NUGENIA

Nuclear Generation II&III Alliance

ENIQ POSITION ON

Qualification of Inspection Techniques using Full Matrix Capture (FMC) & Total Focusing Methods (TFM)

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Executive Summary

This Position Paper has been developed as a consensus document amongst the members of NUGENIA Technical Area 8 (TA8) – European Network for Inspection and Qualification (ENIQ), and specifically the Sub-Area for Inspection Qualification (SAQ). It aims to provide guidance on how to qualify Full-Matrix Capture (FMC) / Total Focusing Method (TFM) and relative techniques within the ENIQ framework, including the identification of specific influential and essential parameters and any other special considerations to be applied. This document reflects the current technology, at the time of writing, and will be updated to reflect new technological developments when necessary.

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NUGENIA Technical Area 8

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1. Introduction

The European Methodology for Qualification of Non-Destructive Testing [1] developed within the European Network for Inspection and Qualification (ENIQ) (often referred to as ENIQ Methodology) has been used in Europe and other specific countries worldwide for the inspection qualification of Primary Circuit Components of Nuclear Power Plants (NPP) for over 30 years. These inspections are generally in the form of Ultrasonic, Radiographic or Eddy Current Testing (UT, RT, ET), although the methodology is not limited to these examples. The Inspection Qualification process can be very time consuming and costly, so the nuclear licensee will only carry out qualification or requalification where it is necessary to comply with their country's regulatory requirements.

Many of the Ultrasonic techniques that are deployed for the inspection of NPPs were qualified during the manufacturing or pre-service inspection stages, up to 30 years ago. The techniques deployed at that time were conventional pulse-echo Ultrasonic Testing and Time-of-Flight Diffraction (ToFD). In most cases, as the equipment and techniques have developed over the years, the qualified inspections have not been upgraded due to the time and cost to qualify them. In recent years as new NPPs have been built or specific requirements have demanded, more advanced techniques such as Phased Array UT (PAUT) have been successfully qualified and deployed. ENIQ Recommended Practice 2 – Strategy and Recommended Contents for Technical Justifications [2] provides examples of essential parameters for PAUT inspections.

Advancements in equipment hardware and software have brought Full-Matrix Capture (FMC) / Total Focusing Method (TFM), and other acquisition schemes using the TFM algorithm, to a point where they can be reliably deployed for nuclear inspections. FMC is typically used for specialised cases where inspection is through (an) irregular interface(s), or a higher sizing resolution is required compared to conventional ultrasonic methods.

This position paper aims to provide guidance on how to qualify FMC/TFM and relative techniques within the ENIQ framework, including the identification of specific influential and essential parameters and any other special considerations to be applied. This document reflects the current technology, at the time of writing, and will be updated to reflect new technological developments when necessary.

2. Full Matrix Capture/TFM

FMC/TFM according to ISO 23865 [3] is an assembly of a data acquisition scheme and an imaging scheme. The data acquisition scheme, namely FMC, involves firing sequentially all elements of an array of a PAUT probe, whereby each element firing is accompanied by reception on all elements separately (Figure *1*).

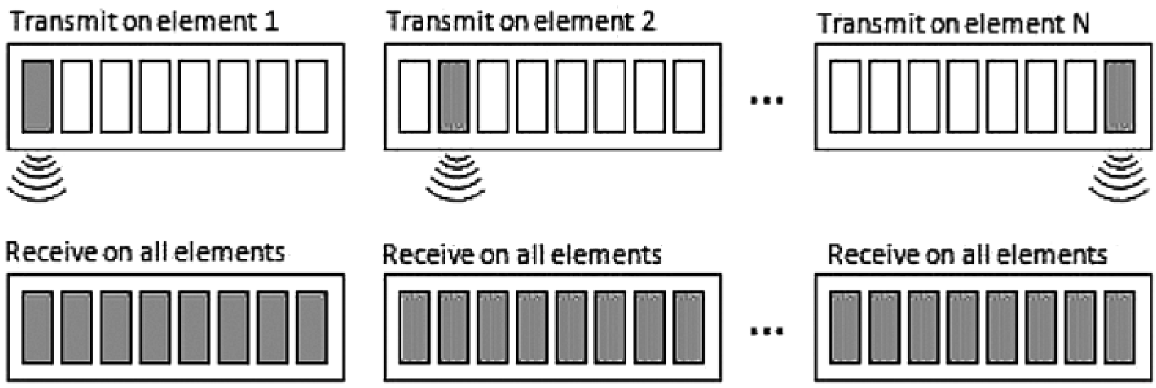

Figure 1 FMC data acquisition, n° time domain signals are obtained.

