focus on Saint-Marcel plant

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COMPONENT MANUFACTURING
SAINT MARCEL FACTORY
BURGUNDY - FRANCE

- **STMA Plant**
  - **Comissioning: 1975**
  - **Surface: 40 000 m²**
  - **Lifting capacity: 1 000T**
  - **~ 1100 employees**

An history boosted by the development of the nuclear industry worldwide

A 22-ha site with a workshop surface of more than 40,000 m², a lifting capacity of 600/450 tons opening onto a dock connected to the Saône river

1974 French CP1 contract signature for 16 reactors PWR 900 MW type.

1975 **Commissioning of the Saint-Marcel plant for the manufacturing of Steam Generators and Pressurizers**

1981 Delivery of the FOAK 1,300 MW Steam Generator (Paluel 1)

1986 **Centralization of all heavy components manufacturing operations in Saint-Marcel workshop**

2003 First deliveries of US program components: Prairie Island SG

2005 Start of the extension of the workshop >50 M€ investments

2009 Delivery of the heavy components for the first EPR NPP (OL3, Finland)

2015 Delivery of the first replacement Steam Generators in the frame of the EDF major re-fit (Paluel 2)

2017 **Start of Hinkley Point C EPR components manufacturing**

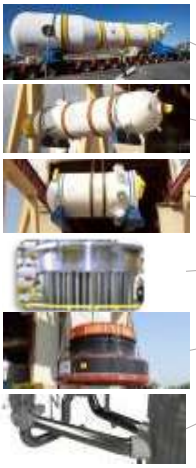
2019 Renewal of the Machining utilities

2020 Dematerialization of the workstation in the workshop

2021 Delivery of the first 1,300 MW replacement Steam Generators of the ND contract

2022 **Delivery of HPC1 Reactor Pressure Vessel**

688 heavy components manufactured for 106 reactors in 11 countries



	Delivered	Ongoing
Steam Generators	368	40
Pressurizers	75	2
Reactor Pressure Vessels	82	2
Reactor Vessel internals	82	2
Replacement Closure Heads	81	1
Main Coolant Lines		2
	688	49

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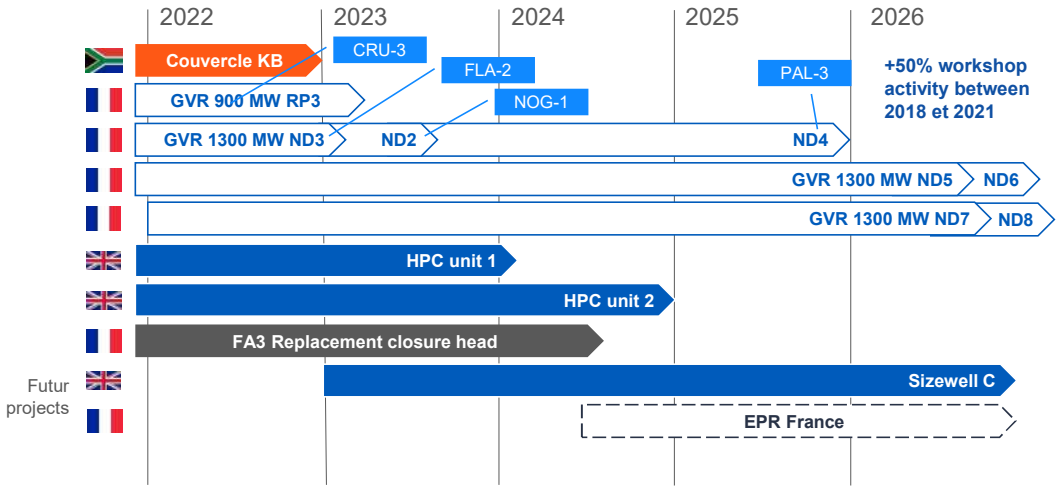
Ongoing and Future projects



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Content

1. Introduction/Framatome presentation

2. **HPC Inspection Qualification program**

3. Qualified RPV EoM inspection

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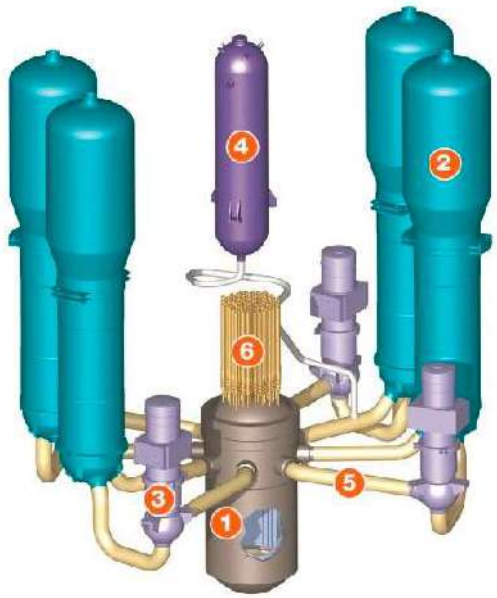

High Integrity Components (HIC)

Number	Component
1	Reactor Pressure Vessel (RPV)
2	Steam Generators (SG)
3	Reactor Coolant Pump (RCP)
4	Pressurizer (PZR)
5	Main Coolant Line (MCL)
6	Vessel cover Head (RPVH)

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Welds grouping according High Integrity Components

IQ Group	Description
1 bis	RPV circ welds
2 bis	RPV inlet and outlet nozzles welds
3 bis	SG primary head to TubeSheet weld
4	PZR nozzle to shell welds
5 bis	SG secondary Circ Welds
5H	SG Steam Outlet nozzle weld
7	SG secondary Nozzle-to-Shell weld
9	RCP Bowl Major Repair Welds
10	SG and RPV Dissimilar Metal Welds (Safe Ends)
11 A&B	Main Coolant Line Welds (F-F & F-C)
15	PZR Circ welds

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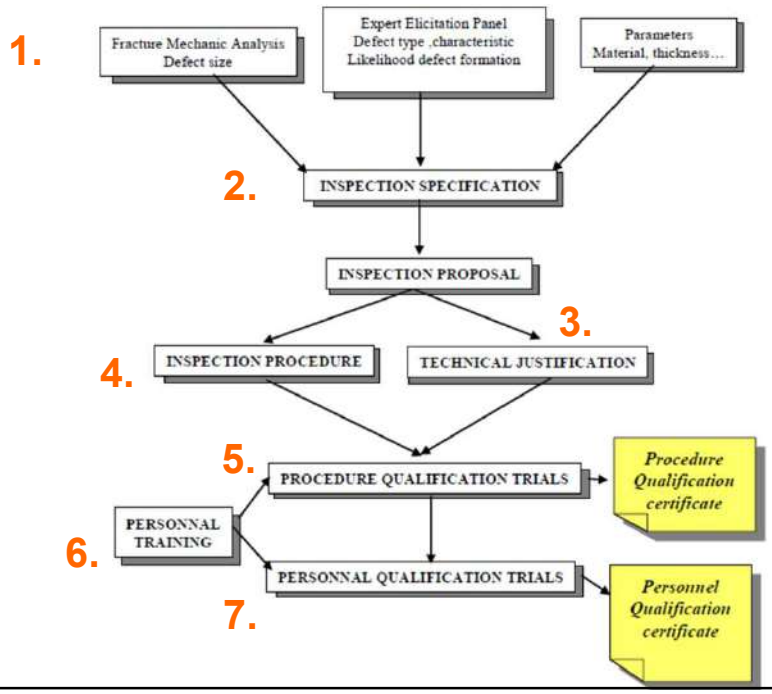
IQ process



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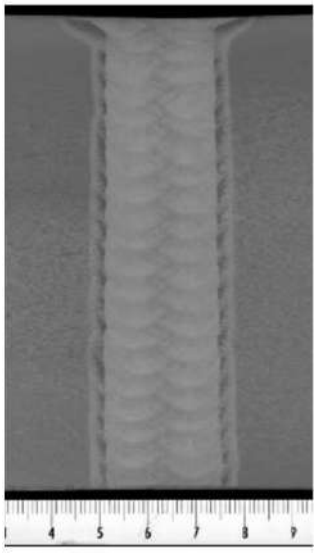
Step 1: Target defect definition

Input data:

- Low Alloy Ferritic steel (fine grains)
- Automatic Narrow-gap Submerged Arc welding (SAW 121)
- Nearly 0° fusion faces
- Thickness range: 100 to 260 mm
- Weld root and cap removed by machining



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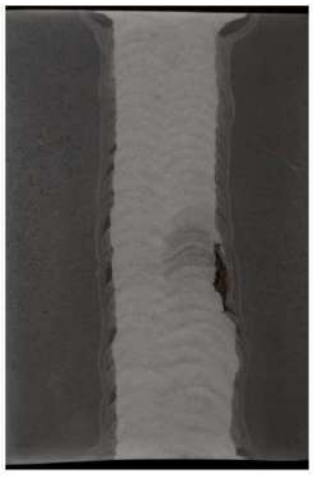
Step 1: Target defect definition

Output from the Expert Elicitation Panel meetings:

- Type: Planar (Crack or Lack of Side Wall Fusion)
- Size: 10x60 mm or 5x30 mm according component thickness and residual stress level
- Position: whole weld volume+HAZ
- Tilt: vertical (±10°) according narrow-gap chamfer geometry
- Orientation: parrallel or transverse to weld direction (±5°)



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Step 2: Inspection specification

Primary requirement defect: target planar defects for which qualified detection capability is required. Highly reliable detection, characterization, sentencing and rejection

Secondary requirement defect: detection capability to be assessed and documented only.

Highly reliable detection

Highly reliable detection can be termed as when multiple beams (angles, directions) produce recordable signals, or when smaller numbers of beams produce signals significantly exceeding the recording level.

Step 2: Inspection specification

***Sizing accuracy**: Length ± 15 mm*
No through wall extent sizing required

***Location accuracy**:*

- *Along Welding Direction: Location of Defect Centre ± 25 mm*
- *Perpendicular to Welding Direction: Location of Defect Centre ± 10 mm*
- *Depth: Location of Defect Centre ± 10 mm*

Step 3: Technical Justification

Section 1 Introduction – A description of the inspection to be qualified

Section 2 Summary of Relevant Input Information – A summary of the requirements of the inspection specification

Section 3 Overview of the Inspection System - An overview of the NDT inspection system in terms of the inspection method and techniques to be deployed and the procedures, equipment and personnel to be used.

Section 4 Analysis of the Influential and Essential Parameters – All Input and NDT System parameters that, if changed outside the working range or tolerance, could have an adverse effect on the outcome, shall be listed.

Section 5 Physical Reasoning - A qualitative assessment and justification, using physical reasoning, of the essential parameters that have the greatest influence on inspection performance

Step 3: Technical Justification

Section 6 Modelling – Used to back up the claims made in Section 5.

Presents predictions that help show that the inspection performance stated in the inspection specification can be achieved.

Section 7 Experimental Evidence -Evidence from practical experiments that back up the claims made in Sections 5 and 6.

Section 8 Parametric Studies -These are additional investigations of essential parameters identified in Section 4, which are performed to supplement the evidence presented in Sections 6 and 7**.**

Section 9 Equipment capabilities, Data Analysis rules and Personnel Requirements (Experience, Training and certifications)

Section 10 Review of Evidence Presented

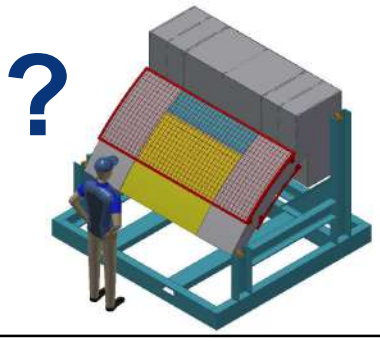
Section 11 Conclusions and Recommandations

Step 4: Inspection procedures

Step 5: Procedure assessement trials

Step 6: Operators training

Step 7: Operators individual qualification trials on Test pieces



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Content

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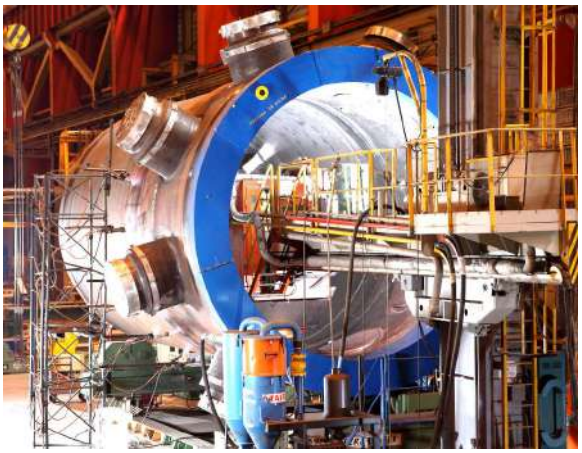
HPC RPV in numbers

Technical Caracteristics:

- Height: 10 meters
- Diameter: 8 meters
- Weight: 400 tonnes
- Base material: 16MND5
- Thickness: 250 mm
- Inner Stainless steel cladding



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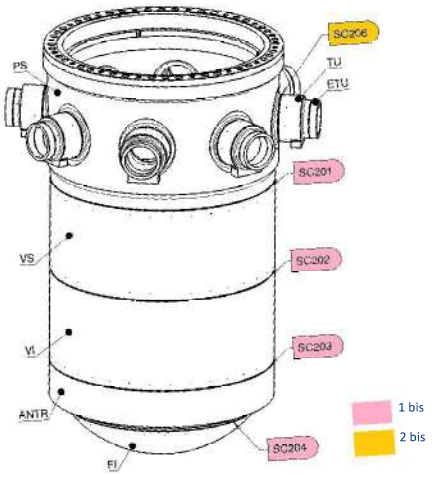
RPV examination

20 HIC Welds:

- 8x Safe End Welds ⇨ IQ Gr10 (Manual UT)
- 4x Circular Shell Welds ⇨ IQ Gr1bis (Automated UT)
- 8x Nozzle Welds ⇨ IQ Gr2bis (Automated UT)



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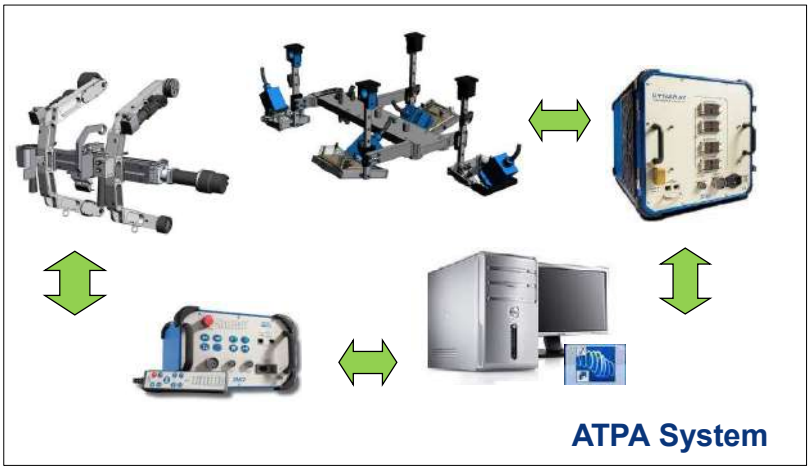
Advanced UT implementation



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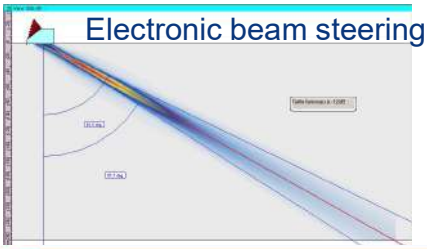
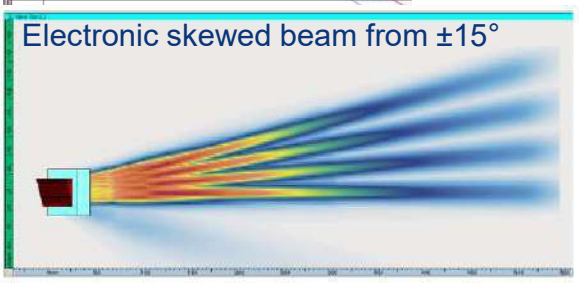
2D matrix Phased Array Pulse-Echo





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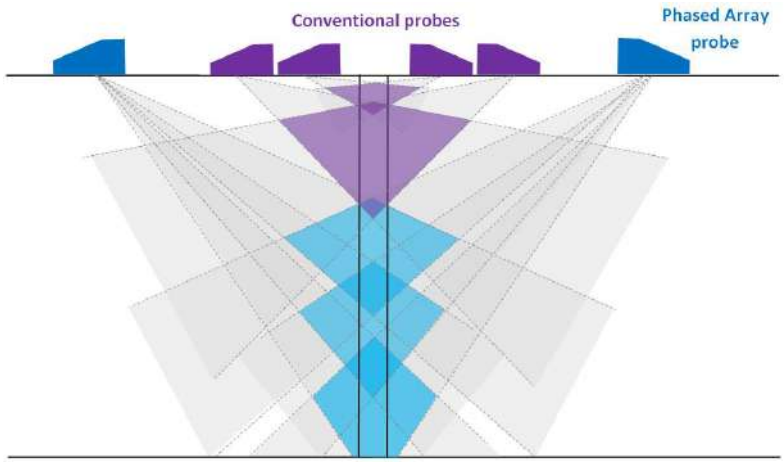
+ ToFD (whole thickness coverage)



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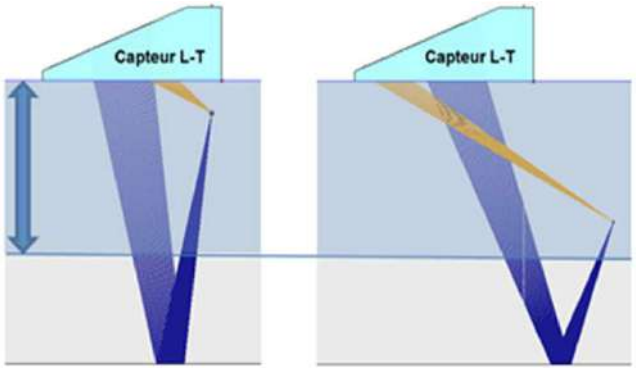
+ LLT tandem technique

≈2/3



Single Linear PA probe configuration ⇨ 2/3 upper part coverage

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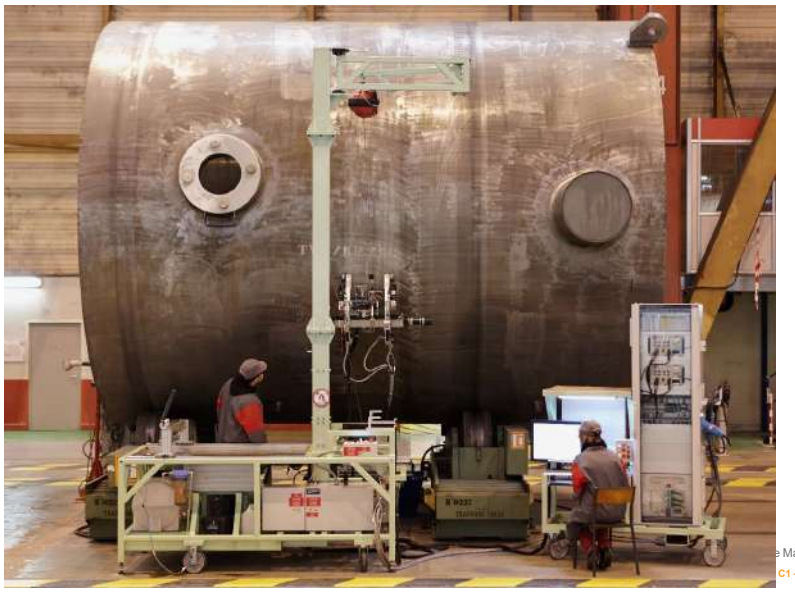
In-site Implementation (overall view)



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OD Manipulator

Shell inspection

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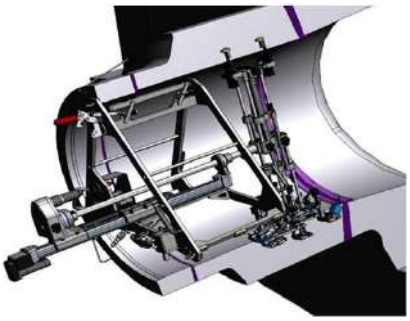
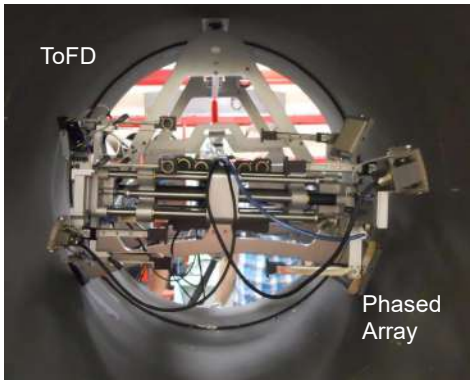
RPV inlet and outlet nozzles inspection

ID Nozzles manipulator





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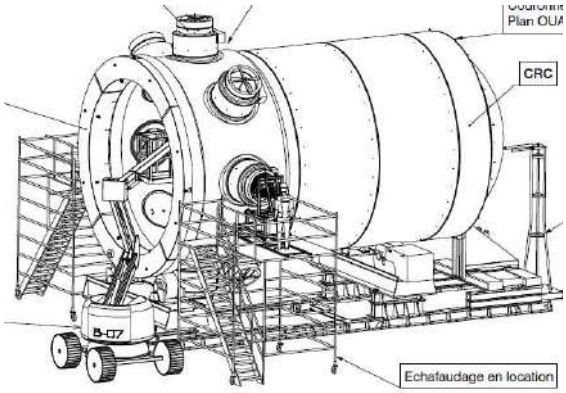
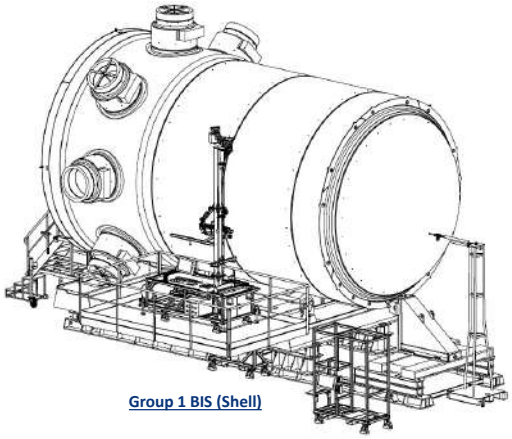
HPC RPV End-of-Manufacturing shell welds inspection



Group 2 BIS (Nozzles)



Group 1 BIS (Shell)

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Conclusion

- **Since nearly 50 years, FRAMATOME used to manufacture nuclear heavy components based on RCC-M or ASME codes.**
- **For HPC manufacturing program, FRAMATOME had implemented a novel way to develop and validate weld inspection strategy.**
- **Inspection Qualification program is structured on ENIQ approach.**
- **FRAMATOME had qualified 11 inspections (Manual and Automated UT).**
- **In 2022, for the first time, Automated UT techniques have been implemented in parallel for the RPV End-of-Manufacturing Inspection.**

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Non-destructive testing of components used in MARIA research reactor.

Marcin Kowal[1], Bogdan Zając[1], Grzegorz Olszewski[1]

[1]National Centre for Nuclear Research, Otwock, Poland

E-mail address (corresponding author): marcin.kowal@ncbj.gov.pl

Abstract text (1/2 – 1 A4 page)

This work aims to provide examples of non-destructive testing carried out in the MARIA research reactor, explicitly focusing on ultrasonic testing of the reactor's cladding and eddy current testing of its sheaths.
Non-destructive methods enable evaluation of the technical condition of the reactor and its components without the need for dismantling or destroying samples. In our work, we focus on two techniques: ultrasonic and eddy current testing.
The ultrasonic technique is one of the most important non-destructive methods in material engineering. In the case of the MARIA reactor, this method is used for detecting and evaluating damage to the reactor's cladding. The second technique is eddy current testing. This non-destructive method allows evaluation of the thickness of the reactor's sheaths and developed due to corrosion oxide layers.
In conclusion, non-destructive testing methods such as ultrasonic or eddy current testing are essential techniques for evaluating the technical condition of the MARIA reactor. They are frequently used at National Center for Nuclear Research. Tests are carried out without damaging studied components. Utilizing these techniques makes it possible to quickly detect any potential damage or defects, enabling a prompt response and minimizing the risk of failure.

Keywords: non-destructive testing; reactor Maria; scientific reactor; UT; ET.

Nuclear Facilities Operations Department

Materials Physics Department

Materials Research Laboratory

Fundamental Research Department

Nuclear Equipment & Technology Department

Department of Complex Systems

Radioisotope Production Centre POLATOM

Nuclear Equipment Division (HITEC)

Science and Technology Park (PNT)

National Centre for Nuclear Research Poland (NCBJ)

Location: Otwock / Świerk 35 km from Warsaw

The largest Research Institute in Poland:

- over 1000 Employees,
- the research staff includes 76 Professors & 200 PhDs
- PhD School ca. 80 Students

Research achievements:

- over 500 reviewed papers, with over 16 000 citations/year

Research projects:

- over 117 projects funded by H2020, EURATOM, NCN, NCBR, FNP, RPO
- success rate for EU projects ca. 35%

Scientific cooperation:

- International cooperation with the largest Laboratories in the world JRC, CERN, DESY, Grenoble, JParc, FAIR, Julich, ESS, JINR, T2K, XFEL and many Universities…

Scientific and Industry Centres

NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

Interdisciplinary Division for Energy Analyses

Non-destructive testing of components used in MARIA research reactor

Nuclear Facilities

National Centre for Nuclear Research Poland (NCBJ)

We export **radiopharmaceuticals** to 80 countries worldwide ~100% of the Polish market (excluding Positron Emission Tomography PET) which representing

>30% * I-131

16-18% * Mo-99

Global demand

More than 17 million patients under treatment !!!

Medicinal products certified quality system:

ISO: PN-EN ISO 9001:2015-10 cGMP and GLP

PhDs

ions/year

NCN, NCBR, FNP, RPO

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sities…

Radioisotope Production Centre POLATOM

Nuclear Equipment Division (HITEC)

Science and Technology Park (PNT)

Scientific and Industry Centres

NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

Interdisciplinary Division for Energy Analyses

* Peak/maximum demand covered by Polatom due to refurbishments at other research reactors

Non-destructive testing of components used in MARIA research reactor

Nuclear Facilities

National Centre for Nuclear Research Poland (NCBJ)

Ds

ns/year

CN, NCBR, FNP, RPO

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FAIR,
es…

Radioisotope Production Centre POLATOM

Nuclear Equipment Division (HITEC)

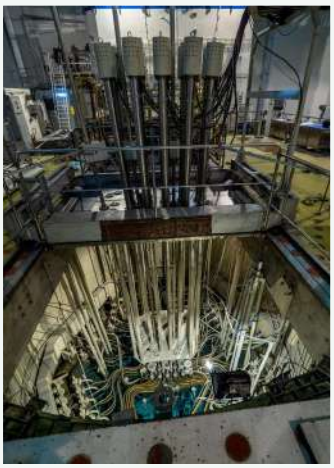
Science and Technology Park (PNT)

Scientific and Industry Centres

NOMATEN Centre of Excellence in Multifunctional Materials for Industrial and Medical Applications

Interdisciplinary Division for Energy Analyses

Research Nuclear Reactor MARIA



Reaktor MARIA

- Built in year 1974
- Upgrade in 1992, 2011, and 2017….2024 new neutron infrastructure !!!
- Pool type reactor
- Moderator H_2O, Be
- 30 MW thermal
- Neutron flux
  - thermal: max. $4 \cdot 10^{14}$ n/cm^{2}s
  - fast: max. $2 \cdot 10^{14}$ n/cm^{2}s

Non-destructive testing of components used in MARIA research reactor

Research Nuclear Reactor MARIA

MARIA reactor applications:

- production of radioisotopes (POLATOM)
- testing of fuel and structural materials for nuclear power sector
- neutron modification of materials (Materials Research Laboratory)
- research in neutron and condensed matter physics
- neutron radiography
- neutron activation analysis
- neutron beams in medicine
- training in the field of reactor physics & technology

Reaktor MARIA

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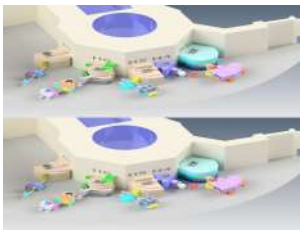
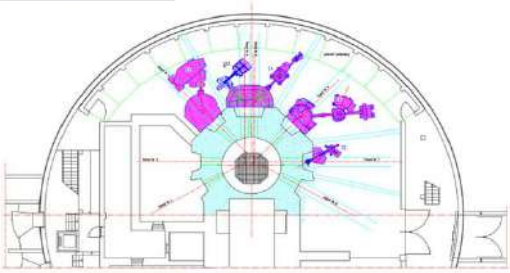
Research Nuclear Reactor MARIA

New research instruments for the MARIA reactor….year 2024
NCBJ cooperation with HZB Helmholtz-Zentrum Berlin für Materialien und Energie



E1	Thermal neutron	Spectrometer
E2	Flat Cone	Diffractometer
E3	Residual	Stress Analysis Diffractometer
E4	Two-Axis	Diffractometer
E5	Four-Circle	Diffractometer
E6	Focusing	Diffractometer

Visualisation of the MARIA reactor experimental hall after upgrading



Reaktor MARIA

HZB Helmholtz Zentrum Berlin

Materials Research with new Neutron Infrastructure:

- *Neutron Radiography NR – NDT Testing of ready elements i.e. Microcracks analysis, Porosity after casting, Weldments quality control etc.*
- *Analysis of internal and residual stresses deep within a crystalline material*
- *Determination of the atomic and magnetic structure of a crystalline solids, gasses, liquids or amorphous materials.*
- *Measurements of highly-textured elements*

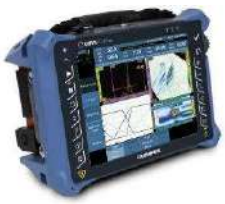
Non-destructive testing of components used in MARIA research reactor

NCBJ Materials Research Laboratory – Non-Desctructive Testing NDT Division

- MRL is subdivided into:
  - ✓ the Laboratory for Structural, Corrosion and Chemical Testing
  - ✓ the Laboratory of Mechanical Testing
  - ✓ **the Laboratory of Non-Destructive Testing**
  - ✓ and the Workshop of Hot Chambers

Non-Destructive Testing Division is available to perform tests in the scope of:

- Visual Testing method (**VT**)
- Penetration Testing method (**PT**)
- Magnetic Particle Testing method (**MT**)
- Ultrasonic Testing method (**UT**)
- Eddy Current Testing method (**ET**)



UT defectoscope Olympus OmniScan MX2

ET defectoscope Olympus Nortec 600D

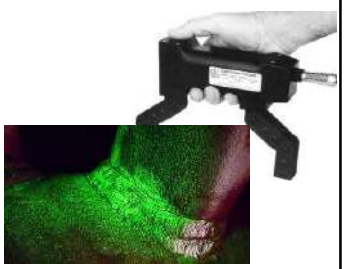
Accredited NDT Testing
Polish Centre for Accreditation
Accreditation number AB 025

AB 025

Financed by Project HTGR

VT Flexible Videoendoscope
Mentor Visual iQ - Waygate Technologies

Penetrant method

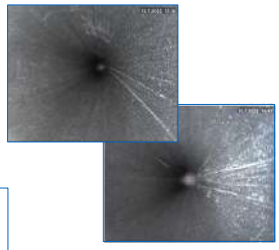


Magnetic particle method

Non-destructive testing of components used in MARIA research reactor

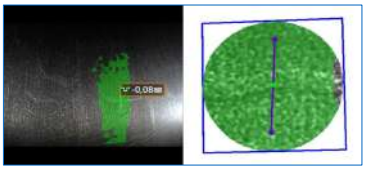
NCBJ Materials Research Laboratory – Non-Desctructive Testing for Industy and Research project, examples

AISI 316L seamless pipes NDT testing for ITER Blanket System components (First wall panels cooling system) – commissioned by ITER's supplier



Supply of Normal Heat Flux First Wall (FW) Panels for ITER Blanket System INSPECTION NOTIFICATION

***Visual Testing VT** – visual inspection outer / inner Surface*
***Ultrasound thickness test UTT** – wall thickness*
***Direct measurements** – pipes dimensions*
Magnetic permeability

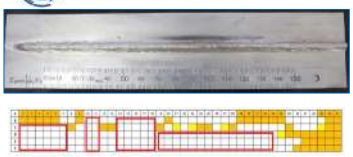


Cold drawing effects depth Analysed by VT Flexible Videoendoscope

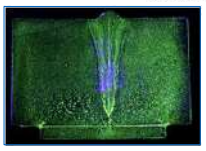
EUROfusion

EUROFER 97 after Electron Beam Welding NDT testing
in cooperation with Karlsruher Institut für Technologie

KIT



Ultrasound testing UT



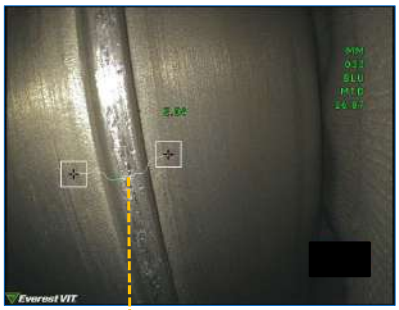
Magnetic particle inspection MT

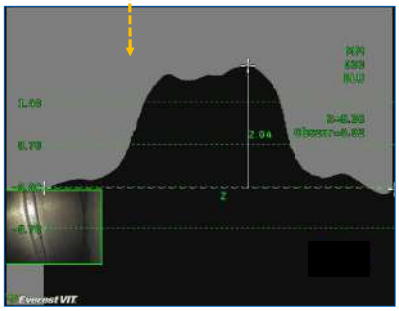
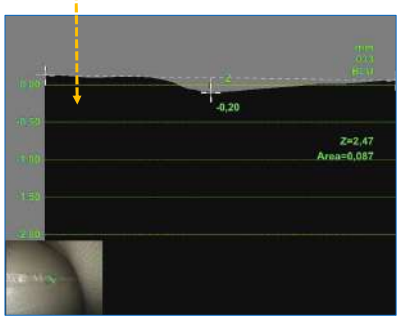
Weld cross-section

Non-destructive testing of components used in MARIA research reactor

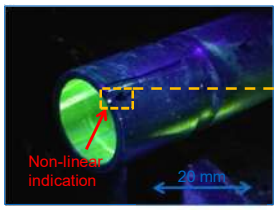
Visual Testing example

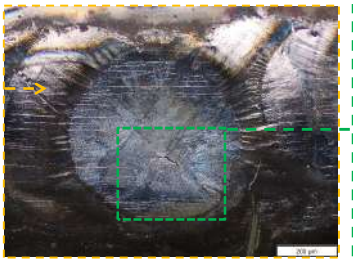
- Stereo 3D measurement allows to check the indicated profile.
- Depth of scratch measurement.

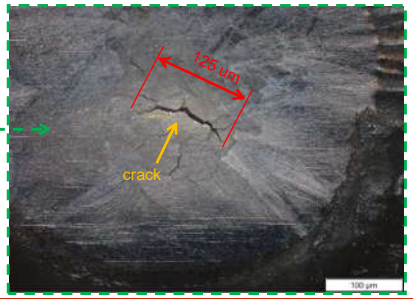


Penetrant Testing examples





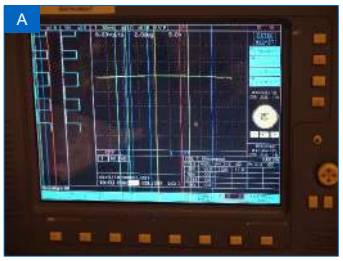


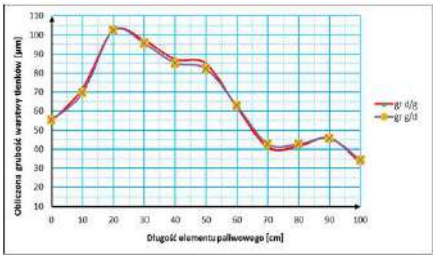
- Control rod – assessment of laser welding process

- Zirconium fuel sheat – assessment of TIG welding

Eddy Current Testing example

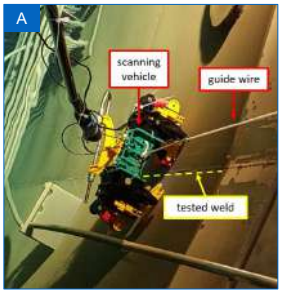
- Aluminium oxide thickness evaluation in the spent fuel element.

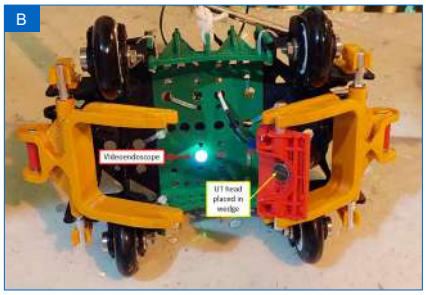




Ultrasound Testing example

- Prototype of Maria reactor shell weld scanning vehicle





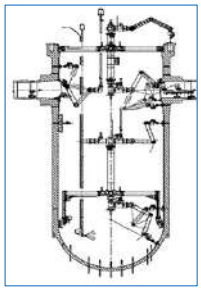


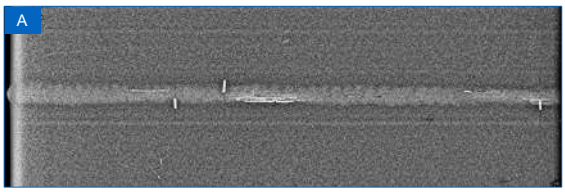
Foto from: *Rodzaje badań NDT stosowanych przez przemysł mgr inż. Bogdan Zając LBM NCBJ_30.11.2017*

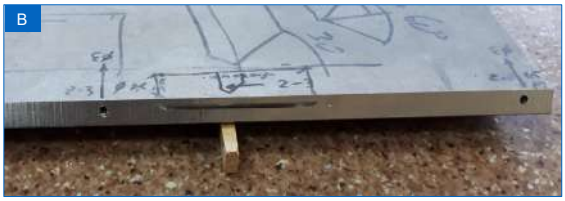
Non-destructive testing of components used in MARIA research reactor

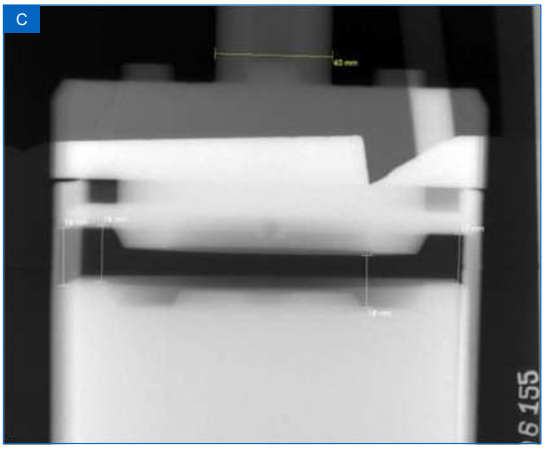
Radiographic Testing examples

- The purpose of this study was to evaluate the width of the expansion gap located at the top of exploited graphite blocks.

- Examples of artificial weld discontinuity;







Marcin Kowal
Materials Research Laboratory
National Centre for Nuclear Research
E-mail: marcin.kowal@ncbj.gov.pl

Thank you!

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

www.ncbj.gov.pl

16. Structural Health Monitoring (SHM)

The presentations in this session are listed in the table below.

Structural Health Monitoring (SHM)	**Chair:** Ignacio Real Rubio (Iberdrola)
In-service, on-stream, ultrasonics for NDE and process monitoring in Nuclear	Tim Stevenson, Will Vickers, David Martin (Ionix Advanced Technologies Ltd)
Characterization and Monitoring of ID Cracking in Pressurized Piping Using Surface Strain Measurements - Phase 1 - Unwelded Carbon Steel Piping	James J Wall (EPRI) & Brian P. Hohmann (Hohmann Engineering)
Low-cost structural health monitoring system for engineering applications	Ceri A. Middleton (Univ. Liverpool) et al.
Passive Guided Wave Tomography for Corrosion Monitoring under Varying Environmental Conditions	Tom Druet (CEA) et al.
Real-time ultrasonic measurement of component temperature gradients – development of a tool for better high-cycle thermal fatigue monitoring	Laurence Clarkson & Frederic Cegla (Imperial College)

In-service, on-stream, ultrasonics for NDE and process monitoring in Nuclear

Tim Stevenson[1], Will Vickers[1] and David Martin[1]

[1]Ionix Advanced Technologies Ltd, Huddersfield, United Kingdom.

E-mail address (corresponding author): tim.stevenson@ionix.at

With the ever-increasing demand for energy, increasing existing power generating plant availability, productivity and efficiency are increasingly important strategies alongside the development and delivery of new stations.
To this end, the Industrial Internet of Things (IIOT) has played an increasing role in gathering data on a wide range of industrial processes to gain insights in to improving process parameters, such as temperature, flow and pressure, and more recently has crossed over in to non-destructive evaluation (NDE) techniques, such as ultrasonic testing of wall thickness for pressure vessels and process piping whilst plant is operational, but is often limited by the high temperatures and high-shine environments found in nuclear applications.
The HotSense™ ultrasonic platform has been successfully implemented into the nuclear sector for in-service, on-stream continuous installed structural health monitoring, and in-process weld integrity.
Based on a proprietary piezoelectric material technology, the platform has been successfully deployed on high pressure steam piping for continuous monitoring of erosion/wall-loss from condensate, and on cooling water lines for gas void detection and level sensing. By way of validation, sensors have been retrofitted to piping for continuous operation at temperatures up to 600 °C and with simultaneous radiation exposure of 11 MGy (gamma) and 2.6×10^{18} cm^{-2} (neutron flux).
The data collected using ultrasonic time-of-flight has provided several case-studies which are presented.

- Real time wall loss as a result of steam condensate erosion of a piping circuit on an operational European power plant in lieu of manual UT measurements to reduce dose and improve operational efficiency.
- Gas-void monitoring and level sensing of cooling water lines in pressurized water reactors for compliance and plant digitalization.
- In-situ ultrasonics submerged in molten salt and molten tin and lead (Pb-Bi) metals for characterizing cooling efficacy and for ultrasonic inspection of submerged vessels.

In addition, the same platform has been modified for high-temperature, automated, weld inspection using ultrasonic time-of-flight-diffraction. This technology is shown to detect and size defects in welds without the need for shutdown or isolation, and presented is on-going work to integrate these sensors into robotic arc-welding platforms for in-process integrity assessment.

Keywords: high-temperature, ultrasonics, gas void, erosion, weld integrity

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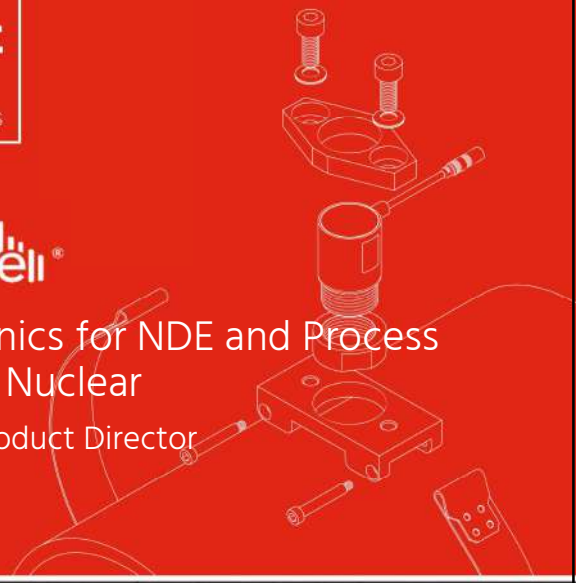
ADVANCED TECHNOLOGIES

hotsensell®

In-Service, On-Stream, Ultrasonics for NDE and Process Monitoring in Nuclear

Dr William Vickers, Product Director



Commercial in Confidence

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Who Are Ionix

Enabler	Compliance	Profitability
HPZ Ceramics & OEM	hotsensell UT Inspection	hotsensell Monitoring
HPZ Piezo Custom Assemblies Complete Devices and Solutions	High / Low Temperature Ultrasonic Probes Dual and Angled Beam Couplants and Accessories	Non-Invasive Ultrasonic Monitoring Intrinsically Safe Installed Probes Flexible Measurement Collection

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Introduction to Ionix

Who we are

Established 2011
Commercialised new piezo and ultrasonic technology
UK Based – HQ, Huddersfield, West Yorkshire, UK

Developer and Manufacturer of Piezoceramics, Sensors and Solutions
for monitoring systems in extreme environments

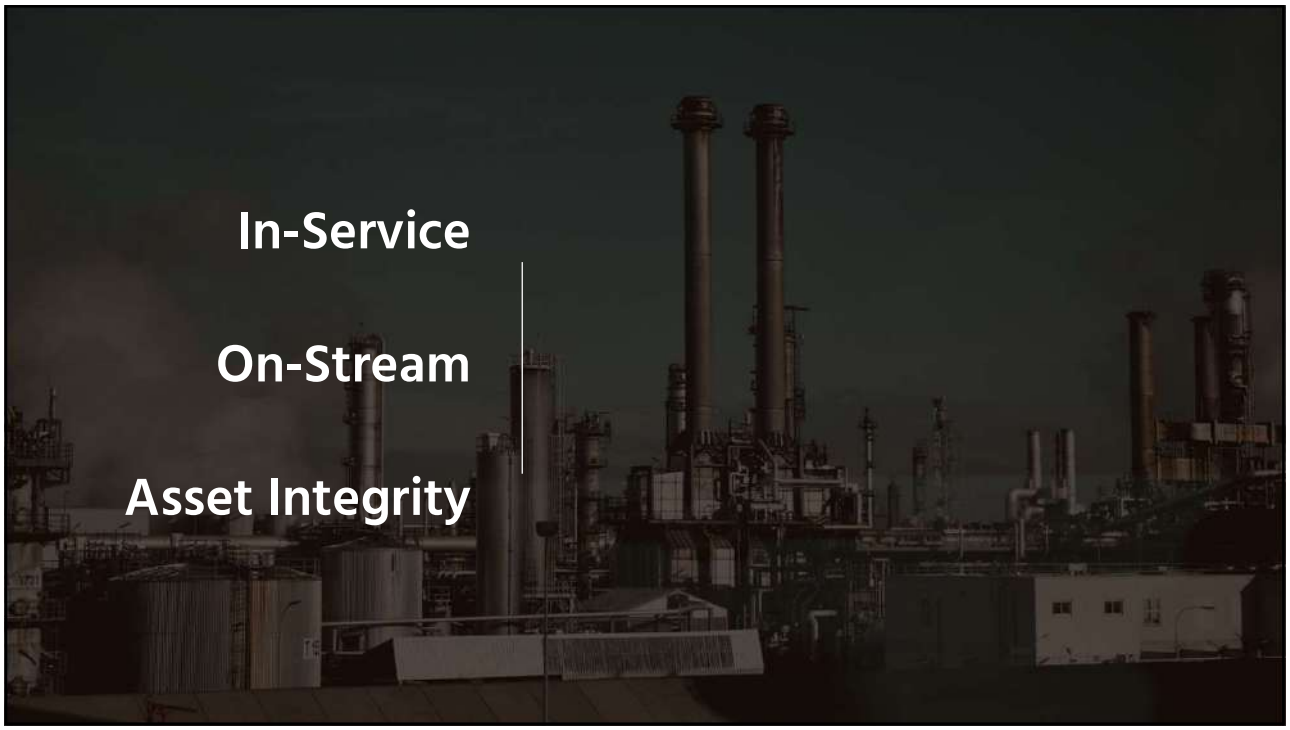
Multi-disciplined in-house team:

- Piezoceramic production
- In-house circuit printing
- Ultrasonic expertise
- System specialists
- Mechanical design
- Test facilities

Tailored solutions:

- Bespoke solutions for your most demanding challenges
- Customised transducers / sensors
- Monitoring systems expertise/consultancy

Built from the ground up



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In-Service, On-Stream, Asset Integrity

What?

