Safety Analysis of SMR with PAssive Mitigation strategies - Severe Accident

International Workshop on SMR Safety for a Sustainable Short-term Deployment

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Abstract

The first SASPAM-SA open workshop, held at the IRSN headquarters in Fontenay-aux-Roses (Paris) on October 17–18, 2024, promoted international exchange of information and practices related to Water Cooled Small Modular Reactor (SMR) safety considering the outcomes from the current ongoing Horizon Euratom SASPAM-SA project, other EU-Projects and other international initiatives (e.g. European SMR Pre-partnership, IAEA, OECD/NEA, ETSON, etc.). The workshop's objective is to share the advancements of the current major research activities on LW-SMR safety and give the opportunity to discuss the main results. This allows to identify the needed knowledge development, in the view of additional short-term research actions, to support the SMR European licensing process.

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Executive Summary

The first SASPAM-SA open workshop, held on October 17–18, 2024, at the IRSN headquarters in Fontenay-aux-Roses (Paris, France), facilitated international discussions on LW-SMR safety. The event focused on sharing research progress, identifying knowledge gaps, and defining short-term R&D priorities to support SMR European licensing processes.

Key topics included:

- Accident scenarios in LW-SMRs and related phenomenology.
- Capabilities of safety computer codes to predict LW-SMR phenomenology in transient conditions.
- Applicability of existing experimental database to characterize LW-SMR phenomenology in steady-operational and transient conditions.
- Analyses of the current Severe Accident (SA) mitigation strategies and features (e.g. IVMR, hydrogen management) and related modeling aspects.
- Computer code guidelines and best practices for LW-SMR modelling.
- Applicability of tools and methods to determine the needed extent of the Emergency Planning Zone (EPZ) for LW-SMR.
- Applicability of high-fidelity tools for the safety analysis of LW-SMRs.
- Safety of LW-SMR integrated into a hybrid energy system.
- Safety research in standardization and nuclear safety.

The workshop provided a state-of-the-art review, integrating results from the Horizon Euratom SASPAM-SA project and other EU and international initiatives (IAEA, OECD/NEA, ETSON, European SMR Pre-Partnership, etc.).

Over the past decade, significant progress has been made in SMR safety research through Euratom-funded projects and broader international research initiatives. These efforts have led to enhanced expertise in advanced SMR designs, improved modeling capabilities, and strengthened safety assessment frameworks. However, some gaps still remain and must be addressed from both phenomenological deterministic perspective (e.g., thermal-hydraulics, SA progression including uncertainty) and probabilistic perspective:

- Importance of accident management strategies and the need for a graded approach to licensing and compliance, tailored to SMR-specific features.
- Importance of experimental data in validating computational to be used to simulate SMR DBA, BDBA and SA scenarios.
- Development of advanced models to enhance computational tool predictive capabilities of SMR-specific features, such as passive system performance, hydrogen distribution and mitigation, small containment behavior, and IVMR efficiency.
- Needed to define and optimize SMR EPZs by balancing safety, public acceptance, and operational feasibility.
- Regulatory frameworks must evolve to ensure SMR compatibility with hybrid energy systems, while international collaboration will be crucial in establishing best practices for multi-use SMR deployment and fostering harmonized safety standards.

- Need for harmonizing regulatory frameworks across different European countries to streamline international licensing efforts and facilitate cross-border deployment of SMRs.
- Importance of international collaboration in advancing SMR safety innovation.

This report gives an overview of the contributions presented at the workshop and the main insights on the needed knowledge development, in the view of additional short-term research actions, to support the SMR European licensing process.