As a result, each element firing produces as many A-Scans as the number of receiving elements and the total number of A-Scans equals n^2, where n is the number of active elements in the array. Since a separate A-scan is generated from each receiving element, the raw FMC data is incomprehensible without applying the TFM algorithm. The TFM algorithm applies calculated delay and sum beamforming to the FMC data in order to generate a fully focused image (e.g., focused on every pixel). The main benefit, however, of decoupling the beamformer from the data acquisition, is the convenience and flexibility with which the FMC can be treated, leading to the benefits of FMC/TFM as itemised below:

- A fully-focused image is generated and FMC/TFM has the potential to improve sizing and positioning accuracy over PAUT throughout the inspection volume. Inspection coverage can also be improved as FMC relies less on specific and multiple stand-offs/scan lines and produces a fully focused image throughout the thickness of the inspection volume, removing the need for active focusing at several discrete depths required by other techniques.
- Due to the small element size typically used for FMC/TFM, there is a smaller dead zone when compared to PAUT, and near surface resolution is therefore improved.
- Because of the large quantity and diversity of the different A-Scans collected, and because of the high sensitivity of the technique to low amplitude coherent signals, FMC images can be generated for different imaging paths (multimodal TFM) which might allow better detection, characterisation and sizing.
- Adaptive (Iterative) TFM (ATFM) is capable of focusing through irregular surfaces.
- Ease of inspection setup as explicit definition of focal point(s) or depth(s) is not required, since TFM focuses everywhere in the ROI.
- The above benefits can be obtained partially or fully from other ultrasonic techniques but can be achieved in a far more convenient manner by using FMC/TFM.

A detailed comparison between the established PAUT techniques and that of FMC/TFM is presented in Annex A of ISO 23865.

The TFM imaging process originated from the synthetic aperture radar and was introduced in NDT as the Synthetic Aperture Focusing Technique (SAFT). The acronym TFM refers to the processing algorithm itself or the imaging scheme. A variety of different types of acquisition can be used to collect the raw data to be processed by the TFM algorithm, such as FMC, Half Matrix Capture (HMC), Sparse Matrix Capture (SMC), Virtual Source Aperture (VSA), and Plane Wave Imaging (PWI).

This document focuses primarily on FMC/TFM, but its principles can be used to qualify other related techniques listed above.

3. Qualification to the ENIQ Methodology

The Qualification of a NDT system using FMC should follow the same process as for any other inspection to be qualified using the ENIQ Methodology [1]. For the purpose of this paper, a PAUT inspection of Primary Circuit Components of a civil NPP should be used as a comparison, as most of the essential parameters will be the same.

At the start of the qualification process, the objective of the inspection is set out. This is usually in the form of an inspection specification that details the component parameters and the defects to be detected, sized and/or located, with the associated performance requirements. The Qualification Level and Approach will then be set depending on the safety significance of the component to be inspected, as per ENIQ Recommended Practice 8 [4]. For a primary circuit component, this will usually consist of a Technical Justification (TJ) supported by practical trials using representative test pieces.

The TJ will be constructed as per the guidance in ENIQ Recommended Practice 2 [2] and should contain justification through theory, modelling, and practical tests, that the NDT system will meet its objective. One critical part of constructing the TJ is to identify the influential and essential parameters. The essential parameters of an inspection are those influential parameters which if changed in value would alter the outcome of an inspection in such a way that the inspection could no longer meet its defined objectives [2].

Examples of the essential parameters for an inspection can be found in the Appendix of ENIQ RP2 [2], including examples for PAUT in Appendix 3. The majority of the essential parameters for the components, defects, performance requirements, pulse-echo ultrasonics and PAUT will be similar to an FMC inspection however, there will be some additional parameters that must be considered. Section 5 of this paper will detail such parameters and provide examples for an FMC inspection.