- Making assessment of asset integrity using non-destructive methods while plant is operating, often at high temperatures

Why?

- Always know the status and condition of a plant
- Reduce outage frequency and length with optimised, predicative and preventative maintenance

Who?

- NDT inspectors - enabling inspection of critical assets outside of shutdown
- Plant operators- utilising trends to predict status and impact of processing conditions

When?

- Routine pre-shutdown inspection
- Monitoring of defects or areas of concern

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In-Service, On-Stream, Asset Integrity

Challenges

1. Equipment temperature limitations

- Ultrasound routinely used for quantitative assessment of thickness or crack detection and sizing
- Limited to ~150°C, steam containing pressure vessels >200°C

2. High temperature performance

- Applying standard equipment to high temperature applications challenging
- Safety risk and ambiguous results – utilisation avoided

3. Measurement precision

- Operator variability leads to low precision and poor detection of short term change

4. Access challenges

- Higher frequency data collection for trending exposes personnel to great risks
- Costs of maintaining access e.g. scaffolding, cladding and insulation removal, installation etc

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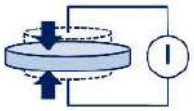
High Temperature Stability

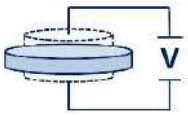
1 Transforming Pressure to Power



Common Applications

- Sensors
- Pressure monitoring
- Vibration control
- Flow detection
- Microphone
- Energy harvesting

2 Transforming Power to Pressure



Common Applications

- Actuator, Micro - positioner
- Transducer (Ultrasound, Sonar)
- NDE Thickness/ Corrosion monitoring
- Medical Imaging
- Loudspeaker
- Fluid control

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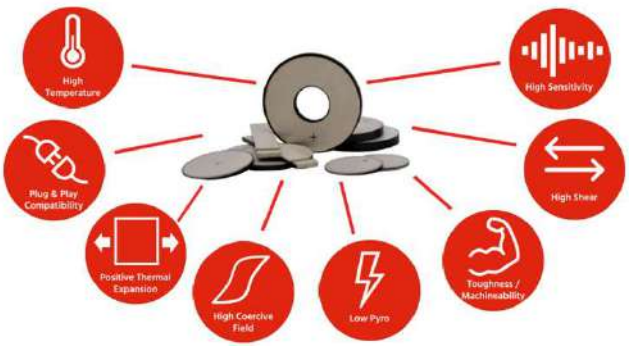
High Temperature Stability

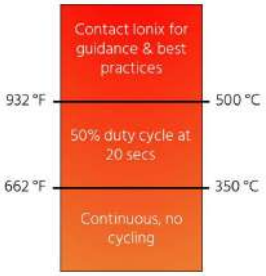
Standard Piezo (PZT)	Ionix HPZ
200 - 250 °C High sensitivity lost above temperature limit	Up to **580 °C** High sensitivity retained
Small movement/ stroke	**4x** higher movement
Highly brittle, prone to mechanical failure	**3 - 4x stronger** Finer features Reduced failure

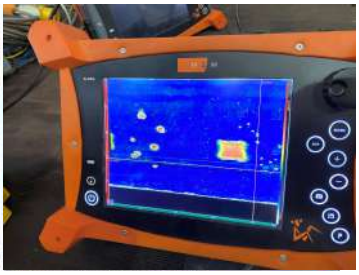


HotSense™ on-stream UT inspection solution

High Temperature Stability

- In-service, high resolution, automated UT
  - Low-cost UT technique
  - 2.5, 5 MHz duals, with 2X wear resistance
  - Wide operating temperatures -55 to +550 °C (-67 to 1,022 °F)
  - Automated/ robotic scanners and no duty cycling up to 350 °C / 662 °F
  - Compatible with existing UT equipment and training
  - Corrosion maps to identify accelerated corrosion and CMLs as per API 571
  - Immediate benefit of **asset intelligence without shutdown**

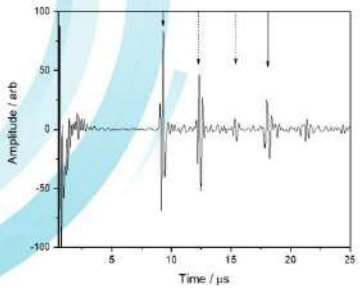




High Temperature Performance

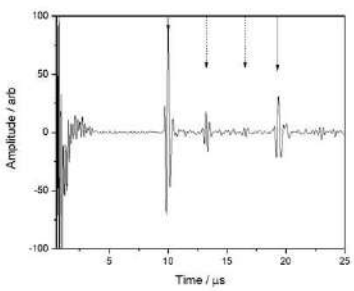
- Steel is the most common material of construction for high temperature, pressure containing components and pipe circuits
  - Different grades exhibit different properties
- Heat affects the ultrasonic signals in steel by several mechanisms
  - Velocity is a factor of density, Poisson's ratio and elastic modulus
  - Attenuation is a combination of absorption and scattering
- The effect on the UT signal in steel can be observed below – what do you notice between the two A-scans?

DL BW BW2DL2



5 MHz, at 20 °C

DL BW BW2 DL2



5 MHz, at 350 °C

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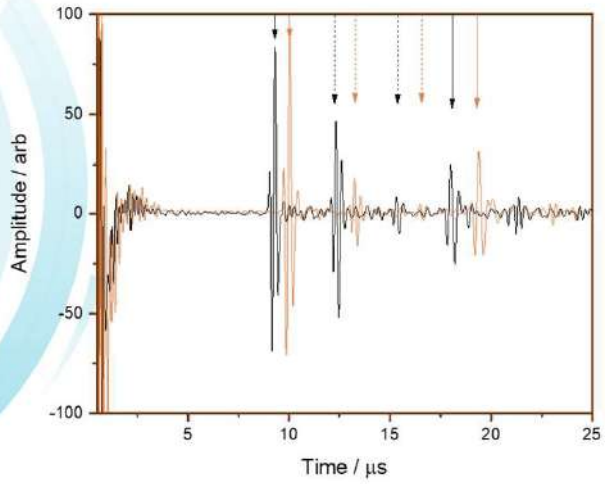
High Temperature Performance



- Reduced amplitude of backwall reflections
- Shift in TOF of all peaks

Notice, temperature effects the component under test *and* the transducer

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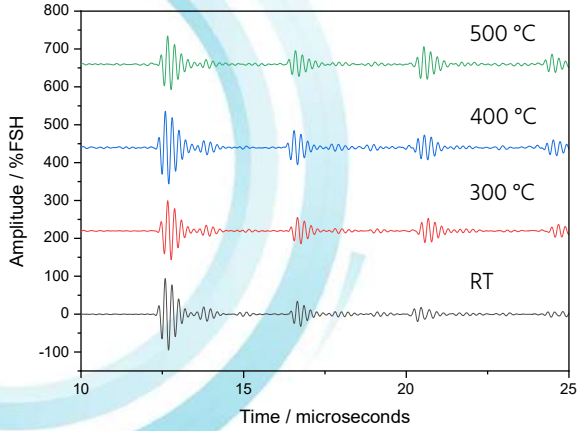
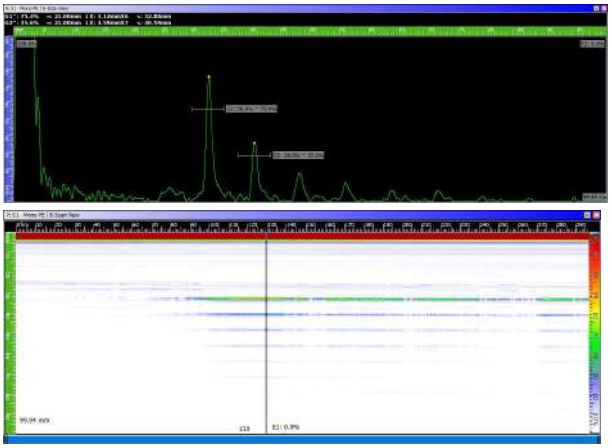
High Temperature Performance

hotsense® | Powered by ionix **HS582i**



Cal. Block, 12 mm / 0.5 "thick. AGC.



550 °C on in-service 6" sch 40 carbon pipe

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HS582i high temperature thickness measurements hotter than 510˚C

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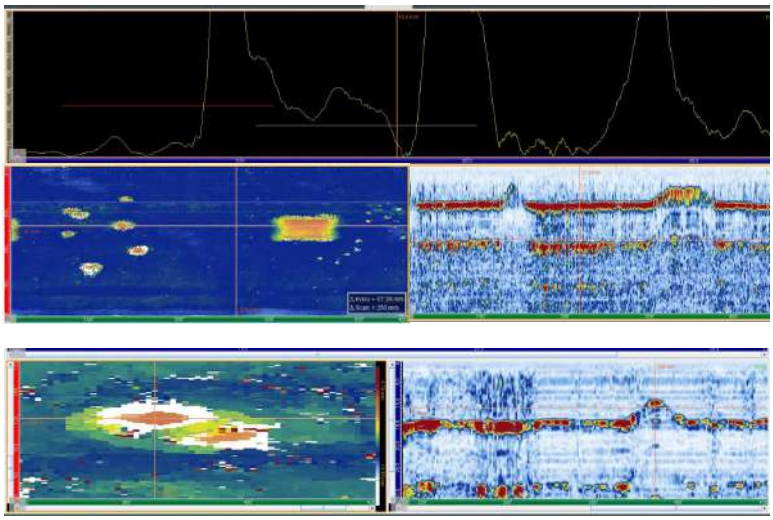
On-stream wall thickness

Corrosion mapping, HOIS 2021

- Good POD for pits and larger defects even at elevated temperature
- Pit clusters (>2:1 height to width) were detected by tip indication only
- TCG applied to suppress noise at elevated temperature
- Rapid setup with no cooling
- Higher accuracy than PAUT with no gradient in an associated wedge



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On-Stream Weld Inspection

HotSense™ TOFD

- Continuous operating temperature up to 350 °C
  - No duty cycling, no thermal gradients.
  - Stable and repeatable lateral wave
- 2-3 X wear resistance compared to conventional probes
  - Suitable for a wide range of scanning surfaces
- Integrated wedges
  - High sensitivity across the temperature range
  - Short approach to get closer to weld caps
- Compliant to ISO 22232-2 and ASTM E/1065
  - Compatible with commercial UT flaw detectors and scanners/crawlers

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High-temperature TOFD defect detection

- Evaluation undertaken with Inspection Service Provider / HOIS
- 8" NPS Sch 120 carbon steel ex-service pipe
- Test block heated to stable surface temperature of 200 °C
- 5 MHz, 6 mm, 60 deg wedge probes used (non-profiled)
- Echo 6 HT pumpable couplant (AIT 421 °C)
- Full circumferential scan of butt weld

Diameter	Material	Wall thickness	Weld cap
8" NPS	Carbon steel	Sch 120 Nominal wt = 18 mm	~50 mm wide

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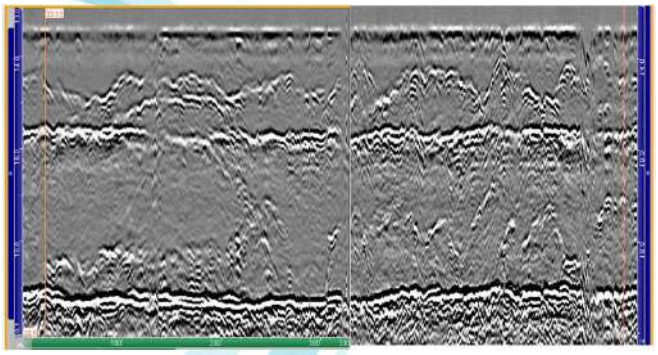
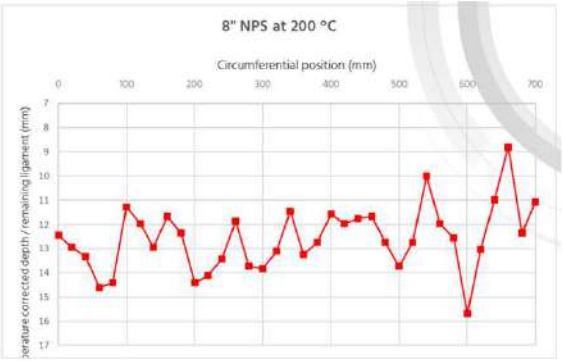
High-temperature TOFD weld root corrosion





- Velocity correction of 5745 m/s according to ISO 16809
- **Remaining ligament within 0.2 mm of benchmark ambient temperature TOFD scan.**

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Measurement Precision

UT Operator Variability

- Manual ultrasonic inspection prone to “operator variability”
- Amplified at high temperature = +/- 0.25mm precision thickness measurements
- Not suitable for short term trending

Installed UT Probe

- Fixed, installed probes high precision = +/- 0.025mm
- Higher precision enables detection of change

Key features

- High temperature stable
- Radiation resistant
- Rugged and robust
- Low profile for installation in confined spaces

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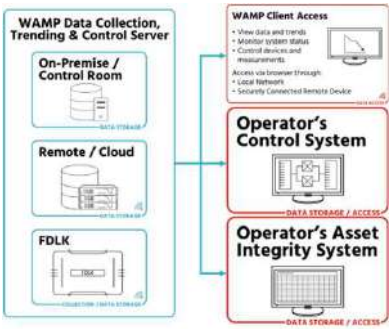
Access Challenges

Remote Data Collection

- Data collection using standard gauges from safe location
- Automated, wireless systems
- Data direct to control room or server
- High frequency data collection for trending

Safety

- Remove personnel from Hazardous locations
- Reduce dosage cost
- Improve plant overall safety



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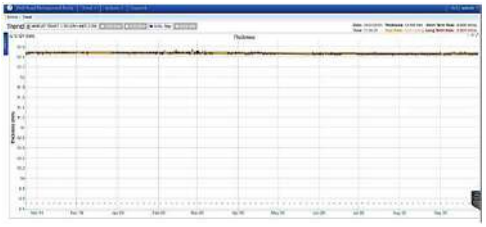
Asset Intelligence

Minimum Thickness		Corrosion Rate (mm/y)	Minimum Requirement Thickness	Rem. Life last insp (yrs)	Next Inspection	Remark
Previous Thickness	Actual Thickness					
10.40	10.80	-0.080	3.3	-93.75	1969	NOT MEASURABLE
10.80	10.30	0.100	3.3	70.00	2021	Accepted
11.00	10.40	0.120	3.3	58.17	2021	Accepted
10.80	10.40	0.080	3.3	88.75	2021	Accepted
10.50	10.60	-0.020	3.3	-385.00	1900	NOT MEASURABLE
10.70	10.40	0.060	3.3	118.33	2021	Accepted
10.20	10.10	0.020	3.3	340.00	2021	Accepted
10.80	10.50	0.060	3.3	120.00	2021	Accepted
10.30	11.30	-0.200	3.3	-40.00	1996	NOT MEASURABLE
9.80	10.30	-0.100	3.3	-70.00	1981	NOT MEASURABLE
9.00	8.90	0.020	3.3	280.00	2021	Accepted
8.90	8.60	0.060	3.3	88.33	2021	Accepted
9.90	9.70	0.040	3.3	160.00	2021	Accepted
7.60	9.10	-0.300	3.3	-19.33	2006	NOT MEASURABLE
7.50	8.70	-0.240	3.3	-22.50	2005	NOT MEASURABLE
7.90	8.70	-0.160	3.3	-33.75	1999	NOT MEASURABLE
8.90	10.60	-0.340	3.3	-21.47	2005	NOT MEASURABLE
11.20	10.60	0.120	3.3	60.83	2021	Accepted
7.60	8.30	-0.140	3.3	-35.71	1998	NOT MEASURABLE
7.60	8.50	-0.180	3.3	-28.89	2001	NOT MEASURABLE
10.80	8.10	0.540	3.3	8.89	2020	Accepted
8.90	8.10	0.160	3.3	30.00	2021	Accepted
10.60	8.60	0.400	3.3	13.25	2021	Accepted
9.00	8.70	0.060	3.3	90.00	2021	Accepted
10.70	8.00	0.540	3.3	8.70	2020	Accepted
8.40	8.10	0.060	3.3	80.00	2021	Accepted
10.40	8.90	0.320	3.3	17.19	2021	Accepted



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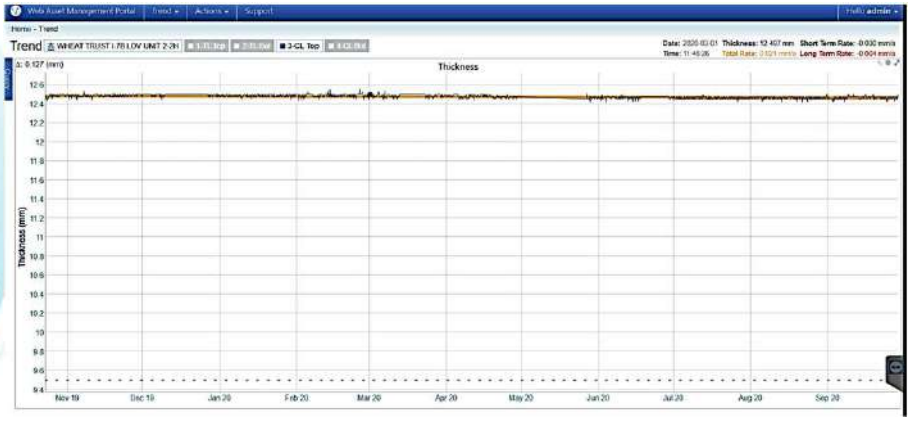
Asset intelligence



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Monitoring vs Manual Inspection

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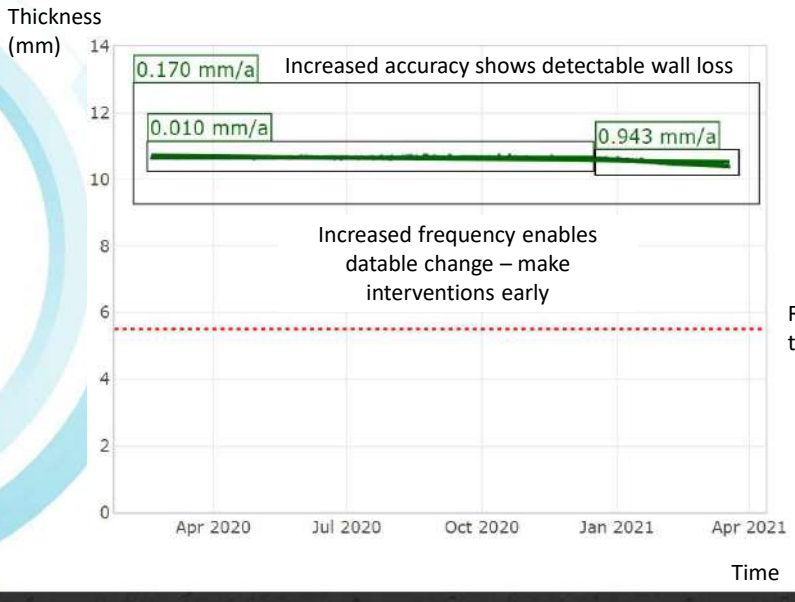
Monitoring vs Manual Inspection



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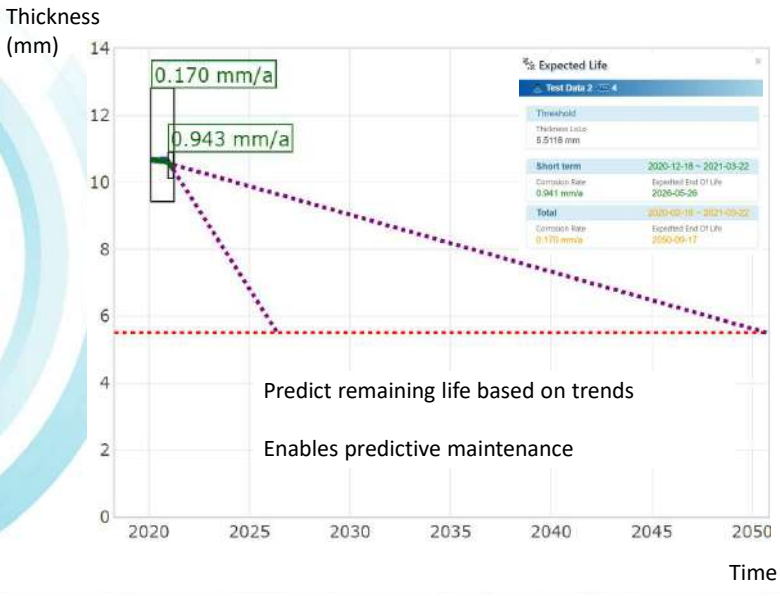
Predictive Maintenance



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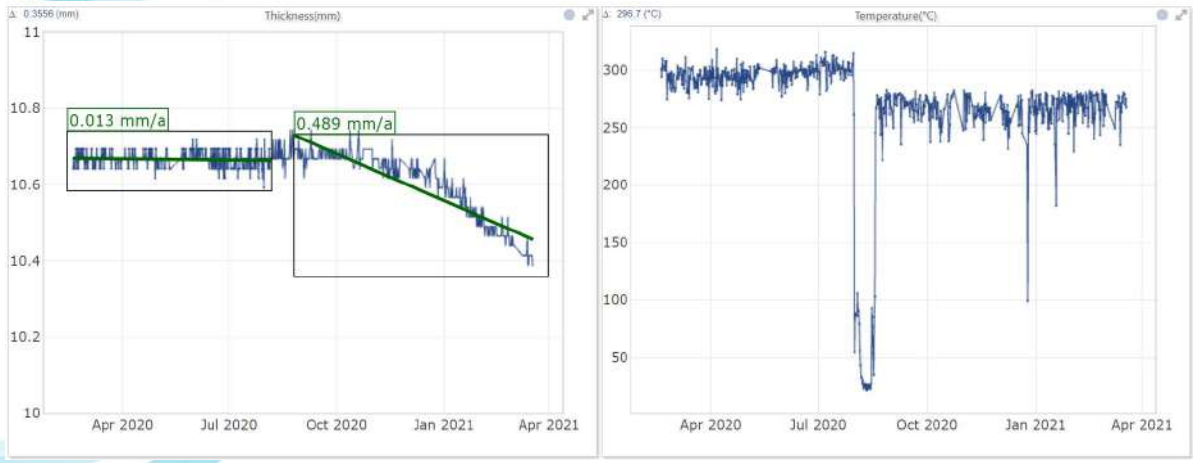
Detecting Changes



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Optimising The Management And Maintenance Of Steam Pipes And Vessels

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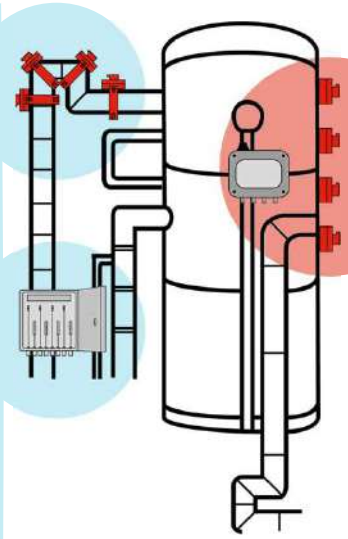
Flow Accelerated Corrosion

Challenge:

- Impact on maintenance budget and forecasting with extended outages
- Often overlooked and detected in late stages
- Requires replacement and frequent inspection
- High temperature >150 °C / 302 °F

Ionix solution:

- Installed HotSense™ ultrasonic sensors
- High precision wall thickness trends for predictive maintenance
- **Always know the remaining life to plan and reduce outage costs**



Steam Separator Erosion

Challenge:

- Loss of plant availability and increased outages
- Sudden wall loss with unpredictable trend
- Failure catastrophic with loss of production
- High temperature >200 °C / 392 °F

Ionix solution:

- Installed HotSense™ ultrasonic sensors with trend transmitted to control room
- **Production and maintenance effectively managed to hit operations targets**

ix

Case Study – Erosion Monitoring of Steam Separators – Green Energy

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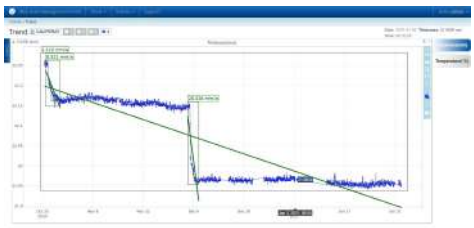
Challenge
- Previous failure of steam separators due to erosion - Loss of production and injury to personal
- Erosion locations high on separator requiring working at height
- Wall loss rates not uniform and unpredictable
- High temperature >230 °C

Solution
- 4 x HotSense™ 380 installed under insulation during plant operation
- CALIPERAY with FDLK data collection server
- Thickness measurements automatically collected every 1 hour and transmitted to plant control system

Value
- Wall loss trending to predict maintenance
- Shutdowns minimized – ROI achieved in hours
- Safety increased



Case Study – Flow Accelerated Corrosion Monitoring of Steam Lines – Nuclear Energy

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Challenge
- Previous failure of steam containing pipes due to FAC
- Monitoring required of replacement parts
- 230 °C DN600 pipes and elbows
- High ambient temperature prevents manual measurements

Solution
- 12 x HotSense™ 380 installed during shutdown
- Thickness trends collected using Measurement Hub
- Upgraded to CALIPERAY and FDLK automated, wireless system

Value
- Non-linear wall detected and related to process conditions
- Predictive maintenance and process control implemented
- No subsequent failures of plant since monitoring

Case Study – Gas Void Detection of Cooling Lines – Nuclear Energy

ionix

Challenge

- Gas voids in cooling lines cause knocking and entrainment on pumps when in use
- Currently manually inspected using UT probe and gauge
- Many pipes require scaffolding install and insulation removal
- Requires exposing staff to radiation and hazards such as working at height
- Sensors required to survive >280°C transient temperatures

Solution

- HotSense™ 380 installed during shutdown on the base of the pipes and used to detect gas void and water level
- CALIPERAY and WAMP upgraded to stream data to control room

Value

- Gas voids detected and monitored without exposing staff to hazards and reducing dose
- Plant safety improved and shutdown time and costs reduced

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Dr William Vickers
E: will.vickers@ionix.at

MINIMISING RISK & ENHANCED PRODUCTIVITY	REDUCED COST	ENHANCED SAFETY	INCREASED INTELLIGENCE
Lower risk of unplanned outage, maximising plant availability & production rate, reducing risk of varying crude slate	Reduced operating cost. Lower installation cost	Reduced manual operation, continuous asset monitoring, minimising risk of loss of containment	Optimising asset integrity management decisions such as maintenance and corrosion inhibition strategy

Nondestructive Characterization and Monitoring of Cracking in Pressurized Piping Using Surface Strain Measurements

James J Wall[1, 2,*] and Brian P. Hohmann[3]

[1] Nuclear Sector, Electric Power Research Institute (EPRI), 1300 W. T. Harris Blvd., Charlotte NC 28262 USA

[2] G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA

[3] Hohmann Engineering Associates, 500B Falls Blvd., Quincy, MA 02169 USA

[*] *Corresponding Author: jwall@epri.com*

ABSTRACT

Conventional nondestructive evaluation techniques, such as ultrasonic testing, are commonly used to inspect primary loop piping in nuclear power plants for cracks per US Code of Federal Regulations and ASME requirements. Such inspections can be time consuming, leading to significant cost to utilities and dose to personnel, and are in some materials, such as cast austenitic stainless steel, difficult to impossible due to their microstructural characteristics. The approach utilized here is an alternative approach to inspection and monitoring of piping and component welds which circumvents the limitations in conventional ultrasonic testing due to inhospitable microstructures. This EPRI Technology Innovation funded work consisted of a feasibility study to determine if monitoring of surface strains in pipes in real time may be used to detect, size and characterize the growth rate of cracks in pressurized pipes using strain gauges. The goal of this Phase 1 research was to increase the Technology Readiness Level to facilitate a follow on Phase 2 study on characterization of simulated fusion line cracks in welded wrought austenitic stainless steel piping. The overall goal (Phase 1 + 2) is to demonstrate feasibility of the approach for future application to primary loop piping and component welds.

Theory: When a pipe is pressurized, the pressure of the fluid within it exerts a 2-dimensional (axial and hoop) stress in the pipe, which causes the pipe to strain axially and tangentially. If a crack is present, the pressurized fluid will exert additional forces normal to the crack faces. These forces, which are proportional to the surface area of the crack faces, will cause a local strain in the adjacent intact pipe material, which will in theory present itself locally on the surface – much like a compact tension specimen under tensile load. For an axial flaw, for example, this strain will be oriented in the hoop direction.

This presentation will show the results of a Phase 1 feasibility study that utilized 10” (25.4 cm) OD Schedule 120 carbon steel pipes with EDM simulated ID linked axial flaws of varying depth and width, and which were instrumented with strain gauges mounted transverse to the ID cracks on the OD surfaces. The pipes were pressurized in steps up to 2,300 psi (16 MPa) (approximate PWR operating pressure) while strain data was collected in situ. The strain vs crack area data showed a clear

decrease in surface strain transverse to the flaws as a function of flaw surface area at the target pressure, indicating that the hydrostatic pressure exerted by the fluid caused the cracks to generate bending moments in the adjacent pipe material which could clearly be measured on the pipe surface. Plans for Phase 2 of the project on welded wrought stainless steel pipes with simulated flaws along weld fusion lines are currently underway.

Keywords: Non-Destructive Evaluation (NDE), Strain Data,

.

Characterization and Monitoring of ID Cracking in Pressurized Piping Using Surface Strain Measurements

Phase 1 – Unwelded Carbon Steel Piping

Dr. Joe Wall, EPRI
Principal Technical Leader, Plant Support / NDE Program

Dr. Brian Hohmann
Hohmann Engineering Associates

2023 NDE in Nuclear - Sheffield, UK
June 26 – 29, 2023

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Using Surface Strains to Characterize Cracking – Outline

- Introduction and Goal of the Research
- Experimental Setup
  - Flaw Simulation
  - Strain Gauge Placement
  - Pressurization Experiments
- Results
- Phase 2 Proposed Research
- Conclusions

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Using Surface Strains to Characterize Cracking - Introduction

- Regulatory agencies require regular inspection of primary loop piping and components for degradation that occurs during plant operation.
  - Manual ultrasonic examinations are expensive and often subject technicians to significant radiation dose.
- Goal: To develop a very simple method to monitor cracks / suspect indications during operation (e.g., at operational temperature).
  - Determine if they are arrested or growing.
    - If growing - estimation of, e.g., crack growth rates.
      - Make better informed repair decisions.
- In Phase 1 of this work, which was funded by EPRI TI, surface strain measurements were assessed as a method to monitor flaws.

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Experiments

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Using Surface Strains to Characterize Cracking - Experiments

- In this Phase 1 study 10 inch (25.4 cm) diameter, 2 foot (61 cm) length Schedule 120 (0.84 inch [21.4 mm] wall thickness) pipes were used.
- Cracking flaws with variable length and width were generated in the pipe samples using EDM notching.

Sample Serial No.	Nominal Notch Length (in.)	Measured Notch Length (in.)	Nominal Notch Depth (in.)	Measured Notch Depth (in.)	Measured Notch Width (in.)	Notch Orientation
79615	0.50	0.498	0.125	0.1249	0.0192	Longitudinal
79616	1.00	0.998	0.250	0.2498	0.0192	Longitudinal
79617	1.50	1.497	0.375	0.3754	0.0203	Longitudinal
79618	2.00	1.999	0.500	0.4975	0.0404	Longitudinal
79619-1	2.00	1.997	0.375	0.3734	0.0393	Longitudinal
79619-2	0.50	0.497	0.125	0.1246	0.0190	Circumferential
79620*	-	-	-	-	-	

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Using Surface Strains to Characterize Cracking - Experiments

- The theory is that when pressurized, the fluid in the pipes will exert normal forces on the flaw faces and generate strains in the transverse and longitudinal directions on the pipe surface.
- Strain gauges were placed on the OD of the pipes transverse (across) and longitudinal (parallel) to the ID flaws as well as in areas where no flaws were present.
- The pipes were capped and pressurized in steps up to 2,300 psi (16 MPa), approximate PWR primary loop pressure.
- The strain as a function of pressure was measured using the transverse and longitudinally mounted strain gauges in each sample.

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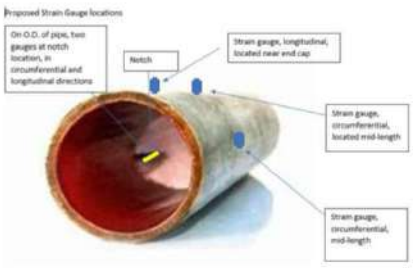
Using Surface Strains to Characterize Cracking - Experiments

Strain gauge instrumentation and capping of samples containing simulated flaws



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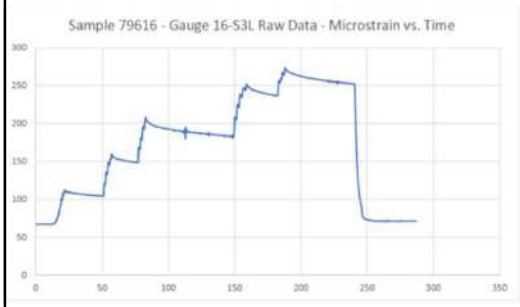
Using Surface Strains to Characterize Cracking - Pressurization

- The capped pipes were pressurized in steps of 500 psi (3.4 MPa) and strain data was collected during pressurization.
- A manual pump was used for the pressurization.



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Surface Strain Measurement Data Collected During Pressurization

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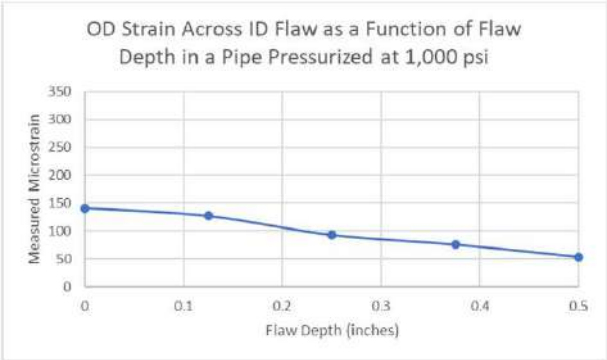
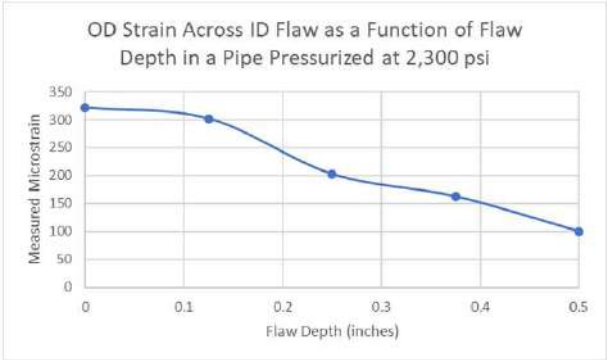
Using Surface Strains to Characterize Cracking - Results

The hoop strain measured on the OD of the carbon steel pipe using a strain gauge located above simulated axial flaws was highly dependent on flaw depth at 1,000 psi (7 Mpa) and 2,300 psi (16 Mpa), which are approximate BWR and PWR primary loop operating pressures, rsp.





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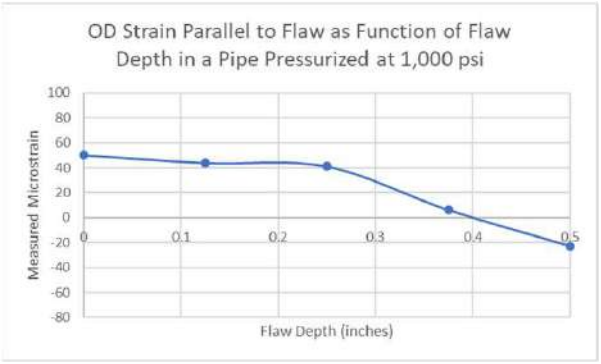
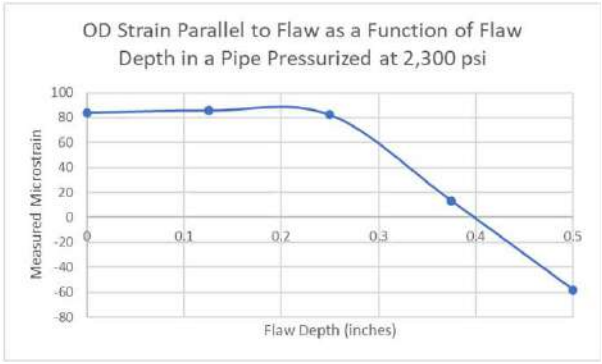
Using Surface Strains to Characterize Cracking - Results

The longitudinal strain measured on the OD of the carbon steel pipe using a strain gauge located adjacent to the simulated axial flaws was also highly dependent on flaw depth, going from tension to compression.





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Using Surface Strains to Characterize Cracking – Phase 2

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Using Surface Strain Dynamics to Characterize Cracking - Phase 2

- In Phase 2 we will determine if simulated cracks along the fusion lines of welded wrought stainless steel pipes can be characterized.
  - 1 foot (30.5 cm) L x 10 inch (25.4 cm) OD Schedule 120 pipe sections will be J-groove welded to form 2 foot (61 cm) L pipe mock ups. UT exams will be done to confirm weld integrity.
  - EDM will be used to simulate cracking along the weld fusion lines with variable flaw depth and width.
  - The pipes will be fitted with OD strain gauges mounted in the axial and hoop directions in the vicinity of the flaws.
  - The pipes will be capped and pressurized in steps to 2,300 psi (16 MPa) while recording strain data.
  - The results should indicate if surface strain measurements can be used to monitor cracking of wrought SS piping welds in LWR primary loop piping.

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Using Surface Strain Dynamics to Characterize Cracking - Implementation

- At the conclusion of the proposed Phase 2 study it should be clear whether pursuing implementation at a pilot plant makes sense.
  - Strain gauges will be installed on the OD of piping welds located across known circumferential cracks.
  - Strain data will be collected periodically during operation, which should indicate whether the crack is growing or arrested. Strain data will be compared to UT exam data for agreement.
- *If successful, this work could offer the industry a very simple and straightforward method to assess if cracks are growing or arrested and measure their growth rates between outages.*

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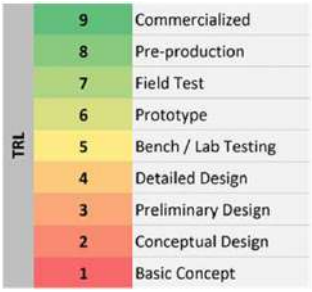
Using Surface Strain Dynamics to Characterize Cracking – Technology Readiness Levels

- Phase 1 proof of concept on unwelded carbon steel pipe sections was successful (TRL 6).
- Phase 2 weld mock ups have been designed and the experiment matrix is under development (TRL: 3-4).
- Phase 2 will include a laboratory feasibility analysis and prototype system will be designed (TRL: 5-6).
- After Phase 2 it will be determined whether field trials should be conducted (TRL 6-7).
- If successful, more complex component geometries will be explored



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Conclusions

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Using Surface Strains to Characterize Cracking - Conclusion

- An experimental study to determine if surface strain measurements can be used to characterize simulated cracking in carbon steel pipe samples was executed.
- The results show that the transverse and longitudinal surface strains are highly dependent on flaw depth.
  - The hydrostatic pressure in the pipes affected the transverse and longitudinal surface strains near the flaws. It appears that forces normal to the crack faces are generating a bending moment in the intact (uncracked) material.
  - The results suggest it might be possible to monitor existing cracks in pressurized piping (e.g., primary loop piping) during operation.
  - The method is simple, fast and should be easy to utilize
- A Phase 2 project to look at the effect of simulated flaws in wrought austenitic stainless steel pipes with girth welds on surface strain is proposed for 2024+.

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Low-cost structural health monitoring system for engineering applications

C. A. Middleton[1]*, P. R. Lambert[1], K. Amjad[1,2], R. J. Greene[3], A. Kupferschmid[4], E. Hack[4], E. A. Patterson[1]

[1]School of Engineering, University of Liverpool, The Quadrangle, Brownlow Hill, Liverpool L69 3GH, UK
[2]UK Atomic Energy Authority, Oxfordshire, U.K.
[3]Strain Solutions Ltd, Dunston Innovation Centre, Dunston Road, Chesterfield, Derbyshire S41 8NG, UK
[4]Empa, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland

E-mail address (corresponding author): ceri.middleton@liverpool.ac.uk

A low cost, low volume integrated sensor system has been designed using COTS (commercial-off-the-shelf) components to be deployed on engineering structures to apply non-destructive evaluation (NDE) techniques for structural health monitoring. The prototype system has been successfully installed and employed on full-scale aerospace tests in Airbus facilities in the UK and France.

Individual rugged modules combine point (resistance strain gauges) and full-field (optical and infra-red) sensors with a credit-card sized board computer for on-board data collection and processing. Modules are deployed at regions of interest on an engineering structure, with data collection, transfer and storage controlled by the user through a custom designed graphical user interface on a control computer connected to all modules.

Using these sensors, a range of NDE techniques are possible, and can be tailored to the individual loading scenario, material, and conditions. For example, visible light camera sensors allow digital image correlation (DIC) with suitable surface preparation, and infra-red cameras allow thermographic methods to be utilised under appropriate loading conditions.

The processing software developed for the system includes algorithms for the generation of DIC and the thermographic method CATE (Condition Assessment by Thermal Emission) data. Further algorithms have also been developed that apply an image decomposition technique to these full-field datasets, allowing quasi real-time quantitative comparison over time, which can be used for condition monitoring. The processing algorithms are not sensor specific, so can be applied to image data from other sensors, allowing historical datasets or datasets from external cameras to be post-processed.

The DIMES project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820951. The opinions expressed in this abstract reflect only the authors' view and the Clean Sky 2 Joint Undertaking is not responsible for any use that may be made of the information it contains.

Keywords: Condition monitoring, damage detection, Thermoelastic Stress Analysis, Digital Image Correlation, microbolometer.

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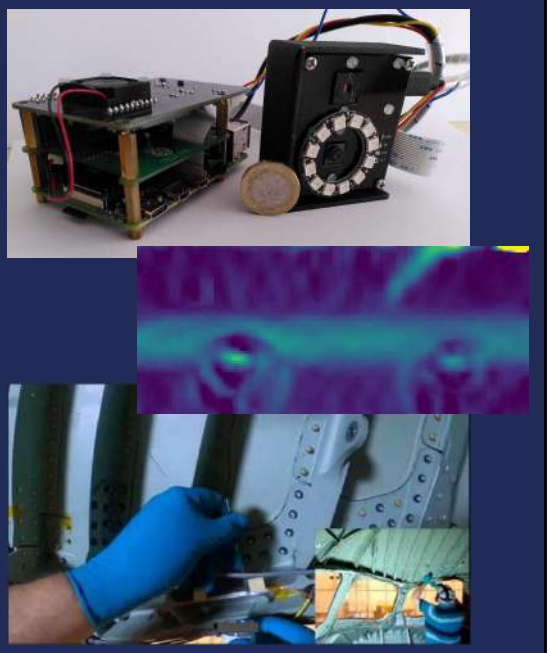
Low-cost structural health monitoring system for engineering applications

C. A. Middleton[1]*, P. R. Lambert[1], K. Amjad[1,2], R. J. Greene[3], A. Kupferschmid4, E. Hack[4], E. A. Patterson[1]

[1]School of Engineering, University of Liverpool, U.K.
[2]UK Atomic Energy Authority, U.K.
[3]Strain Solutions Ltd, U.K.
[4]Empa, Switzerland

NDE in Nuclear: June 2023



DIMES project

HORIZON 2020 Clean Sky 2 DIMES 2019 2021

UNIVERSITY OF LIVERPOOL Strain Solutions Ltd Empa DANTEC DYNAMICS AIRBUS

Development of Integrated MEasurement Systems

Aim: To mature & validate disruptive technologies for their use in next-generation aircraft.

Specifically, to develop and demonstrate an automated measurement system that integrates a range of measurement approaches to enable damage and cracks to be detected and monitored as they originate at multi-material interfaces in an aircraft assembly

…aerospace, but outputs are applicable to all other sectors…

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 820951. The opinions expressed in this presentation reflect only the authors' view and the Clean Sky 2 Joint Undertaking is not responsible for any use that may be made of the information it contains.

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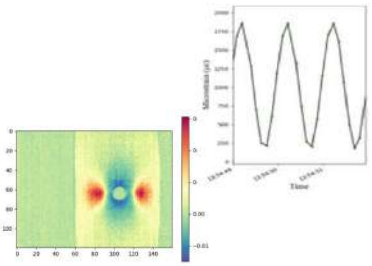
Structural health monitoring

Monitoring engineering structures for changes: in test, in-service

- Condition monitoring
  - Early detection of damage to allow repair, replacement, redesign
  - Damage location and tracking (metals: cracks, composites: delaminations)
  - Current inspections are labour and time intensive
  - Looking for more efficient, cost-effective methods

- Model validation/updating
  - Measurement data to compare with/feed into numerical simulations

Measurement techniques



NDE (Non-destructive evaluation) techniques

Point source

- Resistance Strain Gauges (RSG)

→ *record of load/strain experienced at sensor*

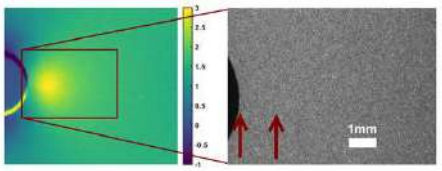
Full-field

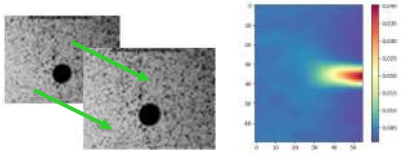
- Infrared techniques: Thermoelastic Stress Analysis (TSA)

→ *representation of surface stresses*

- Digital Image Correlation (DIC):

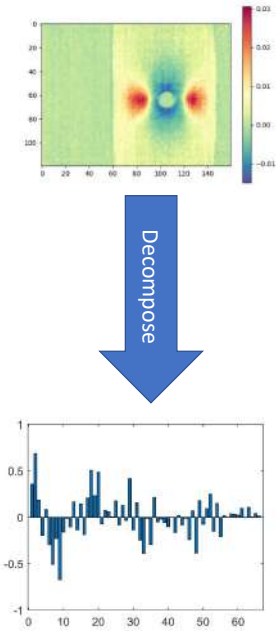
→ *displacement fields → strain fields*





Data processing

- Produces a lot of data: full-field, months+ of testing
  → *orthogonal decomposition*
- Decomposition reduces dimensionality of original data, whilst retaining useful information
- Feature vector units are the same as the original data
- Easier to compare data and uncertainties
- (Physical and virtual data grids rarely align)
- (Feature vectors are invariant to small changes in grid)



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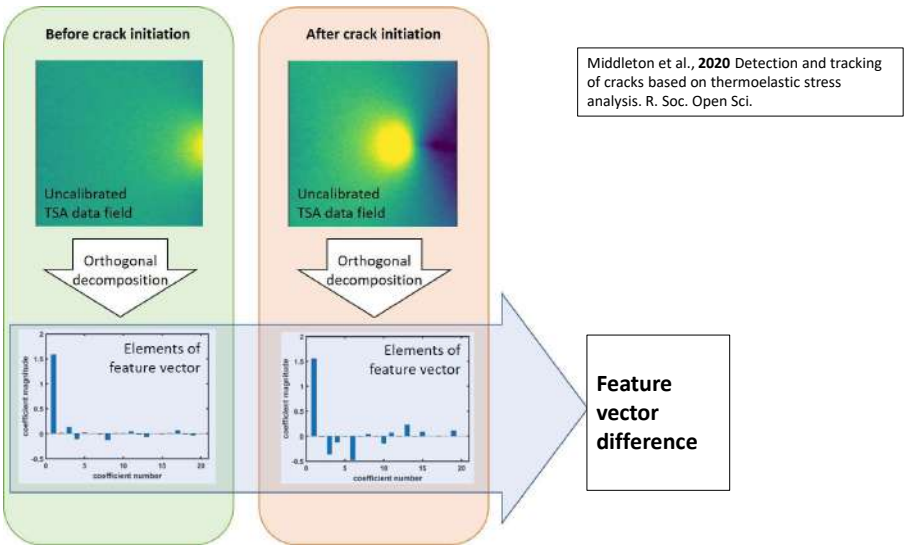
Data processing: orthogonal decomposition



Middleton et al., **2020** Detection and tracking of cracks based on thermoelastic stress analysis. R. Soc. Open Sci.