List Of Abbreviations And Acronyms

AM	Accident Management
AMHYCO	Accident Management for Hydrogen and Carbon Monoxide Risks
AMR	Advanced Modular Reactor
ASNR	Nuclear Safety and Radioprotection Authority
ASSAS	Artificial Intelligence for Severe Accident Simulators
ATF	Accident Tolerant Fuel
BDBA	Beyond Design Basis Accident
BT	Becker Technologies (Germany)
CCVM	CSNI Code Validation Matrices
CEA	Commissariat à l'Énergie Atomique et aux Énergies Alternatives (France)
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)
CHF	Cririical Heat Flux
CNL	Canadian Nuclear Laboratories (Canada)
CNSC	Canadian Nuclear Safety Commission (Canada)
CFD	Computational Fluid Dynamics
CSARP	Cooperative Severe Accident Research Program
CSNI	Committee on the Safety of Nuclear Installations
CWC	Containment Wall Condenser
DBA	Design Basis Accident
DSA	Deterministic Safety Analyses
EASI-SMR	Ensuring Assessment of Safety Innovations for SMRs
EDF	Électricité de France (France)
ENEA	Agenzia Nazionale per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile (Italy)
ENEN	European Nuclear Education Network (Belgium)
EPZ	Emergency Planning Zone
EPR	Emergency Preparedness and Response
ERVC	External Reactor Vessel Cooling
EU	European Union
ETSON	European Technical Safety Organizations Network
GCDb	Generic Containment Database
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
GSR	General Safety Requirements
HARMONISE	Towards Harmonization in Licensing of Future Nuclear Power Technologies in Europe
HBU	high-burnup
IAEA	International Atomic Energy Agency Austria)
iPWR	integral PWR
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
IVMR	In-Vessel Melt Retention
JAEA	Japan Atomic Energy Agency (Japan)
KAERI	Korea Atomic Energy Research Institute (South Korea)
KIT	Karlsruhe Institute of Technology (Germany)
LEI	Lithuanian Energy Institute (Lithuania)
LP	Lumped Parameter
LW	Light Water
LWR	Light Water Reactor
L-LWR	Large LWR

LW-SMR	Light Water Small Modular Reactor
MCSAFER	Multi-scale Safety Evaluation for Water-Cooled SMRs
MSR	Molten Salt Reactor
NEA	Nuclear Energy Agency (OECD) (France)
OC	Organizing Committee
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Analyses
R&D	Research and Development
SA	Severe Accident
SACO	Safety Condenser
SAM	Severe Accident Management
SC	Scientific Committee
OECD	Organization for Economic Co-operation and Development
PAR	Passive Autocatalytic Recombiners
PASTELS	Passive Systems: Simulating the Thermal-hydraulics with Experimental Studies
PECCS	Passive Emergency Core Cooling Systems
PCCS	Passive Containment Cooling Systems
PIRT	Phenomena Identification Ranking Table
PRHR	Passive Residual Heat Removal System
PSI	Paul Scherrer Institute (Switzerland)
PSS	Passive Safety Systems
RIPB	performance-based
R&D	Research and Development
R&D&I	Research and Development and Innovation
SA	Severe Accident
SASPAM-SA	Safety Analysis of SMR with Passive Mitigation Strategies – Severe Accident
SC	Scientific Committee
SSC	Structural Systems and Components
SMR	Small Modular Reactor
SNL	Sandia National Laboratories (USA)
SNETP	Sustainable Nuclear Energy Technology Platform
ST	Source Term
SUJB	State Office for Nuclear Safety (Czeck Republic)
TANDEM	Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix
TRISO	TRi-structural ISOtropic
TSO	Technical Support Organization
UPM	Universidad Politécnica de Madrid
USNRC	United States Nuclear Regulatory Commission (USA)
VADD	Validation Database Directory
VDRs	Vendor Design Reviews
VTT	Technical Research Centre of Finland (Finland)
V&V	Verification and Validation

1 INTRODUCTION

1.1 TECHNICAL BACKGROUND

Nowadays Light Water cooled SMR (LW-SMR) are one of the key design options for the near-term deployment of nuclear reactor technology due to their generally recognized advantages (inherent safety, design simplicity, possibility of simplified batch production, reduction of construction time, reduce capital and operational cost, etc.) and to their level of technological and licensing readiness.

The advanced technological and licensing readiness of LW-SMR is a result of starting from the well-proven-established operating Large-Light Water Reactor (L-LWR) technology, incorporating their operational plant experience/feedback, and including moderate evolutionary design modifications to increase the inherent safety of the plant. Therefore, it is envisaged to benefit from the operating L-LWR knowledge and know-how as a base of the SMR technology, minimizing the technological risks connected with innovative technological solutions proposed in innovative SMRs (that differ significantly from existing operating reactors). Therefore, several LW-SMR concepts are in an advanced design state and ready to be licensed[1]. Construction and certification activities are currently on-going and are expected to further increase and accelerate.