Once the Qualification body (QB) has reviewed the TJ and is content that the inspection will meet its objectives, a practical assessment of the equipment, techniques and procedure will be made, ideally using representative defects and test pieces. Guidance on the use and manufacture of test pieces can be found in ENIQ Recommended Practice 5 - Guidelines for the Design of Test Pieces and Conduct of Test Piece Trials [5]. Section 4 details the specific considerations for test pieces and defects used for qualification.

4. Considerations for the Qualification of FMC/TFM

The Qualification of FMC/TFM and similarly other novel inspection techniques are being pursued by Inspection Vendors and Licensees due to the improved sizing accuracies and improved imaging that can be achieved over conventional UT methods. However, this can pose various challenges to Inspection Vendors and Qualification Bodies. Some of these challenges are listed in this section. The Inspection Qualification of novel inspection techniques, despite its challenges, should be encouraged if it is justified by improvements in inspection capability and reliability, and the rigour applied by the QB should be the same as for conventional techniques.

Inspection techniques using synthetic aperture focusing, as regards Inspection Qualification, differ fundamentally from more conventional techniques in that the raw data, A-Scans in the case of ultrasonic techniques, are not displayed, are not accessible and cannot be verified. In addition, the algorithm might have been adapted to perform additional operations such as apodisation, adaptive focusing, coherence weighting etc. that can be seen to further adapt the original ultrasonic responses. The inability to validate the existence and correctness of the original ultrasonic signals and the potential for alteration of the original ultrasonic responses makes these techniques more challenging to qualify as data quality checks are generally not performed at the raw data level.

For novel techniques, significant gaps in historical evidence, references and general knowledge might exist. Therefore, the inspection vendors and QBs can be more reluctant to use and attempt to qualify novel techniques in the place of more well-established ones. The additional effort required for the generation of sufficient evidence to be included in the TJ must be forecasted at the qualification planning phase. In addition, gaps in knowledge of the personnel involved in designing, implementing, and assessing novel inspection techniques must be identified and addressed with relevant training and experience gained.

Relevant standards might be absent or might be in their infancy and lacking crucial information. Therefore, it might be more challenging to justify the equipment selected and the equipment calibration and sensitivity checking routines for a novel inspection technique.

4.1. Technical Justification

The role of a TJ is to justify that the inspection will meet the performance requirements set in the inspection specification. Typically, these requirements will be set as a specific range of defects to be detected, located, sized, and characterised in a specific area of a weld, or of a component, with a certain confidence. Tolerances in sizing and positioning are usually given by the licensee. The TJ can be used to justify that the inspection will detect, locate, size, and characterise all probable defects that satisfy the criteria of the inspection specification.

In the following paragraphs, specific guidance is given for the completion of the most significant sections of a TJ when justifying a novel inspection. The guidance below is not exhaustive, and the reader is encouraged to read ENIQ Recommended Practice 2 [2].

One of the key initial tasks of a TJ is to identify the influential and essential parameters of the inspection (TJ-Section 4). The essential parameters are given specific values or tolerances outside of which the inspection results are compromised. These parameters are further addressed and justified in the following sections of the TJ, if necessary. For novel techniques there will be less existing information for the definition of essential parameters and more effort will be required for their identification and justification. Several parameters that might apply to FMC/TFM inspections are identified in Section 5 of this document.

The physical reasoning section (TJ-Section 5) of a TJ is where theoretical justification is presented to support the equipment, techniques, and parameters selected for the inspection. Section 5 is also required to describe the basic principles of the algorithms used (or how version control is managed), the beam-to-defect interactions, and different detection mechanisms, as well as justify coverage of the inspection area. Some essential parameters requiring further justification, from TJ-Section 4, should also be treated in this section. The inspection data for FMC/TFM comprises of raw elemental a-scan data and reconstructed data. In contrast to more traditional techniques, the raw a-scan data is not, in general, possible to be evaluated directly and is only useful after reconstruction. All evaluation is done on reconstructed data. There's been significant development in the reconstruction techniques in recent years and retaining the raw a-scan data would potentially allow future re-evaluation with enhanced reconstruction algorithms. However, the raw data is extremely voluminous and storing it requires significant storage capacity. Thus, the decision on whether to store the raw elemental a-scan data, reconstructed data or both is significant and should be considered in the TJ.

In Section 6 of a TJ (ENIQ Recommended Practice 6 [6]), predictions via modelling may be used to guide or support technique and equipment selection and to complement the evidence found in the rest of the TJ. For some novel techniques, the available simulation tools might be limited. This section should justify that the simulations performed are relevant, the simulation tools are validated, and the simulation results agree with the experimental results of TJ-Section 7.