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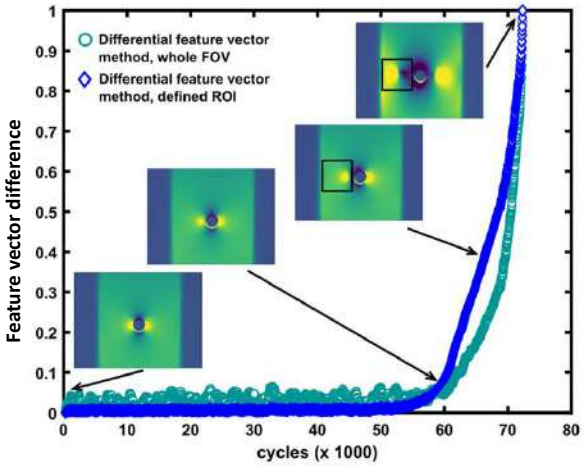
Data processing: orthogonal decomposition



Middleton et al., **2020** Detection and tracking of cracks based on thermoelastic stress analysis. R. Soc. Open Sci.

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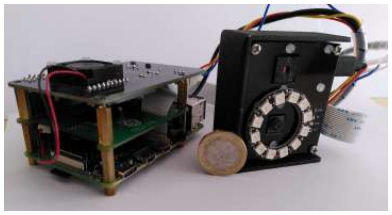
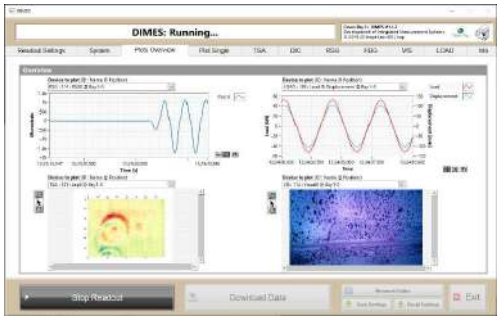
System

1. Sensor modules attached to the test object.
2. Network Attached Storage (NAS) where all data is stored.
3. Control computer with a bespoke Graphical User Interface (GUI) for data collection, access and visualisation.





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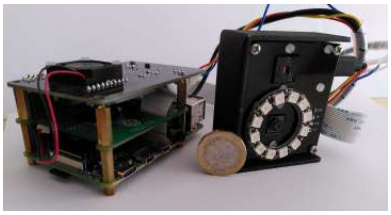
Sensor units



COTS (commercial off the shelf components)

~£60

~£20

~£280

+ PoE hat, PCBs, lights, connectors, cables …

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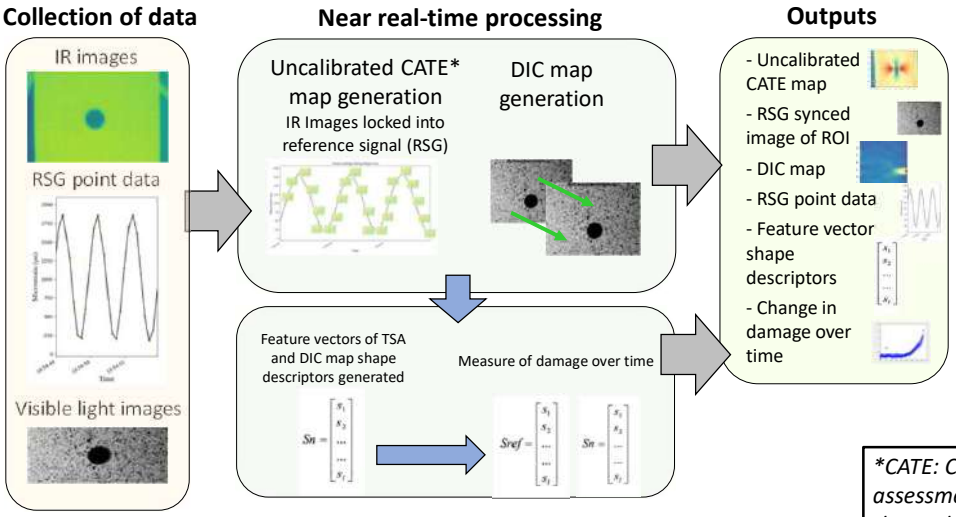
System flow



**CATE: Condition assessment by thermal emission*

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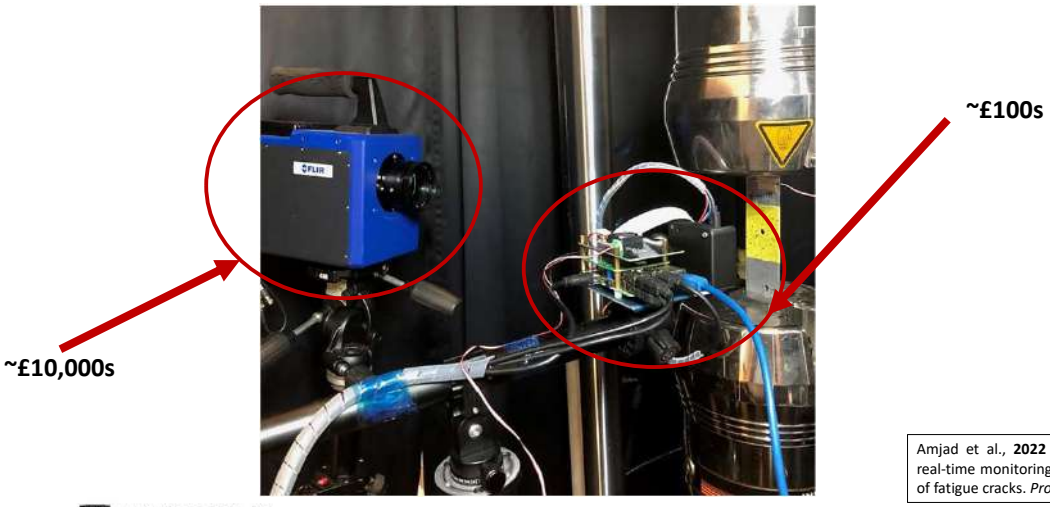
Lab testing: simple fatigue

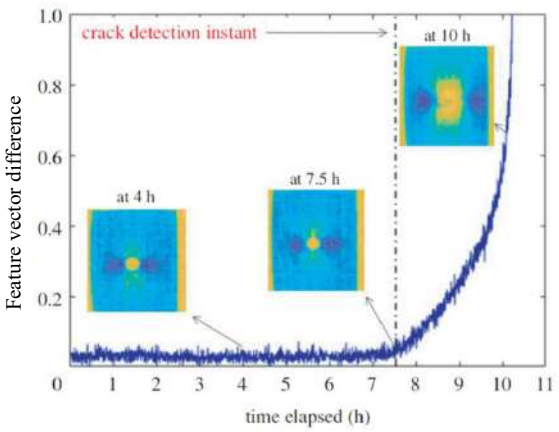


Amjad et al., **2022** A thermal emissions-based real-time monitoring system for in situ detection of fatigue cracks. *Proc. R. Soc. A*

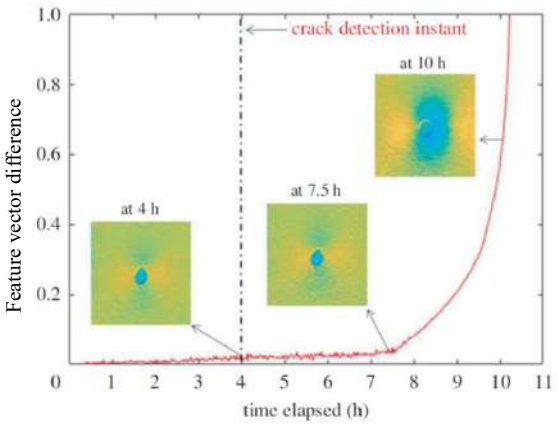
Lab testing: simple fatigue

Amjad et al., **2022** A thermal emissions-based real-time monitoring system for in situ detection of fatigue cracks. *Proc. R. Soc. A*

COTS system

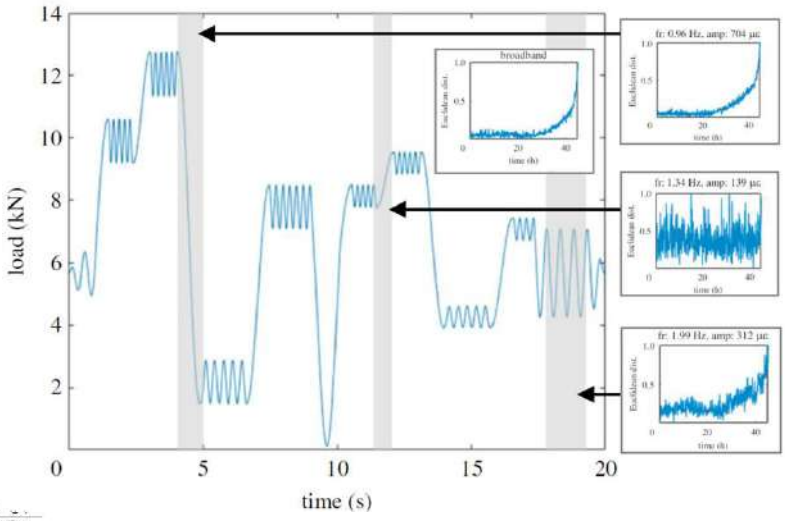


Traditional system



Lab testing: flight cycle

Amjad et al., **2022** A thermal emissions-based real-time monitoring system for in situ detection of fatigue cracks. *Proc. R. Soc. A*



Industrial application

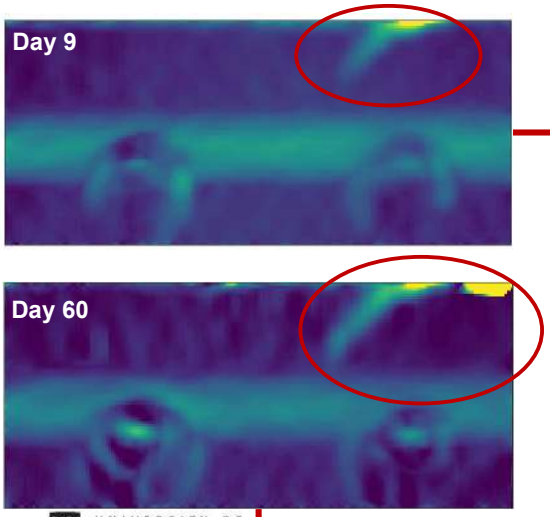
Airframe tests

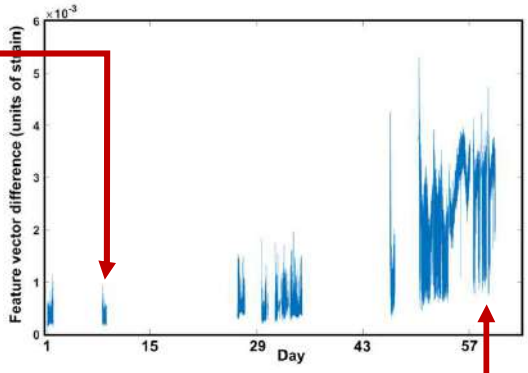
- Airbus: wing - fatigue

Remote installations:

- Airbus: fuselage - pressurisation cycling
- NRC-Canada: wing - fatigue

Industrial application: Fuselage





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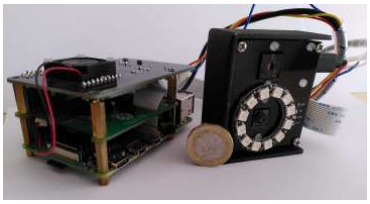
Summary



- Developed an integrated SHM system using COTS technology: low cost and footprint.
- Combines point-sensor technique (RSG) with full-field techniques (CATE, DIC).
- Operator controls and accesses data using a bespoke GUI.
- Data is collected and processed in near real-time.
- System gives damage location and growth information.
- Successfully implemented in industrial tests
  - → inform decisions for condition monitoring or test protection on useful timescales
  - → continuous output for historical comparisons
  - → small, replaceable - orders of magnitude cheaper than traditional sensor systems

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Future

- Use arrays of multiple sensors
- Develop capability for use in extreme environments (hot, cold, …)
- New case studies
  - Broaden user experience
  - Looking for people who want to use it

More information:

www.integratedtesting.org

ceri.middleton@liverpool.ac.uk

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Passive Guided Wave Tomography for Corrosion Monitoring under Varying Environmental Conditions

T. Druet[1], A. Thomas[1], A. Recoquillay[1], Yann Gélébart[2], Etienne Martin[3], B. Chapuis[1]

[1]Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France
[2]EDF R&D, Les Renardières, France
[3]EDF DI, Saint-Denis, France

E-mail address (corresponding author): tom.druet@cea.fr

The detection and quantification of defects in pipes by non-destructive testing techniques plays a crucial role in several industries (petrochemical and nuclear in particular). Once a defect is detected, assessing its severity enables to schedule maintenance appropriately, hence reducing rupture or leakage risks.
Structural Health Monitoring (SHM) is an approach that consists in instrumenting a structure with permanent sensors to monitor its health status throughout its life. Guided elastic waves are particularly suitable for SHM applications on thin structures (such as plates, tubes or tanks) thanks to their ability to propagate over long distances and their high sensitivity.
Our group works since several years on an original SHM approach for the detection and quantification of corrosion in pipes called "guided waves passive tomography". This technology is based on the combination of guided elastic wave tomography algorithms and a passive method such as the so-called ambient noise cross-correlation. It allows to obtain absolute and precise maps of the thickness of an area surrounded by a distribution of sensors without emitting waves, simply by analyzing the elastic noise that exists naturally in the pipe (due to vibrations, turbulences of the moving fluid, etc.). The type of corrosions imaged by this technique are thickness losses on extended areas of size often higher than the centimeter.
We will present recent advances in the technology, in particular the capacity of the tomography algorithms to work in an ‘absolute’ mode, i.e. without a baseline, thanks to an automatic calibration using solely the data of the current acquisition. This makes the diagnosis very robust to environmental fluctuations and inherent variabilities in the structure. Experimental validations of the method will be presented and results on the method’s robustness to temperature variations will be shown through acquisitions carried out in a climatic chamber over a wide range of temperatures.

Keywords: Structural health monitoring, Guided waves, Tomography, Passive methods, Temperature.

Passive Guided Wave Tomography for Corrosion Monitoring under Varying Environmental Conditions

Tom Druet, Axel Thomas, Arnaud Recoquillay, Yann Gélébart, Etienne Martin and Bastien Chapuis

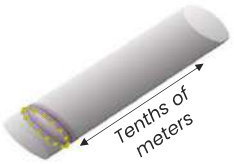
NDE in Nuclear 2023

Introduction

Corrosion in pipes

- *Risks of leakage in several critical industries (nuclear, oil&gas, etc.)*

US NDT



Long range GW NDT

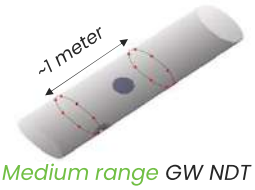
Non Destructive Techniques play a crucial role to prevent these risks

Objective *→ estimation of residual thickness for critical sections of pipe*

Strategy *→ Structural Health Monitoring (SHM) using Guided Waves (GW)*

- *Permanent sensors on the structure: 2 rings of sensors surrounding the critical zone*
- *Guided wave tomography*
  - *Quantitative imaging method*
  - *Without baseline*

This technique can also be used in classical NDT approach



Medium range GW NDT

Outline of the presentation

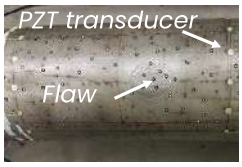
1. **Principles of passive guided wave tomography**
   1. Active and passive acquisitions
   2. Tomography
2. **Guided wave tomography in climate chamber**
   1. Experimental setup
   2. Study of the impact of temperature on absolute tomography
3. **Application for Erosion Monitoring in an Air/Sand Test Loop**
   1. Experimental setup
   2. Thickness reconstruction by passive guided wave tomography
4. **Conclusions**

1. Principles of passive guided wave tomography

Active and passive acquisitions

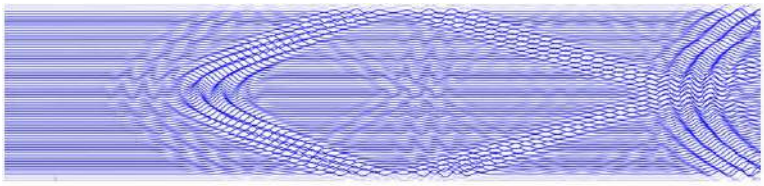
Tomography

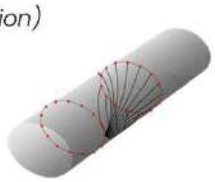
Principles of guided wave tomography



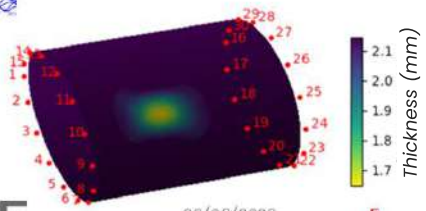
Two main steps for GW tomography

1. *Data acquisition*
   - *Two rings of sensors surrounding the critical zone*
   - *Active or passive acquisitions*
   - *Signal measured for all the couples of sensors (« Full Matrix Capture » acquisition)*



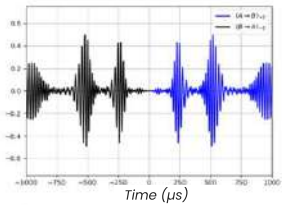


2. *Data processing for tomography*
   - *With or without baseline signal*
   - *Quantitative thickness map of the structure*



Active and passive acquisitions

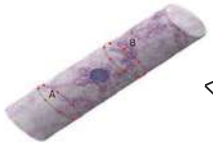
Active acquisition

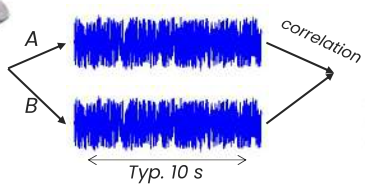


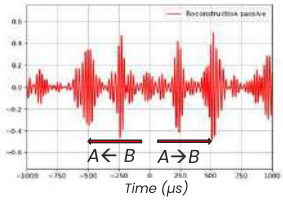
Measurement of ambient noise

Same input data for tomography (time of flight, amplitude, full signal etc.)

Passive acquisition







Advantages of active method
- *Choice of the frequency*
- *Clean signals if environment is not noisy*

Advantages of passive method
- *Measurement during operation (acquisition not perturbed by noisy environment)*
- *Application of excitation as a post-process*
- *No need of emission*
  - *Power consumption*
  - *Simplified electronics (no emission circuitry)*
  - *Allows to use non conventional sensors: for example FBG on optical fibers*

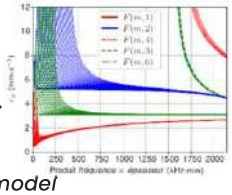
Principles of guided waves tomography

The algorithm is based on a simplified model of the elastodynamic propagation

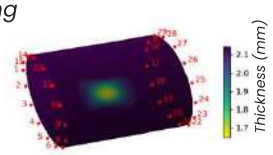
- *Acoustic propagation: scalar wave equation (Helmholtz)*
- *Mono-mode method based on the dispersion curve of the chosen guided mode*

$$\Delta\varphi(\boldsymbol{x}) + k^2(\boldsymbol{x})\varphi(\boldsymbol{x}) = s(\boldsymbol{x})$$

$$\underbrace{\varphi^s(\boldsymbol{x}_j,\boldsymbol{x}_i)}_{\text{Data}} = -\iint G_0(\boldsymbol{x}_j,\boldsymbol{x})\underbrace{O(\boldsymbol{x})}_{\text{Image } O(\boldsymbol{x}) = k^2(\boldsymbol{x}) - k_0^2} G(\boldsymbol{x},\boldsymbol{x}_i)d^2\boldsymbol{x}$$



Conversion of image $O(\boldsymbol{x})$ using dispersion curves to obtain thickness map of the pipe



Advantage and limitation of such model

- *Advantage → fast computing*
- *Limitation → limited to imaging of extended corrosion (erosion) areas (generally above 1 cm)*

Possibility to work without baseline signals (using an auto-calibration method)

- *Advantages:*
  - *Robustness against variable environmental conditions or sensor aging*
  - *Absolute thickness estimation → possibility to work on « imperfect » industrial structures*

2. Guided wave tomography in climate chamber

Experimental setup

Study of the impact of temperature on absolute tomography

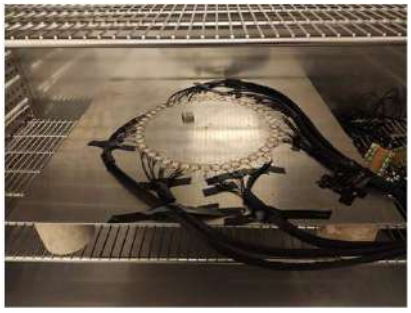
Experimental setup

Varying Environmental Conditions

- *Climate chamber: stabilized temperature stage*
  - *-20°C to 50°C (steps of 10°C)*

3mm thick aluminum plate

- *48 PZT transducers glued on the plate*
- *Hann burst of 5 cycles at 50kHz (λ=23,1mm for A0)*

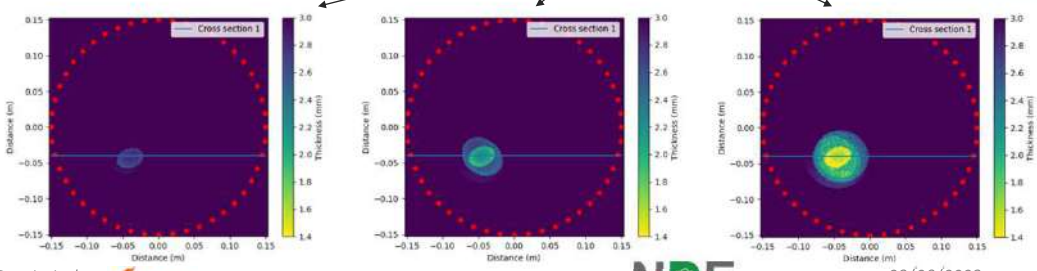


Experimental setup

Defects created by electrolysis

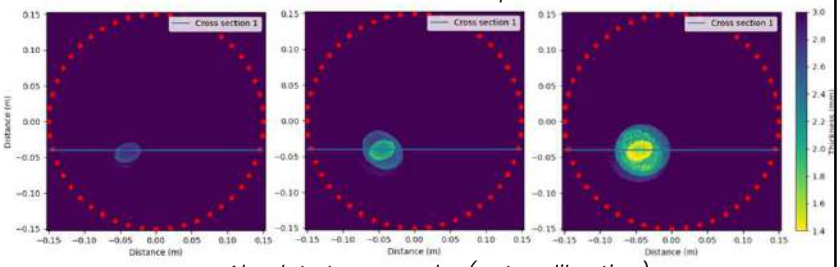
- *3 defects with three different depths*
  - *Elliptic masks to obtain more complex geometries*
- *Go Scan system allows to measure 3 reference maps*
  - *Structured light 3D scanner*

Elliptic masks

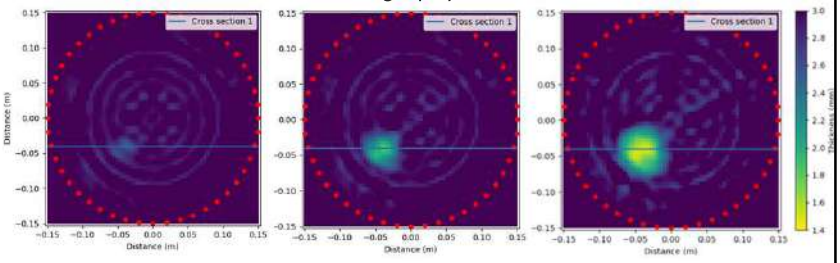


Absolute tomography at ambient temperature (20°C)

Reference maps



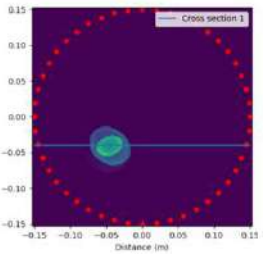
Absolute tomography (autocalibration)



Good reconstruction of the defects

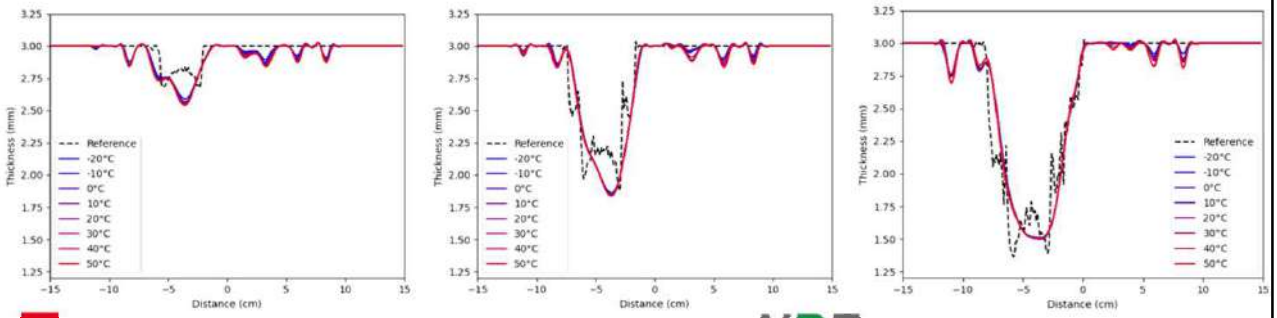
- *The remaining thickness is well estimated for the 3 defects*

Absolute tomography at all temperature levels



Plot of the blue cross section for the 3 defects and all the temperatures

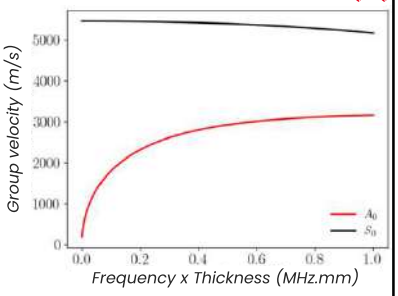
- *The remaining thickness is well estimated*
  - *For the 3 defects*
  - *For all temperatures*
- *Absolute tomography (thanks to autocalibration method) seems to allow to compensate large variations of temperature*

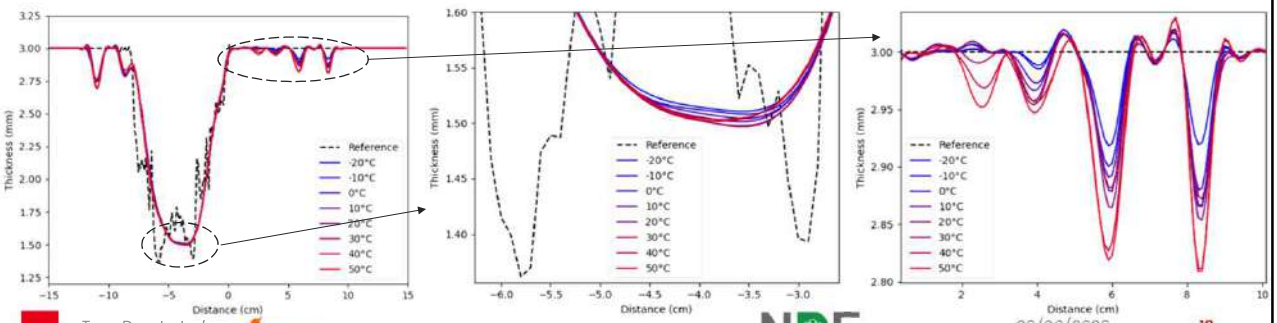


Remaining effect due to temperature

Nevertheless, absolute tomography and more precisely the autocalibration method doesn't compensate for all the effects

- *Zoom in on defect and image background*
  - *Increasing temperature implies a decrease in stiffness (or Young's modulus)*
  - *Which implies a reduction in speeds, including that of mode A0*
  - *A decrease in the speed of the A0 mode translates into a decrease in thickness*
- *However, the remaining variations are of the second order compared to the real thickness of the defect and the precision of the algorithm!*



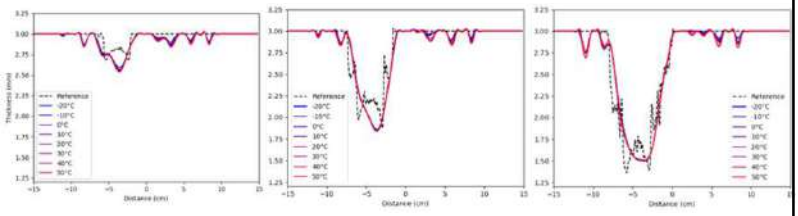


Proof of the robustness of absolute tomography compared to relative tomography

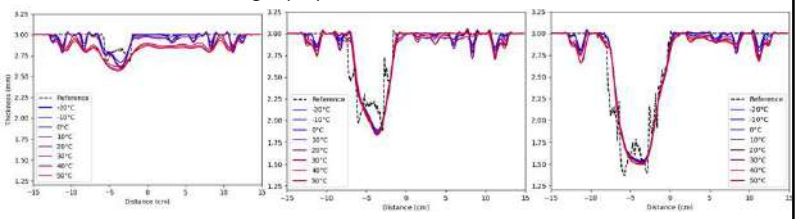
Comparison between absolute and relative tomography

- *In relative tomography a bias in the reconstruction occurs when the baseline is measured at a different temperature from the current state*
- *Absolute tomography appears to be a very attractive method compared to relative tomography to assess the real remaining thickness of the structure in case of varying environmental conditions*

Absolute tomography (autocalibration)



Relative tomography (calibration with a baseline [-20°C])



3. Application for Erosion Monitoring in an Air/Sand Test Loop

Experimental setup

Thickness reconstruction by passive guided wave tomography

Experimental setup

cybernetix
A Technip Energies Company

Test loop → air/sand flow → impact of sand grains generate erosion

- *The engine allows to blow air*
- *The vessel allows to inject progressively the sand: 3h per batch (700kg)*
- *Maximal thickness loss average: around 0,08mm per batch*

PZT instrumentation for tomography

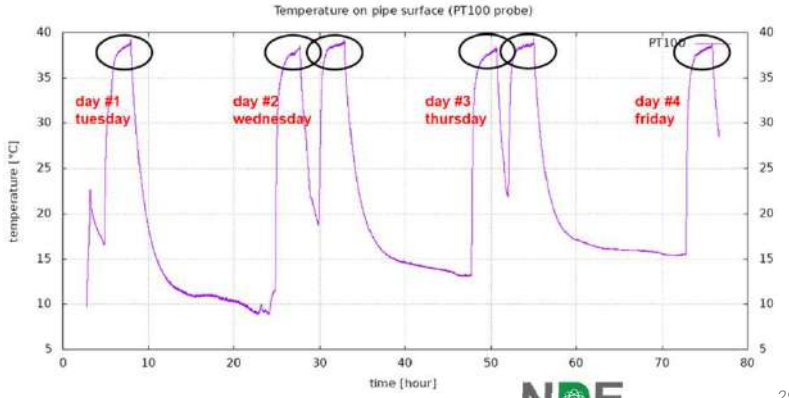
- *Two rings of 16 PZTs bounded on a stainless steel pipe (OD143,1mm ; t7,3mm)*
- *Active and passive measurements during one week (6 batches)*
  - *Active: Hann burst of 5 cycles at 90kHz (λ=22,5mm for L(0,1))*
  - *Passive: Measure of the ambient noise produced by the sand impacts*

Instrumented pipe

Evolution of the temperature during the week

PT100 sensor to monitor the temperature

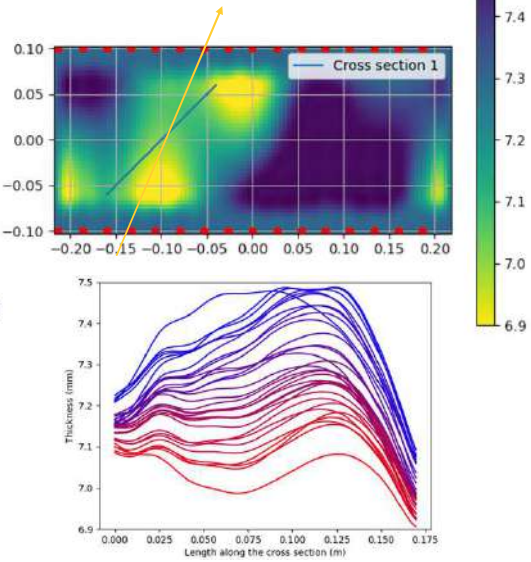
- *Erosion loop starts → increase of temperature to a stage between 37°C and 39°C*
- *Erosion loop stops → decrease to the ambient temperature*
- *The images are computed when the stage materialized by black circles is reached*

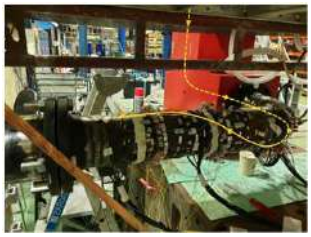


Absolute passive tomography

Erosion produced during test

- *The position of the erosion is coherent with the theoretical impact zone of sand grains coming from the elbow outlet*
- *Thickness loss estimation:*
  - *Reference punctual US measurements: the global maximal thickness loss was estimated at **0.51mm +/- 0.1mm***
  - *Absolute passive tomography → maximum thickness loss of **0.5mm***
- *Absolute passive tomography appears to be a very attractive method*
  - *It gives as good results as in the active case without needing all the electronics to generate waves in the medium and allows to use less intrusive sensors (Fiber Bragg Gratings on optical fibers)*



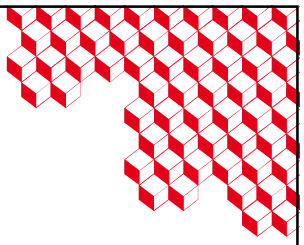


4. Conclusion

Conclusion

Conclusion

- *Guided wave tomography performances for large temperature variations*
- ***Baseline**: can become obsolete if it is not coherent with the EOCs of the current state. For guided wave tomography it introduces a bias within the estimation of the thickness losses*
- *Absolute tomography*
  - ***Robust** to large variations of temperature*
- *Application of passive guided wave tomography to a **representative test case**: a pipe instrumented in an accelerated air/sand erosion test loop*
  - ***Passive** tomography: No need of emission → Allows to use sensors not able to emit waves, for example FBGs on optical fibers*



Thanks

CEA SACLAY
91191 Gif-sur-Yvette Cedex
France
nathalie.guillaume@cea.fr
Standard. + 33 1 69 08 60 00

Real-time ultrasonic measurement of component temperature gradients – development of a tool for better high-cycle thermal fatigue monitoring

Laurence Clarkson[1], Frederic Cegla[1]

[1] NDE Group, Mechanical Engineering Department, Imperial College London, London, United Kingdom

E-mail address (corresponding author): lc3817@ic.ac.uk, f.cegla@imperial.ac.uk

Abstract text (1/2 – 1 A4 page)
Pipe networks within nuclear power plants (NPP) are susceptible to high cycle thermal fatigue (HCTF) failures in so-called mixing zones where fluids of different thermal and hydraulic properties interact. Given the potentially deadly consequences following component failure in NPPs, a non-invasive method for (real time) HCTF progression monitoring is expected to be of great use. HCTF is driven by thermal gradients, therefore, to monitor progression, a technique to determine the inaccessible (interior) temperature distribution of a component is required.

Previous work showed that it is possible to predict the temperature distribution of a mild steel block to within ±2 °C, relative to a resistance temperature device. These predictions were achieved using ultrasonic time of flight measurements from a transducer placed on the accessible surface with the so-called inverse thermal model (ITM) to invert the data. The ITM is based on iterative optimisation of an explicit finite difference formulation of the inverse heat conduction problem, enabling it to obtain the full temperature distribution. The explicit formulation necessitates that the time step of the data must be sufficiently small to ensure a stable solution. Hence, interpolation of the data is often necessary to ensure stability which increases computational expense.

The current work investigated replacing ITM with machine learning models to reduce the computation expense of inverting data and enable real-time monitoring of temperature gradients in NPP components.

Keywords: Thermal fatigue, Ultrasonic thermometry, Machine learning, Structural health monitoring

Real-time ultrasonic measurement of component temperature gradients – development of a tool for better high-cycle thermal fatigue monitoring

Laurence Clarkson, Dr Frederic Cegla, Dr Yifeng Zhang

Non-Destructive Evaluation (NDE) Group, Mechanical Engineering, Imperial College London

FIND-CDT
EPSRC CDT in Future Innovation in NDE

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Overview

- Motivations
- Existing Methods
- Ultrasonic Thermometry
- Data Inversion Methods
- Results
- Conclusions and Future Work

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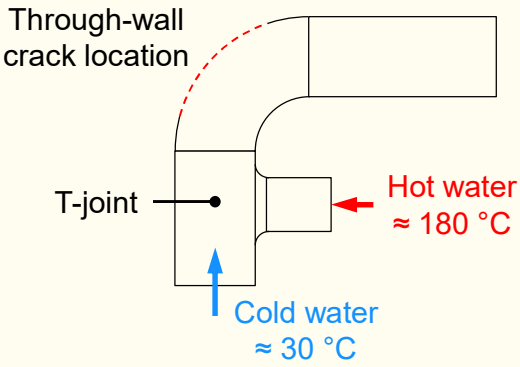
Motivations

- May 1998: An incident at Civaux 1 PWR[1]
  - → Radioactive steam released into the reactor building (30 $m^3 \cdot hr^{-1}$)[1]
  - → High-cycle thermal fatigue (HCTF) via 0.1−1 Hz temperature fluctuations[2]



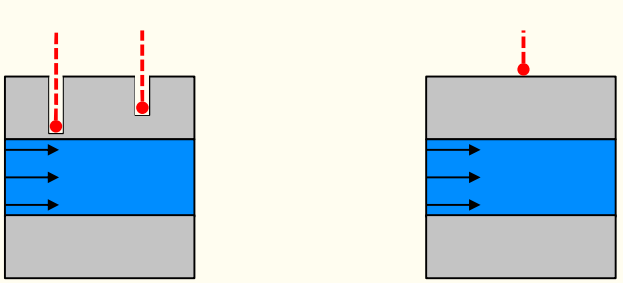
1. Temperature profile estimation
2. Stress estimation
3. Cycle counting
4. Predict/prevent failure

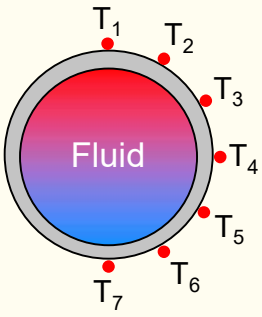
Non-invasively

[1] Couturier J, Schwarz M. EDP Sciences; 2018. doi:10.1051/978-2-7598-2165-5.
[2] Timperi A. *NUCL ENG DES.* 2018;331: 136–146. doi:10.1016/j.nucengdes.2018.02.039.

Existing Methods

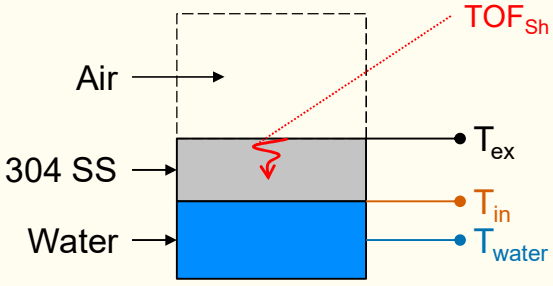
1) Direct measurement[1]: accurate but highly invasive.
2) External surface measurement[2]: low thermal conductivity → inaccuracy.
3) FAMOSi[3]: fluctuations > 1 Hz are undetectable. Thermal striping detection.

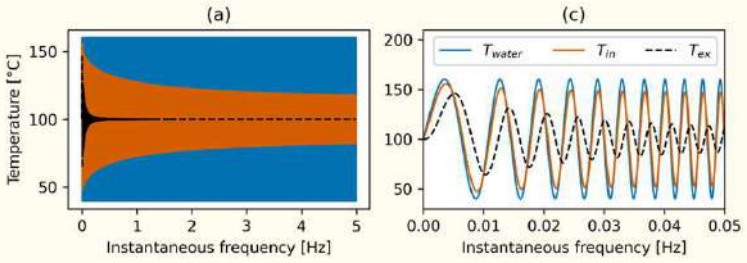




[1] Taler J et al. *Energy*. 2019;175: 645–666. doi:10.1016/j.energy.2019.03.087.
[2] Zhang Y et al. *Struct. Health Monit. 2020*. doi:10.1177/1475921720957592.
[3] Rudolph J et al. Nuclear Power Plants. London: IntechOpen; 2012. doi: 10.5772/37029.

Physical Limitations of Existing Methods





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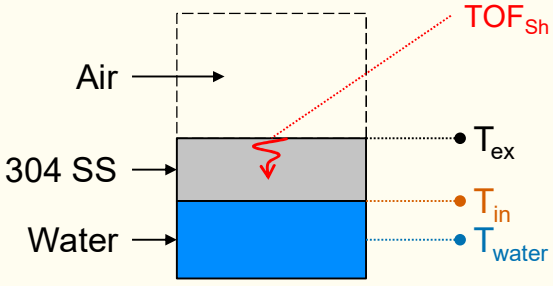
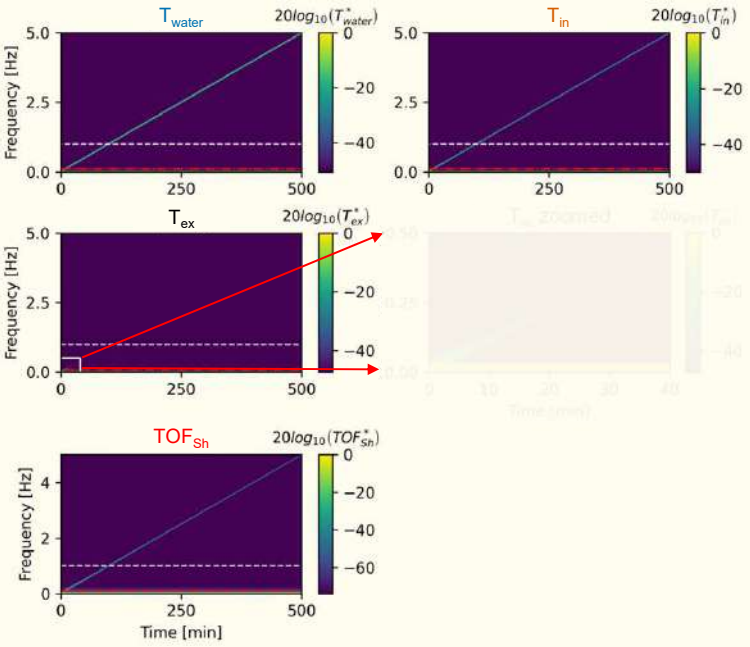
Existing Methods



- External temperature loses sensitivity
- TOF remains sensitive



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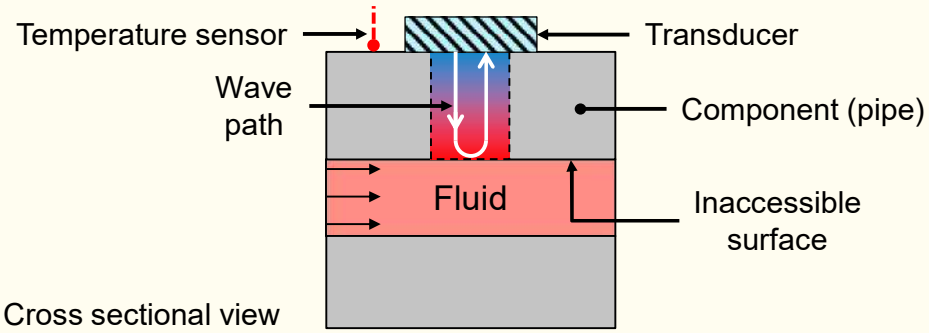
Ultrasonic Thermometry

- Wave velocity is temperature dependent: v = v(T)[1]
  → Thermal profile is encoded into the TOF
- Thermal profiles are recovered via physics-based inversion models



[1] Gajdacsi A. *High Accuracy Ultrasonic Degradation Monitoring.* PhD Thesis. Imperial College London; 2012.

Data inversion – Physics-based

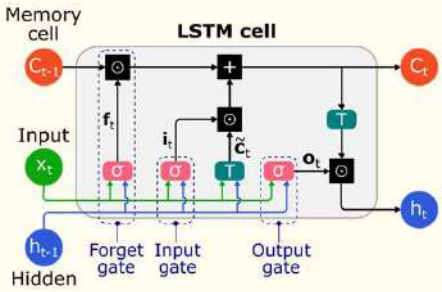
- Inverse thermal modelling (ITM)[1]
  → Solves the inverse heat conduction problem
  → Iterative, explicit finite difference formulation: **conditionally stable**
    → Up-sampling

Can we replace physics-based inversion with machine learning?
- Without loss of performance
- Reduce computational expense

[1] Zhang Y et al. *Struct. Health Monit. 2020.* doi:10.1177/1475921720957592.

The LSTM Architecture

- **L**ong **S**hort-**T**erm **M**emory[1]
- Predictions utilise:
  → Current and historical values of the inputs
- Train using purely simulated training data
- 25-member network ensemble

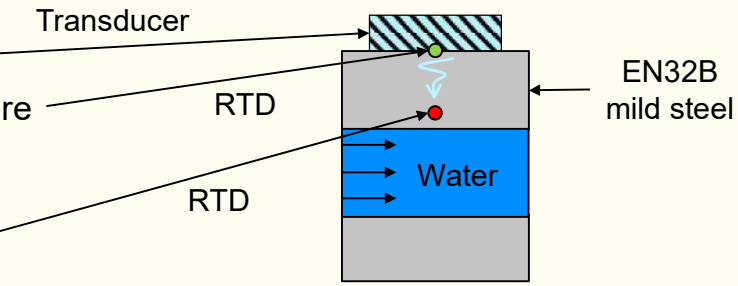


[1] Hochreiter and Schmidhuber. *Neural Comput. 1997.* doi:10.1162/neco.1997.9.8.1735.