Considering the Net Zero Goal by 2050 in Europe and European competitiveness, nuclear energy will have a key role in reaching this target with the aim of contributing to decarbonization in Europe. In view of the envisaged short-term license process in European countries, an R&D program consistent with the European market needs and license requirements is in progress to ensure the implementation of the highest nuclear safety standards. In this regard, the **safety demonstration** is the key action to confirm the adequacy of the safety provisions ensuring the stable and safe operation of an SMR in all the plant states. Within this framework, Euratom Research and Training Programs have a key role in supporting R&D activities, speeding-up licensing process, and securing a leading position for European Intuitions within the international framework. European projects are articulated addressing different topics, in order to support the expected safety demonstration of LW-SMR in Europe, and different actions are in progress or have been recently finished (e.g. ELSMOR, HARMONISE, MCSAFER, PASTELS, SASPAM-SA, TANDEM).

Considering the outcomes from the current on-going Horizon Euratom SASPAM-SA project (organizer of this event) as well as from the other European projects already finished or currently ongoing, as well as other international initiatives (European SMR Pre-partnership, IAEA, OECD/NEA, ETSON, etc.), the workshop's objective is to carry out a state-of-art review to identify remaining knowledge gaps linked to the safety demonstration of LW-SMR. The workshop offered the opportunity to identify the current gaps and how to address them with short-term additional research actions.

1.2 SCOPE, TECHNICAL CONTENT OF THE WORKSHOP AND ORGANIZATION

The focus of the Workshop is to discuss and review the state-of-art and the needed knowledge development on:

[1] https://snetp.eu/2024/10/11/european-industrial-alliance-on-smrs-announces-the-first-batch-of-9-smr-projects-for-the-project-working-groups/

- Accident scenarios in LW-SMRs and related phenomenology.
- Capabilities of safety computer codes to predict LW-SMR phenomenology in transient conditions.
- Applicability of existing experimental database to characterize LW-SMR phenomenology in steady-operational and transient conditions.
- Analyses of the current Severe Accident (SA) mitigation strategies and features (e.g. IVMR, hydrogen management) and related modeling aspects.
- Computer code guidelines and best practices for LW-SMR modelling.
- Applicability of tools and methods to determine the needed extent of the Emergency Planning Zone (EPZ) for LW-SMR.
- Applicability of high-fidelity tools for the safety analysis of LW-SMRs.
- Safety of LW-SMR integrated into a hybrid energy system.
- Safety research in standardization and nuclear safety.

An Organizing Committee (OC) took care of the planning and organization of the meeting on behalf of the SASPAM-SA project. The OC Members are presented in the table below:

Table 1: OC Members.

Member	Institution	Country
Ahmed BENTAIB	IRSN	France
Fulvio MASCARI	ENEA	Italy
Fabrizio GABRIELLI	KIT	Germany
Terttaliisa LIND	PSI	Switzerland
Florian FICHOT	IRSN	France
Nils REINKE	GRS	Germany
Mikko ILVONEN	VTT	Finland
Fabio GIANNETTI	UNIROMA1	Italy

A Scientific Committee (SC) took care of the scientific content of the meeting. The SC members are presented in the table below:

Table 2: SC Members.

Member	Institution	Country
Sanjeev GUPTA	Becker Technologies GmbH	Germany
Claire VAGLIO-GAUDARD	CEA	France
Luis Enrique HERRANZ	CIEMAT	Spain
Andrew MORREALE	CNL	Canada
Mounia BERDAI	CNSC	Canada
Michael MONTOUT	EDF	France
Sylvain TAKENOUTI	EDF	France
Fulvio MASCARI	ENEA	Italy
Ahmed BENTAIB	IRSN	France
Sebastien ISRAEL	IRSN	France
Victor SANCHEZ	KIT	Germany
Egidijus URBONAVICIUS	LEI	Lithuania
Hideo NAKAMURA	JAEA	Japan
Martina ADORNI	OECD/NEA	France
Dave LUXAT	SNL	USA
Tereza Abrman MARKOVÁ	SUJB	Czeck Republic
Shawn CAMPBELL	USNRC	USA
Ville TULKKI	VTT	Finland
Gabriel PAVEL	ENEN	Belgium

The event was announced in April 2024 with the objective to hold the workshop in IRSN Headquarters, 31 av. De la Division Leclerc, Fontenay-aux-Roses, France, October 17th – 18th, 2024.

Accordingly, the workshop agenda (see Appendix A) was arranged with oral presentations and time for discussion. A poster session was considered. The workshop consists of seven sessions organized as follows:

- SESSION 1: Opening remarks and introduction.
- SESSION 2: Overview of SASPAM-SA progress.
- SESSION 3: International initiatives.
- SESSION 4: Discussion of day 1 and closing remarks.
- SESSION 5: European project achievements.
- SESSION 6: Technical presentations.
- SESSION 7: Discussion of day 2 and closing remarks.