Relevant experimental results and parametric studies should be presented in Sections 7&8 of the TJ. In the case of a new inspection using a novel technique, it is more likely that new experimental data will be required to be collected, or that the relevance of existing evidence will require justification.

The equipment, the data analysis process and inspection personnel requirements are justified in Section 9. The selected equipment, equipment calibration, data collection and data analysis might contain intricacies that are not common in conventional techniques. Care shall be taken in identifying these and providing sufficient justification. Assurance that the algorithms involved will remain unchanged post-qualification and implementation of version control methods for the software and setup files involved, should be described in this section. The QB would require justification for any changes to software or setup files. The software version control suggested herein is not intended to add further considerations to what is common practice in conventional qualified inspections but is intended to be a reminder, because novel techniques are expected to require novel software which is likely to be updated in regular intervals. Personnel should be adequately trained in using the equipment and performing data analysis and additional training regimes might be necessary for novel techniques.

4.2. Inspection Procedure

Inspection Procedures should be written in accordance with ENIQ Recommended Practice 12 [7]. Specific FMC/TFM essential parameters identified in the TJ should be controlled by the Inspection Procedure. Setup parameters should be listed and if setup files are used, the date and timestamp of the file qualified should be included and verified by the operator. In the case of novel techniques and of FMC/TFM specifically, the need for the Inspection Procedure to be prescriptive and user friendly is paramount as the operators, although trained, are less likely to be experts in the specific technique. The lack of experience could lead operators to rely on the Procedures being prescriptive and to follow them more rigorously.

4.3. Test Piece and Defect Design

It is expected that FMC/TFM, and its related techniques, will be selected to provide accurate sizing and/or characterisation, for inspections that are inherently challenging. The design of and quality assurance applied to the Test Piece should allow for the challenges of the specific inspection to be tested and facilitate a fair assessment of the FMC/TFM technique. Similarly, the manufactured defects provide the opportunity to assess the inspection for its claimed capabilities. For example, if a sizing capability range is claimed by the TJ on defects of certain morphology and/or dimension, then the qualification defects should be specified with these claims in mind, and with the aim of enabling conclusive evidence to test the claims made within the TJ. Other considerations linked to the essential parameters for FMC should also be included, such as the material surface condition, dimensions, and grain structure, which should be representative but also at the most challenging end of their working tolerance.

FMC can provide a fully focused image and an improvement in sizing capability over the inspection volume with a single acquisition. Therefore, the manufactured defect dimensions must be manufactured with sufficiently tight tolerances to allow for the assessment of the sizing performance required by the Inspection Specification. Methods of measuring the qualification defects within the test pieces need to provide assurance that the manufacturing tolerances have been achieved. This can be achieved mechanically before the defects are manufactured, but once the Test Piece has been welded, the defect size can alter due to shrinkage or cracking. Usually, the final defect size would be confirmed using conventional UT or radiography, but the measurement tolerances for these techniques are likely to be on par with the performance achieved by FMC/TFM. It is possible that the Test Piece, or a specific sample manufactured under the same conditions, could be destructively tested after the qualification, so that exact mechanical measurements can be achieved, and the actual FMC sizing tolerance calculated.

4.4. Personnel Requirements for the Inspection Vendor and Inspection Qualification Body

Due to the absence of standardised training in accordance with ISO 9712, inspection personnel as well as the QB assessors should be suitably experienced in FMC/TFM and have undergone specific training on the software used for data acquisition and data analysis. Having a qualification in PAUT under ISO 9712 or equivalent should be a prerequisite for inspection personnel carrying out the FMC inspection.

5. Examples of FMC Essential Parameters

The lists given in this section are not exhaustive and the influential and essential parameters have to be defined separately for each inspection considering the way the inspection techniques are deployed and the intricacies of the inspection. Furthermore, FMC acquisition units have differences in the processing or post-processing of data and might have different capabilities dictating the consideration of different essential parameters.

The parameters that are thought to be specific to FMC/TFM, or relative techniques, are given with supporting text as guidance for defining their tolerances. Most parameters are the same as the ones defined in Appendix 3 of [2] for the PAUT technique, these are denoted as “As per conventional/PAUT”.