Training Data

Input variables
- Shear wave TOF
- External surface temperature

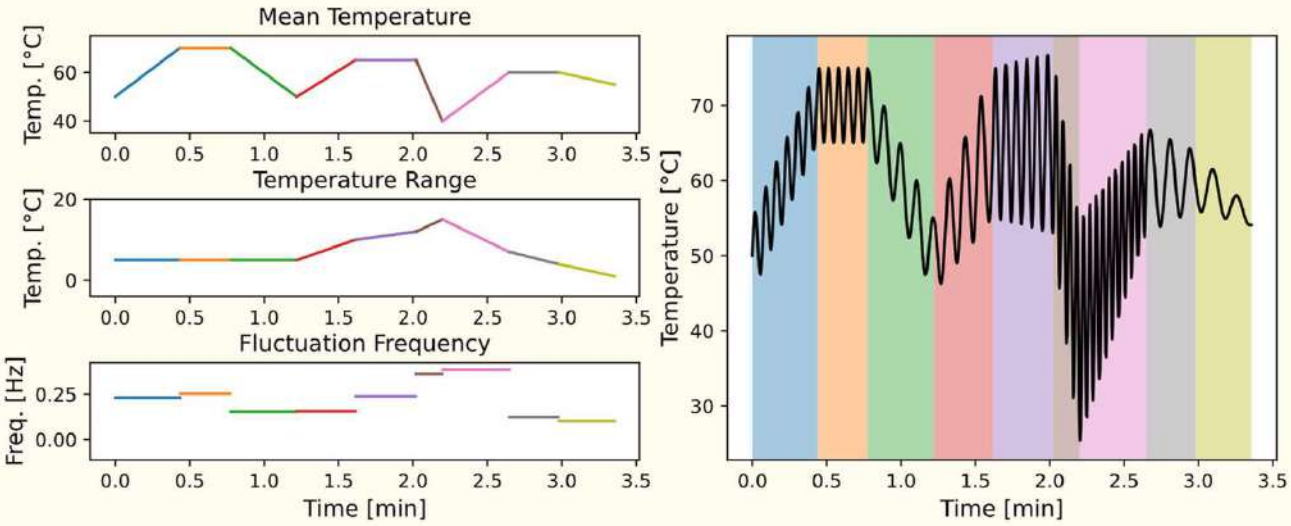
Prediction variable
- Sub-surface temperature



ITM predicts full thermal profile
LSTM predicts a single point

Training Data

- Compute temperature data with a finite difference 1D heat transfer code



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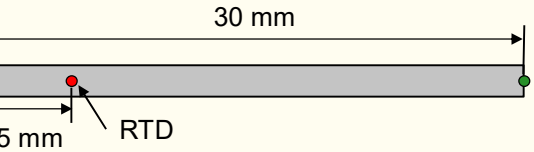
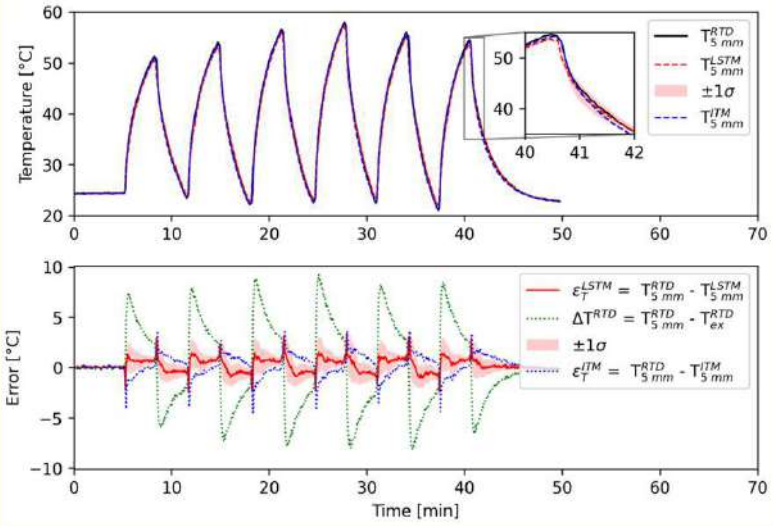
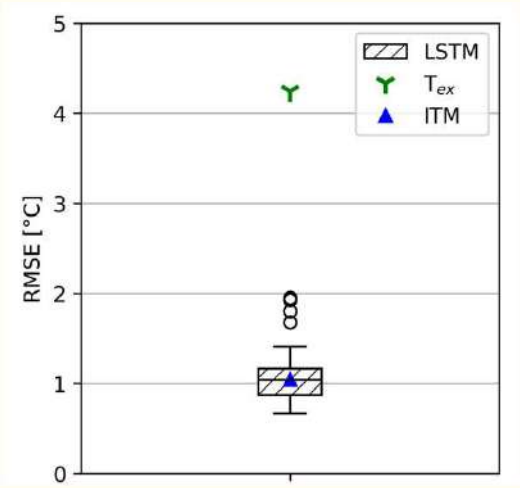
Results - Performance

LSTM is as good as ITM







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Results – Computational Expense

- Repeat computations 20 times $R_t = \frac{\mu_t}{749 \times 4} \times 100$

Physics-based seems slow

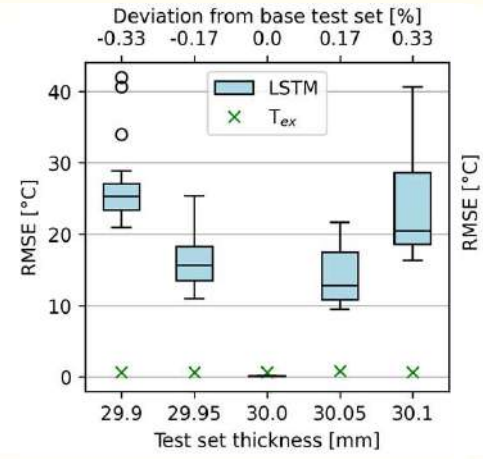
Code runtime is faster than real time ($R_t \ll 100\ \%$)

Method	μ_t [s]	R_t [%]
LSTM ensemble	5.12	0.17
LSTM single	0.237	0.008
ITM	423	14

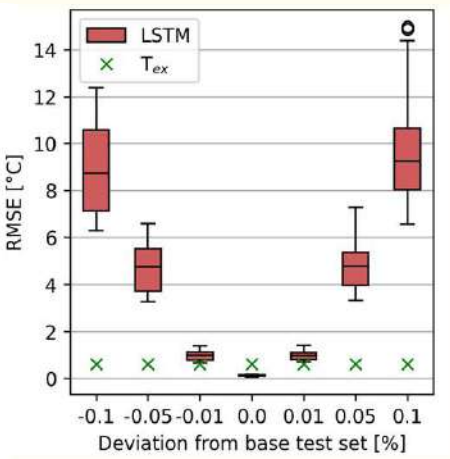
Results – Out-Of-Distribution Data

Experimental data is outside of the training data

Incorrect thickness



Incorrect v(T)



OODD has a large impact

Standard deviation of ensemble predictions indicates OODD

Conclusions

- 25-member LSTM ensemble and ITM both achieved RMSE = 1.04 °C
- ITM and LSTM both achieve real-time ($R_t \ll 100\%$) speeds
- ITM preferred for method transparency

Future Work

- Realistic experiments – high temperature, higher frequency and materials
- High temperature EMAT transducer

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Questions?

lc3817@ic.ac.uk

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Results – Computational Expense

- Repeat computations 20 times

- ITM – full thermal profile, LSTM – one point
- ITM – interpolation

$$C = \frac{\mu_t}{n_T \times n_S \times IF \times EF}$$

Method	n_T	n_S	IF	EF
LSTM ens.	749	1	1	25
LSTM single				1
ITM		151	4000	

Method	μ_t [s]	C [µs]
LSTM ens.	5.12	2.85
LSTM single	0.237	6.32
ITM	423	0.0134

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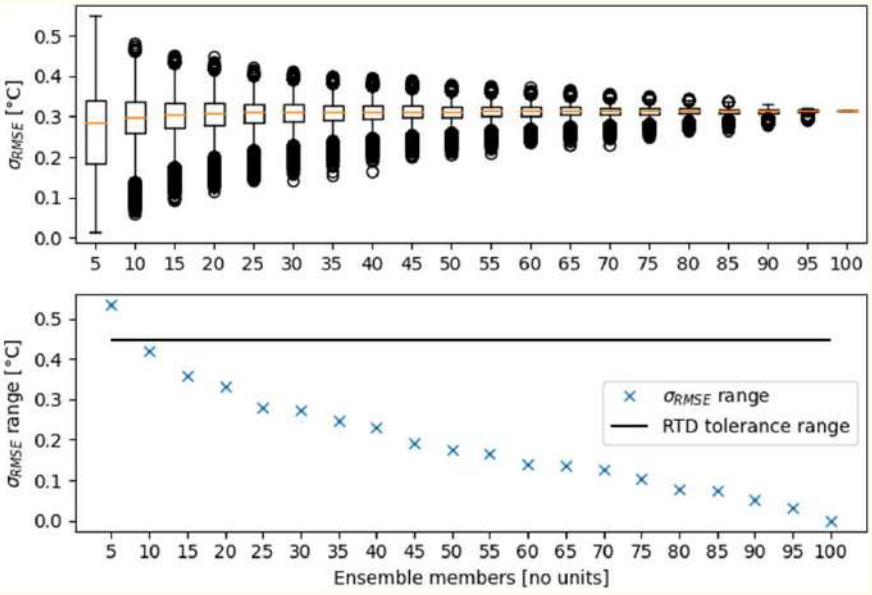
Ensemble Size



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17. NDE of Coarse Grained Materials & NDE of Complex Geometries (I)

The presentations in this session are listed in the table below.

NDE of Coarse Grained Materials & NDE of Complex Geometries (I)	**Chair:** Pierre Calmon (CEA)
Comparison of flaw detectability of different phased array ultrasonic techniques used in centrifugally cast stainless steel	Shan Lin and Shoji Hajime (both CRIEPI)
Advanced Ultrasonics for Cast Austenitic Stainless Steel Examination	Mark Dennis, Terrill Massey, George Connolly (EPRI)
Estimation of columnar crystal orientation by machine learning for centrifugally cast stainless steel	Keiji Watanabe (CRIEPI) et al.
Geometry Measurement of Core Baffle of VVER-1000 Type Reactors of NPP Temelín	Petr Vlček & Miroslav Žamboch (UJV)
Nozzle Weld Inspection In A 3D Environment	Paul Hillman, Johan Berlanger, Guy Maes (Eddyfi Technologies)

Comparison of flaw detectability of different phased array ultrasonic techniques used in centrifugally cast stainless steel

Shan Lin [1] and Shoji Hajime [1]

[1]Central Research Institute of Electric Power Industry, Yokoshuka, Japan

E-mail address (corresponding author): shanlin@criepi.denken.or.jp

Abstract text (1/2 – 1 A4 page)

Cast stainless steel (CSS) is widely used in nuclear power plants, particularly PWR primary coolant systems. The JSME Fitness-for-Service Code requires periodic in-service inspection of welds in such systems by ultrasonic testing (UT), but anisotropy and heterogeneity of CSS hinder flaw detection and sizing. Besides conventional phased array ultrasonic technique, FMC/TFM and PWI proposed recently are considered the most promising techniques to overcome such difficulties. In this report, we tried to clarify the difference of flaw detectability among these three kinds of phased array ultrasonic techniques (PAUTs) by using flat centrifugally cast stainless steel (CCSS) specimen and curved CCSS specimens. We introduced notches and side-drilled holes (SDHs) in the flat CCSS specimen and notches or fatigue crack in curved CCSS specimens and we used a 64-element linear array probe mounted on an angled wedge. Main results obtained from experiments are as follows.

(1) Under same gain, echo intensities by FMC/TFM and PWI are much higher than those by the conventional PAUT, however, the result of SN ratio is opposite.

(2) Flaw detectability of FMC/TFM is inferior to that of the conventional PAUT for CCSS.

(3) Without the image process based on phase coherence factor (PCF), flaw detectability of PWI is equivalent to that of the conventional PAUT for CCSS.

(4) Making use of PCF, SN ratio of echoes by PWI are much superior to that by the conventional PAUT, therefore, it is expected that more reliable UT results can be obtained by PWI than by the conventional PAUT.

Keywords: Centrifugally Cast Stainless Steel, Nondestructive Examination, Phased Array Ultrasonic Technique, FMC/TFM, PWI.

NDE
NDE in Nuclear 2023
Cutlers' Hall in Sheffield, United Kingdom
27-29 June 2023

Comparison of flaw detectability of different phased array ultrasonic techniques used in centrifugally cast stainless steel

Shan LIN and Shoji HAJIME
Central Research Institute of Electric Power Industry

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Contents

- Background and motives
- Conventional PAUT, FMC/TFM and PWI
- Comparison of results among different PAUTs
  - > Isotropic medium (Stainless steel specimen)
  - > Flat CCSS (Centrifugally Cast Stainless Steel) specimen
  - > Curved CCSS specimen
- Conclusions

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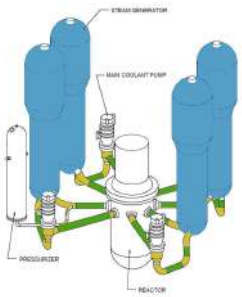
Background and motives

- Cast stainless steel is widely used in pumps, valves, etc., in nuclear power plants, especially, centrifugally cast stainless steel (CCSS) is extensively employed in primary coolant system of pressurized water reactors.
- In order to maintain the integrity of nuclear power plants, detection and sizing of flaws in CCSS by ultrasonic testing techniques is required by Japan Society of Mechanical Engineers Rules on Fitness-for-Service for Nuclear Power Plants.
- CCSS has complex microstructures, such as coarse grains, anisotropy, heterogeneity and so on.
- Coarse grains results in high attenuation and scattering noise.
- Anisotropy and heterogeneity causes velocity variations and beam skewing.
- Detection and sizing of flaws in CCSS is a big challenge for ultrasonic test.



Centrifugally cast
Statically cast

http://www.nrc.gov/reading-rm/basic-ref/students/for-educators/04.pdf

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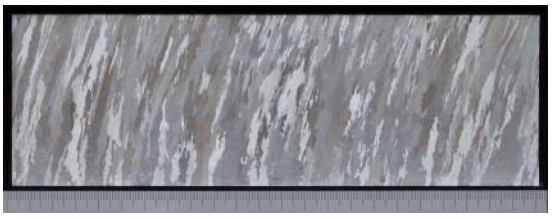
Background and motives (Cont'd)

- Phased array ultrasonic technique (PAUT) is considered the most promising solution.
- Besides the conventional PAUT, FMC/TFM and PWI have been proposed and have shown advantages over the conventional PAUT for some materials.

- In this study, we intend to see if we can get any benefits by using FMC/TFM and PWI for CCSS.



Macrography of CCSS with inclined columnar grains

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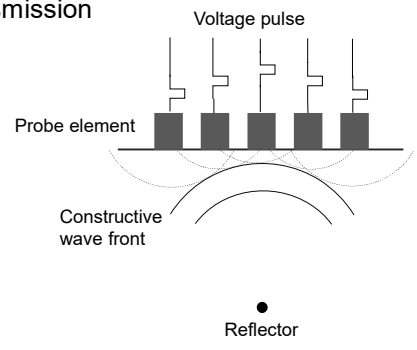
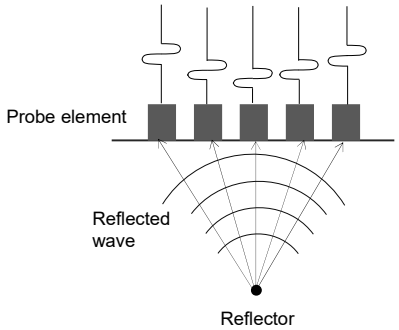
Conventional phased array ultrasonic techniques

Transmission



Reception



- Only the delayed and summed A-Scan signals are transferred to the phased array equipment for display and recording
- Individual raw signals are not stored

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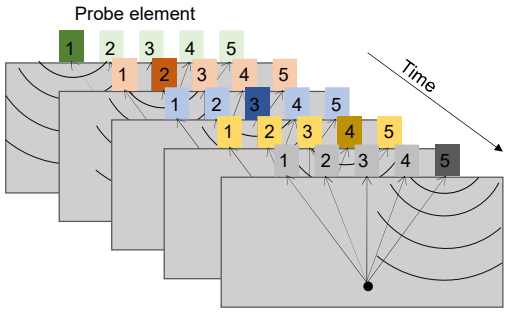
Data acquisition scheme in FMC

- FMC consists of capturing and recording A-Scan signals from every transmitter-receiver pair in an array probe
- From raw A-Scan signals stored, it is possible to generate UT imaging for any given focal law (aperture, angle, focus depth), and for improved algorithms (e.g. TFM) through post processing

Firing element and reception elements



Stored data matrix

Receiving element

Firing element	1	2	3	4	5
1	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}
2	A_{21}	A_{22}	A_{23}	A_{24}	A_{25}
3	A_{31}	A_{32}	A_{33}	A_{34}	A_{35}
4	A_{41}	A_{42}	A_{43}	A_{44}	A_{45}
5	A_{51}	A_{52}	A_{53}	A_{54}	A_{55}

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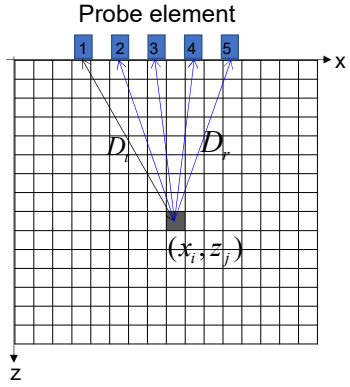
Imaging scheme in TFM

- A delay law is created for every pixel in the TFM frame
- Summation of elementary A-Scan is done for every pixel, using local focal law
- Every pixel has a dedicated focal law perfectly focused to its location



$$I(x_i, z_j) = \left| \sum_{t=1}^{n} \sum_{r=1}^{n} s_{tr}(t_p) \right|$$

$$t_p = (D_t + D_r)/c$$

s_{tr} : Received signal for transmitter-receiver pair,

c : Sound velocity

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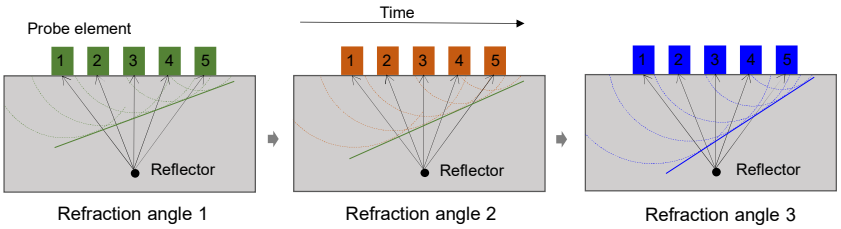
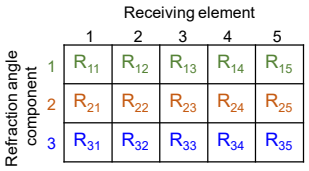
Data acquisition scheme in PWI

- A technique consisting of sequential transmission of plane waves in several directions in the inspection medium, recording of the reflected or diffracted waves for each transmission with all the elements, and post-processing of the received signals with a delay-and-sum algorithm to focus on every point
- From raw A-Scan signals, it is possible to generate UT imaging for any given focal law / beam (aperture, angle, focus depth), and for improved algorithms through post processing

Firing element and reception elements



Stored data matrix



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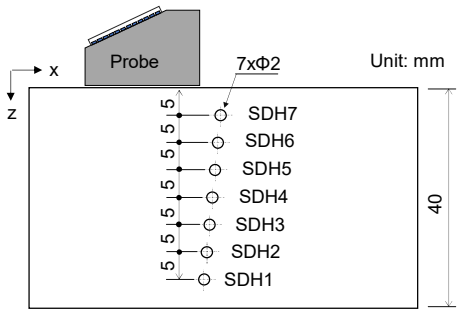
Configuration of flat SS specimen and testing conditions



Stainless steel specimen with SDHs

Main testing conditions

		Conventional PAUT	FMC/TFM	PWI
Probe	Frequency (MHz)	1 or 2		
	Number of elements	64		
	Pitch (mm)	0.6		
	Width of element (mm)	0.5		
	Length of element (mm)	20		
Beam angle	Refraction angle (degrees)	0~55	N/A	0~55
	Resolution of refraction angle (degrees)	1	N/A	5
Focalization	Type	True depth	N/A	True depth
	Depth (mm)	20	N/A	1000
Wedge	Wedge angle (degrees)	16.5		
	Longitudinal sound velocity (m/s)	2330		
	Height of first element (mm)	30		
TFM	Region of interest (mm)	N/A	60x55	
	Frame resolution		256x256	
	Depth resolution		0.04λ (0.08λ)	
	Width resolution		0.04λ (0.08λ)	
	Amplitude fidelity (dB)		0.02 (0.1)	
Filter	LPF (MHz)	5		
Acquisition rate (Hz)		44.6	46.4	113.0
Hard gain (dB)		30 (16)	29 (13.5)	26 (6)

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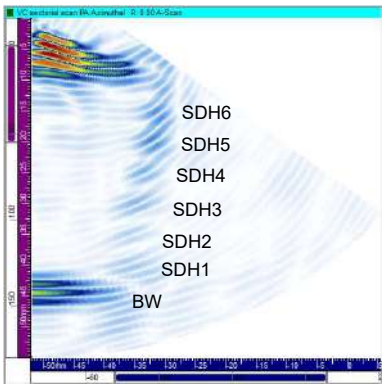
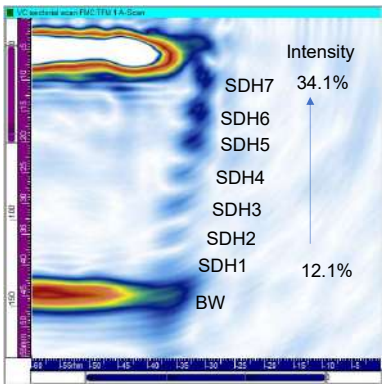
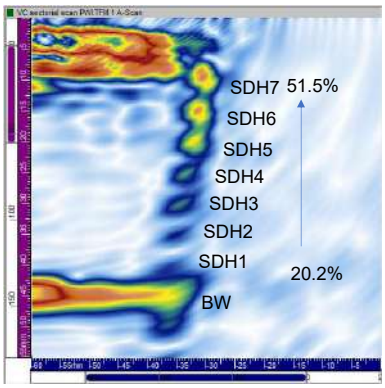
Results with a 1-MHz linear array probe



Conventional PA



FMC/TFM

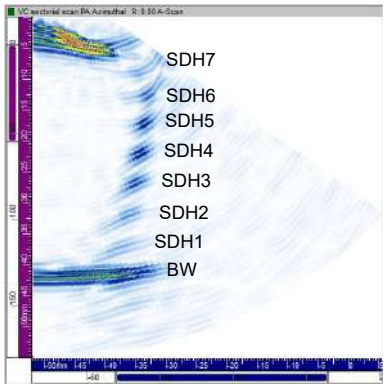


PWI

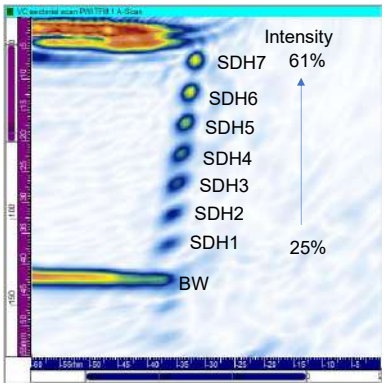
Recognizability Conventional PA < FMC < PWI

© CRIEPI Conventional PA < FMC/TFM < PWI

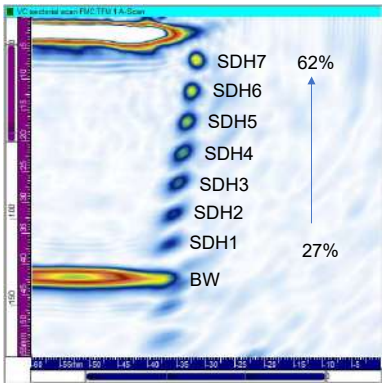
Results with a 2-MHz linear array probe



Conventional PA



FMC/TFM



PWI

Recognizability Conventional PA < FMC ≒ PWI

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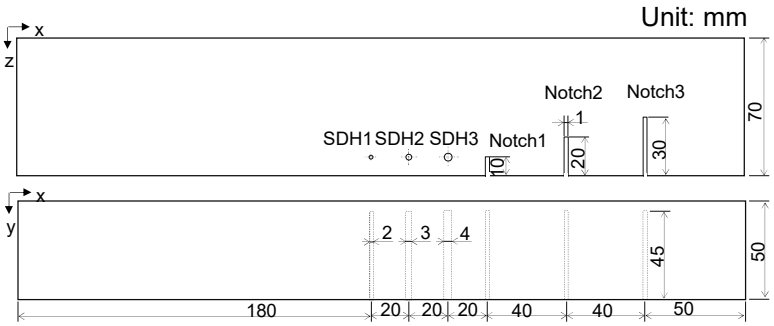
Dimensions and macrography of flat CCSS specimen

Configuration



Macrography

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Main testing conditions

		Conventional PAUT	FMC/TFM	PWI
Probe	Frequency (MHz)	1 or 2		
	Number of elements	64		
	Pitch (mm)	0.6		
	Width of element (mm)	0.5		
	Length of element (mm)	20		
Beam angle	Refraction angle (degrees)	0~55	N/A	0~55
	Resolution of refraction angle (degrees)	1	N/A	5
Focalization	Type	True depth	N/A	True depth
	Depth (mm)	70	N/A	1000
Wedge	Wedge angle (degrees)	16.5		
	Longitudinal sound velocity (m/s)	2330		
	Height of first element (mm)	30		
TFM	Region of interest (mm)	N/A	100x90	
	Frame resolution		256x256	
	Depth resolution		0.06λ (0.12λ)	
	Width resolution		0.07λ (0.14λ)	
	Amplitude fidelity (dB)		0.1 (0.2)	
Filter	LPF (MHz)	5		
Acquisition rate (Hz)		44.6	46.4	113.0
Hard gain (dB)		30	29	26

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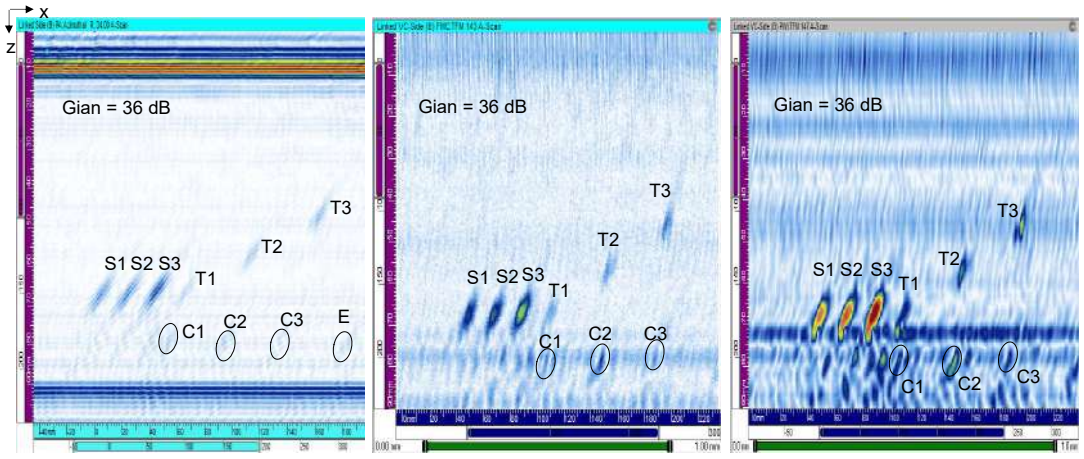
Side views at frequency of 1 MHz

Conventional PAUT FMC/TFM PWI



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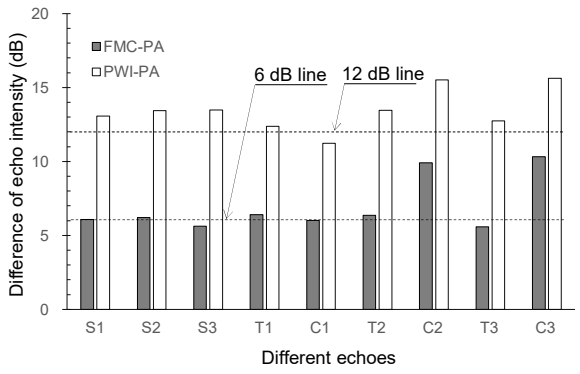
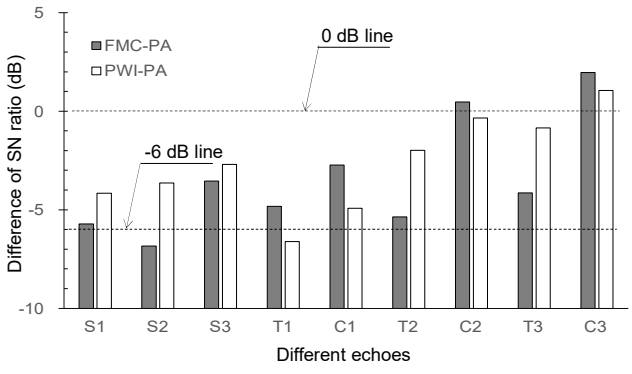
Comparison of echo intensity and SN ration at frequency of 1 MHz

Difference of echo intensity for different PAUTs



Difference of SN ratio for different PAUTs



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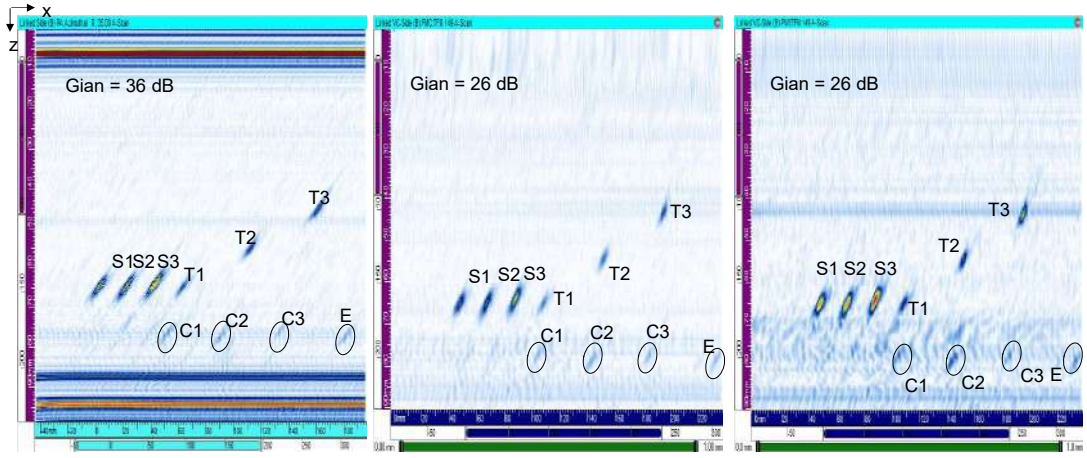
Side views at frequency of 2 MHz

Conventional PAUT | FMC/TFM | PWI



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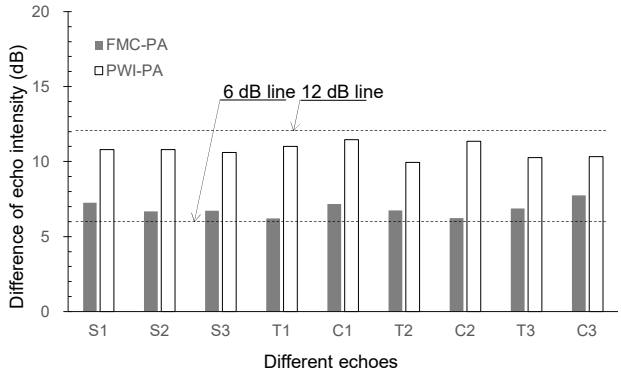
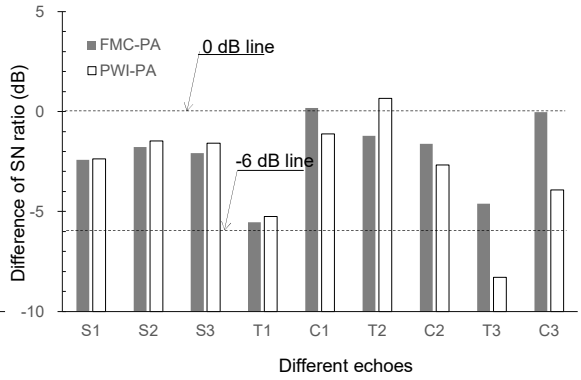
Comparison of echo intensity and SN at frequency of 2 MHz

Difference of echo intensity for different PAUTs



Difference of SN ratio for different PAUTs



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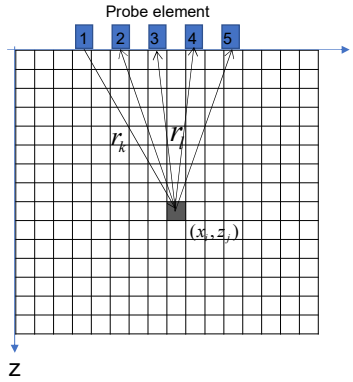
Denoising method with phase coherence factor, PCF



$$I(x_i, z_j) = w_{PCF}(x_i, z_j)\left|\sum_{k=1}^{n}\sum_{l=1}^{n} s_{kl}(t_p)\right|$$

$$t_p = (r_k + r_l)/c$$

s_{kl} Received signal for transmitter-receiver pair, kl

c Sound velocity

$w_{PCF}(x_i, z_j)$ Phase coherence factor

$$w_{PCF}(x_i, z_j) = 1 - \min\left[\sigma(\varphi_{kl}(t_p)), \sigma(\varphi^A_{kl}(t_p))\right]/\sigma_0 \ ^*$$

$$\sigma_0 = \pi/\sqrt{3}$$

$\varphi_{kl}(t_p)$ instantaneous phase

σ Conventional deviation

$$\varphi^A_{kl}(t_p) = \begin{cases} \varphi_{kl}(t_p) - \pi, & \varphi^A_{kl}(t_p) > 0 \\ \varphi_{kl}(t_p) + \pi, & \varphi^A_{kl}(t_p) < 0 \end{cases}$$

* J. Camacho, M. Parrilla and C. Fritsch: Phase Coherence Imaging, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 56(5), pp.958-974, (2009)

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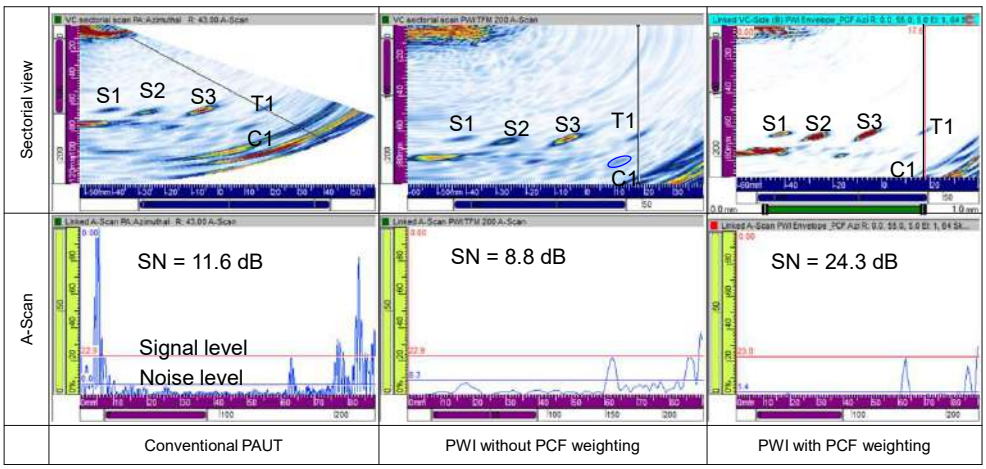
Effect of PCF on improvement of SN ratio



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Contents

- Background and motives
- Conventional PAUT, FMC/TFM and PWI
- Comparison of results among different PAUTs
  - > Isotropic medium (Stainless steel specimen)
  - > Flat CCSS (Centrifugally Cast Stainless Steel) specimen
  - > Curved CCSS specimen
- Conclusions

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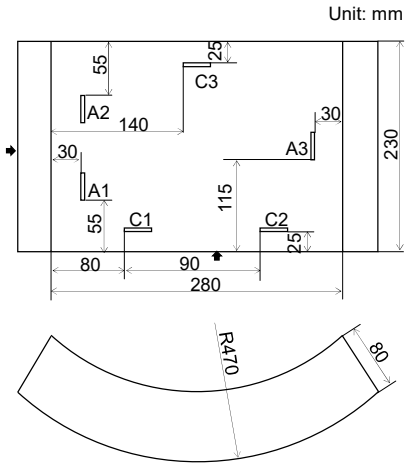
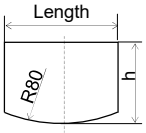
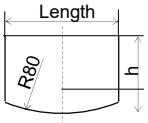
Curved SS specimen with notches

Configuration





Shape of notches introduced axially

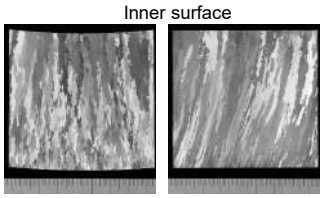


Shape of notches introduced circumferentially

Dimensions of notches

	C1	A1	C2	A2	C3	A3
Length	30					
Width	1					
h	10		20		30	

Macrography



(a) Axial section (b) Circumferential section

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Comparison of flaw detectability and SN ration among different PA techniques

Echo		Detectability			Maximum echo intensity (%)			Difference of echo intensity (dB)			Maximum noise intensity (%)			Difference of SN ratio (dB)		
		PA	FMC	PWI	PA	FMC	PWI	PA	FMC	PWI	PA	FMC	PWI	PA	FMC	PWI
C1	T	○	○	○	12.7	24.6	43.9	0	5.7	10.8	2.8	6.3	9.8	0	-1.3	-0.1
	C	○	○	○	15.4	34.9	79.9	0	7.1	14.3	4.3	8.9	16.5	0	0.8	2.6
C2	T	○	○	○	12.9	33.9	54.3	0	8.4	12.5	2.8	11.3	14.3	0	-3.7	-1.7
	C	○	○	○	21.1	31.3	51.6	0	3.4	7.8	3.9	12.2	15.4	0	-6.5	-4.2
C3	T	○	○	○	9.6	22.3	34.2	0	7.3	11.0	2.4	8.6	13.3	0	-3.8	-3.8
	C	×	×	×	N/A	N/A	N/A	0	N/A	N/A	N/A	N/A	N/A	0	N/A	N/A
A1	T	○	×	○	7.5	N/A	36.9	0	N/A	13.8	2.4	N/A	16.8	0	N/A	-3.1
	C	○	×	○	8.6	N/A	36.2	0	N/A	12.5	2.6	N/A	16.8	0	N/A	-3.7
A2	T	○	×	○	11.3	N/A	48.8	0	N/A	12.7	2	N/A	9.8	0	N/A	-1.1
	C	○	×	△	8.2	N/A	30.8	0	N/A	11.5	2.4	N/A	11.3	0	N/A	-2.0
A3	T	○	△	○	19.5	53.9	108.4	0	8.8	14.9	2.2	17.4	21.6	0	-9.1	-4.9
	C	○	△	○	10.6	27.7	36.5	0	8.3	10.7	3.3	16.9	15.7	0	-5.8	-2.8
Average (dB)									7.0	12.0					-4.2	-2.2

T : Tip echo
C : Corner echo
N/A : Not applicable
PA : Conventional PAUT FMC : FMC/TFM

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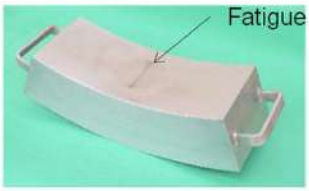
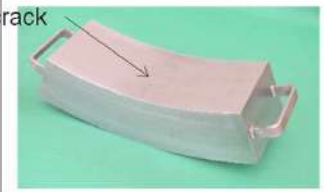
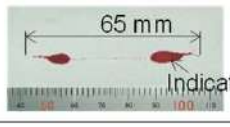
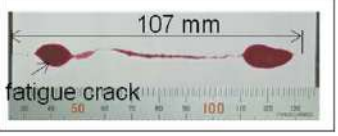
Curved CCSS specimen with fatigue crack

ID	F01	F02
Targeted depth	20 mm	30mm
Specimen configuration		
PT result		

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Comparison of flaw detectability and SN ration among different PA techniques

Crack	Scan direction	Echo	Detectability			Maximum echo intensity(%)			Difference of echo intensity (dB)			Maximum noise intensity (%)			Difference of SN ratio (dB)		
			PA	FMC	PWI	PA	FMC	PWI	PA	FMC	PWI	PA	FMC	PWI	PA	FMC	PWI
F01	A→B	C	○	○	○	21.6	46.9	74.8	0	6.7	10.8	11.5	12.4	23.1	0	6.1	4.7
	B→A	C	△	×	△	8	N/A	28.7	0	N/A	11.1	7.2	N/A	30	0	N/A	-1.3
F02	A→B	C	○	○	○	34.5	66.9	105.7	0	5.8	9.7	12.3	25.7	44.7	0	-0.6	-1.5
	B→A	C	△	×	△	7.3	N/A	21.8	0	N/A	9.5	4.9	N/A	14.1	0	N/A	0.3
Average (dB)										6.2	10.3					2.7	0.6

T : Tip echo
C : Corner echo
N/A : Not applicable
PA : Conventional PAUT FMC : FMC/TFM

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Conclusions

- We detected different specimens using conventional PAUT, FMC/TFM and PWI and compared with respect to SN ratio and flaw detectability.
- For isotropic materials, FMC/TFM and PWI are superior to the conventional PAUT, and the difference between PWI and FMC/TFM disappears while frequency increasing.
- For CCSS, the conventional PAUT and PWI are superior to FMC/TFM, and the difference between PWI without the application of phase of received signals and the conventional PAUT is ignorable.
- However, reconstruction of PWI results by means of PCF, SN ratio rises and recogntion of flaws improves.

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Advanced Ultrasonics for Cast Austenitic Stainless Steel Examination

Mark Dennis[1], George Connolly[1], Terrill Massey[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): mdennis@epri.com

Cast austenitic stainless steel (CASS) materials can be found in safety-related nuclear power plant components, including the primary coolant piping system in pressurized water reactors. CASS components have also been designed for new power plant construction. Volumetric examination of cast stainless steel piping is required, but no current reliable non-destructive evaluation(NDE) techniques exist. The ability to provide a reliable assessment of CASS materials will be essential for life extension and license renewal activities. There remains a level of concern with CASS components because of the possibility of thermal embrittlement over time and the limitations of current volumetric inspection techniques.

While round robin testing of CASS components using ultrasonics has been conducted for decades, flaws still go undetected as many participants continue to use older technology and techniques which have not been shown to be effective. Fortunately for the nuclear power industry, there have been advances made in ultrasonic testing which has improved flaw detection and characterization for other applications and may do the same for CASS.

This research will evaluate ultrasonic signal-to-noise ratios for defects in CASS piping using full-matrix capture and plane wave imaging data acquisition with total focusing method reconstruction techniques. The flaw response results using these more advanced ultrasonic methods will be compared with traditional phased array techniques.

Keywords: Cast austenitic stainless steel, Full matrix capture, Plane wave imaging, Total focusing method, Ultrasonic phased array.

Advanced Ultrasonics for Cast Austenitic Stainless Steel Examination

Thursday 29 June 2023

Mark Dennis, EPRI, Inc.
Terrill Massey, EPRI, Inc.
George Connolly, EPRI, Inc.

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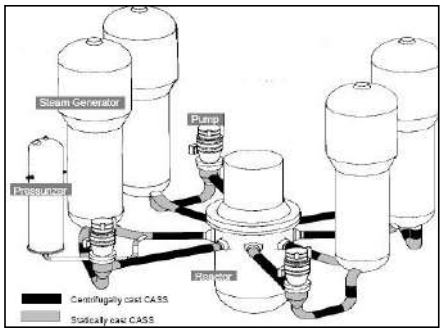
Motivation

- CASS is used in the primary coolant piping system of many Westinghouse-designed PWRs
  - Straight sections of the primary pipe are cast centrifugally
  - Pump casings, valve bodies and elbows and fittings are cast statically
- Reasons for using CASS:
  - Relatively favourable cost; corrosion resistance; ease of welding and fabrication for required shaping
- ASME BPV Sec. XI mandates that the pressure boundary and primary coolant piping be volumetrically inspected
  - The NDE methods typically deployed for the reactor coolant loop (RCL) wrought austenitic piping are conventional ultrasonic testing (UT) and radiographic testing (RT) [1]



CASS Material in the Westinghouse Primary Coolant System [1]

[1] Nondestructive Evaluation: Guidelines for Inspectability for New Plant Components. EPRI, Palo Alto, CA: **2010.** 1021160

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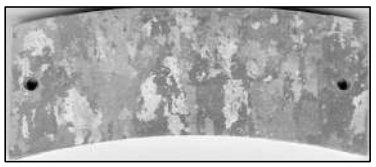
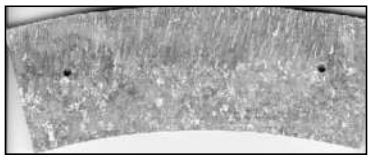
Background

- RCL piping in PWRs contains cast austenitic stainless steel (CASS), which have grain dimensions comparable to wavelength of inspection
  - Grain sizes in the order of several centimetres have been observed
  - Effect on UT results depends on grain structure (examples on right) In practice, the actual structure of CASS material is sometimes not known [1]
- The observed effects are:
  - High attenuation and high noise levels
  - Beam distortion and redirection
  - Must use longitudinal waves
  - Flaws under 20% TWS have generally been very difficult to detect
  - SNR can often be too low for consistent flaw detection and characterisation



Example of CASS coarse-equiaxed structure



Example of CASS mixed grain structure

GRAIN STRUCTURES AND ULTRASONIC EXAMINATION CHALLENGES

Grain structure	Remarks	Mitigation possibilities
Columnar	Significant beam steering; results can be misleading and inconsistent	Major technique modification: Use of lower frequency and larger probes
Fine-equiaxed	Predictable and accurate results can usually be obtained	Usually not required
Coarse-equiaxed	Significant attenuation; shear wave techniques can be ineffective; accuracy is adversely affected	Major technique modification: Use of lower frequency and larger probes
Mixed	Unknown variance and unpredictable results; accuracy is adversely affected and results are inconsistent	Major technique modification: Use of lower frequency and larger probes

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Specimen, Acquisition and Processing

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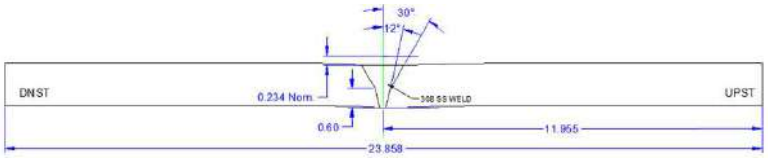
Specimen and Apparatus

- Specimen 347-12-03-AB attributes:
  - Ø12.75in (Ø323.8mm) at OD
  - Ø10.09in (Ø323.8mm) at ID
  - Length: 23.86in. (606.0mm)
  - Thickness: 1.333in (33.9mm)
  - Material: 316 Cast SS; weld material 308 SS
  - Weld angles: 12° and 30°
- Acquisition Instrument: Zetec Emerald
  - Bipolar Square Wave
  - Pulse Width 500ns
- Motion Controller: Zetec ZMC2 with ATCO GPS-1000 Pipe Scanner



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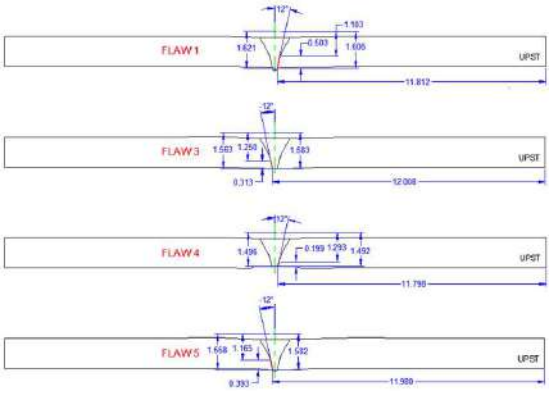
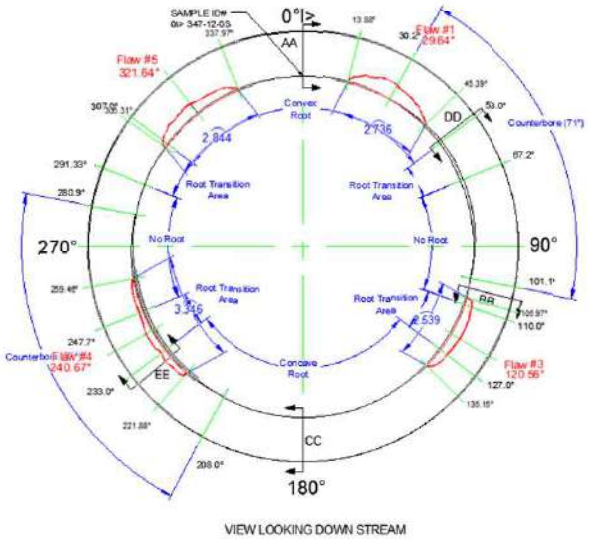
Specimen Flaws



Flaw	Centre	Length	RL	Tilt	Root
1	29.64°	2.736in. (69.5mm)	0.503in (12.8mm)	12°	Convex
3	120.56°	2.539in. (64.5mm)	0.313in. (8mm)	-12°	Flat
4	240.67°	3.346in. (85.0mm)	0.199in. (5.1mm)	12°	Flat
5	321.64°	2.844in. (72.2mm)	0.397in. (10.1mm)	-12°	Convex



VIEW LOOKING DOWN STREAM

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Search Unit

- General Electric Inspection Technologies (GEIT) 115-000-603 Dual Array
  - 1.0MHz, Dual 2x16, Pitch: 0.378in x 0.142in (9.6mm x 3.6mm), Size: 0.756in x 2.283in (19.2mm x 58.0mm)
- GEIT Rexolite Wedge 115-000-497 Contoured in the Axial Direction
  - Wedge Angle: 18.5°, Roof Angle 7.3°, Diameter: 16.75in (425.5mm)
- Coupling provided by running water

SEARCH UNIT ATTRIBUTES

Attribute	Value
Probe	GEIT 115-000-603 DMA
Centre frequency	1.0MHz
Aperture	(16×2) el
Pitch	[9.6,3.6]mm
Wedge	GEIT 115-000-497
Wedge Angle	18.5°
Wedge Roof Angle	7.3°

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Acquisition and Processing

- Two acquisitions with two channels each
  - First acquisition:
    - First channel: PAUT couples elements of each array along its shorter dimension i.e. (16×2) el. becomes (16×1) el.
    - Second channel: Elementary FMC acquisition with Delay Multiply and Sum (DMAS), enveloping and both applied in post-processing
  - Second acquisition:
    - First channel: No element coupling
    - Second channel: PWI acquisition with DMAS, enveloping and both applied in post-processing
- TFM
  - Frame resolution: (256×256)pix.
  - Grid resolution: (0.25×0.30)mm (λ≈6mm)
- DMAS
  - General information about DMAS principles available in the literature [2,3]

ACQUISITION ATTRIBUTES

Attribute	Value
Scan Resolution	0.6654in. (16.9mm)
Index Resolution	0.0394in. (1.0mm)

ACQUISITION ATTRIBUTES

Acquisition	Scan Speed	Channel	Scan Type	Scan Angles	Active focus
First	17.8mms^{-1}	PAUT	Azimuthal L	0° to 70° in 1° increment	Half path 1.5in. (38.1mm)
		FMC	L-L	*n/a**	None
Second	12.7mms^{-1}	PAUT	Azimuthal L	0° to 70° in 1° increment	Half path 1.5in. (38.1mm)
		PWI	L-L	0° to 70° in 5° increment	Half path 39in. (990.6mm)

* STF angles in post-processing: 0° to 70° in 1° increment

[2] Lim, H. B., Nhung, N.T. T., Li., E.-P., Thang, N. D. *Confocal Microwave Imaging for Breast Cancer Detection: Delay-Multiply-and-Sum Image Reconstruction Algorithm* IEEE. Trans. Biomedical Eng. 55(6) 1697-1707 **2008**
[3] Matrone, G., Savoia, A. S., Magenes, G., Caliano, G. *The Delay Multiply and Sum Beamforming Algorithm in Ultrasound B-Mode Medical Imaging* IEEE. Trans. Medical Imaging 34(4) 940-949 **2014**

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Selected UT Results

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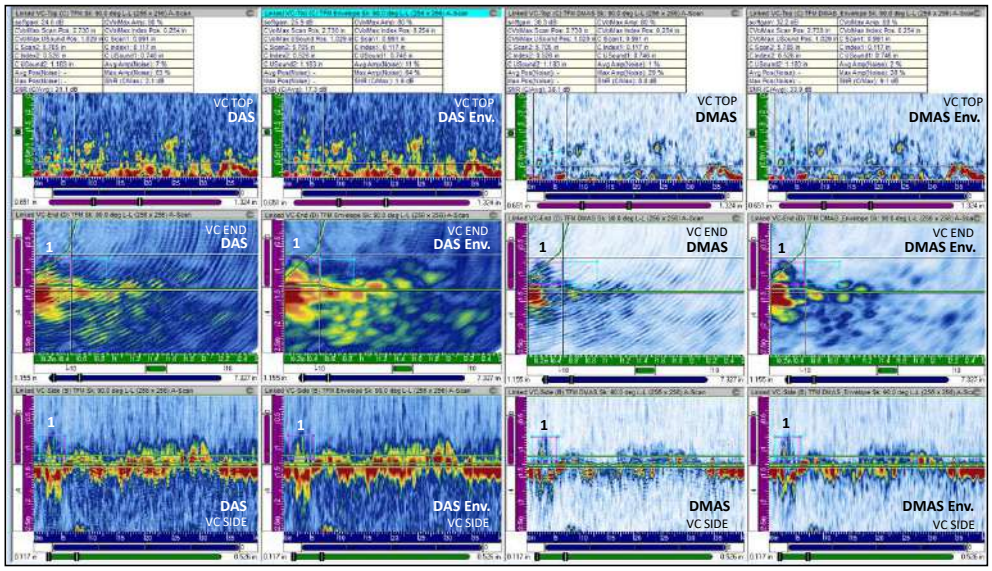
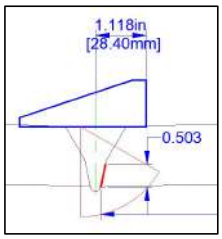
Flaw 1 Far Side: FMC/TFM

Selected UT Results





Search unit and flaw **1**

First acquisition:

- Flaw bounding box in magenta
- Noise bounding box in cyan
- Weld boundary in green

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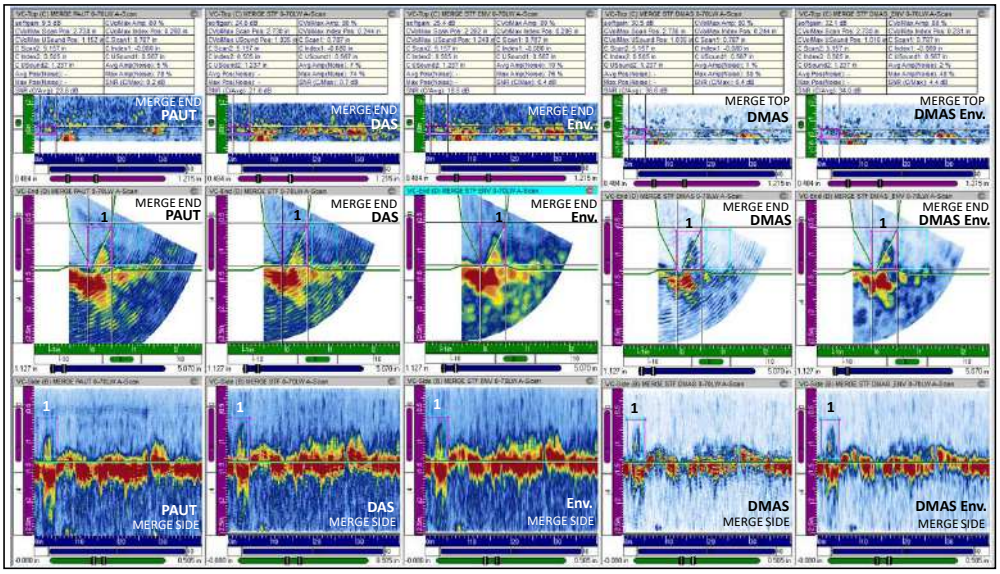
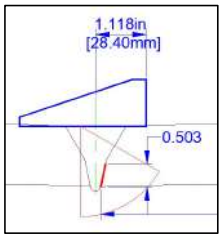
Flaw 1 Far Side: FMC/STF

Selected UT Results





Search unit and flaw **1**

First acquisition:

- Flaw bounding box in magenta
- Noise bounding box in cyan
- Weld boundary in green

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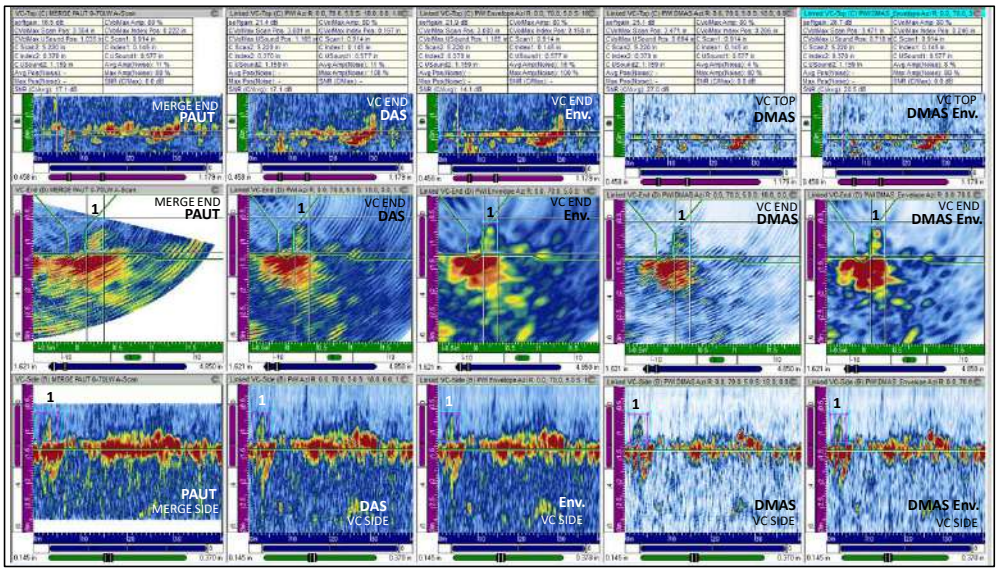
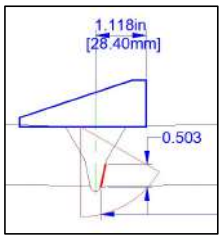
Flaw 1 Far Side: PWI/TFM

Selected UT Results





Search unit and flaw **1**

Second acquisition:

- Flaw bounding box in magenta
- Noise bounding box in cyan
- Weld boundary in green

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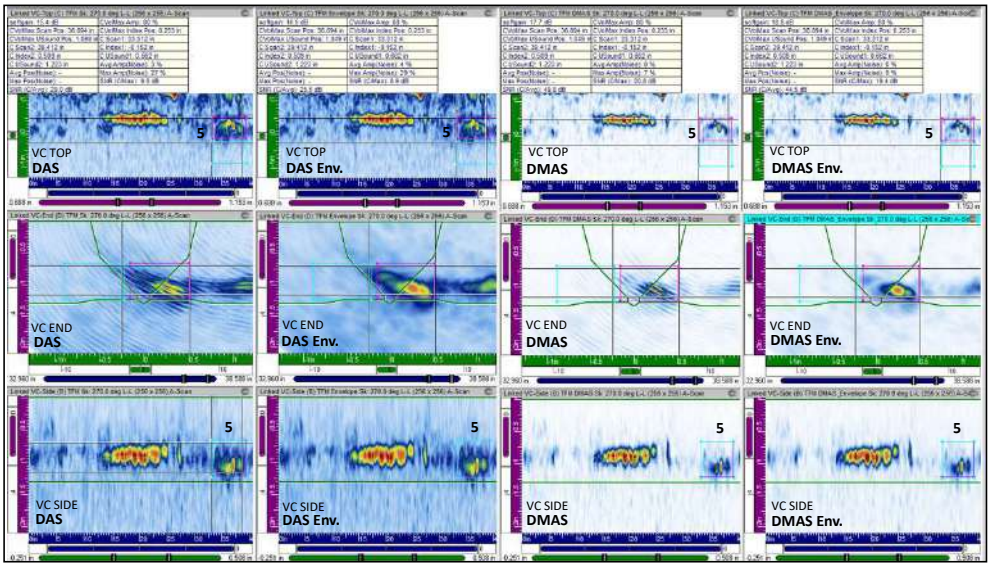
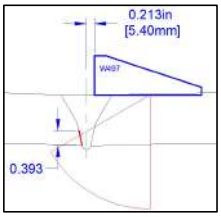
Flaw 5 Far Side: FMC/TFM

Selected UT Results





Search unit and flaw 5

First acquisition:

- Flaw bounding box in magenta
- Noise bounding box in cyan
- Weld boundary in green

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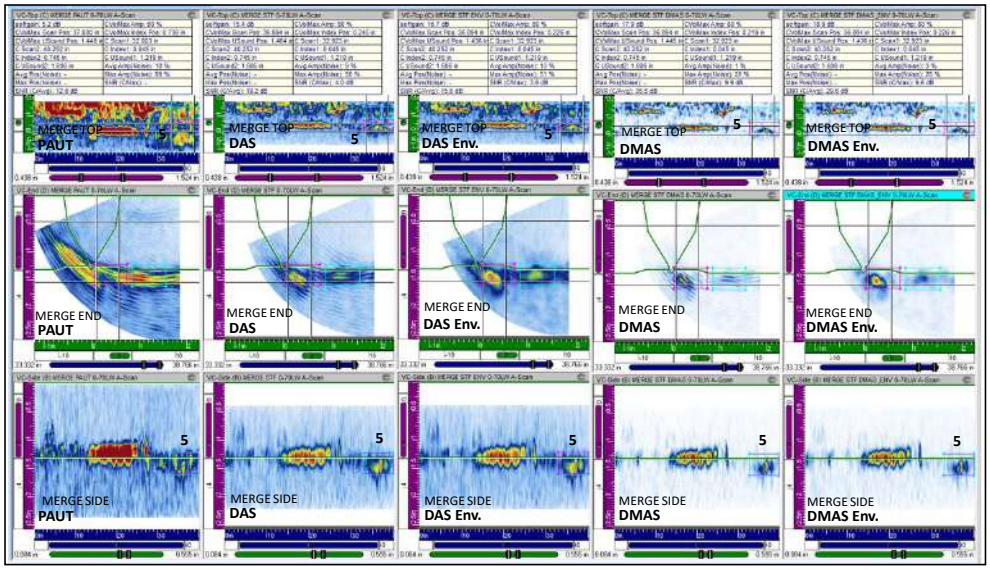
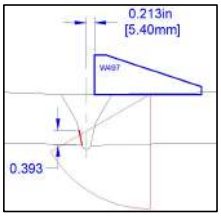
Flaw 5 Far Side: FMC/TFM

Selected UT Results





Search unit and flaw 5

First acquisition:

- Flaw bounding box in magenta
- Noise bounding box in cyan
- Weld boundary in green

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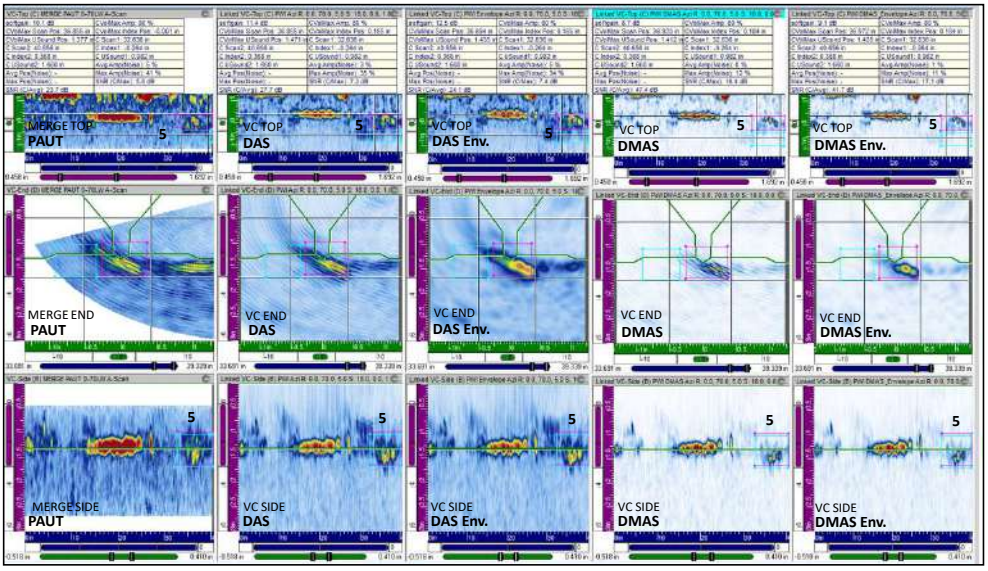
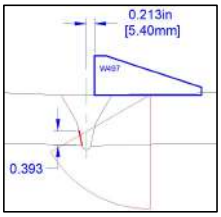
Flaw 5 Far Side: PWI/TFM

Selected UT Results





Search unit and flaw 5

Second acquisition:

- Flaw bounding box in magenta
- Noise bounding box in cyan
- Weld boundary in green

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Summary

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Collated Results

- All techniques detected flaws with adequate SNR (≥6dB) with L waves
  - Minimum SNR: 11.2dB
  - Average SNR: 26.1dB
- SNR summary for first acquisition (PAUT, FMC/TFM and FMC/STF):
  - DAS slightly lower SNR values than PAUT
  - DMAS gave strong improvement to measured SNR values; many in excess of 12dB
  - Enveloping slightly reduces the SNR

FIRST ACQUISITION

			FMC/TFM				FMC/STF			
Flaw	Side	PAUT	DAS	DAS Env.	DMAS	DMAS Env.	DAS	DAS Env.	DMAS	DMAS Env.
1	Far	23.6	*21.1*	*17.3*	**38.1**	33.9	*21.6*	*18.5*	**36.6**	34.0
	Near	28.3	*23.3*	*19.8*	40.1	35.3	*23.9*	*20.4*	**40.6**	36.1
3	Far	23.4	*21.7*	*18.1*	**36.4**	32.0	*20.0*	*16.6*	33.3	29.6
	Near	23.3	*18.5*	*15.1*	32.0	26.6	*20.2*	*17.0*	33.8	31.6
4	Far	27.1	*18.1*	*14.2*	31.3	*25.0*	*20.8*	*18.7*	29.6	*24.5*
	Near	23.5	*20.0*	*16.4*	**37.8**	31.7	*14.0*	*11.2*	*21.6*	*17.3*
5	Far	12.8	**29.0**	**25.5**	**49.8**	**44.5**	19.2	15.6	**35.5**	**29.6**
	Near	26.6	*23.9*	*20.1*	**40.2**	36.9	*22.0*	*18.3*	35.7	31.8

SECOND ACQUISITION

			PWI			
Flaw	Side	PAUT	DAS	DAS Env.	DMAS	DMAS Env.
1	Far	17.1	17.1	*14.1*	27.0	20.5
	Near	21.7	*21.3*	*17.6*	**37.2**	30.6
3	Far	20.6	21.3	*17.4*	**34.4**	27.9
	Near	22.3	*22.2*	*18.6*	**36.5**	32.0
4	Far	25.9	*23.8*	*20.3*	**38.9**	32.8
	Near	22.4	24.1	*20.4*	**40.2**	34.2
5	Far	23.7	27.7	24.1	**47.4**	**41.7**
	Near	24.0	*23.4*	*19.6*	**38.6**	33.3

SNR 12dB greater than the corresponding PAUT value highlighted in **blue**
SNR worse than the corresponding PAUT value highlighted in *red*

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Summary

- DMAS provided the best SNR improvement versus PAUT (see table on right)
  - FMC/TFM DMAS on average was 14.6dB better than PAUT
  - FMC/STF DMAS on average was 9.8dB better than PAUT
  - PWI/TFM DMAS on average was 15.3dB better than PAUT
- In many cases, DMAS SNR values are at least 12dB stronger
  - Offers potential for superior detection and characterisation for flaws in CASS
- Postprocessing times dependent on computing power
  - DMAS in conjunction with enveloping adds heavy computation burden
  - Future software and instrumentation improvements may reduce processing times

AVERAGE SNR SUMMARY (dB) for DMAS

Flaw	Side	FMC/TFM	FMC/STF	PWI/TFM
1	Far	**38.1**	**36.6**	27.0
	Near	40.1	**40.6**	**37.2**
3	Far	**36.4**	33.3	**34.4**
	Near	32.0	33.8	**36.5**
4	Far	31.3	29.6	**38.9**
	Near	**37.8**	*21.6*	**40.2**
5	Far	**49.8**	**35.5**	**47.4**
	Near	**40.2**	35.7	**38.6**

SNR 12dB greater than the corresponding PAUT value highlighted in **blue**
SNR worse than the corresponding PAUT value highlighted in *red*

PROCESSING TIMES (min.)

Acquisition	Processing	Laptop*	Desktop**
FMC	DAS	5	<1
	DAS Env.	6	<1
	DMAS	6	<1
	DMAS Env.	86	10
PWI	DAS	2	<1
	DAS Env.	2	<1
	DMAS	2	<1
	DMAS Env.	12	<1

* 16GB RAM; I7-4700MQ CPU; 2.4GHz
** 128GB RAM; I9-7900X CPU; 3.3GHz

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Estimation of columnar crystal orientation by machine learning for centrifugally cast stainless steel

Keiji WATANABE[1], Shan LIN[1],Masaki NAGAI[1],
Rikuya HISAMOCHI[2], Naoki TOMITA[2] and Masahiro FURUYA[2]

[1]Materials Science Division, Energy Transformation Research Laboratory,
Central Research Institute of Electric Power Industry, Yokosuka, Japan
[2]Graduate School of Advanced Science and Engineering, Waseda University, Tokyo, Japan

E-mail address (corresponding author): wkeiji@criepi.denken.or.jp

Abstract

Centrifugally cast stainless steel (CCSS) is widely used in PWR primary coolant systems. The JSME Fitness-for-Service Code requires periodic in-service inspection of welds in such systems by ultrasonic testing (UT), however the anisotropy and heterogeneity of CSS make flaw detection and sizing difficult. Most CCSS is composed of columnar crystal grains, and the orientation of the crystal grains affects the accuracy of UT. Therefore, it is important to know the orientation of columnar crystal grains in order to appropriately set the test conditions to improve the accuracy of UT. In this study, we tried to estimate the columnar crystal orientation from side views containing backwall echoes by machine learning (ML). We prepared several CCSS specimens with different columnar crystal orientations and acquired side views for each specimen. In the acquisition, we used a linear array probe and scanned the probe over the surface of specimens immersed in water. We applied ML to these side view images and investigated the applicability of ML in the estimation of the orientation of columnar crystal grains in CCSS. The learning accuracy of the ML method, which classifies ordinary side view images, was less than 50%, while the local interpretable model-agnostic explanation (LIME) method, which selects important images for estimating the direction of columnar crystal growth, improved the learning accuracy to nearly 90%. The results suggest that it is possible to estimate the orientation of columnar crystal grains in CCSS by ML.

Keywords: Centrifugally Cast Stainless Steel, Columnar Crystal Orientation, Phased array ultrasonic technology, Machine Learning, Local interpretable model-agnostic explanation method.

Estimation of columnar crystal orientation by machine learning for centrifugally cast stainless steel

Central Research Institute of Electric Power Industry
WATANABE Keiji, LIN Shan, Nagai Masaki

Waseda University
TOMITA Naoki, HISAMOCHI Rikuya, FURUYA Masahiro

NDE in Nuclear 2023

June 28, 2023

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Contents

- Background
- Objectives
- Preparation of Centrifugally cast stainless steel (CCSS) specimens with different crystal orientation of columnar grains
- Determination of crystal orientation of columnar grains based on Dataset 1
- Determination of crystal orientation of columnar grains based on Dataset 2
- Conclusions

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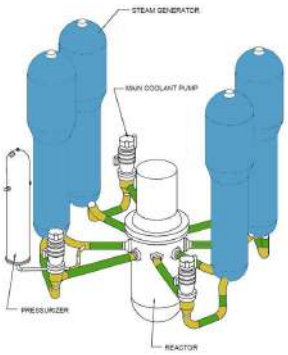
Background

- Centrifugally cast stainless steel (CCSS) is extensively used in primary coolant system of pressurized water reactors.
- In order to maintain the integrity of nuclear power plants, detection and sizing of flaws in CCSS by ultrasonic testing techniques is important and required.
- However, CCSS, especially those with columnar grain structures is a challenging material for UT.
- Previous studies revealed that the crystal orientation of columnar grains severely influenced the accuracy of UT.



Centrifugally cast
Statically cast

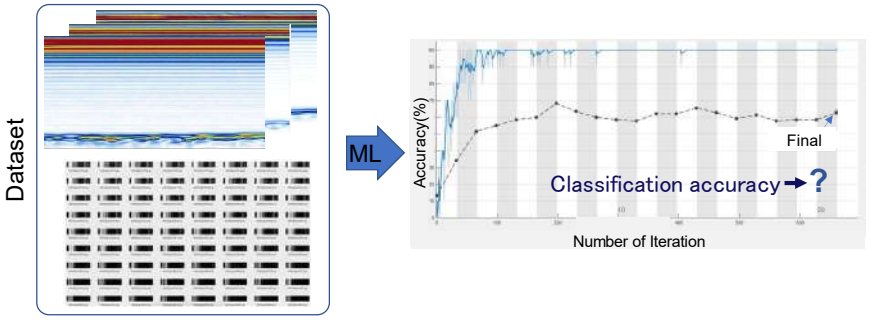
http://www.nrc.gov/reading-rm/basic-ref/students/for-educators/04.pdf

Background (contd.)

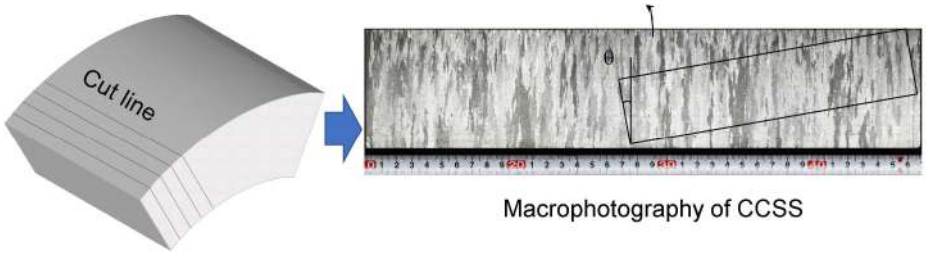
- Determination of the crystal orientation of columnar grains is a matter of importance for appropriate setting of testing conditions so as to improve the accuracy of UT.
- Nevertheless, there is no existing non-destructive method to measure the crystal orientation of columnar grains of CCSS.
- **Machine learning** could be a solution to the problem.

Objectives

◆To evaluate the applicability of machine learning in identifying the crystal orientation of columnar grains based on side-view data images obtained by phased array ultrasonic technique (PAUT).



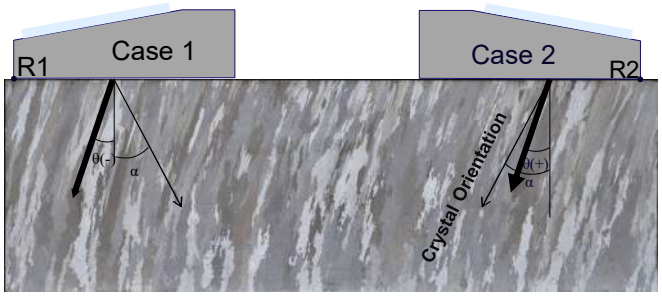
CCSS Specimen with different crystal orientations of columnar grains



Macrophotography of CCSS

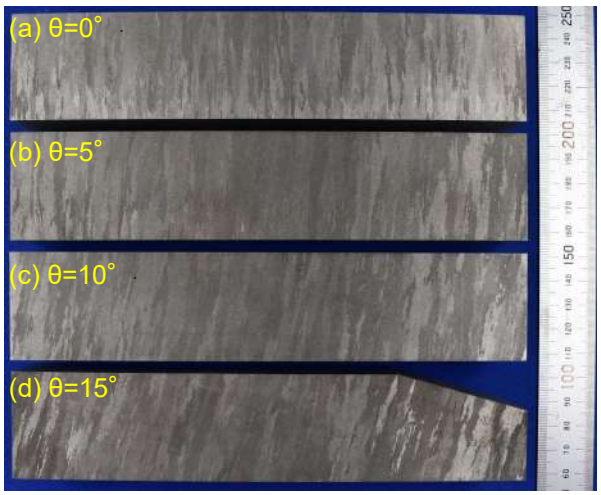
Material : CF-8M
Thickness : 80 mm

Definition of crystal orientation of columnar grains



- Taking the rear corner of angle-beam probes (R1, R2) as the reference point. If columnar grains grow toward the reference point, then its crystal orientation is defined as positive. Otherwise, the crystal orientation is negative.
- The crystal orientation becomes negative for Case 1, but positive for Case 2.
- Angle of crystal orientation: Angle between the vertical direction and the crystal orientation direction.

Prepared CCSS specimens with different crystal orientations of columnar grains



Height=40 mm

Inspection method

Method		PAUT(Water immersion)
Array probe	Number of elements	64
	Element size	0.5 mm ×20 mm
	Element pitch	0.6 mm
Wedge	Angle	16.2°
	Mode	Longitudinal wave
	Longitudinal sound velocity	5920 m/s
Beam angle	Refraction angle	0~55°
	Resolution of refraction angle	1°
Focalization depth		40 mm
Data collection		Semi-automatic one-line scanning (using wired encoder)
Scan length		100 mm
Data sampling rate		1.0 mm

Determination of crystal orientation of columnar grains based on Dataset 1

Collection of Dataset 1

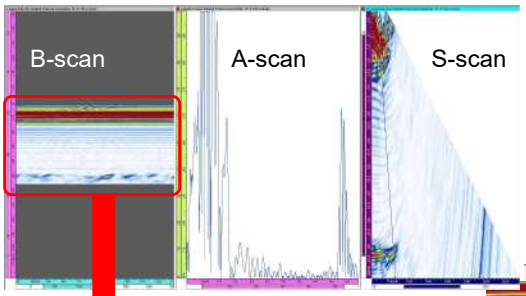
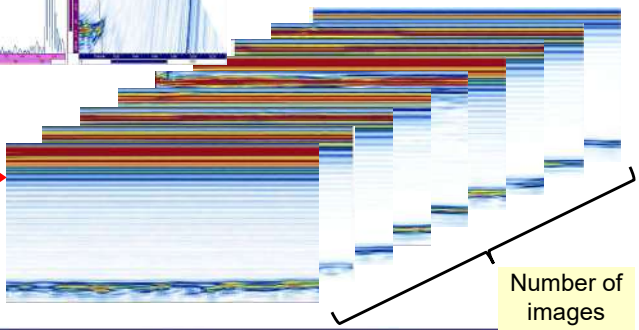


Image Size (Scanning x Beam path)
501# x 255##[pixel]



#The number of pixels is larger than the number of image data(101) obtained from the testing, and the same number of image data is lined up.。
The number of pixels is less than the number of image data (836) obtained from the testing, and the number of image data is reduced due to compression.

Number of images : 448

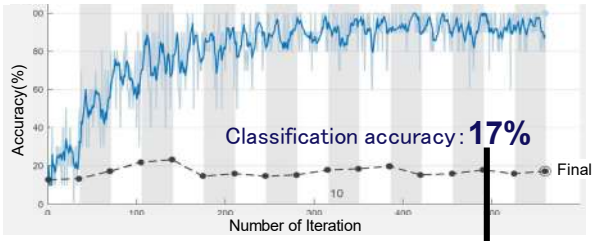
ML system used in this study

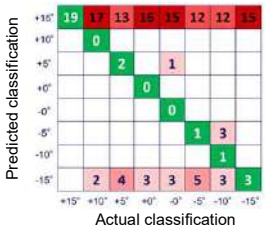
- Transfer learning using AlexNet (Performed on the MATLAB)
  - AlexNet (One of the major convolutional neural network (CNN) architecture) contained eight layers; the first five were convolutional layers, some of them followed by max-pooling layers, and the last three were fully connected layers.
  - In our previous work, it was found that Alexnet can be used to detect defects in austenitic stainless steel piping welds from PAUT images with high accuracy.

Classification of columnar crystal orientation by machine learning

With all B-scan images

- Classification by ML for all cross-sectional images
  (501 × 255 pixels) Number of images: 448 -





Confusion Matrix

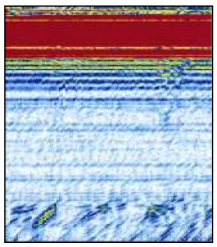
Why the low classification accuracy?

Consideration (Why the low classification accuracy?)

◆ Image classification architecture（Dataset 1）

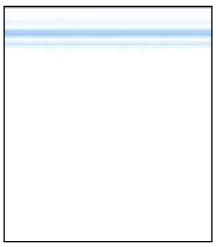
Bottom echo

Refraction angle = 5°



Refraction angle = 30°

Bottom echo embedded in other echoes.



Refraction angle = 45°

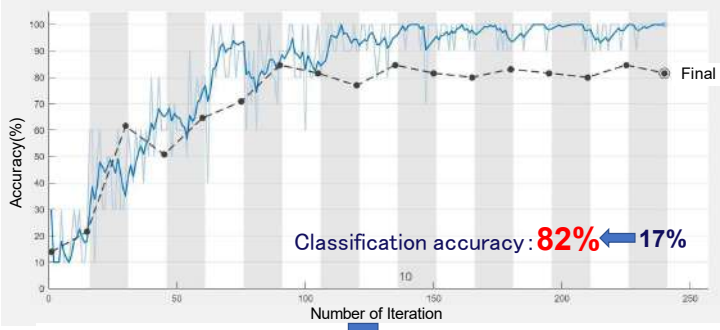
No apparent bottom echo

- Refraction angle at which bottom echo is observed (0-44°)
  : Sensitivity adjusted so that bottom echo is 50%.
- Refraction angle at which bottom surface echoes are not observed (45°-55°)
  : Sensitivity is not adjusted.

Classification of columnar crystal orientation by machine learning

◆ Image classification architecture（Dataset 1）

- Only cross-sectional images with angles of refraction from 0-44° observed in the bottom echo of Dataset 1 (Number of images: 360) -



Improved classification accuracy

Area of significant effect on classification accuracy

◆ Analyze which area of image data has most significant effect on the classification accuracy of crystal orientation.

Local Interpretable Model-Agnostic Explanations (LIME)

Areas used for classification are identified for each image, and then overlaid on the image to detect the critical areas.

Focus on the area below the image

Image data focusing on bottom echoes

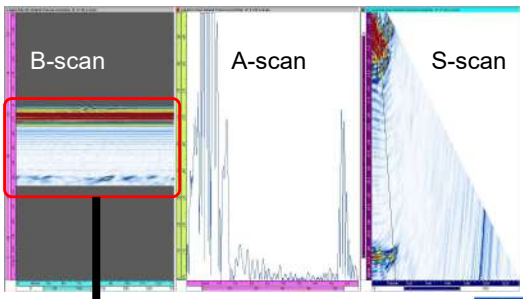
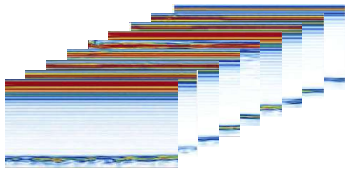


Image Size (Scanning x Beam path)
501 x 41 [pixel]

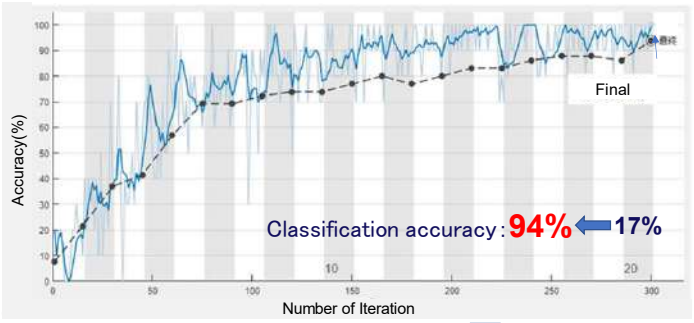
Number of images : 360

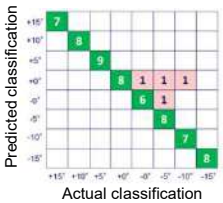


Extraction of image areas where bottom echoes were observed

Classification of columnar crystal orientation by machine learning

- Only cross-sectional images of the area around the bottom echo of Dataset 1 (Number of images: 360) -





Confusion Matrix

Improved classification accuracy

Determination of crystal orientation of columnar grains based on Dataset 2

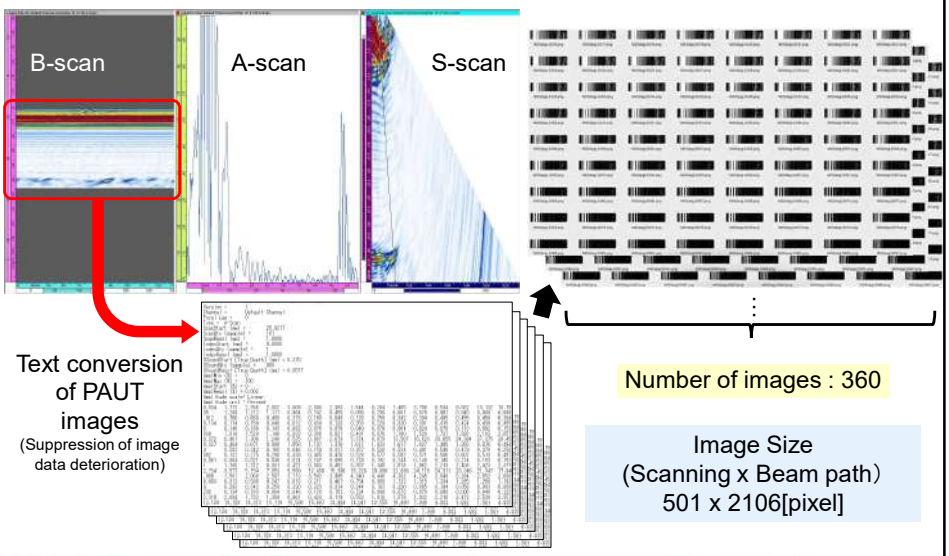
Inspection method

Method		PAUT(Water immersion)
Array probe	Number of elements	64
	Element size	0.5 mm ×20 mm
	Element pitch	0.6 mm
Wedge	Angle	16.2°
	Mode	Longitudinal wave
	Longitudinal sound velocity	5920 m/s
Beam angle	Refraction angle	0~55°
	Resolution of refraction angle	1°
Focalization depth		40 mm
Data collection		Semi-automatic one-line scanning (using wired encoder)
Scan length		100 mm
Data sampling rate		0.2 mm

⬇

Refinement of the data collection pitch in probe scanning direction and the Resolution in beam path direction

Preparation of Dataset 2



Text conversion of PAUT images
(Suppression of image data deterioration)

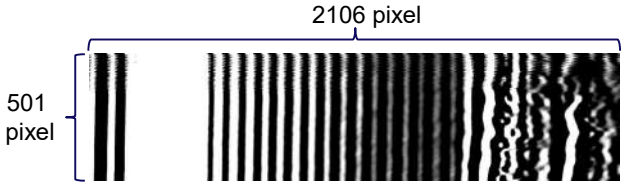
Number of images : 360

Image Size
(Scanning x Beam path)
501 x 2106[pixel]

Classification of columnar crystal orientation by machine learning

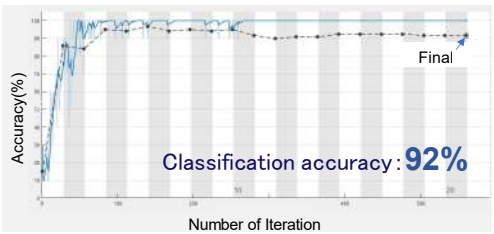
◆ Example of extracting the bottom area from the Dataset 2

-Case with reflected waves from the bottom-



Refraction angle at which bottom echo is observed (0-44°)

Number of images: 360

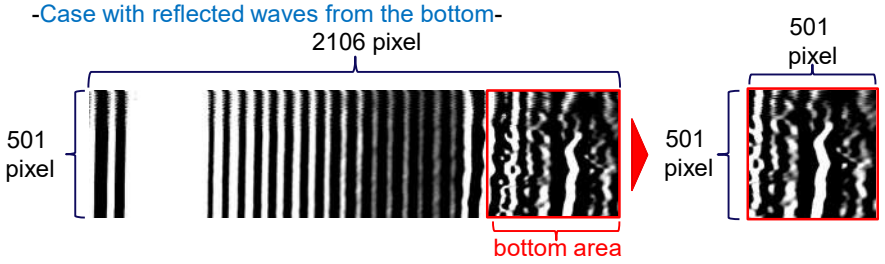


No improvement in classification accuracy

Classification of columnar crystal orientation by machine learning

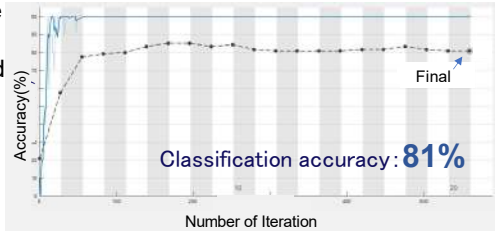
◆ Example of extracting the bottom area from the Dataset 2

-Case with reflected waves from the bottom-



Refraction angle at which bottom echo is observed (0-44°)

Number of images: 360



No improvement in classification accuracy

Conclusions

◆ The possibility of using machine learning (ML) to estimate the direction of columnar crystal orientation from PAUT data (cross-sectional images) of CCSS specimens was examined.

◆ Results show that it is possible to estimate the columnar crystal orientation of CCSS from PAUT data with an accuracy of up to 94%.

◆ It is necessary to investigate further the factors (UT conditions, UT image data, etc.) involved in improving the classification accuracy for the columnar crystal orientation of CCSS.

Geometry Measurement of Core Baffle of VVER-1000 Type Reactors of NPP Temelín

Petr Vlček[1], Miroslav Žamboch[1], Lukáš Húska[1]

[1]ÚJV Řež, a. s., Hlavni 130, Husinec - Rez, Czech Republic

E-mail address (corresponding author): petr.vlcek@ujv.cz

Abstract

The article describes design of measuring device and the actual procedure of measuring the core baffle of VVER-1000 type reactors. This device was developed at UJV Rez, plc. And it is used for geometry measurement of the core baffle. The measurement is performed to assess the current state of core baffle, which may be affected by the development of the degradation mechanism of radiation swelling and its influence on the geometry of the core baffle.
The degradation mechanism of radiation swelling causes increase of failures in the crystal lattice of the metal, which in consequence leads to an increase in the volume of the material and can and also result in a change in the geometry of the mentioned component. The macroscopic change in geometry can affect the component's ability to provide the required safety function.
Therefore, a measuring device was designed and manufactured in the laboratories of the ÚJV Řež, a. s.. which would enable accurate measurement of selected dimensions of the core baffle in the specific conditions of the reactor. The dimensions that are most affected by the development of radiation swelling according to the computational evaluation are measured.
The measuring device was designed to allow measurement of the absolute distance of the opposite surfaces of the inner surface of the core baffle. The device consists of four measuring arms connected by a frame. Dimensional measurements is carried out using inductive sensors and optical sensors. The measuring device is equipped with cameras to determine the position. High accuracy, resistance of the device to ionizing radiation and hydrostatic pressure are essential for successful measurement.

The first geometry measurement of core baffle was carried out at the second unit of the Temelín NPP in 2022.

Keywords: core baffle, radiation swelling, geometry measurement, VVER-1000 reactor

Geometry Measurement of Core Baffle of VVER-1000 Type Reactors of NPP Temelin

Petr Vlček, Miroslav Žamboch

NDE in Nuclear, Sheffield
27. - 29. 6. 2023

MEASUREMENT OF CORE BAFFLE DIMENSION

- Degradation mechanism of radiation swelling
- Geometry measurement of core baffle
- Development of measuring device
- Measurement at Temelin NPP

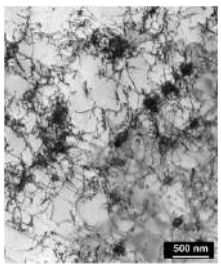
ASSESSMENT OF DEGRADATION MECHANISM SWELLING

- Based on the computational evaluation of radiation swelling, operational experience of other WWERs, there was a need to develop a measuring device.
- Development and construction of measuring equipment in 2016-2020 according to the approved design and schedule
- Preparation of measurement at NNP 2021-2022
- The measurement performed in 2022 on Temelin NPP unit 2, and 2023 on unit 1

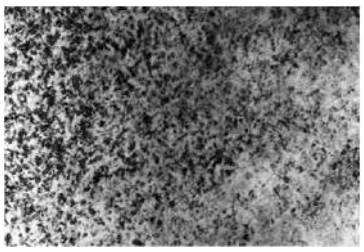
3

SWELLING AND RADIATION CREEP DAMAGE

- change in microstructure (Frankel loops, dislocation density increase, nanocavities, microcavities)
- degradation of mechanical properties (Elongation, Fracture toughness, Yield strength, Tensile strength)
- increase in volume of heavily loaded area of material (neutron flux & temperature)



Dislocation structure of 08Ch18N10T steel prior irradiation



Irradiation defects in 08Ch18N10T steel after irradiation, Frank loops, perfect dislocation loops,"black dots".

4

4

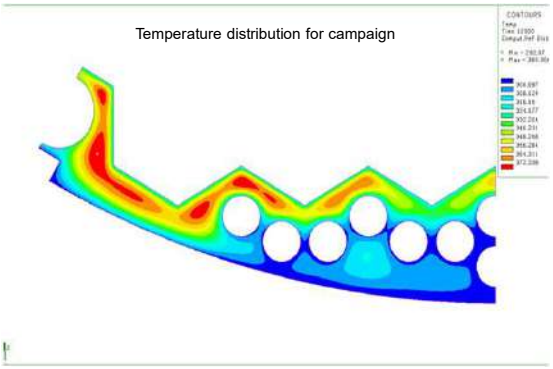
SWELLING AND RADIATION CREEP DAMAGE

Conditions for swelling

- ❑ high temperature over 350 °C
- ❑ high neutron dose

As consequence – macroscopic (measurable by NDT method) change in geometry of RVI components: Core baffle

- uneven distribution of temperature around the core baffle circumference
- differences between campaigns



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CORE BAFFLE OF TEMELIN NPP

Description of core baffle

- ❑ diameter max. 3486 mm
- ❑ 6 rings connected with screws on the outer surface
- ❑ the shell contains cooling holes
- ❑ 6 threaded rods attach the core baffle to the shaft bottom

Model of core baffle – front view

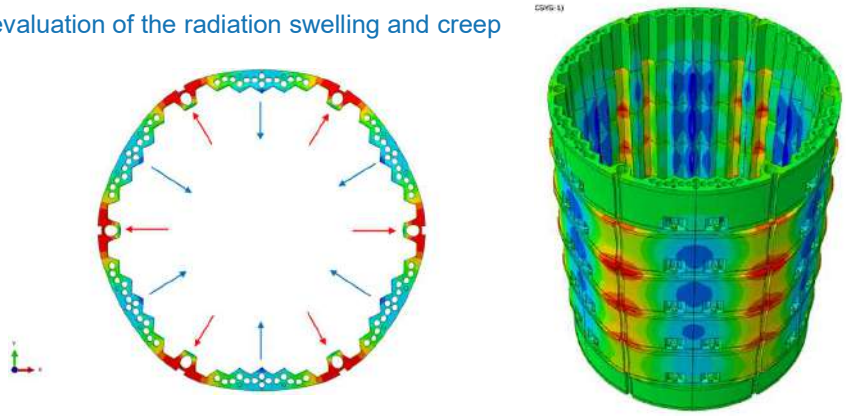
Model of core baffle

6

MEASUREMENT OF CORE BAFFLE

Swelling manifestation of core baffle

- ❑ development degradation mechanism "Radiation swelling" predicted based on calculations for 60/80 years of operation
- ❑ actual evaluation of the radiation swelling and creep



Deformation of core baffle due to swelling

7

7

MEASUREMENT OF CORE BAFFLE

Why measure core baffle?

- ❑ Provides the information about the actual state of core baffle and demonstrate the functionality of the component for the next operation.
- ❑ Repeatedly measuring the same parts of component allows to predict the effect of radiation swelling.
- ❑ To verify and to refine the computational model of radiation swelling development.