5.1. Input Group Parameters

5.1.1. Component Group Parameters

Influential or Essential Parameter	Specific Guidance for FMC/TFM
Geometry of the component	Depending on propagation modes considered, the outer and inner surfaces might need to be parallel and the component thickness to be consistent and known. Significant variations in thickness can affect the reconstruction of propagation modes that use the back-wall.
Access restrictions	As per conventional/PAUT
Surface condition	As per conventional/PAUT
Weld crown configuration	To be considered if surface variability is likely to affect the processing algorithm.
Weld root configuration	Variations on the back-wall geometry and thickness will have larger effect on reliability and accuracy if propagation modes use the backwall (see “Geometry of the component” parameter)
Wall thickness of the straight pipe	If the reconstruction uses half skip modes, the wall thickness has a strong influence and should be carefully checked
Diameter of the pipe	As per conventional/PAUT
Counterbore	As per conventional/PAUT
Counterbore dimensions	Variations on the back-wall geometry and thickness will have larger effect on reliability and accuracy if propagation modes use the backwall (see “Geometry of the component” parameter)
Weld mismatch (misalignment)	Can affect pitch-catch FMC.
Macrostructure of base material	As per conventional/PAUT
Macrostructure of the weld	As per conventional/PAUT
Presence of buttering	As per conventional/PAUT

Temperature	As per conventional/PAUT
Error of form	If Adaptive TFM is used, it should be demonstrated that the error of form of the component under inspection is within the domain of validity of the algorithm.

5.1.2. Defect Related Parameters

Influential or Essential Parameter	Specific Guidance for FMC/TFM
Type of defect	As per conventional/PAUT
Length of defect	As per conventional/PAUT
Degradation mechanism	As per conventional/PAUT
Shape of the defect	As per conventional/PAUT
Through-wall extent of the defect	As per conventional/PAUT
Position of the defect through the thickness of the component	As per conventional/PAUT
Tilt angle of the defect	As per conventional/PAUT
Skew angle of the defect	As per conventional/PAUT
Roughness/branching of the defect	As per conventional/PAUT
Presence of residual stresses	As per conventional/PAUT
Defect mechanical measurement tolerances	As per conventional/PAUT

5.2. NDT Inspection System Group Parameters

5.2.1. Procedure Parameters

Influential or Essential Parameter	Specific Guidance for FMC/TFM
Wave mode	As per conventional/PAUT
Probe type	As per conventional/PAUT
Probe configuration (pulse echo, tandem, pitch/catch, etc.)	As per conventional/PAUT plus FMC and PWI

Probe size	As per conventional/PAUT
Frequency	As per conventional/PAUT
Natural angle of the array	Define natural wedge refraction angle and range of angles that contribute to the TFM reconstruction.
Pulse length	As per conventional/PAUT
Sensitivity for scanning and recording	Consult ISO 23865
Scanning speed	Active aperture element count and focal grid resolution significantly affect the maximum scanning speed achievable due to the number of A-Scans collected.
Scanned area on component surface	As per conventional/PAUT
Personnel training, experience, and qualification	Specific training and experience is required on equipment and software applied. If no formal ISO9712 qualification exists then specific in-house training may be required.
Sizing method	Consult ISO 23865
Characterisation and detection methods	As per conventional/PAUT
Recording/identification criteria	As per conventional/PAUT
Data analysis scheme	As per conventional/PAUT

5.2.2. Equipment Parameters

Essential Parameter	**Specific Guidance for FMC/TFM**
Hardware pulser/receiver and data acquisition	As per conventional/PAUT
Cables	As per conventional/PAUT
Transducers	As per conventional/PAUT
Scanner	As per conventional/PAUT

5.2.2.1 Hardware Pulser / Receiver and Data Acquisition

Essential Parameter	**Specific Guidance for FMC/TFM**
Vertical linearity (screen height)	As per conventional/PAUT