8

8

MEASUREMENT OF CORE BAFFLE

Conditions for the implementation of control

- Measurements in the water - the equipment must withstand hydrostatic pressure present in the reactor shaft depth.
- Measurements at high doses of radiation up to 1000 Sv/hour.
- Coolant temperature - maximum 50 ° C.
- Time limitation - effect on the reactor shutdown time.
- Requirements for a high measurement accuracy.

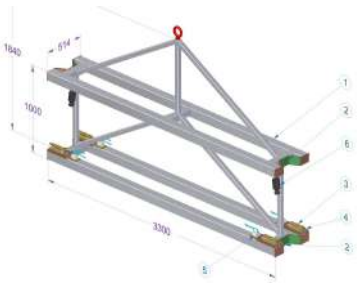
Specific requirements for measuring equipment

9

MEASUREMENT OF CORE BAFFLE

The measurement principle

- measurement accuracy requirement was ± 0,25 mm
- absolute distance measurement of two oposite paraller surfaces
- measuring device:
  - optical sensors
  - inductive touch sensors
  - electric spirit level



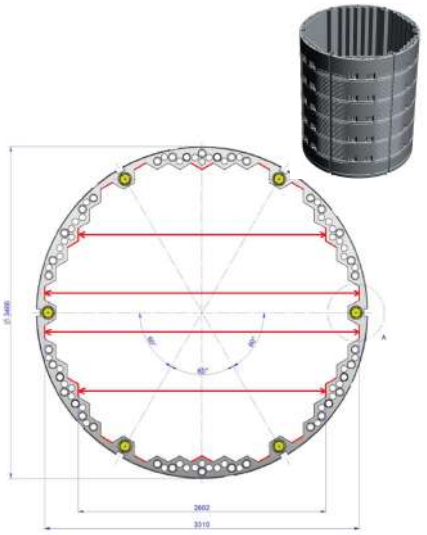
First desing proposal

10

MEASUREMENT OF CORE BAFFLE

The measurement principle

- ❑ Measurement of the distance between selected surfaces of the core baffle (areas around the threaded rod and the middle segment).
- ❑ Measurement at different selected height level (according to z axis).
- ❑ Measurement in three angle position (rotation twice by 60 °).
- ❑ This method of measurement corresponds to the measurement carried out during assembly Inspection.



The measured distance in core baffle

11

MEASUREMENT OF CORE BAFFLE

Verification of the measurement principe

The prototype of measuring device

The measuring device in core baffle mock-up

The measuring device in core baffle mock-up

12

MEASUREMENT OF CORE BAFFLE

Example of prototype testing

Workplace in experimental hall with tank and construction of prototype.

Front prototype design with inductive sensor and sliding plastic.

13

MEASUREMENT OF CORE BAFFLE

Activities performed with the prototype device

- ❑ construction and manufacture of device skeleton
- ❑ development of optical sensor
- ❑ installation of individual sensors, spirit level, thermometers, etc. to the prototype structure
- ❑ installation of control hardware.
- ❑ development of control software
  - commissioning and tuning of sw. to display the measured data
- ❑ design tests
  - verification of the hermeticity prototype construction
  - manipulation of the prototype
  - sensor control

14

MEASUREMENT OF CORE BAFFLE

Testing of radiation resistance

- ❑ Measurement of radiation level inside core baffle.
- ❑ Verification of radiation resistance in irradiation well.

Boxes with alanine dosimeter

Irradiation well in UJV Rez

15

15

MEASUREMENT OF CORE BAFFLE

Finally measuring device

- ❑ 4 measuring arms
- ❑ 2 inductive sensors operated by pneumatic system and optical sensor
- ❑ electrical spirit level
- ❑ lights with cameras
- ❑ guide wheels

The model of measuring device

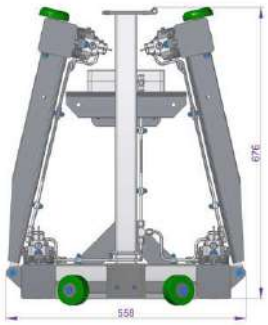
16

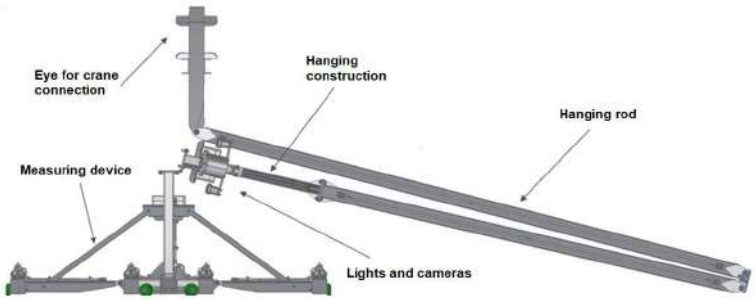
16

MEASUREMENT OF CORE BAFFLE

Transport and installation of device

- dimension requirements for transport
- manipulation by polar crane
- connection by hanging construction and hanging eye





17

17

MEASUREMENT OF CORE BAFFLE

Photo measuring device

Switchboards – input measuring and control connector connections

Completation of measuring device

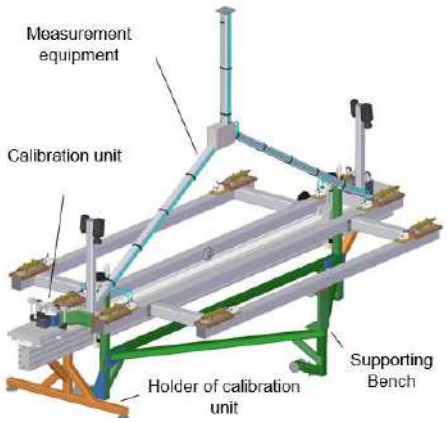
18

18

MEASUREMENT OF CORE BAFFLE

Calibration system

- The calibration system consists of a supporting bench, a fixed and movable measuring tables, a laser and a control and evaluation electronics.
- Accuracy of calibration system is ± 5 μm for measuring up to 3,3 m.
- System is being by the company ÚPT AV ČR.
- The accuracy of the calibration system is metrologically verified.



Calibration unit with measuring device

19

MEASUREMENT IN TEMELIN NPP

Preparation for measurement at NPP

- series for measuring tests
- preparation of documentation for the measurement process including quality assurance
- assembly/disassembly process and plan manipulation in reactor hall
- decontamination procedure

Measuring device after assembly with personal UJV Rez

20

MEASUREMENT IN TEMELIN NPP

Photo from measurement

The device in reactor pressure vessel

Lowering the device into the reactor

21

SUMMARY

- The device according to specific technical requirements was developed for the measurement of the VVER 1000 NPP Temelin core baffle.
- Successful initial measurement at Temelín NPP, unit 1 and 2.
- Repeated measurements are planned in the future to determine the trend of swelling development.
- Necessary for assurance of LTO 60+ for VVER 1000 (and larger reactors)

22

Thank you for attention

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ÚJV Řež, a. s.
Hlavní 130, Řež
250 68 Husinec, Czech Republic

e-mail: petr.vlcek@ujv.cz
www.ujv.cz

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PEOPLE | INNOVATION | TECHNOLOGY

Nozzle Weld Inspection In A 3D Environment

Paul Hillman[1], Johan Berlanger[1], Guy Maes[1]

[1]Eddyfi Technologies, Quebec City, Canada

E-mail address (corresponding author): PHillman@Eddyfi.com

The non-destructive inspections of complex geometries, such as nozzle welds, with phased array ultrasonic testing (PAUT) can be challenging. Beam misalignment with the weld due to the 'saddle geometry' can lead to incorrect coverage of the region of interest as well as difficulty in accurate positioning and sizing of indications.

This presentation describes the challenge and an innovative inspection approach through use of the UltraVision® 3D software package for inspection technique design, acquisition and analysis in a 3D environment to increase the technique efficiency and probability of detection.

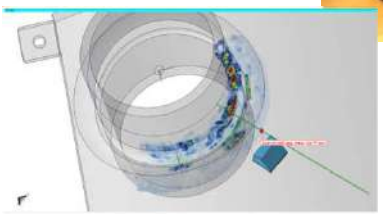
Steps described in the presentation will include design and validation of the inspection technique for nozzle welds using 3D CAD files, raytracing, scanner simulation and coverage maps. As well as Simulation and validation of acoustic beams for optimized 2-D matrix array probes. Possible scanner approaches will be discussed, and an example of acquisition shown.

Captured data will be shown to be analysed and reconstructed in the 3D environment with description of available tools to aid in a successful inspection.

Keywords: NDT, phasedarray, Inspection, Nozzle, 3D

Eddyfi Technologies

NOZZLE WELD INSPECTION IN A 3D ENVIRONMENT



June 29, 2023
NDE in Nuclear 2023, Sheffield UK

Presented by Paul Hillman

Co-Author – Johan Berlanger, Guy Maes

AGENDA

Eddyfi Technologies

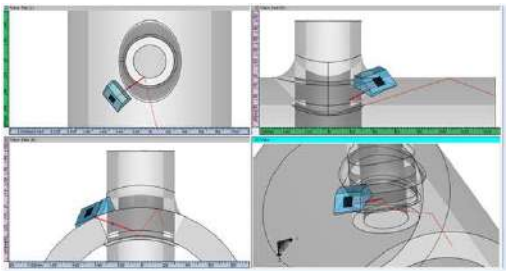
- The challenge
- Data presented with Eddyfi (Zetec) UltraVision® 3D
  - Designing a setup
  - Data Acquisition
  - Analysis
- Conclusions

ULTRAVISION
COMPLETE UT AND PHASED ARRAY INSPECTION PACKAGE

THE CHALLENGE

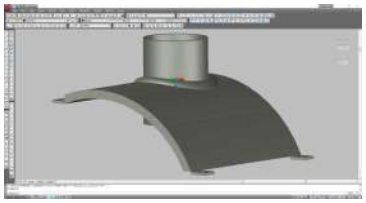
- Beam interaction changes for all circumferential positions
- Beam skewing effect of saddle surface geometry
- Adequate coverage of weld volume for all circumferential positions
- Appropriate beam interaction with fusion faces and weld volume, half and full skip
- Correct plotting of indications in volume considering real beam path for characterisation, positioning and sizing

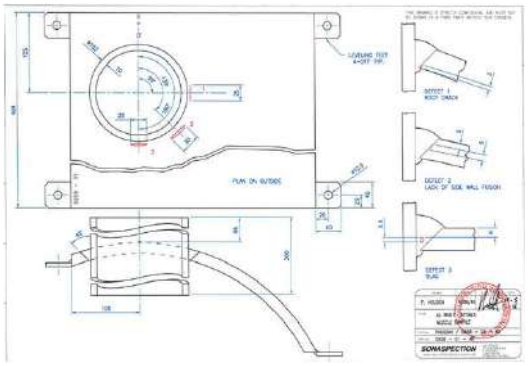
Nominal 55° Shear wave



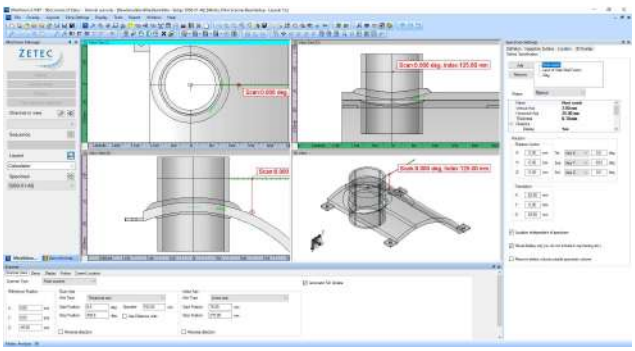
TEST PIECE

- Sonaspection Nozzle sample from Phoenix ISL
  - OD 170.3mm through OD 609.6mm
  - 3 embedded flaws
    - Root crack, 3mm heigh, 25mm long
    - LoSWF, 5mm heigh, 30mm long
    - Slag, 3.5mm heigh, 25mm long
- CAD model created from drawing - .SAT format for UltraVision 3D import

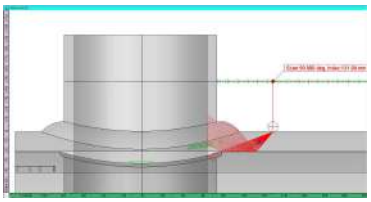


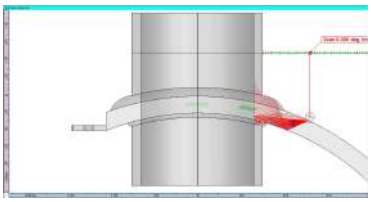


IMPORTING & POSTULATING FLAWS



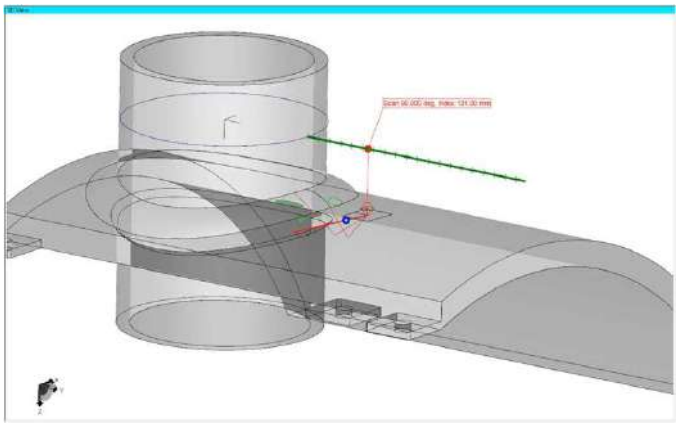
- Adding flaws into model allows them to act as reflectors for ray tracing
- Represents beam interaction and reflection to correctly assess probe position and beam properties required





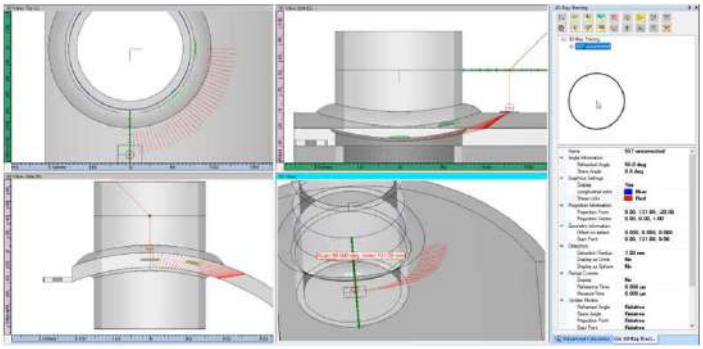
SADDLE GEOMETRY SKEWING

- 3 beams shown 40T, 55T, 70T
- Aligned with radial axis at 0° and 90° positions
- As probe rotates from axial to circumferential beams skewed in 1st leg
- Skewing reciprocates around full circumference
- Effects differ per angle based on sound path and backwall reflection point



CALCULATING SKEW CORRECTION

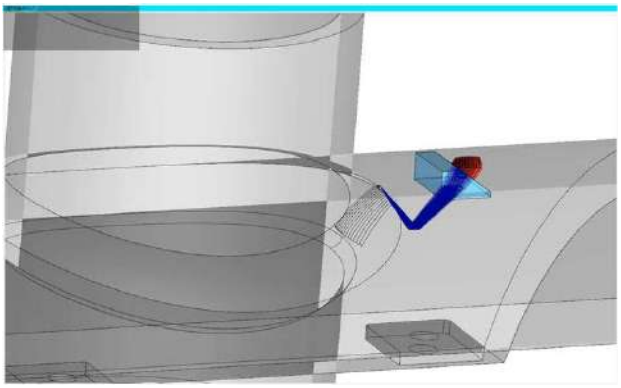
- Beams postulated along the scan axis
- Align ray command corrects skew of beams to align with radial axis
- Required skew plotted for range of refracted angles

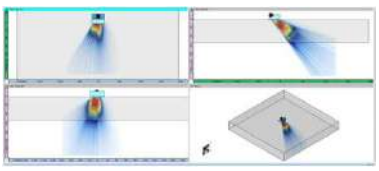


Radial position 131mm			
Scan	Refracted angle		
(°)	40T	55T	70T
0.0	0.0	0.0	0.0
2.5	1.3	0.7	0.4
5.0	2.5	1.5	0.8
7.5	3.8	2.2	1.2
10.0	5.0	2.9	1.5
12.5	6.2	3.6	1.9
15.0	7.3	4.3	2.2
17.5	8.4	4.9	2.6
20.0	9.5	5.6	2.9
22.5	10.5	6.1	3.2
25.0	11.4	6.6	3.5
27.5	12.2	7.1	3.7
30.0	12.9	7.6	3.9
32.5	13.6	7.9	4.1
35.0	14.1	8.2	4.3
37.5	14.5	8.5	4.4
40.0	14.8	8.6	4.5
42.5	15.0	8.7	4.5
45.0	15.1	8.8	4.6
47.5	15.0	8.7	4.5
50.0	14.8	8.6	4.5
52.5	14.5	8.5	4.4
55.0	14.1	8.2	4.3
57.5	13.6	7.9	4.1
60.0	12.9	7.6	3.9
62.5	12.2	7.1	3.7
65.0	11.4	6.6	3.5
67.5	10.5	6.1	3.2
70.0	9.5	5.6	2.9
72.5	8.4	4.9	2.6
75.0	7.3	4.3	2.2
77.5	6.2	3.6	1.9
80.0	5.0	2.9	1.5
82.5	3.8	2.2	1.2
85.0	2.5	1.5	0.8
87.5	1.3	0.7	0.4
90.0	0.0	0.0	0.0

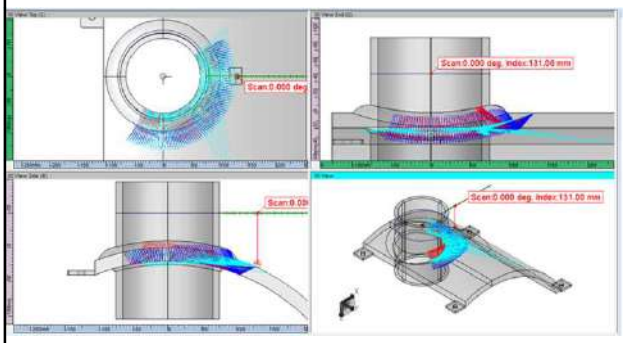
PROBE APPROACH – 2D MATRIX ARRAY

- AM 5MHz 9x7el
- 2D matrix array allows for beam steering, focussing and skewing in secondary plane
- Focal laws generated to cover 40 to 70 degree refracted for -15 to +15 degree refracted angles
- No physical skewing of probe required, data acquired in single pass
- Small footprint allows conformity of wedge



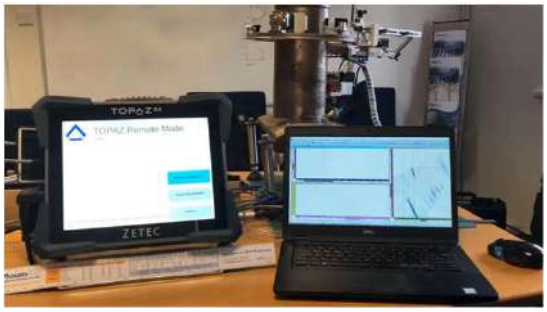


COVERAGE MAP



- Represents coverage of selected beams for every scan position
- Helps to ensure that all areas of interest are adequately included.
- In extreme conditions the coverage map can reveal areas on complex geometries that are missed when setup is assumed from another area.

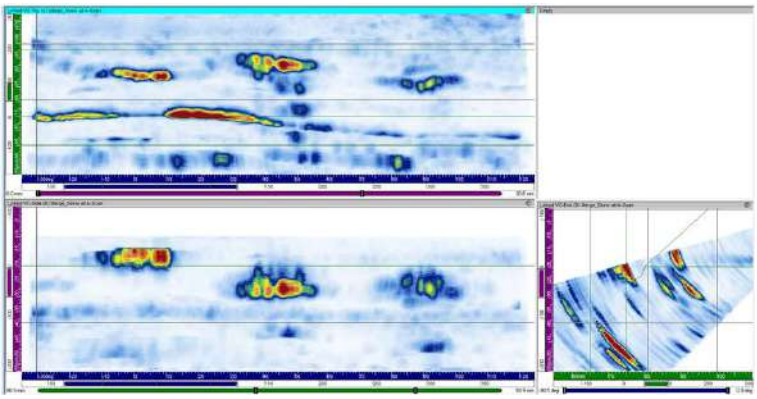
ACQUIRING DATA



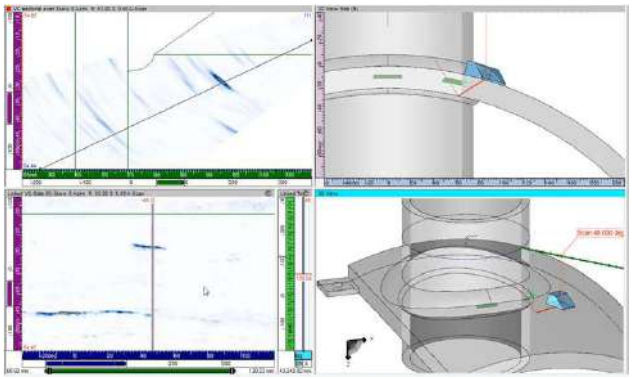
- Eddyfi Topaz64 remotely controlled from UltraVision 3
- Phoenix ISL automated Nozzlescan scanner
- Eddyfi AM 2D Matrix array with 55SW wedge
- Data acquired in single pass
  - 1 index offset
  - All refracted and skew angles

ANALYSIS – MERGED DATA

- Merged dataset of all refracted and skew angles
- Soft gates assist with isolation of indications
- 3 indications clearly identified in B-scan view
- 2D overlay assists with location but not accurate for complex geometry



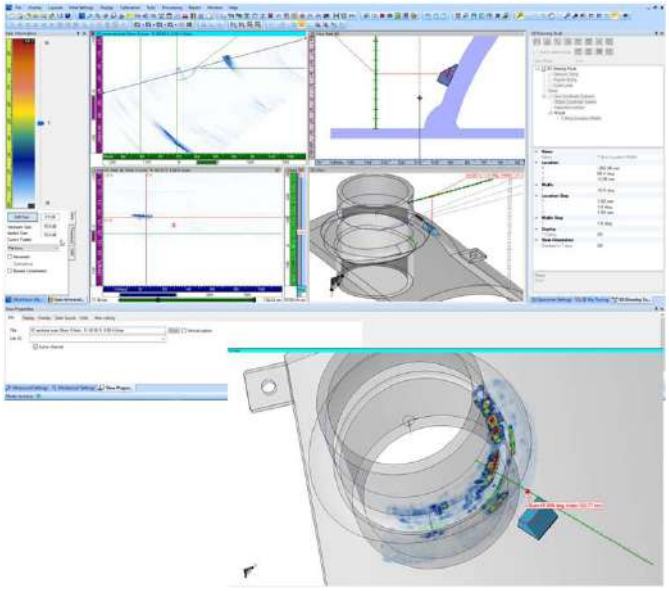
ANALYSIS – 3D RAY TRACING



- 3D and 2D views linked
- 3D ray created with 2D view cursor parameters
- Helps to screen data and identify locations of indications
- Range cursors show time of flight of cursors from 2D data views

ANALYSIS – 3D DATA PLOTTING

- Plotting of data considering 3D geometry and beam paths
- Aids in positioning and characterisation in complex specimens
- Combined 2D and 3D data views
- Cutting planes, allow isolation of view in complex CAD model



CONCLUSIONS

- Advanced software tools allowing design of inspection technique in 3D environment assist in the success and recording of complex geometry inspections.
- Accounting for real world beam path and interactions and correcting for skew effects ensure correct weld coverage.
- Use of 2D matrix array probes allows electronic skewing whilst maintaining one physical skew angle with data merging in analysis.
- Plotting data in a 3D environment helps in characterisation, proper location and sizing of indications.

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THANK YOU

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18. NDE Modelling & Simulation

The presentations in this session are listed in the table below.

NDE Modelling & Simulation	**Chair:** Iikka Virkkunen (Trueflaw)
TFM imaging simulations of defects near or in the weld bevel: modelling approach and advances on new hybrid finite element tools	N. Leymarie (CEA) et al.
Evaluation of Ultrasonic Simulation Software	Mark Dennis, Terrill Massey, George Connolly (EPRI)
Probabilistic Graphical Model for Sizing Assessment in Ultrasonic Testing of Dissimilar Metal Weld	Mohammed Siddig (VTT)

TFM imaging simulations of defects near or in the weld bevel: modelling approach and advances on new hybrid finite element tools

N. Leymarie[1], A. Imperiale[1], J. Barras[1], P. E. Lhuillier[2], A. Schumm[2], Y. Gelebart[2], E. Demaldent[1]

[1]Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France
[2]EDF R&D, EDF Lab Les Renardières, Département Matériaux et Mécanique des Composants, 77818 Moret-sur-Loing, France

E-mail address (corresponding author): nicolas.leymarie@cea.fr

In many safety-critical industries with inspection requirements, and particularly in the nuclear sector, ultrasonic testing (UT) of welded components remains an area of continuous improvement. Monitoring and imaging defects near or within a weld bevel often presents several difficulties related to both local geometry deformations and material property variations. For several years, the CEA LIST and EDF R&D teams have been working in cooperation on the development of advanced UT simulation tools to meet these challenges. Integrated into the CIVA software platform, new hybrid approaches coupling ray models and finite elements (FE) can handle both 2D and 3D inspection configurations, with FE calculations performed in the part to accurately simulate all wave propagation and diffraction phenomena. Although the computation time remains higher than for standard ray-based approaches, these results can serve as a reference improving reliability and opening new perspectives on the validation strategy of simulation tools. In order to achieve reliable results, this approach needs to be supported by a knowledge base of relevant weld model data. Benefiting from the research actions carried out for several decades on the characterisation of the anisotropy and attenuation properties of the weld as well as on the description of the variations within the bevel, we propose a complete parameterisation of the weld, pertinent for UT, via the CIVA interface.
In this presentation, we propose to review the newly developed functionalities, both on the material part related to the weld, with the integration of the MINA model, and on the bevel geometry part. We then discuss the coupling methodology dedicated to inspection simulations as well as the selected automated meshing procedures which do not require any particular expertise. Finally, TFM imaging simulations are presented by comparing the results obtained through a standard ray-based approach with the new module exploiting the FE computational core.

Keywords: UT simulation, weld modelling, anisotropy, MINA-like description, TFM imaging

TFM imaging simulations of defects near or in the weld bevel: modelling approach and advances on new hybrid finite element tools

N. Leymarie[1], A. Imperiale[1], J. Barras[1], P. E. Lhuillier[2], A. Schumm[2], Y. Gelebart[2], E. Demaldent[1]
[1] Université Paris-Saclay, CEA, List
[2] EDF R&D, EDF Lab Les Renardières

NDE in Nuclear 2023

SNETP Sustainable Nuclear Energy Technology Platform

Outline

1. **Parametric descriptions for UT simulations**
   - Bevel shapes of butt joint welding
   - Advanced material properties for austenitic welds
   - Realistic crack geometries
2. **Modelling approaches**
   - Modal ray-based approach and limitations
   - New hybrid FE tools as reference solutions – CIVA FE perspective
3. **TFM imaging simulation using CIVA - FE perspective**

1. Parametric description for UT simulations

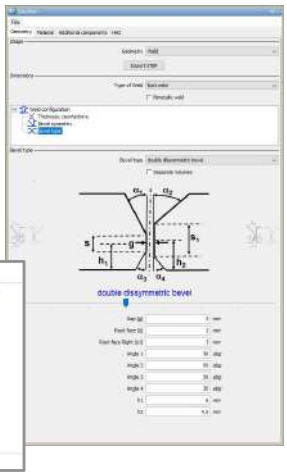
Weld properties and defects

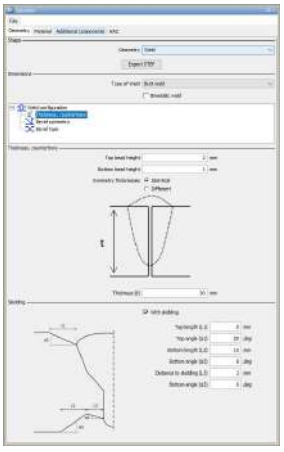
Parametric description of bevel geometries

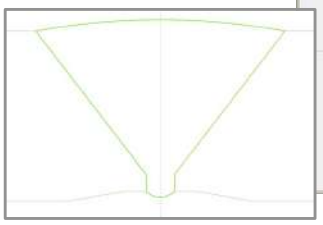
CIVA NDE

Wide range of parametric butt welding geometries

- Including nominal geometries of bevels…
  - V, J, U shapes (single and double)
  - with or without root
- … and more generic shapes (if necessary)
- Other relevant and useful parameters
  - Top and bottom weld beads
  - Counterbore…







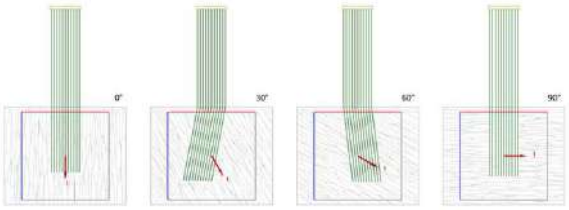
Parametric description of austenitic weld properties

Specificities of austenitic welds

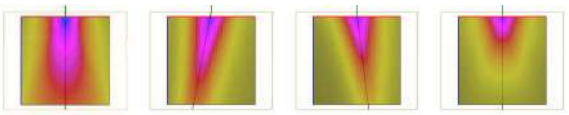
- Columnar grain microstructure:
  - preferential texture <100> around grain elongation axis
  - ⇒ Effective material for UT simulations: anisotropic (quasi-hexagonal) damped material whose symmetry axis is correlated with the elongation axis

Effective stiffnesses (GPa)	C_{11}	$C_{22} = C_{33}$	$C_{12} = C_{13}$	C_{23}	C_{44}	$C_{55} = C_{66}$
Real Part	220	245	135	110	80	110
Imaginary Part	1.6	12	2	2.5	2.7	4.3

Anisotropic effective material properties



Energy deviation w.r.t. wavefront direction

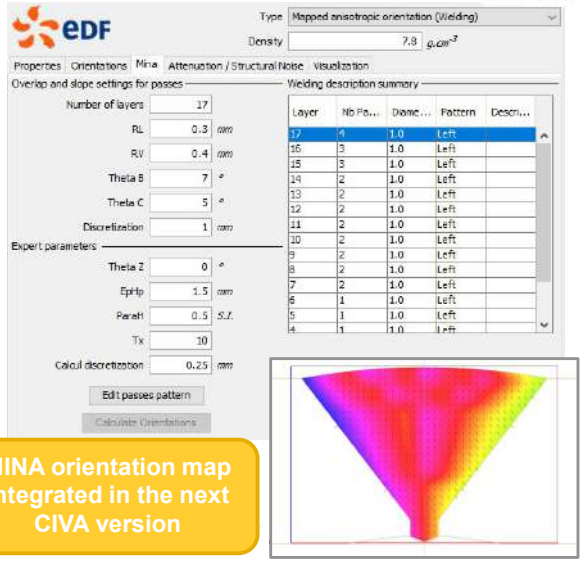


Damping variations w.r.t. wavefront direction

Parametric description of austenitic weld properties

Specificities of austenitic welds

- Columnar grain microstructure:
  - preferential texture <100> around grain elongation axis
  - ⇒ Effective material for UT simulations: anisotropic (quasi-hexagonal) damped material whose symmetry axis is correlated with the elongation axis
- Grain orientation variation in multi-pass welds
  - 2D description in the plane normal to the deposit axis of the welding passes where deposit axis = extrusion direction (planar or cylindrical essentially)
  - Scalar data (angle) to define fiber orientation
    - Piecewise descriptions,
    - Orientation laws or grid angle data



MINA orientation map integrated in the next CIVA version

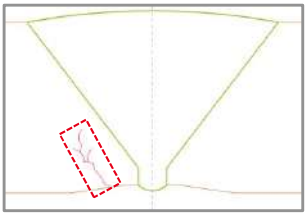
Parametric crack description

Account for complex shaped cracks

- Stress Corrosion Cracking (SCC)

SCC image

Quad mesh representation



Import and positioning in the CIVA scene

Parametric variation on the position of crack nodes

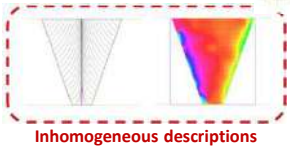
2. Modelling approaches

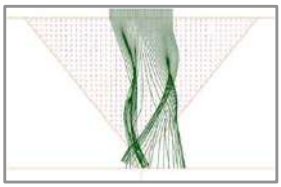
Ray-based approach and hybrid FE solution

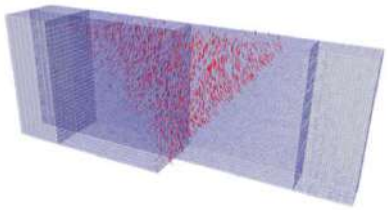
Wave propagation models in smoothly inhomogeneous weld descriptions

Modelling options available

- Ray-based approach
  - Modal decomposition
  - Straight ray tracing in homogeneous parts replaced by curved ray paths computations
    + reduced HF artefacts (w.r.t. piecewise description)
    - iterative schemes increasing computation time
- Transient spectral FE approach (next CIVA version)
  - Full wavefield simulation
  - Optimized FEM solution using spectral high order elements
    + efficient iterative scheme (mass-lumped technique)
    + low memory footprint
    - Increasing time computation with center frequency value of the probe, especially in 3D



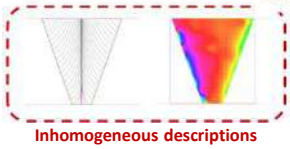


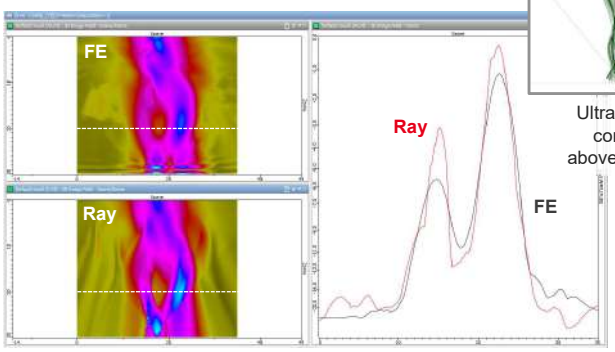


FE hybrid solutions for beam radiation and ultrasonic inspection

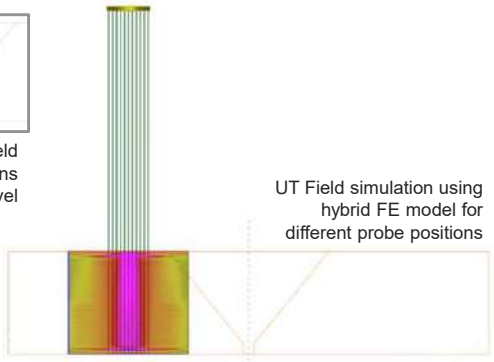
Quantify ray artefacts – FE as reference solution

- Good agreement on wavefront (ToF) and beam energy splitting
- Amplitude discrepancies depending on probe position observed locally close to caustic zones





Ultrasonic field comparisons above the bevel



UT Field simulation using hybrid FE model for different probe positions

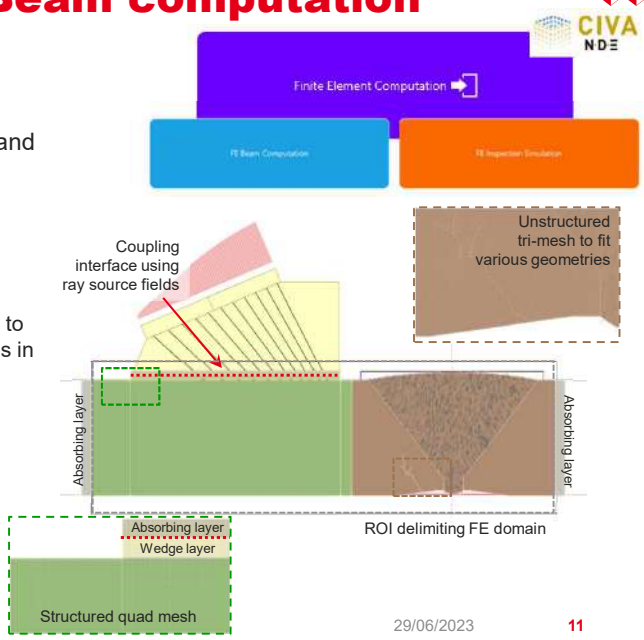
FE hybrid solutions for Beam computation and echo response

Coupling principle

- FE Beam solution for calculating ultrasonic fields and FE Inspection solution for UT simulation
  - Calculation of the current source field usin the **ray model in the wedge or coupling medium**
  - **FE calculation in the component, taking into account the surrounding environment**
  - Echo response determined using reciprocity principle to the surface of the part of calculations of radiated fields in reception (mechanical position and R shots)

Automatic meshing procedure

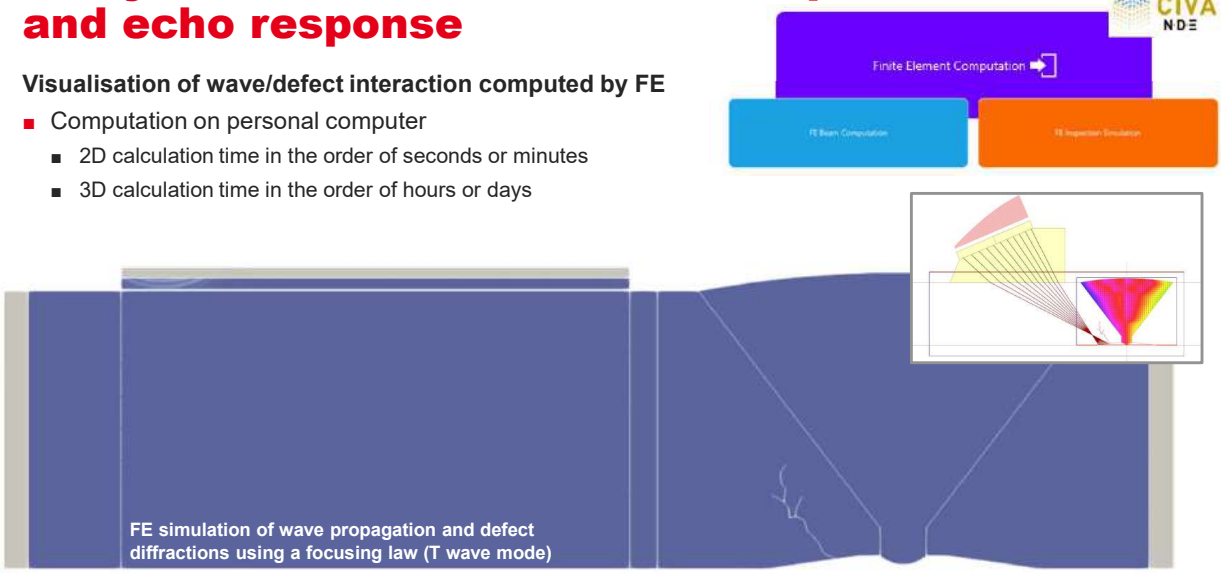
- Delimiting the FE domain according to the ROI
- Coexistence of quad- or tri-meshes depending on the complexity of each ME



FE hybrid solutions for Beam computation and echo response

Visualisation of wave/defect interaction computed by FE

- Computation on personal computer
  - 2D calculation time in the order of seconds or minutes
  - 3D calculation time in the order of hours or days



FE simulation of wave propagation and defect diffractions using a focusing law (T wave mode)

3. TFM imaging simulation using CIVA

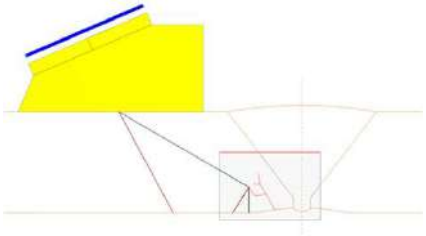
Example of TFM imaging results

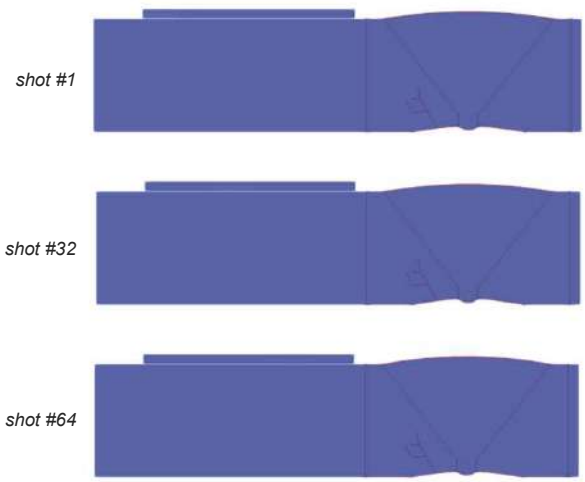
FMC acquisition

- One FE calculation for each of the 64 transmit shots
- For each of them a synthesis of the elementary A-Scans for all the active receivers

Application case

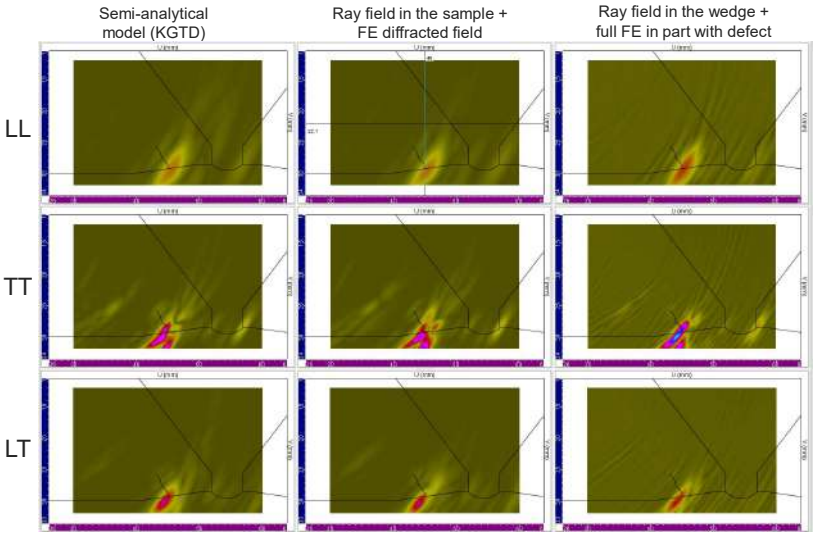
- PAUT L60 wedge probe @ 2.25 MHz
- Linear, 64 elements, pitch 0.6 mm
- Homogeneous assumption for imaging

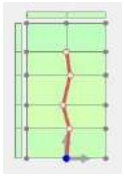




Example of TFM imaging results

Model comparisons – simple shape defect

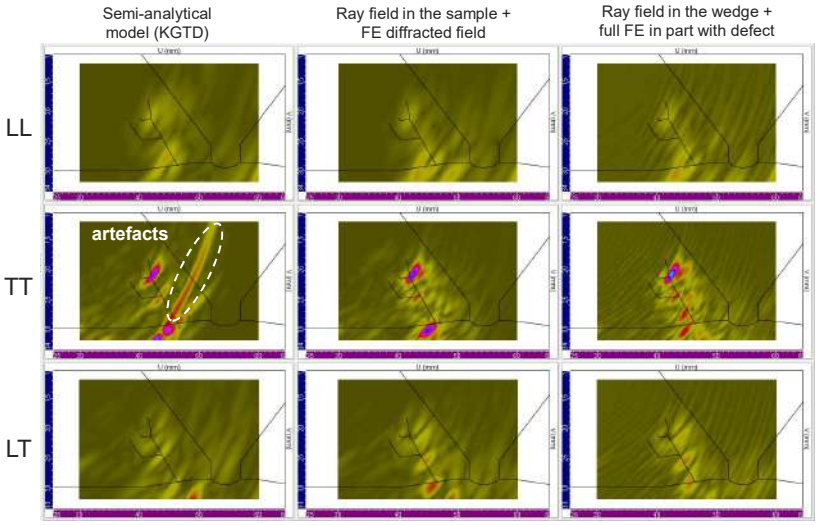


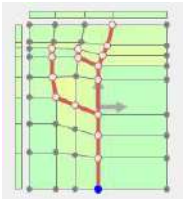


Comparable results with differences of less than 2.5 dB

Example of TFM imaging results

Model comparisons – complex shape defect

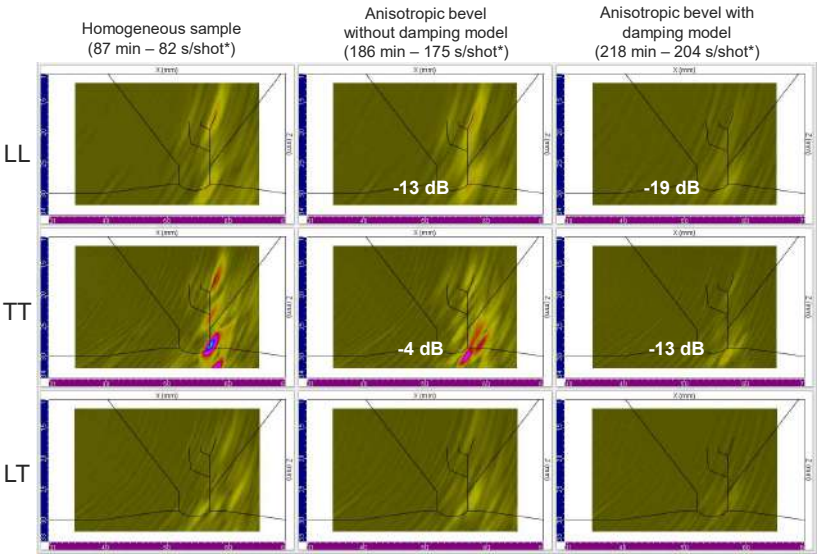


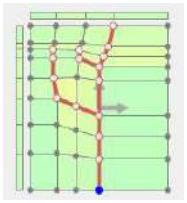


Artefact on KGTD and satisfactory results for FE diffraction model

Example of TFM imaging results

Bevel description effect – defect in the bevel





Influence of welding characteristics predicting various performance losses w.r.t. modes

(*) calculation performed on [Dual CPU] Intel Xeon Platinum 8276L 56 cores @ 2.20GHz – 512Go

Conclusion

Advanced tools to facilitate parametric studies for UT simulations

- bevel geometry
- mechanical properties using MINA orientation map
- complex defect shapes

New FE (next CIVA version)

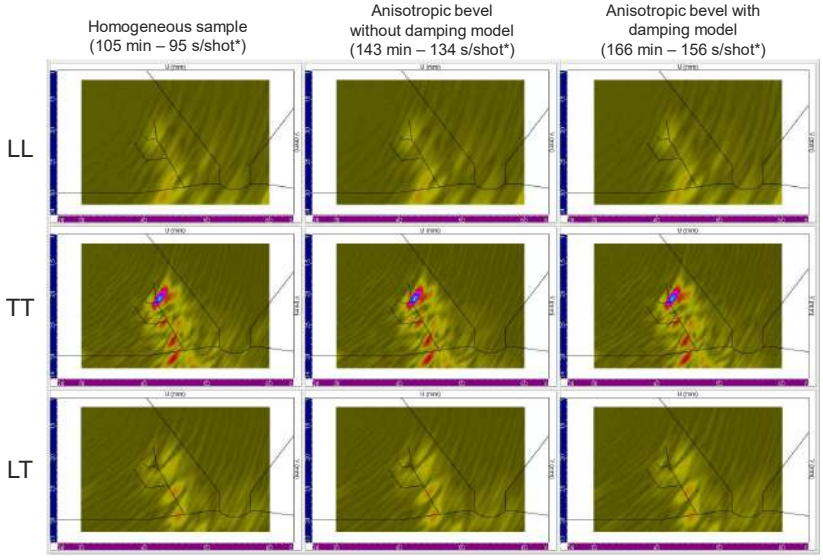
- full wave propagation without meshing expertise
- reference solutions for beam radiation and UT inspection

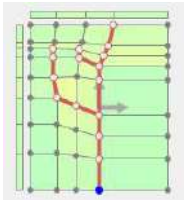
Thank you for your attention

Contact : nicolas.leymarie@cea.fr

Example of TFM imaging results

Bevel description effect – defect in front of the bevel





Virtually no influence of bevel material properties for this defect position

(*) calculation performed on [Dual CPU]
Intel Xeon Platinum 8276L
56 cores @ 2.20GHz – 512Go

Evaluation of Ultrasonic Simulation Software

Mark Dennis[1], George Connolly[1], Terrill Massey[1]

[1]EPRI, Charlotte, NC, USA

E-mail address (corresponding author): mdennis@epri.com

Modeling and simulation technology can potentially replace and/or augment physical development and testing. Simulations can also be used to assist non-destructive evaluation (NDE) examiners in the analysis of large quantities of data images to improve flaw detection results, and to optimize or design new probes or NDE techniques. In order for simulation tools to be used in confidence they must be evaluated and validated for particular applications.

This research will evaluate two ultrasonic simulation tools: CIVA and OnScale. The first case study involves a widely used stainless steel miniature angle beam reference block, also called a Rompas block. This block contains a 1-in.-radius (25.4-mm-radius), a 2-in.-radius (50.8-mm-radius), and a 0.078-in.-diameter (2.0-mm-diameter) side-drilled hole. A 2.25-MHz transducer mounted on a 45° shear wave wedge was used to examine this reference block. The simulated time of flight and amplitude of these reflectors are compared against the experimental values.

In the second study, a stainless steel welded plate containing two notches are investigated. The simulated acquisitions were reproduced with CIVA using a homogeneous anisotropic weld model and also a heterogenous weld based upon Ogilvy's approximated grain structure model. The OnScale simulation procedure involved six different simulations involving two different weldment geometries and three different weld material property models. A 1.5-MHz 45° shear wave search unit was used throughout this study. The simulated ultrasonic results from CIVA and OnScale are compared to corresponding experimental results.

Keywords: Austenitic stainless steel, CIVA, OnScale, Ultrasonic weld simulation.

Evaluation of Ultrasonic Simulation Software

Thursday 29 June 2023

Mark Dennis, EPRI, Inc.
Terrill Massey, EPRI, Inc.
George Connolly, EPRI, Inc.

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Outline

- Software comparison (OnScale vs CIVA) against experimental results
- Two case studies:
  - **1.** Angle beam reference block: *Rompas block*
    - Simulated ToF and reflector amplitudes are compared against experimental values
  - **2.** Welded plate with two EDM notches
    - CIVA weld modeling procedure
    - OnScale weld modeling
    - Comparative results and discussion

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First Case Study: *Rompas Block*

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Block and Instrument

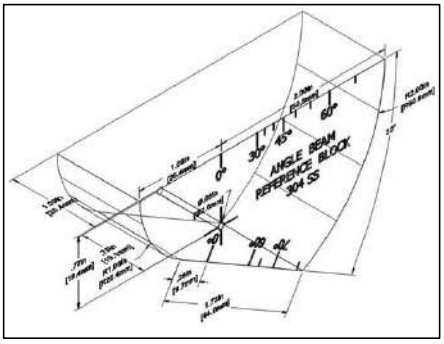
First Case Study: Rompas Block

- Rompas Block:
  - Angle beam reference block containing:
    - Ø2mm SDH
    - R1in. curved reflector
    - R2in. curved reflector
  - Material: 304 SS
- Scanned using Zetec DYNARAY
  - Scan resolution: 1mm (0.039in.)
  - Probe faces both curved reflectors with motion along top face

SEARCH UNIT ATTRIBUTES

Attribute	Value
Probe Size	Ø0.375in. (Ø9.5mm)
Centre frequency	2.25MHz
Incident angle	45°

Angle beam reference block with shear wave probe and wedge



Angle beam reference block orthographic view with dimensions

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Simulation

First Case Study: Rompas Block

- CIVA
  - Geometry imported as 2D CAD and extruded
  - SDH inserted as native CIVA defect
  - Scan: 76 steps
- OnScale
  - 2D model
  - Complete geometry imported as 2D .stp files
  - Scan: 56 steps

SPECIFIC CIVA MODEL ATTRIBUTES

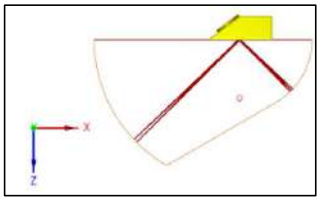
Attribute	Value
Computation Mode	3D
Mode Count	496
SDH Interaction Type	SoV
Specimen Option Computation	Specular Model
Half Skip Count	4

MATERIAL PROPERTIES (BOTH MODELS)

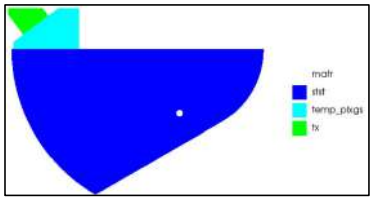
Component	ρ	c_L	c_T
Block	7890kgm^{-3}	5790ms^{-1}	3100ms^{-1}
Wedge	1180kgm^{-3}	2680ms^{-1}	1320ms^{-1}

SPECIFIC ONSCALE MODEL ATTRIBUTES

Attribute	Value
Wavelength	1.19mm
Elemental dimension	0.048mm
Scan position count	56



CIVA model visualization with T rays traced with reflection



OnScale model visualization showing material assignment

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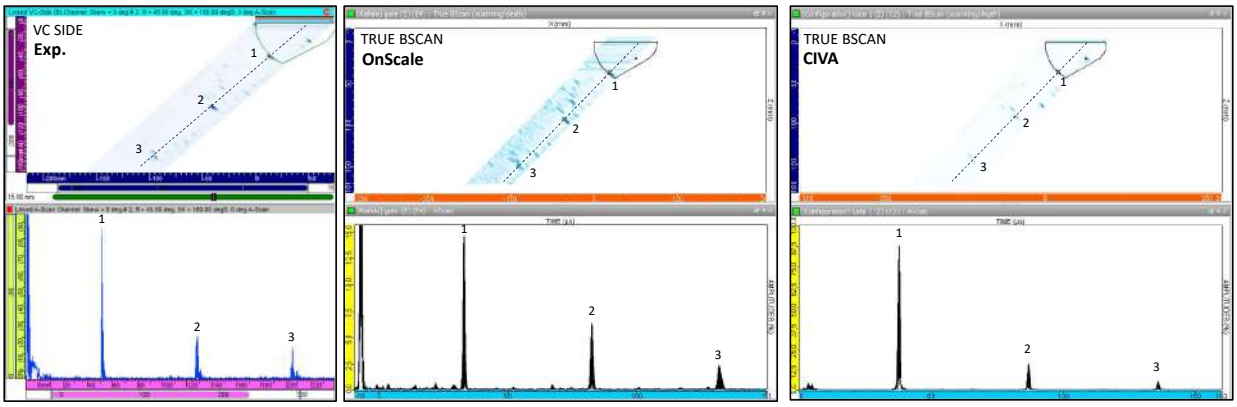
Simulation Comparison

First Case Study: Rompas Block

- Reference signal (first reflection from the R1in. face) for both time and amplitude
- Reflections from the R2in. face shown comparatively
  - First three successive reflections identified



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Collated Results

First Case Study: Rompas Block

- Simulations tends to slightly overpredict ToF
  - Average ToF difference between experiment and CIVA: 0.72µs
  - Average ToF difference between experiment and OnScale: 0.80µs
  - These differences correspond to 1.12mm and 1.24mm of shear wave half-path distance in stainless steel
- Greater variation in simulation performance with respect to reflector amplitude
  - CIVA tends to slightly underpredict reflection amplitude (σ=2.4dB)
  - OnScale tends to slightly overpredict reflection amplitude with a greater variation (σ=5.1dB)

TIME OF FLIGHT (µs)

Reflector	Exp.	OnScale	CIVA
SDH	0.80	1.48	1.46
R1in. (first)*	0.00	0.00	0.00
R1in. (second)	48.41	49.15	48.70
R1in. (third)	97.51	98.29	98.32
R2in. (first)	16.16	16.80	16.62
R2in. (second)	65.35	66.20	65.36
R2in. (third)	113.75	114.88	115.86

AMPLITUDE (dB)

Reflector	Exp.	OnScale	CIVA
SDH	-14.1	-16.3	-15.9
R1in. (first)*	0.0	0.0	0.0
R1in. (second)	-10.2	-6.7	-17.1
R1in. (third)	-13.7	-12.7	-26.0
R2in. (first)	-0.7	1.2	-1.2
R2in. (second)	-11.4	-6.7	-15.9
R2in. (third)	-13.9	-12.7	-26.0

* used as reference reflector for both amplitude and time

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Second Case Study: Plate Weld

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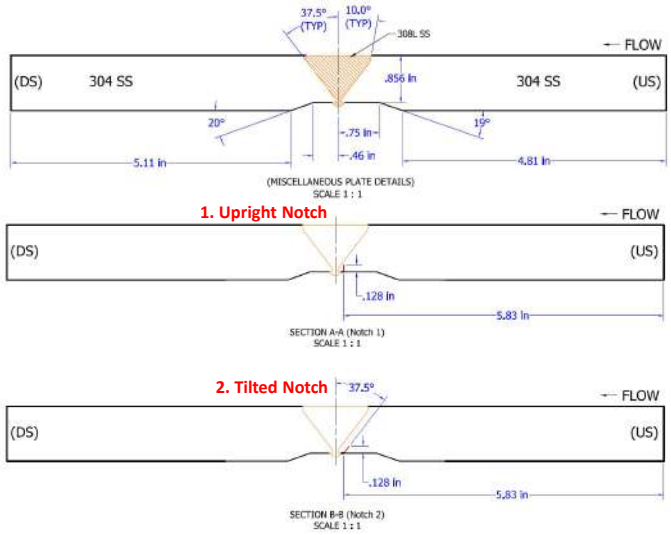
Specimen Attributes

Second Case Study: Plate Weld

- Stainless steel welded plate designed in-house at EPRI
  - Overall dimensions:
    - 12.0in.×11.95in.×1.0in. (304.8mm×303.5mm×25.4mm)
  - Longitudinal sound speed 5650ms^{-1};
  - transverse sound speed 3060ms^{-1};
  - Density: 7800kgm^{-3}
- Single element probe:
  - Centre frequency 1.5MHz
  - Conventional wedge: 45° for shear waves
  - Crystal diameter 0.375in. (9.53mm)
  - Coupled using water

FLAW ATTRIBUTES

Notch	1	2
Length	1.50in. (38.1mm)	1.50in. (38.1mm)
Height	0.128in. (3.25mm)	0.128in. (3.25mm)
Tilt	0.0°	37.5°
Side	US	US



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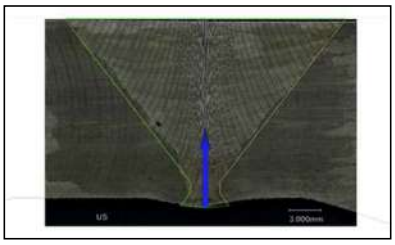
CIVA Weld Model

Second Case Study: Plate Weld

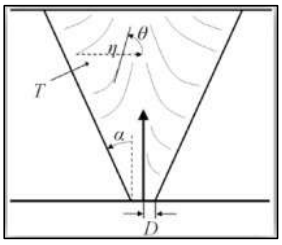
- Weld model:
  - Simplified cross-sectional structure
  - Material: Parametric Anisotropic Orientation (Welding)
  - Law Type: Ogilvy [1]
  - Weld macrography used to select weld parameters
- CIVA simulation details:
  - Neither attenuation nor structural noise is applied
  - CIVA computation mode set to 2D (reduction in computational burden with little loss of accuracy)
  - CIVA accuracy parameter set to 1
  - Sensitivity zone size: 60mm×20mm×50mm
  - Typical computation time: 10h on a 4-core workstation per B-Scan
  - Computed 120 shear wave modes with three half skips

OGILVY WELD MODEL LAW PARAMETERS

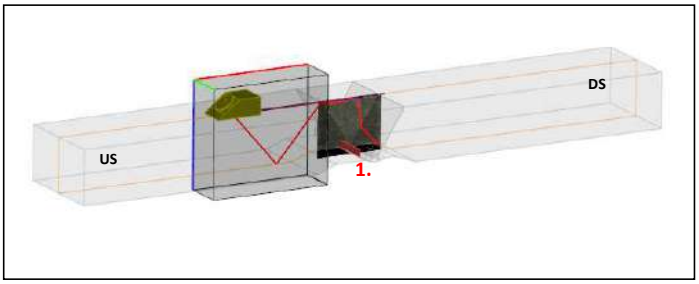
Parameter	Value
T	1.0
D	2.0mm
α	37.5°
η	0.8



Example of weld macrography



Significance of Ogilvy weld model law parameters [2]



CIVA model at upright notch showing traced ray and sensitivity zone

[1] Ogilvy, J. A. *Computerized ultrasonic ray tracing in austenitic steel using RAYTRAIM: Ray-tracing in anisotropic inhomogeneous media* **1985** NDT Int. 18(2) 67-77
[2] Connolly, G. D., Lowe, M. J. S., Temple, A. G., Rokhlin, S. I. *The application of Fermat's principle for imaging anisotropic and inhomogeneous media with application to austenitic steel weld inspection* Proc. R. Soc. A 465 (**2009**)

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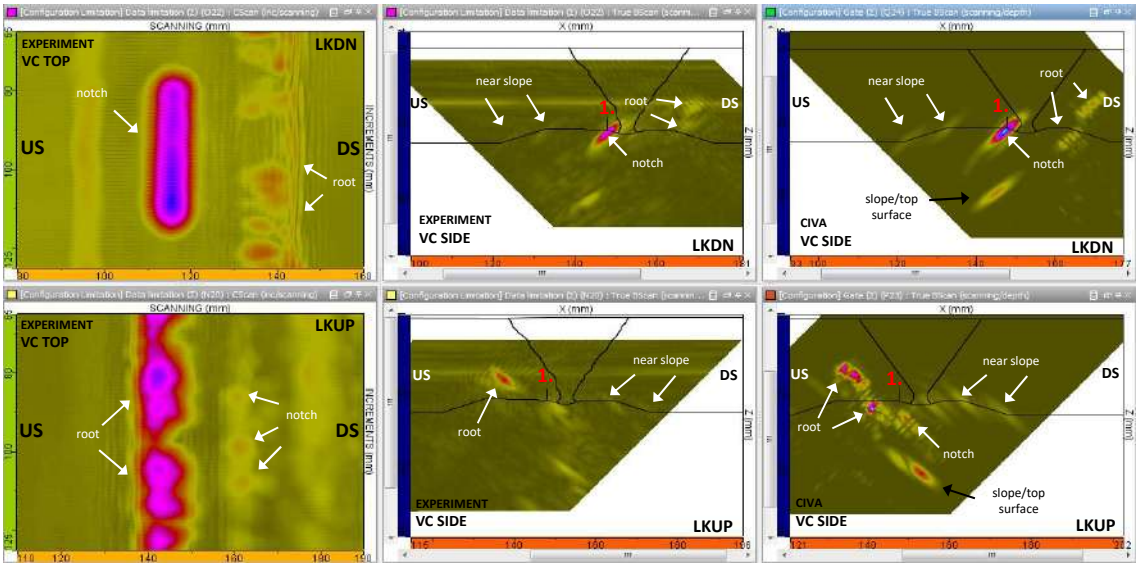
CIVA: Upright Notch

Second Case Study: Plate Weld



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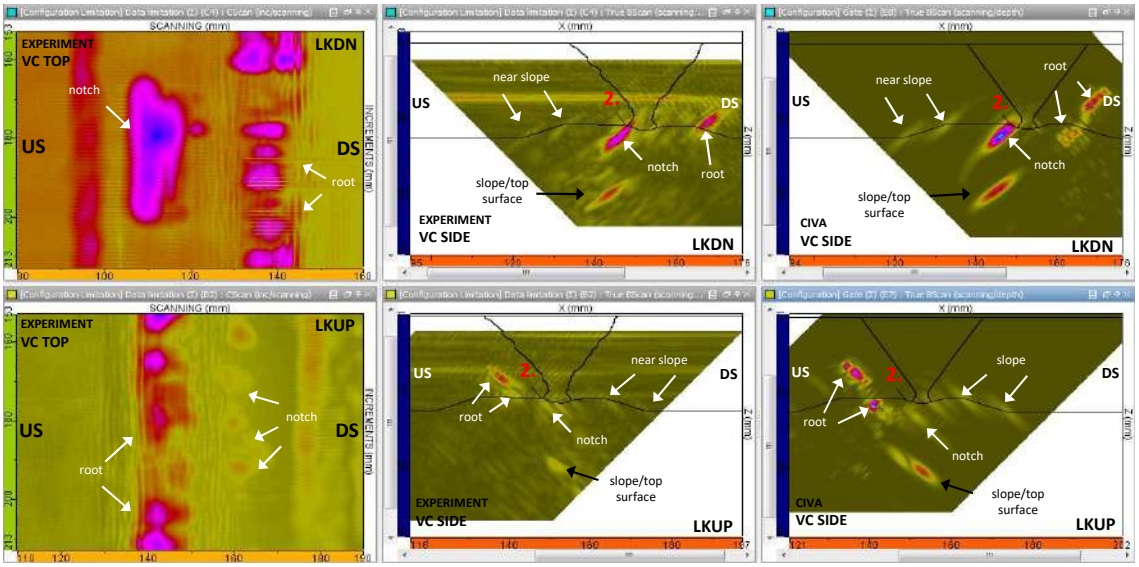
CIVA: Tilted Notch

Second Case Study: Plate Weld



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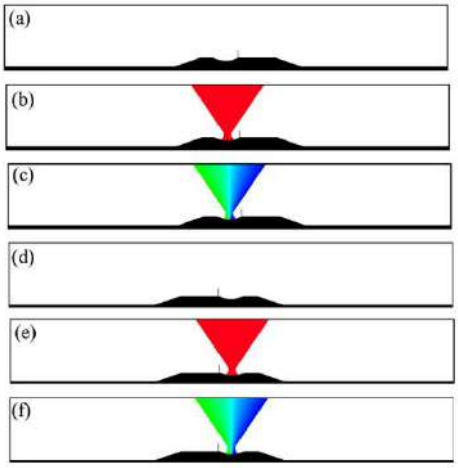
OnScale Weld Model

Second Case Study: Plate Weld

- A script developed in-house at EPRI is used to generate the Ogilvy mapping (elastic constant isograds) and the entire weldment geometry
  - Illustrated on right; colors indicate isograd orientation (red=horizontal; cyan=vertical)
- B-Scans carried out with probe step of 1mm in range [-30,60]mm where origin is along weld centerline
  - A-Scan introduced by pressure load; waveform matches that used in CIVA simulation
- 20 elements per wavelength
- Simulation time is 65µs, allowing sufficient time for multiple full skips
- Model is truncated behind the wedge to reduce simulation time
- Measures are taken to reduce internal sound reverberation within the wedge:
  - Transverse waves are suppressed within the wedge
  - Impedance matching to suppress reflections from front, top and back of wedge
  - "Pseudo-wedge" material placed behind the probe face so as to prevent reflections from the probe face



(a) LKUP; homogeneous and isotropic weld
(b) LKUP; homogeneous and anisotropic weld
(c) LKUP; inhomogeneous and anisotropic weld
(d) LKDN; homogeneous and isotropic weld
(e) LKDN; homogeneous and anisotropic weld
(f) LKDN; inhomogeneous and anisotropic weld

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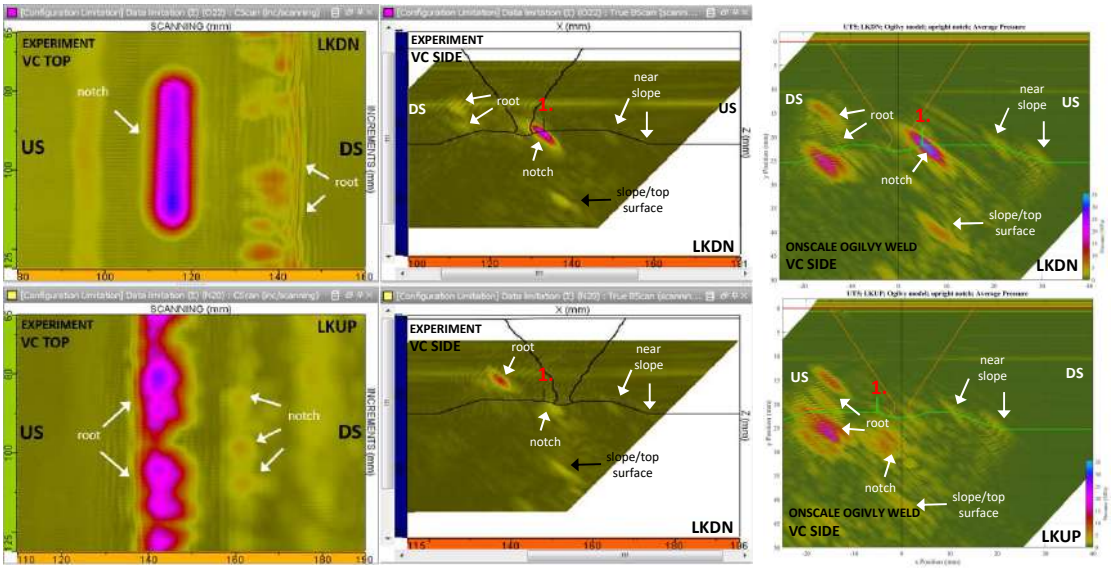
OnScale: Upright Notch

Second Case Study: Plate Weld



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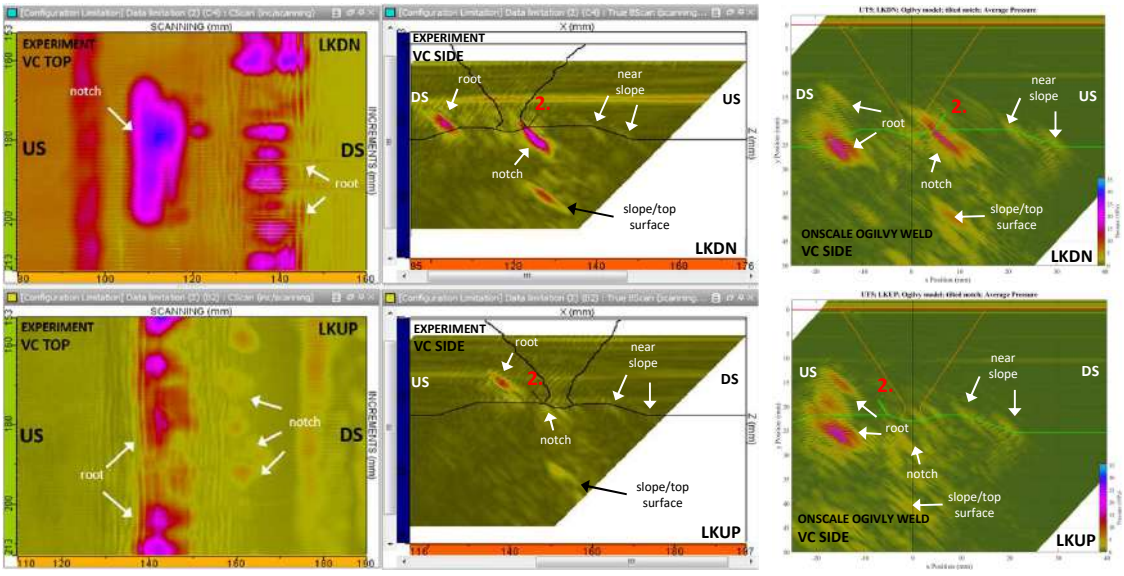
OnScale: Tilted Notch

Second Case Study: Plate Weld



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Collated Results

Second Case Study: Plate Weld

- Tables show reflection strengths relative to the reference reflector (SDH of Ø2mm at 12mm depth)
  - LKDN where flaws on near side of weld; larger distance between weld root and near slope
  - LKUP where flaws on far side of weld; smaller distance between weld root and near slope
- General observations
  - Better agreement in LKDN than in LKUP: Slope/top surface; upright notch and tilted notch
  - Better agreement in LKUP than in LKDN: Root
  - CIVA amplitude predictions for near slope far stronger than those of OnScale
  - CIVA amplitude predictions for notches looking through the weld stronger than those of OnScale

LKDN AMPLITUDES BY FEATURE (dB)

Echo	Exp.	CIVA	OnScale
near slope	-14.60	-12.88	0.50
slope/top surface	-4.54	-1.50	3.36
root	8.82	1.74	5.89
upright notch	9.08	10.99	7.47
tilted notch	1.26	4.98	5.13

LKUP AMPLITUDES BY FEATURE (dB)

Echo	Exp.	CIVA	OnScale
near slope	-17.00	-12.85	0.53
slope/top surface	-8.92	-2.73	1.59
root	5.09	5.12	6.08
upright notch	-5.29	-4.50	3.39
tilted notch	-8.67	-12.17	2.13

Detailed CIVA results published in EPRI Report #3002015980
Detailed OnScale results published in EPRI Report #3002018470

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Summary

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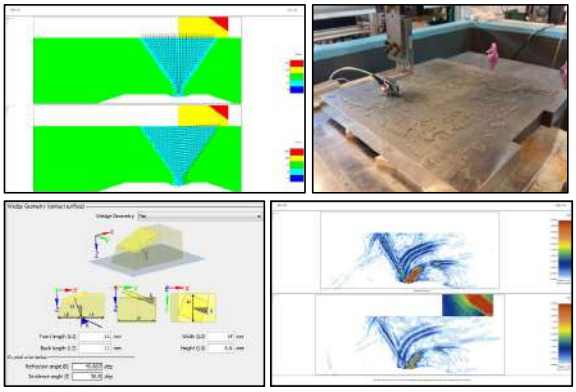
Summary

- Quantitative simulation and experimental comparison for two different case studies:
  - Simpler case: *Rompas block*
  - More complex case: Plate weld
  - Varied success with reflection amplitude predictions by simulation
- Ongoing drivers for modeling and simulation direction:
  - Identification and resolution of capability gaps
  - Need for accurate input parameters
  - Develop framework of best practice for conducting ultrasonic modeling and simulations
  - Supplement ultrasonic data for the EPRI UT simulator [3,4]



[3] *Technical Basis for Use of the EPRI Virtual Nondestructive Evaluation Ultrasonic Simulator in the Performance of Appendix VIII Hands-On Practice*. EPRI, Palo Alto, CA: **2020**. 3002017729
[4] *Plant Modernization Business Case: Cost-Benefit Analysis for Implementation of the EPRI Virtual NDE (VNDE) Ultrasonic Simulator*. EPRI, Palo Alto, CA: **2021**. 3002020581

Reports #3002015980 and #3002018470 available at epri.com

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Probabilistic Graphical Model for Sizing Assessment in Ultrasonic Testing of Dissimilar Metal Weld

Mohammed SIDDIG

VTT Technical Research Centre of Finland, Espoo, Finland

E-mail address (corresponding author): mohammed.siddig@vtt.fi

This work investigates an approach for evaluating the uncertainty associated with flaw sizing in Ultrasonic Testing in nuclear inspections using Bayesian Belief Networks (BBN). BBN graphically represents the probabilistic relationship between the sizing accuracy and some of the variables that cause its deviation.

The data for BBN training was collected from sizing information of Round-Robin trials reported in the literature and supplemented with sizing results obtained using the Ultrasonic Testing module of CIVA Non-Destructive Evaluation software. The test specimen used in the Round-Robin exercise and simulations was a dissimilar metal welded pipe. Given the available data, the variables considered causing sizing inaccuracy are the flaw's actual depth, tilt angle, and position in relation to inner and outer surfaces.

The proposed approach quantified the probabilities of flaw depth measurement variations. It gives the results in interactive Directed Acyclic Graphs (DAGs), which enables a user-friendly interface for examining various scenarios of sizing uncertainty.

Keywords: Ultrasonic Testing, sizing evaluation, Bayesian Network

Probabilistic Graphical Model for Sizing Assessment in Ultrasonic Testing of DMW

Mohammed Siddig
VTT Technical Research Centre of Finland

Contents

Background

Motivation and objective

Evaluating sizing accuracy with Bayesian Belief Network

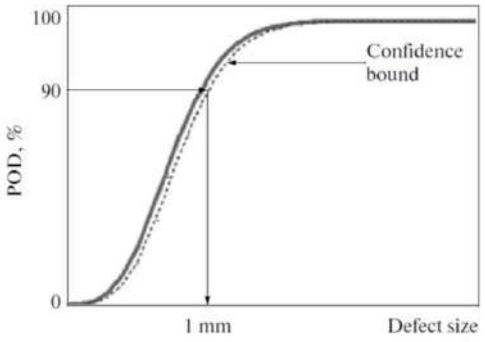
- BBN model overview
- Dataset
- Sizing assessment's network construction and learning
- Example results and analysis

On the anvil

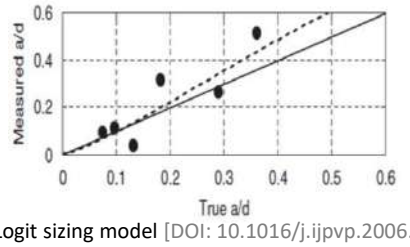
Summary

Background

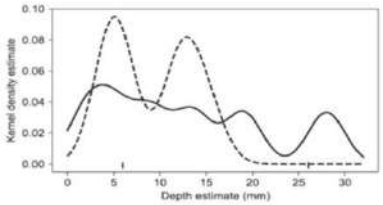
- Reliability of Detection



- Reliability of Sizing



Logit sizing model [DOI: 10.1016/j.ijpvp.2006.06.002]



Kernel density estimates [DOI:10.1016/j.nucengdes.2021.111297]

Motivation and objective

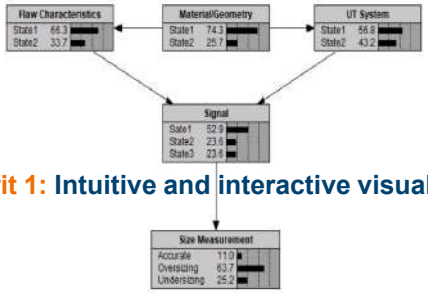
Research on sizing reliability is limited compared to that on detection reliability.

Flaw sizing accuracy is crucial for structural integrity assessment.

The objective is to evaluate the uncertainty associated with flaw sizing in Ultrasonic Testing (UT) of Dissimilar Metal Weld (DMW) using Bayesian Belief Networks (BBN).

Evaluating sizing accuracy in UT with BBN

- BBN model overview
  - **Nodes** representing the system variables
  - **Links** representing causal relationships
  - **States** of the variables
  - **Probabilities** specifying the belief that a node will be in a particular state



Merit 1: Intuitive and interactive visualisation

Merit 2: Versatility

- **Conditional Probability Tables** (CPTs)

Flaw information			Likelihood of sizing accuracy		
Flaw Depth	Position	Tilt angle	Accurate size	Under-size	Oversize
5 mm	Outer surface	10°	0 %	50 %	50 %
5 mm	Outer surface	0°	0 %	75 %	25 %
5 mm	Inner surface	10°	5 %	55 %	40 %
5 mm	Inner surface	0°	10 %	20 %	70 %

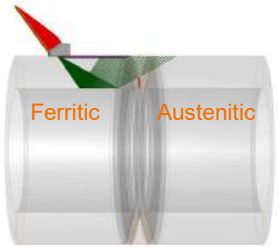
- **Learning** from data to update the CPTs

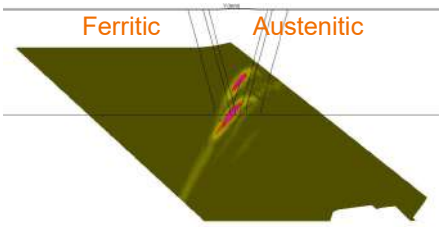
Merit 3: Flexible data requirements

- **Inference** $P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$

Dataset

- Experimental data: UT of DMW collected from a Round Robin trial reported in the literature*.
  - 8 flaws inspected by 7 teams
- CIVA simulation results: 8 flaws measured by 2 inspectors.

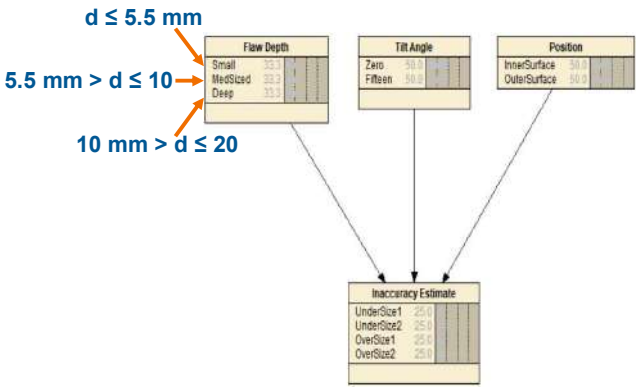




*[DOI: 10.1784/insi.2008.50.11.616]

Network construction and learning

- Netica application software
- The dataset was classified based on the flaw depth extent.
- Different positions and tilt angles.
- Bayes learning algorithm

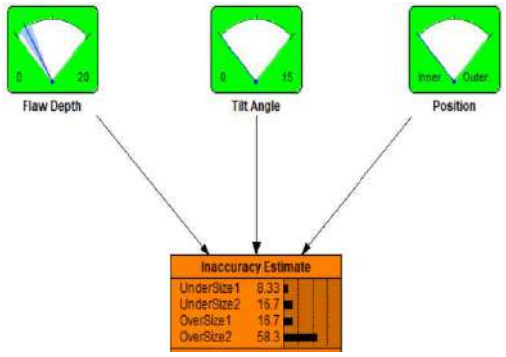


UnderSize1: Measured depth is up to 20% smaller than the actual depth.

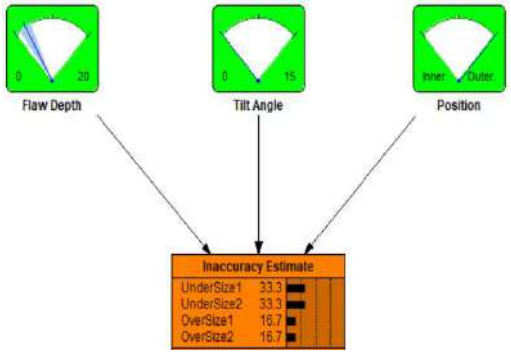
UnderSize2: Measured depth is above 20% smaller than the actual depth

Example results and analysis

Influence of defect position



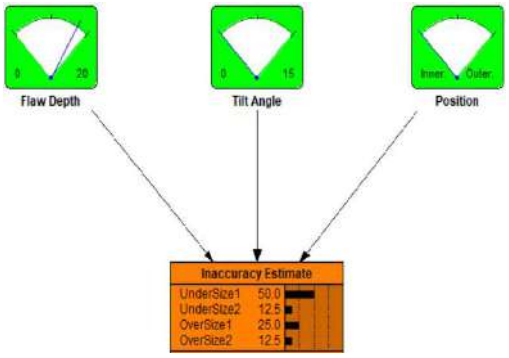
Beliefs in sizing inaccuracy when an inner surface-breaking flaw has a depth ≤ 5.5 mm with no tilt



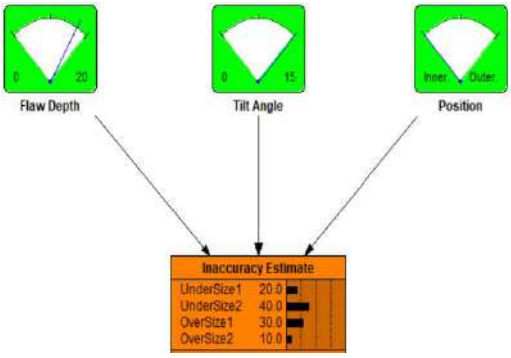
Beliefs in sizing inaccuracy when an outer surface-breaking flaw has a depth ≤ 5.5 mm with no tilt

Example results and analysis

Influence of defect orientation



Beliefs in sizing inaccuracy when an inner surface-breaking flaw has a depth of 17 mm with no tilt

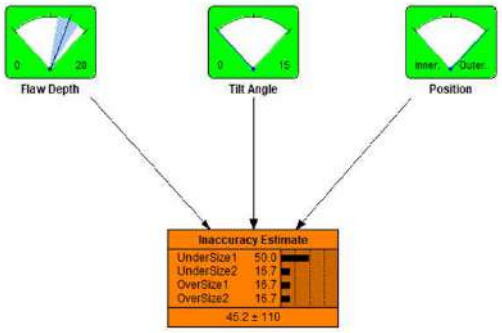


Beliefs in sizing inaccuracy when an outer surface-breaking flaw has a depth of 17 mm and is tilted with 15°

Example results and analysis

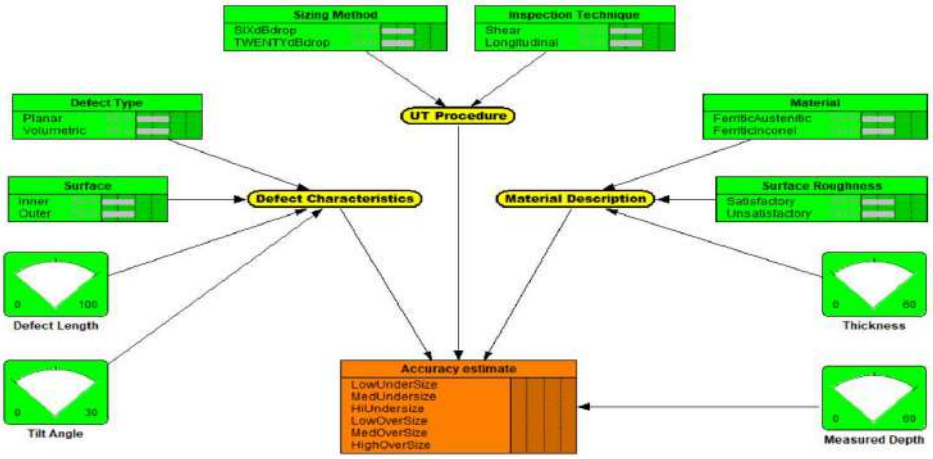
Interactive interface

- The users can manually enter their inspection findings in the network nodes and observe the changes.
- Possibility of **backcasting** scenarios.



On the anvil

Experiments and simulations to include more variables



Summary

- BBN is a practical tool for analysis and decision-support.
- BBN can be used for sensitivity analysis to quantify the influential parameters impact.
- Easy handling of the inputs and intuitive visualisation support the utilisation of BBN models by users of different backgrounds.

beyond
the obvious

Mohammed.Siddig@vtt.fi

19. NDE of Complex Geometries (II)

The presentations in this session are listed in the table below.

NDE of Complex Geometries (II)	**Chair:** Etienne Martin (EDF)
Robotized adaptive 3D ultrasonic technique for the inspection of a complex nuclear component with a matrix array	David Roue (CEA) et al.
Flexible wedge phased array transducers for inspecting variable-geometry or complex components	Philippe Dumas et al. (Imasonic)

Robotized adaptive 3D ultrasonic technique for the inspection of a complex nuclear component with a matrix array

David ROUE [1], Ekaterina IAKOVLEVA [1], Thomas DESREZ [1], Allain ILANITH [2], Etienne MARTIN [2], Frédéric REVERDY[3]

[1] CEA LIST, Gif-sur-Yvette, FRANCE
[2]EDF, Saint-Denis, FRANCE
[3]EDDYFI, Les Ulis, FRANCE

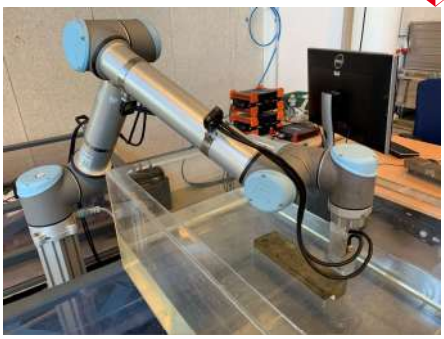
E-mail address (corresponding author): david.roue@cea.fr

The performances of an ultrasonic process can be quickly degraded when the component to be inspected presents a variable surface condition (grinding wave, welding bead). If this irregular surface is known, an inspection process based on multi-element technology is able to guarantee the detection and characterization performances obtained on a regular surface. Following the numerous works already carried out by the CEA to treat surface variations in a single direction (2D effect) and in the frame of a CEA-EDF R&D collaborative program, CEA is assessing the feasibility of a robotic phased array ultrasonic process in immersion to tackle the more difficult problem of a complex surface in two directions (3D effect). This communication presents this new process based on the use of a 256-element matrix array. After a first FMC acquisition, the 3D surface of the component is extracted from the TFM images. Then, from this reconstructed surface, coherent focused ultrasound beams are computed by the CIVA software. The associated delay laws are then loaded and applied in real time by the electronic device during a second acquisition. To realize all these robotized acquisitions, many software developments (CIVA, Acquire) have been made in collaboration with the company Eddyfi.

Keywords: Matrix Array, Robotic, Ultrasonic.

Robotized adaptive 3D ultrasonic technique for the inspection of a complex nuclear component with a matrix array

David Roué, Ekaterina Iakovleva, Thomas Desrez, Pierre Calmon / CEA-List
Ilanith Allain, Etienne Martin / EDF
Fréderic Reverdy / Eddyfi Technologies



NDE in Nuclear 2023

SNETP Sustainable Nuclear Energy Technology Platform

Eddyfi Technologies

Outline

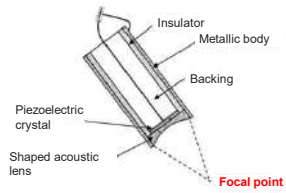
- Background-context
- Description of the adaptive UT technique
- Experimental validation and test
- Conclusions & Perspectives

1. Background-context

Inspection of an irregular surface with arrays

Background: Array techniques and irregular surfaces

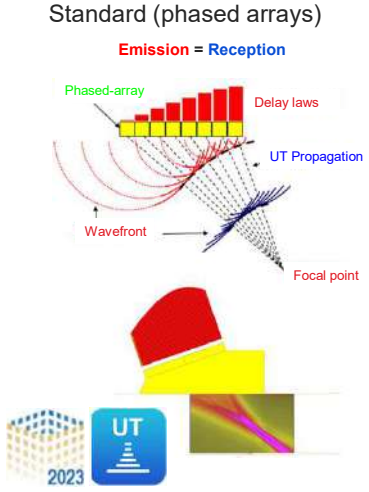
Single element techniques



Ultrasonic probes (UT) / © Intercontrôle

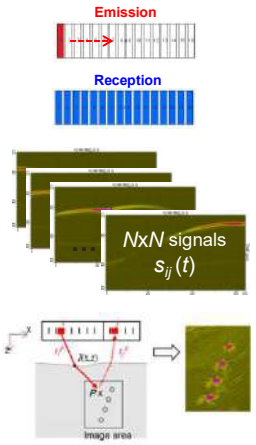
Array techniques

Standard (phased arrays)



Focalization

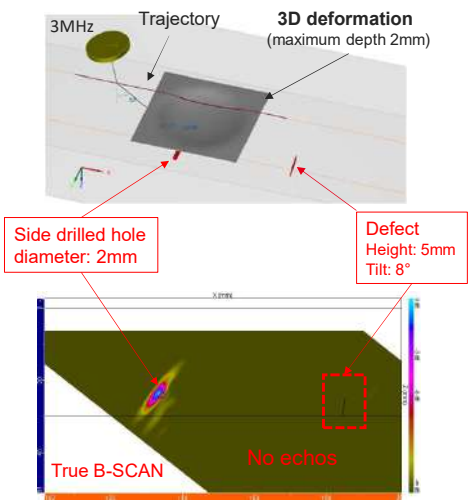
Advanced (TFM) imaging



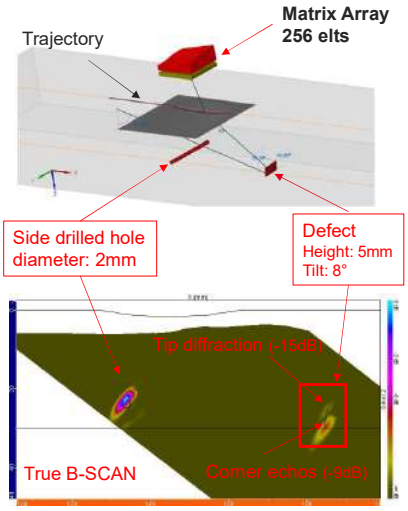
FMC/TFM

Background: Array techniques and irregular surfaces

Single element technique



Phased Array technique



Dynamic focus laws taking into account on **irregular** surface

➔ When the surface is known, it is possible to compute adapted delay laws for each probe position to keep a correct focalization along the probe trajectory

2. Description of the UT technique

Adaptive UT with matrix array

Adaptive US inspection technique with a matrix array

Requirements :

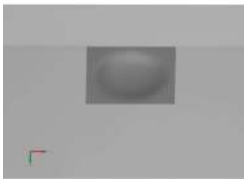
- To be able to inspect in immersion a large area exhibiting a 3D deformation
- To use the same probe for the surface extraction and the inspection → Matrix array
- To reach a scanning speed up to 50 mm/s

Principle of the technique :

- ❑ Step 1 : Acoustic extraction of the 3D surface (Acquisition n°1)
- ❑ Step 2 : Computation of adapted focus laws for every position in the inspection area
- ❑ Step 3 : Inspection by applying dynamically delay laws (Acquisition n°2)

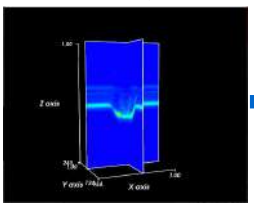
Step 1 : 3D surface reconstruction by TFM imaging

Surface to be reconstructed

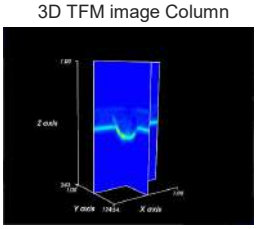


Depression 50x50mm²
Depth 2mm

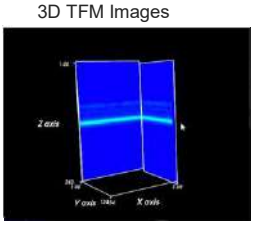
3D TFM image Line



3D TFM image Column



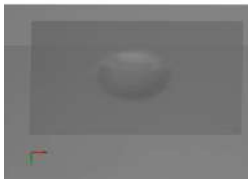
3D TFM Images



Surface extraction

(Image segmentation by applying thresholding)

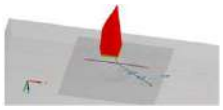
UT reconstructed surface



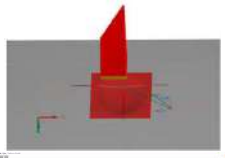
Steps 2 & 3 : Focalization with adapted laws

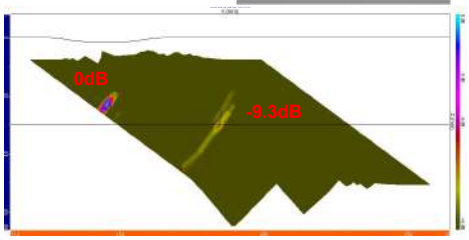
UT measured profile

Step 2 :
Computation of dynamic laws on reconstructed UT profile

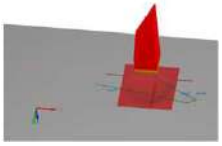


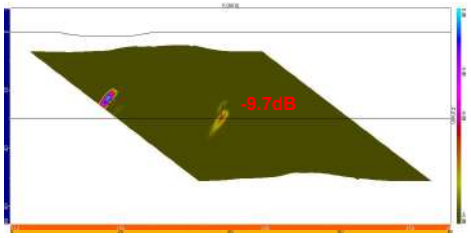
Step 3 :
Application of dynamic law computed on UT profile on CAD profile (to check)





Reference
Dynamic laws computed on theoretical profile





General process diagram

Immersion tank

Robotic Arm
UR10

Encoders conversion
"Robox"

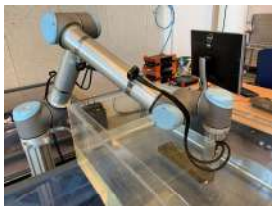
Matrix Array 256 el.

m2m
Panther 2x128

UTPA Acquisition system

NDT Simulation and Analysis platform

General process diagram (step 1)



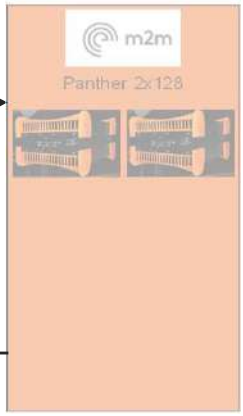
Immersion tank

Robotic Arm

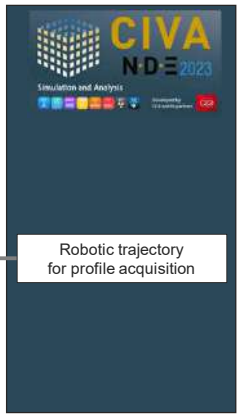
UR10

Encoders conversion

"Robox"



UTPA Acquisition system



NDT Simulation and Analysis platform

Matrix Array 256 el.