Horizontal linearity (time base)	As per conventional/PAUT
Averaging rate	As per conventional/PAUT
Points per A-scan sampling	As per conventional/PAUT
Pulse amplitude of the emitter	As per conventional/PAUT
Pulse width of the emitter	As per conventional/PAUT
Pulse fall time of the emitter	As per conventional/PAUT
Pulse rise time of the emitter	As per conventional/PAUT
Bandwidth of receiver	As per conventional/PAUT
Available gain of receiver	As per conventional/PAUT
Band pass filter of receiver	As per conventional/PAUT
Time base setting	Sufficient to accommodate the longest traced ray required to generate the TFM within the ROI
Sampling gate	As per conventional/PAUT
Scan type (for example, azimuthal, linear, static, depth)	As per conventional/PAUT
Applied gain—encompassing hardware gain and focal law gain	As per conventional/PAUT
Compression	As per conventional/PAUT
Digitizing frequency	At least 5 times the center frequency of the probe ISO 23865
Element configuration (element arrangement / wiring sequence)	As per conventional/PAUT
Frequency filters	Sufficiently broadband to be able to receive at least two times the center frequency of the probe. Lower and higher ends to be set to reasonable values
Minimum wedge footprint	As per conventional/PAUT
Pitch catch / pulse echo	As per conventional/PAUT
Triggering (acquisition scheme)	FMC/HMC/SMC/VSA/PWI/SAFT etc.
Primary propagation modes and inclusion angles.	TFM can be applied to various wave modes: LLL, TTT, LLT, TLL, TT, LL. Their use and effectiveness must be justified in the TJ and the operators trained on how to use the different options. L= Longitudinal Wave

	T= Transverse Wave
Recurrence / PRF of individual channel / focal law	As per conventional/PAUT
Voltage	As per conventional/PAUT
Sound beam velocity (velocity in part)	As per conventional/PAUT
ROI Size	Sufficient to cover the inspection volume but reasonable size to allow desired frame rate.
ROI Position	In relation to probe position and inspection volume
Refraction angles related to probe and ROI position	The detection angles that the relative positions of transducer and ROI impose require to be defined.
Focal grid resolution	A balance between amplitude stability, inspection speed and size of defect to be detected must be defined. Typically, $<\lambda/5$
Amplitude stability between pixels (amplitude fidelity)	Check according to ISO 23865
Delay Law characteristics	In the case of PWI and VSA
Data storage/Data transfer	Consider data storage and transfer due to large amount of data stored with FMC. File size reduction techniques such as storing only the FMC images and not the FMC data could be used.
Algorithm specific adaptations (Apodisation, Adaptive Focusing, Coherence Weighting)	Where any adaptations to the TFM algorithm exist. What are their limitations and their effects on the resulting image?

5.2.2.2 Cable

Essential Parameter	Specific Guidance for FMC/TFM
Cable type/maximum length/intermediate connectors	As per conventional/PAUT
Impedance	As per conventional/PAUT

5.2.2.3 Probe

Essential Parameter	Specific Guidance for FMC/TFM

Probe type	Linear, matrix or dual matrix
Probe frequency	As per conventional/PAUT
Probe index point	As per conventional/PAUT
Beam shoe angle	As per conventional/PAUT
Probe shoe angular deviations (squint angle)	As per conventional/PAUT
Bandwidth	As per conventional/PAUT
Probe separation	As per conventional/PAUT
Pulser/receiver connection	As per conventional/PAUT
Element size	As per PAUT
Element pitch	As per PAUT
Height to the middle of the first element	As per conventional/PAUT
Probe Elevation	To allow an appropriate near field length
Primary axis offset at the middle of the first element	As per conventional/PAUT
Secondary axis offset at the middle of the first element	As per conventional/PAUT
Primary axis position of wedge reference	As per conventional/PAUT
Secondary axis position of wedge reference	
Total crystal size (combined element size)	As per conventional/PAUT
Total number of elements used	To allow inspection at a distance away from the probe and within the near field
Velocity in wedge material	As per conventional/PAUT
Wedge contour	As per conventional/PAUT
Spacing (kerf)	As per conventional/PAUT
Probe Bandwidth	Typically>60% (ISO 23865)
Element damping	Sufficient to reach the required bandwidth e.g. 60%

5.2.2.4 Scanner

Essential Parameter	Specific Guidance for FMC/TFM
Linearity of the scanner	As per conventional/PAUT
Repeatability	As per conventional/PAUT
Resolution	As per conventional/PAUT
Water path (for immersion inspection)	As per conventional/PAUT
Backlash	As per conventional/PAUT

References

[1] *European Methodology for Qualification of Non-Destructive Testing - Issue 4*, ENIQ Report no. 61, The NUGENIA Association, 2019.

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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 70 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 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.

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