General process diagram (step 1)

Acquisition n°1 : Data surface collection (2 FMC)

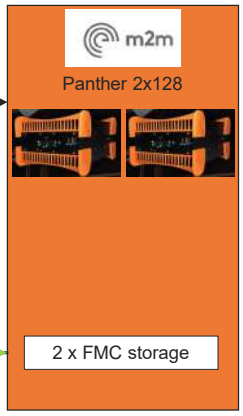
Immersion tank

Robotic Arm

UR10

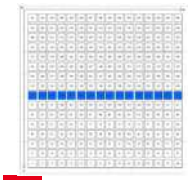
Encoders conversion

"Robox"



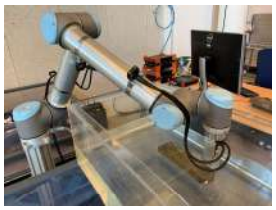
UTPA Acquisition system

NDT Simulation and Analysis platform



Matrix Array 256 el.

General process diagram (step 2)



Immersion tank

Robotic Arm

UR10

Encoders conversion

"Robox"

m2m

Panther 2x128

2 x FMC storage

UTPA Acquisition system

UT DATA n°1

CIVA NDE 2023

3D surface reconstruction from 2 x FMC

Robotic trajectory n°2 for Inspection

Compute adapted delay law for each position

NDT Simulation and Analysis platform

Matrix Array 256 el.

General process diagram (step 3)

Immersion tank

Robotic Arm

UR10

Encoders conversion

"Robox"

m2m

Panther 2x128

Delay laws storage

UTPA Acquisition system

Delay laws transfer

CIVA NDE 2023

Robotic trajectory n°2 for Inspection

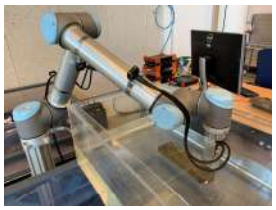
Compute adapted delay law for each position

NDT Simulation and Analysis platform

Matrix Array 256 el.

General process diagram (step 3)

Acquisition n°2 : Adaptive Inspection with corrected focused beam



Immersion tank

Robotic Arm

UR10

Encoders conversion

"Robox"

m2m

Panther 2x128

Delay laws storage

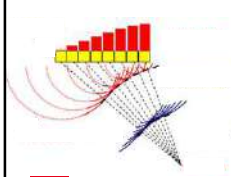
Fire dynamic laws on probe position

UTPA Acquisition system

CIVA N-D-E 2023

Robotic trajectory n°2 for inspection

NDT Simulation and Analysis platform



Signal acquisition

Matrix Array 256 el.

General process diagram (step 3)

Immersion tank

Robotic Arm

UR10

Encoders conversion

"Robox"

m2m

Panther 2x128

UT Data

UTPA Acquisition system

UT DATA n°2

CIVA N-D-E 2023

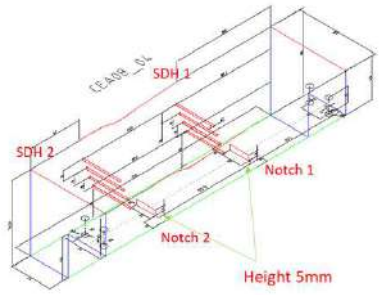
DATA analysis : corrected view, automation…

NDT Simulation and Analysis platform

Matrix Array 256 el.

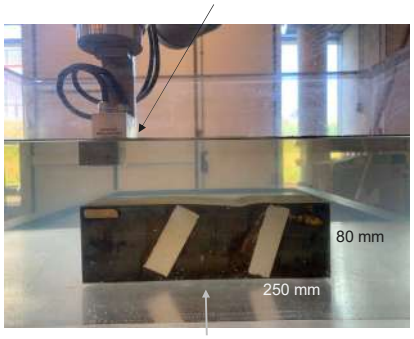
3. Experimental validation

Experimental validation configuration



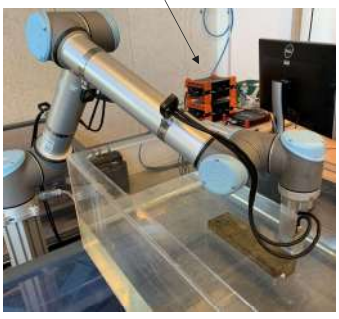
- Matrix array 256 elts
- Aperture: 33,3 x 33,3 mm²
- Frequency: 3 MHz
- Water path : 40 mm
- Maximum scanning speed: 80 mm/s

Matrix Array



Demonstration bloc

Acquisition system

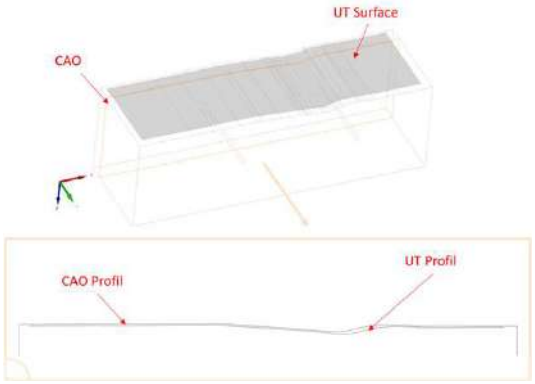


Matrix array with robot and Panther acquisition system (Eddyfi)

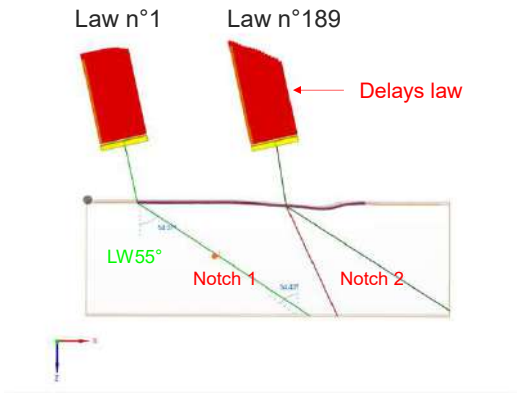
Step 1 & 2

- Step 1: 3D Surface extraction

  Scanning 5mm x5mm



- Step 2: Dynamic delays law

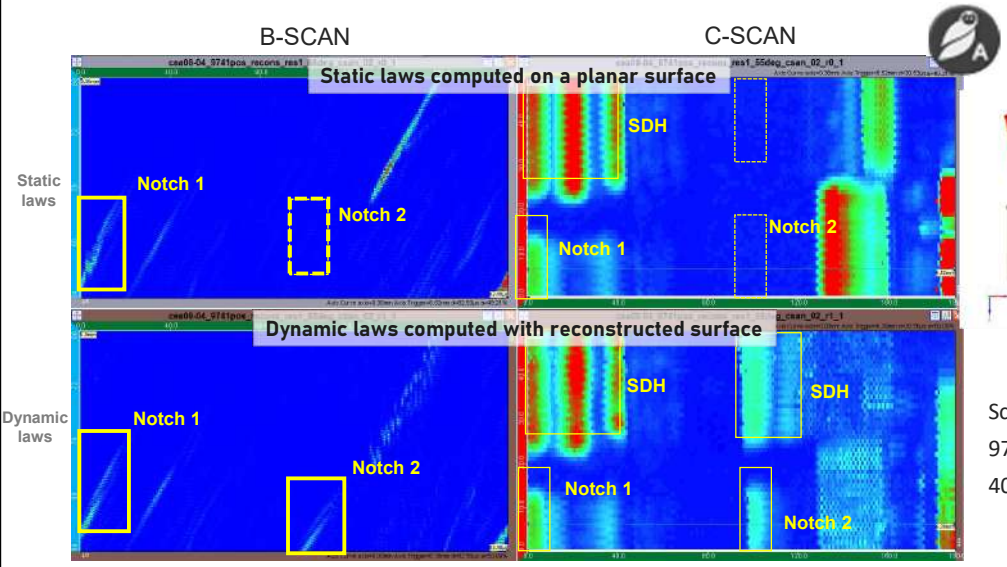


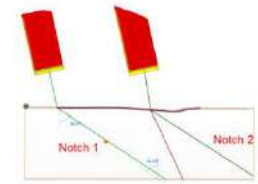
Step 3 - Video

Le contrôle ultrasonore multiéléments robotisé s'adapte aux surfaces perturbées

© CEA 2022

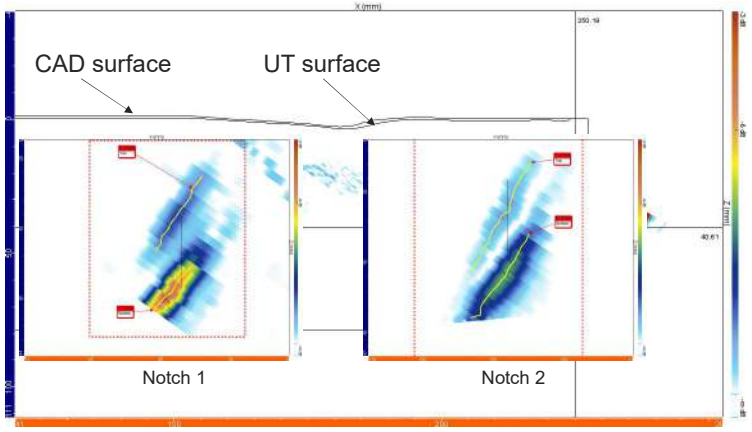
Uncorrected views during acquisition





Scanning: 1mm x 1mmm
9741 dynamic laws
40 mm/s

DATA Analysis with CIVA software (corrected-views)



Characterization (sizing) of 5mm notches

CIVA automatic segmentation tools		
	Notch 1	Notch 2
Top (dB)	-13,5	-17
Bottom (dB)	-4,7	-9
Height (mm)	5,9	4,3

Calibration on SDHØ2

5. Conclusions & Perspectives

Conclusions & Perspectives

Conclusion

- ✓ A new robotic 3D inspection method using a 256 elements matrix array probe was developed.
  It implements :
  - 3D surface reconstruction method, using a sparse grid and matrix probe sub-apertures (perf. example : 160 x 240 mm² → 2400 positions → 3D TFM processed in 3 min on office PC)
  - A fast algorithm (ray based) for rapid dynamic adapted delay law computation (Perf example : 66000 dynamic laws computed in 8 min).
  - A new functionality on acquisition system PANTHER to dynamically change delay law on position change (Up to 400k dynamic laws in acq. syst. memory)
- ✓ First results give a good agreement with references (simulated and experimental data)

Perspectives

- ✓ Full method will be implemented in CIVA software (intended : 2024)
- ✓ Transfer to a in-service inspection company is under discussion

Thank you for your attention!
David Roué
david.roue@cea.fr
NDE in Nuclear 2023
SNETP
Eddyfi Technologies

Flexible wedge phased array transducers for inspecting variable-geometry or complex components

Philippe DUMAS[1], Arnaud MEMBRE[1], Stephane Oster[1], Valentin Richard[1]

[1]Imasonic SAS, Voray sur L'Ognon, France

E-mail address (corresponding author): Philippe.dumas@imasonic.com

Keywords: Phased Array, Flexible Wedge, Ultrasonic,

The transmission of ultrasound from the transducer into the inspected component is a determining factor in the performance of ultrasound inspections.

Various coupling solutions exist to ensure this transmission. The most frequently used are:

- Immersion of the component in water tank: This coupling presents the best acoustic performance (low attenuation, coupling homogeneity, no intermediate interface). However, the inspected parts need to be fully immersed and thus complex control systems are required.
- Coupling by direct contact with a liquid couplant, or via a rigid wedge or a delay line with liquid couplant at the interfaces: This coupling requires simpler control systems for the inspection, but the homogeneity of the couplant film and attenuation in the wedges deteriorate the signal.

The geometry of the inspected part can make the coupling more difficult to setup, particularly if the surface is complex or varies from one point to another. The problem becomes critical when the dimensions of the transducer are large in comparison with the local curvature of the interface.

The use of transducers that are flexible, or that are fitted with a flexible wedge, improves the quality of the coupling for components with complex or variable geometry, and in some cases, makes it possible to do certain inspections that currently have no solution.

This article presents the recent developments and results obtained in the context of transducers with flexible wedges, in particular:

- Design options;
- Flexible membranes development;

- Mechanical interfaces development for multi-element transducers;
- Mechanical supports development for manual or automated use;
- Acoustic performance tests;
- Wear resistance tests.

These studies have demonstrated the contribution of flexible wedge transducers to various applications, with acoustic performances similar to that of immersion and easy implementation comparable to standard contact inspections, while remaining compatible with an industrial use.

The detailed results will be presented, as well as the possibilities for the future developments of transducers with flexible wedges.

Flexible wedge phased array transducers for inspecting variable-geometry or complex components

P.Dumas – S.Oster – A.Membre
IMASONIC SAS – 70190 Voray sur l'Ognon – France

Content

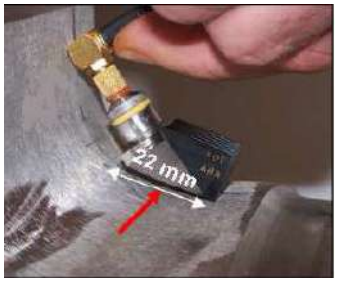
- Background
- Conformable wedge concept
- Examples
- Performance evaluation
- Conclusion

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Background

Coupling problem of contact transducers with

- ➢Variable surface
- ➢Complex geometry



CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Background\Existing solutions

Conformable transducers

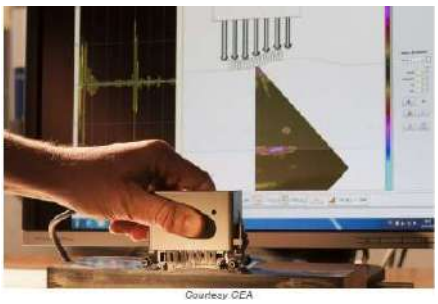
- ➢1D & 2D

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Background\Existing solutions

SMART Flexible concept

- Real time profile surface measurement
- LW and SW in direct contact

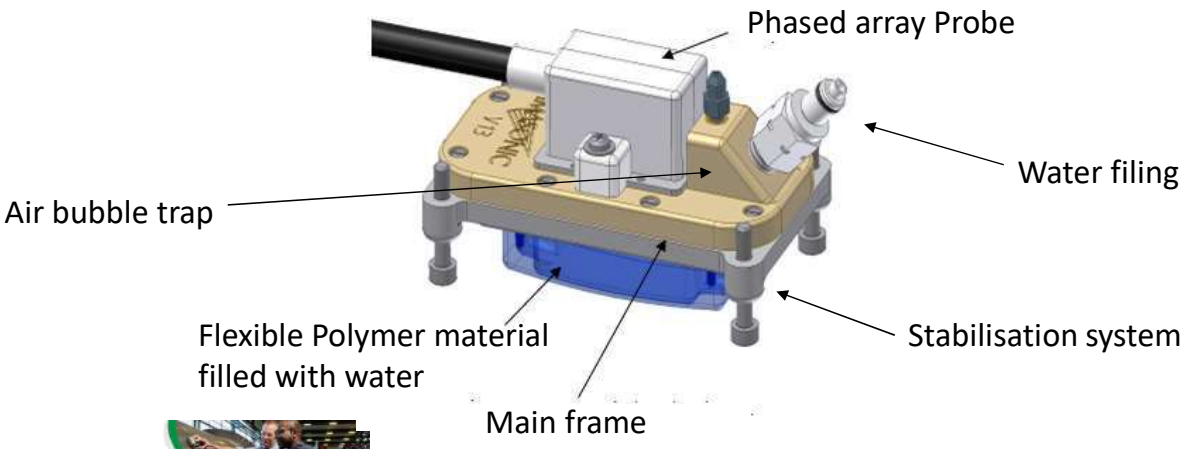


Limitations

- Max frequency 4MHz
- Minimum pitch >1mm
- Price
- Dimensions

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Concept



CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Concept\Target

Targeted Advantages

- compatible with various arrays
- Wide frequency range
- Acoustic performance similar to immersion
- Implementation similar to contact
- Easy maintenance

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Concept\Membrane

Flexible Membrane

- Halogen free
- Robust
- Various shape
- Various flexibility
- Using conditions (T°) similar to PA probes

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Concept\Adaptability

- Compatible with various array types
- Normal or angled incidence

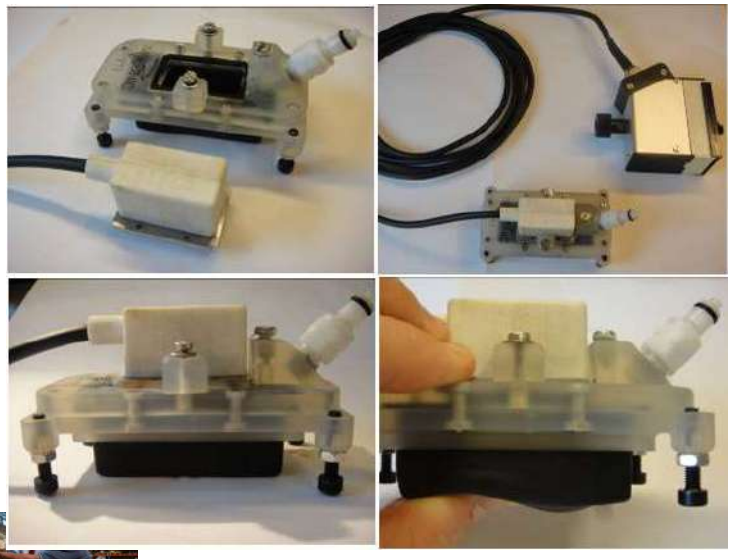
Linear

Matrix

TRL/SE

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Examples\Prototype



CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Examples\Automated

1st generation

- Compatible with scanner for automated use
- Water coupling system
- Air bubble trap inside

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Examples\Manual

2nd generation standard kit

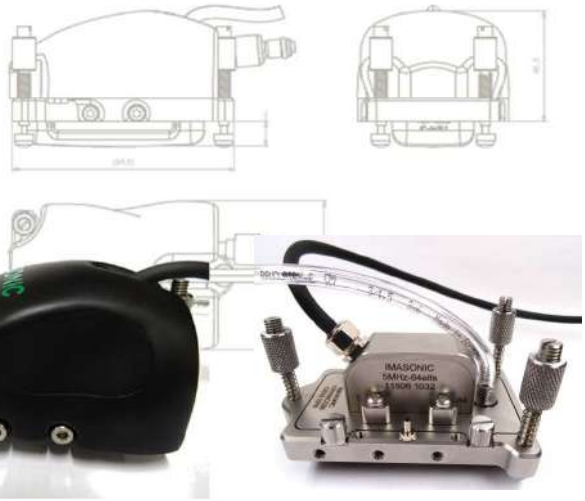
- Handling system for manual use
- Trim setting system
- Bubble trap

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Examples\Compact

2nd generation compact standard kit

- Reduced dimensions
- Improved trim setting system



CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Examples\Integral

3rd generation standard kit

- Integrated probe & frame
- Easy assembly/disassembly with clips
- Advanced bubble trap system
- Compatible with probe holders or manual use

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\Clip

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Examples\Integral

Mechanical size reduction

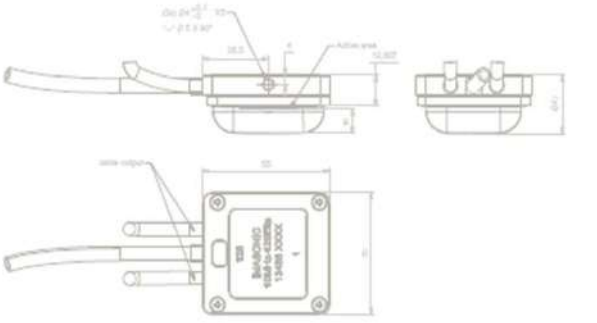
	2nd generation	2nd generation compact	3rd generation
Total length	Active length + 70mm	Active length + 57mm	Active length + 27mm

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Examples\ExtraFlat

Extra Flat integral probe

- 10 MHz
- 128ch
- 22mm overall thickness
- Bubble trap system



CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Example\Integral

TRL/SE arrays

- Matrix arrays
- Integral design
- Easy clip assembly
- Bubble trap

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Membranes

3 different materials

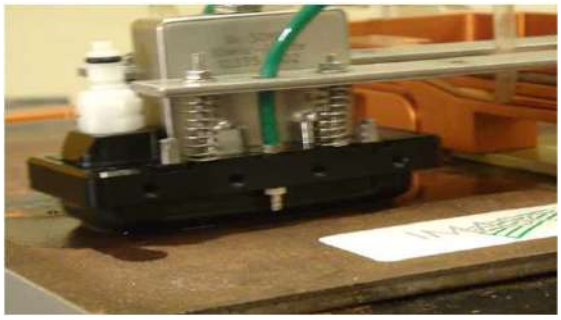
- Black : standard
- Grey : improved flexibility
- Blue : improved resistance

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\WearResistance

Wear resistance tests (1/2)

- Corroded steel piece : Ra : 20 µm
- Standard black membrane
- Speed 10 cm/s
- Load 1 kg
- Coupling with water



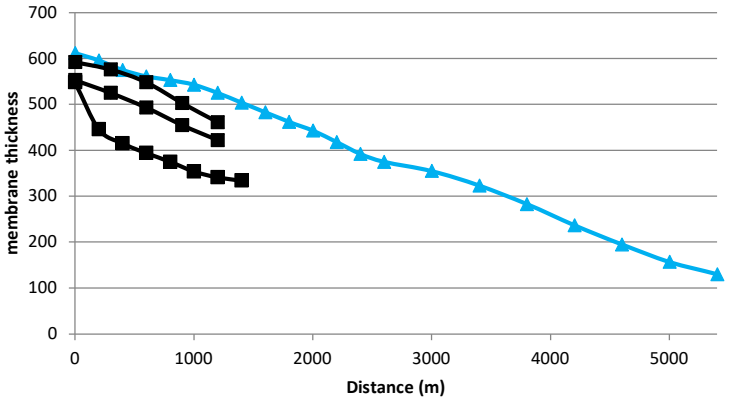
No damage observed after a run of 500 m

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\WearResistance

Wear resistance tests (2/2)

- Abrasive paper
  Ra 12 µm
  replaced every 200m
- Speed 10 cm/s
- Load 1 kg
- Coupling with water



Holes appear after 1km (black) or 5km (Blue)

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\Conformability

Dénomination	Description	Matériau	Photo
Cale Tôle Soudée transparente	- cale stéréo transparente pour contrôle à vue de la conformabilité - cordon de soudure factive = R6.25, larg 10mm, H2.5mm (r2 et r1 entre géométries)	Stéréo Clear View	
Pipe Ø4" avec cordon	- cale stéréo transparente pour contrôle à vue de la conformabilité - cordon de soudure factive = R25, larg 50, flèche 5mm (r2 entre géométries)	Stéréo Clear View	

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\Conformability

Coupling force NOK

Coupling force OK

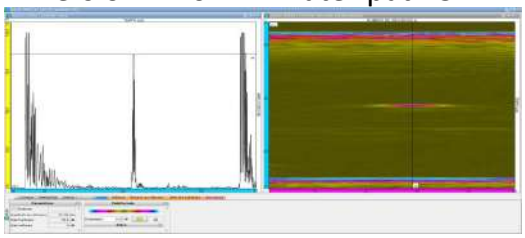
	Cylindical interface	Toroïdal interface
Black	0.20 Kg	0.86 Kg
Grey	0.12 Kg	0.66 Kg
Blue	0.32 Kg	1.98 Kg

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

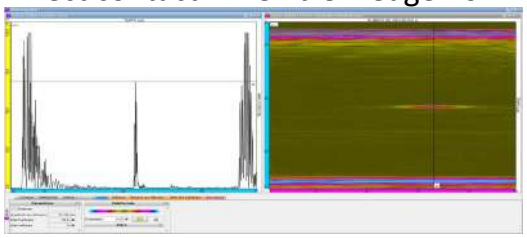
\Performance\Attenuation

- 5MHz Echo on 2 mm SDH 40 m depth

Immersion - 20 mm water path 5MHz



Direct contact – Flexible wedge 20 mm height



	Immersion	Flexible Wedge
FSH	86 %	69%
Gain	54.5 dB	54.5 dB

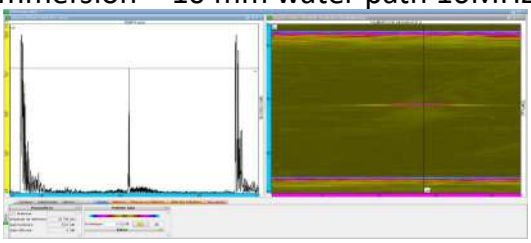
- 1.9 dB at 5MHz

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

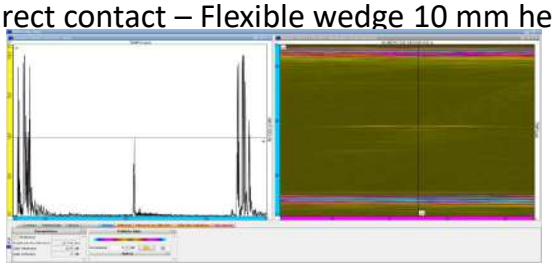
\Performance\Attenuation

- 10MHz Echo on 2 mm SDH 40 m depth

Immersion - 10 mm water path 10MHz



Direct contact – Flexible wedge 10 mm height



	Immersion	Flexible Wedge
FSH	79 %	49%
Gain	61.9 dB	61.9 dB

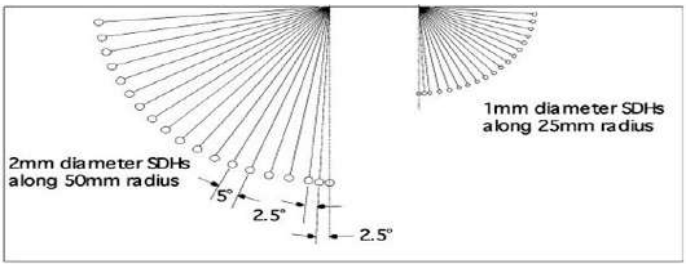
- 4.1 dB at 10MHz

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\ReferenceBlock

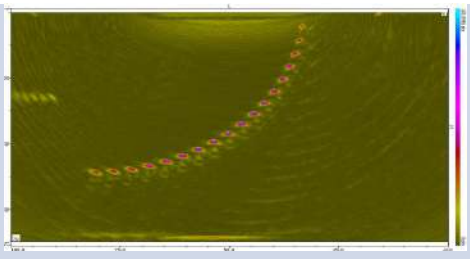
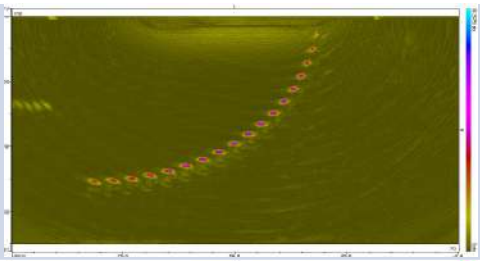
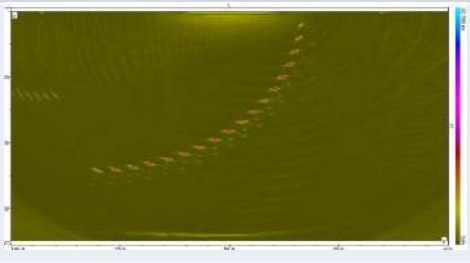
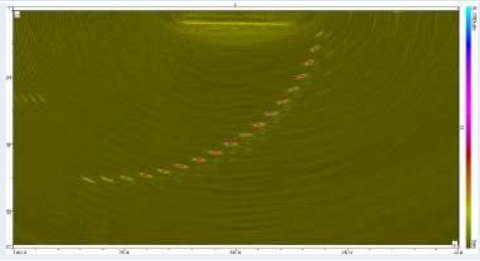
Comparative tests on reference block

- FMC / TFM Acquisition
- ASTM E 2491 Steel Block
- 5 and 10 MHz
- Immersion Vs Flexible wedge



CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

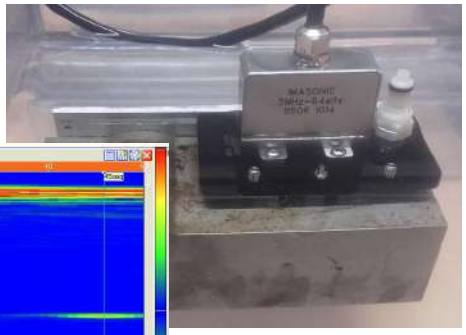
\Performance\ReferenceBlock

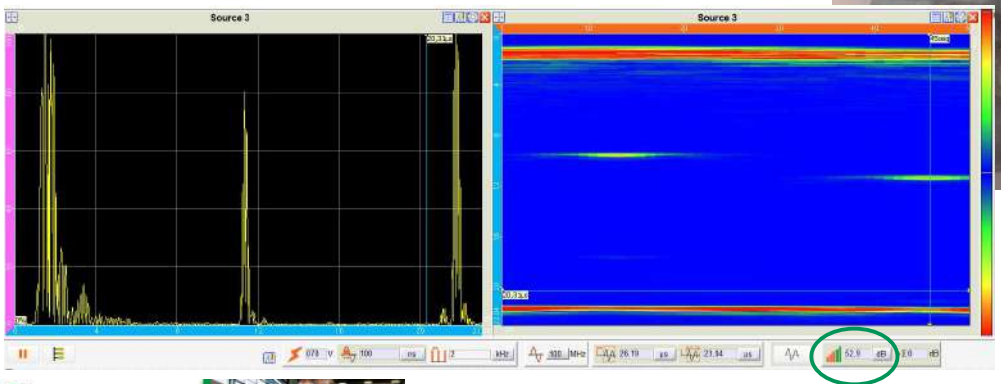
	Immersion	Conformable wedge
5MHz		
10 MHz		

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\Coupling

Immersion (reference)



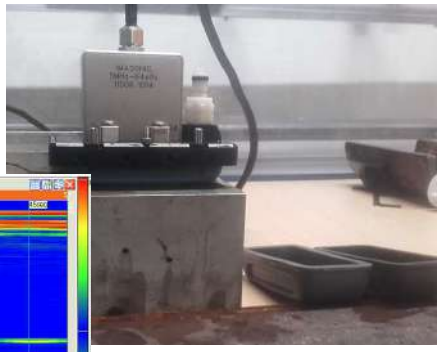


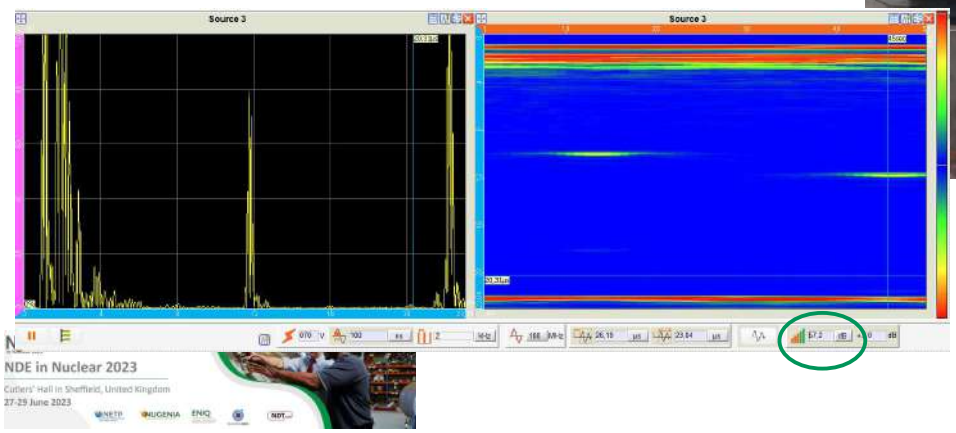
CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\Coupling

Direct contact

- Black membrane





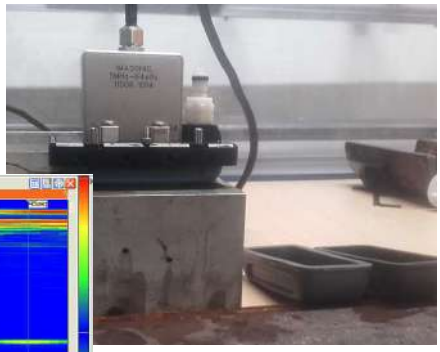
-4.3 dB

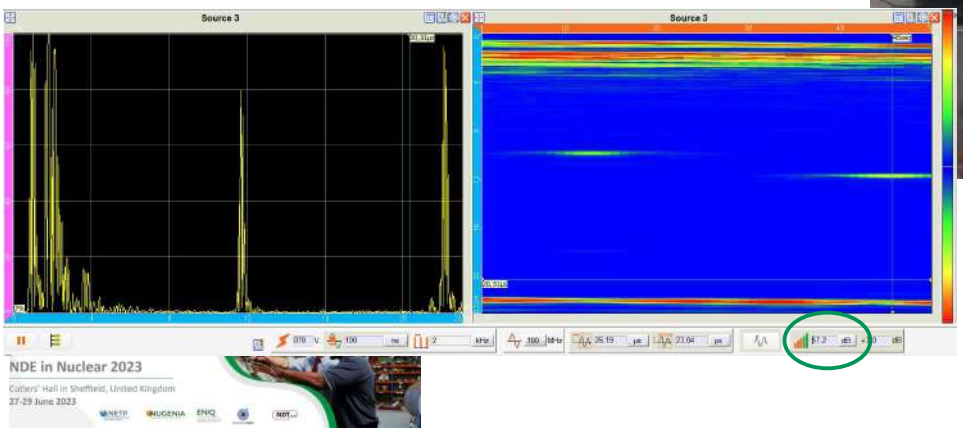
CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\Coupling

Direct contact

- Grey membrane





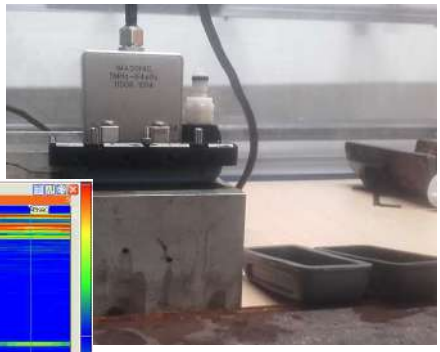
-4.3 dB

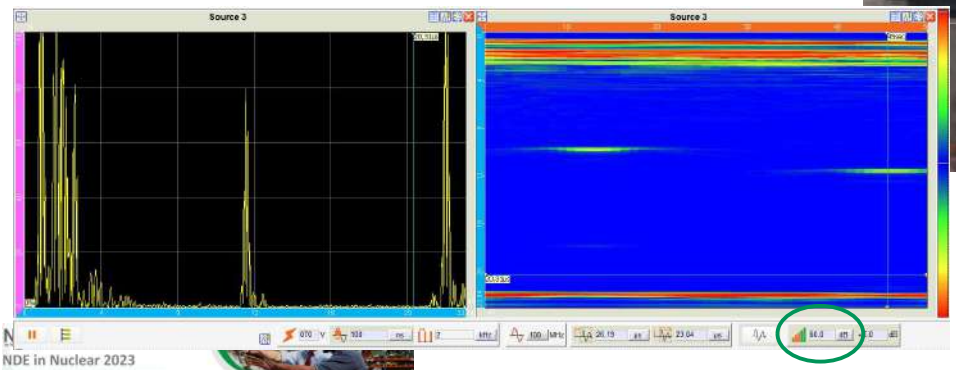
CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

\Performance\Coupling

Direct contact

- Blue membrane





-7.1 dB

CONFORMABLE WEDGE PHASED ARRAY TRANSDUCERS

Conclusion\membranes

	Black	Grey	Blue
Conformability	+	++	-
Mechanical resistance	+	- Limited to smooth surface with couplant	++
Attenuation	OK	OK	OK

Conclusion

Advantages of conformable wedge transducers

- Compatible with various array types
- Performances close to immersion
- Implementation close to contacts with rigid wedges
- Good wear resistance
- Conformability to local radius <10mm

List of participants

First name	Last name	Company Name
John	Abbott	Electric Power Research Institute (EPRI)
Daniel	Algernon	Swiss Association for Technical Inspections (SVTI)
Todd	Allen	Oberon
Peter	Alzén	Swedish Qualification Centre (SQC)
Stavros	Avramidis	Jacobs
Christian	Bast	Westinghouse Electric Germany GmbH
David	Bell	Altrad Babcock
Michal	Benak	VUJE, a.s.
Jorge	Benitez	Swedish Qualification Centre (SQC)
Daniel	Berchtold	Kernkraftwerk Goesgen-Daeniken AG
Johan	Berlanger	Eddyfi Technologies
Madeleine	Best	Lavender International NDT
Pär	Blombergsson	Forsmarks Kraftgrupp AB
Thomas	Bloodworth	Bloodworth Consulting Limited/ Framatome
Christian	Boller	Saarland University
Candice	Boudet	LGI Consulting
Ian	Bradley	Electricite de France (EDF)
Jaroslav	Brom	Research Centre Rez (CVR)
Simon	Butler	IRISNDT
Antonio	Cabeza	Equipos Nucleares, .S.A., S.M.E.
Pierre	Calmon	CEA List
Ladislav	Carbol	ČEZ, a.s.
Paul	Cardwell	Rolls Royce
Frederic	Cegla	Imperial College London

Yassine	Chafai	Framatome-Intercontrole
Vincent	Chardome	Vinçotte SA
Steve	Chengelis	Electric Power Research Institute (EPRI)
Laurence	Clarkson	Imperial College London
George	Connolly	Electric Power Research Institute (EPRI)
Anthony	Croxford	University of Bristol
Chris	Curtis	Jacobs - Inspection Validation Centre (IVC)
Lance	Davis	Nuclear Research & Consultancy Group (NRG)
Francisco Javier	de la Morena Martínez	Tecnatom S.A.
David	Deeney	Sonatest
Nicolas	Domenjoud	Electricite de France (EDF)
Conor	Douglas	Stork Technical Services UK Limited
Tom	Druet	CEA LIST
Sandra	Dugan	Framatome GmbH
Philippe	Dumas	Imasonic
David	Duxbury	Rolls-Royce Submarines
Gavin M.	Edwards	EDF-Energy
Julian	Emslie	Rolls-Royce SMR
Jesper	Enocksson	OKG AB
Leif	Esp	Electric Power Research Institute (EPRI)
Llion	Evans	Swansea University
Max	Eyre	De-Tect Unit Inspection Europe Ltd
Graeme	Falconer	Stork Technical Services UK Limited
Jonathan	Findin	Dekra Industrial AB
Jay	Fisher	Southwest Research Institute
Andrew	Fox	IMechE Argyll Ruane

Alice	Fry	Lavender International NDT
Bob	Grizzi	Electric Power Research Institute (EPRI)
Alan	Guy	Kernkraftwerk Beznau, Axpo Power AG
Michael	Hacker	Oberon
Ted	Hallqvist	Dekra Industrial AB
Scott	Hamel	Electric Power Research Institute (EPRI)
Torsten	Häntzka	Swiss Federal Nuclear Safety Inspectorate (ENSI)
Jukka	Harkola	STUK (Radiation and Nuclear Safety Authority)
Jean-Marie	Henault	Electricite de France (EDF)
Sergio	Hernández Ruiz	Tecnatom S.A.
Paul	Hillman	Eddyfi Technologies
Jeremy	Hodgkins	Rolls-Royce Submarines
Brian	Hohmann	Hohmann Engineering Associates
Ladislav	Horáček	ÚJV Řež, a. s.
Kristoffer	Ingelsson	Swedish Qualification Centre (SQC)
Daniel	Irving	Novosound Ltd
Richard	Jacob	Pacific Northwest National Laboratory (PNNL)
Hyeon	Jae Shin	INDE Systems
Helmut	Jarisch	Westinghouse Electric Germany GmbH
John	Jian	Electricite de France (EDF)
Ola	Johansson	Ringhals AB / Vattenfall
Åke	Jonsson	OKG AB
Anne	Juengert	MPA University of Stuttgart
Philip	Kicherer	Swiss Association for Technical Inspections (SVTI)
Marcin	Kowal	National Centre for Nuclear Research
Roman	Krajcovic	VUJE, a.s.

Petri	Kuusinen	Kiwa Inspecta
Ari	Kuuslaakso	Teollisuuden Voima Oyj (TVO)
Magnus	Kvarnström	Ringhals AB / Vattenfall
Carl	Latiolais	Electric Power Research Institute (EPRI)
Sylvain Didier	Laurent	TENEO
Anders	Lejon	Ringhals AB / Vattenfall
Nicolas	Leymarie	CEA List
Shan	Lin	Central Research Institute of Electric Power Industry (CRIEPI)
David	Lines	University of Strathclyde
Steffi	Lorenz	SONOTEC GmbH
John	Lu	Ontario Power Generation (OPG) Inc.
Gary	Luckett	Evident UK
Petri	Luostarinen	Fortum Power and Heat Oy
David	Mahon	University of Glasgow
Tuomas	Mankki	Inspecta Sertifiointi Oy
Robert	Mård	WesDyne Sweden AB (Westinghouse company)
Philip	Marsden	Unitive Design and Analysis Ltd
Eetu	Martikainen	Teollisuuden Voima Oyj (TVO)
Etienne	Martin	Electricite de France (EDF)
Oliver	Martin	European Commission - Joint Research Centre (EC-JRC)
Terrill	Massey	Electric Power Research Institute (EPRI)
Stefan	Medenbach	MuM GmbH
Steven	Meikle	Electricite de France (EDF)
Grant	Meredith	De-Tect Unit Inspection Europe Ltd
Ceri	Middleton	University of Liverpool
Diego	Molpeceres	Tecnatom S.A.

Olga	Motorina	Dekra Industrial AB
Mike	Mouchet	Electric Power Research Institute (EPRI)
Prabhat	Munshi	Indian Institute of Technology Kanpur
Sylvain	Murgier	Electricite de France (EDF)
Nathan	Muthu	Electric Power Research Institute (EPRI)
Channa	Nageswaran	The Welding Institute (TWI) Ltd
Simone	Nardi	Newcleo
Markus	Nilsson	Lund University
Tarja	Nuoranne	STUK (Radiation and Nuclear Safety Authority)
Joshua	Oppenheimer	Oberon
Patrick	O'Regan	Electric Power Research Institute (EPRI)
Thiago	Osorio	Electric Power Research Institute (EPRI)
Stéphane	Oster	IMASONIC
Christophe	Paillares	Westinghouse Electric France
Simon	Parke	Peak NDT Limited
Alan	Paton	Altrad Babcock
Diana	Pfeil	Westinghouse Electric Germany GmbH
David	Phin	Evident
Jani	Pirinen	Fortum Power and Heat Oy
Christophe	Piron	Eddyfi Technologies
Manuel	Plateau	Vinçotte SA
Craig	Popplewell	TPAC
Niels	Pörtzgen	ApplusRTD
Luka	Posilović	Inetec
Vinooth	Rajendran	Robert Gordon University
Vladimír	Rau	Slovenské elektrárne, a.s.

Ignacio	Real Rubio	Iberdrola S.A.
Matthew	Riding	University of Strathclyde
Ulf	Ronneteg	Svensk Kärnbränslehantering AB
Louis	Rossouw	Nuclear Research & Consultancy Group (NRG)
Paul	Sacker	Crimson Industrial Vision Ltd
Yasemin	Sahin Inc	VTT Technical Research Centre of Finland
Javier	Sanchez	Equipos Nucleares, .S.A., S.M.E.
Philip	Sandersjöö	Dekra Industrial AB
Patricia	Scharpenberg	Westinghouse Electric Germany GmbH
Amy	Schofield	IMechE Argyll Ruane and Sonaspection
Mohammed	Siddig	VTT Technical Research Centre of Finland
John	Skidmore	AOS-TPAC
Daniel	Snögren	Forsmarks Kraftgrupp AB
Josh	Stellakis	Electric Power Research Institute (EPRI)
Karen	Stone	Jacobs
Theodosia	Stratoudaki	University of Strathclyde
Tim	Stubbs	NRL NDT Ltd.
Sumana	Sumana	PEAK NDT Limited
Mannur	Sundaresan	North Carolina A&T State University
Mark	Sutcliffe	The Welding Institute (TWI) Ltd
Szabolcs	Szávai	Bay Zoltán Nonforfit Ltd. for Applied Research
Levnte Csaba	Szekely	Atkins
Mark	Taylor	Inspection Consultants
Raymond	ten Grotenhuis	Ontario Power Generation (OPG) Inc.
Eric	Torra Fernandez	WesDyne Sweden AB (Westinghouse company)

Wouter	Van Eesbeeck	Laborelec NV/SA
Avelino	Vázquez Sánchez	Applus Norcontrol, S.L.U.
Will	Vickers	Ionix Advanced Technologies
Audrey	Vigneron	CEA List
Jan-Albert	Viljoen	Nuclear Research & Consultancy Group (NRG)
Iikka	Virkkunen	True Flaw
Ilpo	Virtanen	Inspecta Sertifiointi Oy
Petr	Vlcek	ÚJV Řež, a. s.
Sam	Wadeson	JME Advanced Inspection Systems
Anthony	Walker	Jacobs
James	Wall	Electric Power Research Institute (EPRI)
Keiji	Watanabe	Central Research Institute of Electric Power Industry (CRIEPI)
Jeff	Weed	CANDU Owners Group (COG)
Miles	Weston	The Welding Institute (TWI) Ltd
Lina	Widfond	WesDyne Sweden AB (Westinghouse company)
Dirk	Willmann	SONOTEC GmbH
Jordan	Wood	Rolls-Royce Submarines
Zandra	Woxö	OKG AB
Toshihiro	Yamamoto	Japan Power Engineering and Inspection Corporation (JAPEIC)
Max	Yates	Sonaspection International Ltd
Kersten	Zaar	viZaar industrial imaging AG
Jie	Zhang	University of Bristol

ENIQ

European Network for
Inspection & Qualification
NUGENIA Technical Area 8

ABOUT ENIQ AND NUGENIA

The **European Network for Inspection and Qualification (ENIQ)** is a utility driven network working mainly in the areas of qualification of non-destructive testing (NDT) systems and risk-informed in-service inspection (RI-ISI) for nuclear power plants (NPPs). Since its establishment in 1992 ENIQ has issued over 60 documents. Among them are the "European Methodology for the Qualification of Non-Destructive Testing" and the "European Framework Document for Risk-Informed In-Service Inspection". ENIQ is recognised as one of the main contributors to today's global qualification guidelines for in-service inspection.

ENIQ is the technical area 8 of NUGENIA, one of the three pillars of the Sustainable Nuclear Energy Technology Platform (SNETP) that was established in September 2007 as a R&D&I platform **to support technological development for enhancing safe and competitive nuclear fission in a climate-neutral and sustainable energy mix.** Since May 2019, SNETP has been operating as an international non-profit association (INPA) under the Belgian law pursuing a networking and scientific goals. It is recognised as a European Technology and Innovation Platform (ETIP) by the European Commission.

The international membership base of the platform includes industrial actors, research and development organisations, academia, technical and safety organisations, SMEs as well as non-governmental bodies.

secretariat@snetp.eu | www.snetp.eu | SNETP | SNE_TP