The 27 technical presentations were divided into 4 technical sessions dedicated to different topics. There were 36 Posters including 16 posters from ENEN2plus young researcher sponsorship.

Table 3: Number of contributions per topic.

Session title	**Number of contributions**
OVERVIEW OF SASPAM-SA PROGRESS	6
INTERNATIONAL INITIATIVES	6
EUROPEAN PROJECT ACHIEVEMENTS	10
TECHNICAL PRESENTATIONS	5
POSTER SESSIONS	16
ENEN2plus Mobility POSTERS SESSION	16

Table 4 shows poster session papers and able 5 shows ENEN2plus Mobility posters session papers.

Table 4: Poster session papers.

Name	Title	Institution	Nationality
Laura Gastaldo	The CALIF3S software – a validation case for the safety study of HTGR-hydrogen production coupling systems	IRSN	France
C. Vázquez-Rodríguez, S. Kelm	Development of a LW-SMR dry containment CFD model with containmentFOAM	JULICH	Germany
J. Bittan, M. Di Giuli	EDF and TRACTEBEL contribution in SASPAM-SA	EDF, TRACTEBEL	France
M. Garcia Martin	CIEMAT contribution in SASPAM-SA	CIEMAT	Spain
F. Gabrielli	KIT contribution in SASPAM-SA	KIT	Germany
F. Mascari, F. Giannetti	SASPAM-SA HORIZON EURATOM project	ENEA	Italy
N. Chaumeix	Hydrogen Safety Analysis	CNRS	France
A. Kaliatka	Issues of severe accidents in LW-SMR modelling using AC2 codes	LEI	Lithuania
R. Gencheva	ASTECv3.1.1 sensitivity studies of FPs relies from the DRYWELL to the ENVIRONMENT in IRIS SMR design after LOCA accident and loss of all passive safety systems	INRNE – BAS	Bulgaria
E. Jia	GOTHIC and MELCOR Benchmarking of the CNL Strong Condensation Containment Apparatus Experiments	CNL	Canada
L. Lebel	Simulation of SBO and SBLOCA in a Small BWR Using MELCOR Code	CNL	Canada
L. Lebel	Benchmarking CFD with Gaussian Plume Models for Near-Field Atmospheric Dispersion	CNL	Canada
Y. Okan	Turkey as a SMR Paradise	Nuclear Industry Association of Türkiye	Turkey
T. Sisay Mekonin	Radiation Dose Assessment for CT scanner, Environmental Sample, and their associated lifetime Cancer risk	Wachemo University	Ethiopia
M.S. Shuaibu	Safety Analysis and Risk Assessment of Small Modular Reactors (SMRs) for Next-Generation Nuclear Power	Nigerian Nuclear Regulatory Authority	Nigeria
F. M. Abdulazeez	Safe and Sustainable Energy for Third World Countries: Harnessing the Potential of Small Modular Reactors	Nigerian Nuclear Regulatory Authority	Nigeria

Table 5: ENEN2plus Mobility Poster Session papers.

Name	Title	Institution	Nationality
Francesco Rizzo	Methodological Approach to perform Inverse Uncertainty Quantification using RELAP5/Mod3.3 and RAVEN	UNIROMA1	Italy
Abdelfattah Ali	Analysis of Passive Heat Removal Loops for Small Modular Reactors at Supercritical Pressure	Egyptian Atomic Energy Authority	Egypt
Alessandro Morandi	Activation Analysis and Safety Considerations for Compact Tokamak Operations with Deuterium-Helium3 Fuel	POLITO	Italy
Cristiano Ciurluini	Development of a 0D Model for the investigation of In Vessel Melt Retention in integral Pressurized Water Reactors	UNIROMA1	Italy
Erik Cilia	Case study of a BDBA in a generic SMR reactor using MELCOR code	UNIBO	Italy
Fabio Mancini	Sizing of a SMR pressurizer and transient conditions preliminary evaluation	UNIROMA1	Italy
Gianluca D'Arpa	REPAS application for the analysis of the reliability of passive safety systems	UNIPA	Italy
Gianmarco Grippo	DBA Sequence Analysis in a Generic iPWR: Comparison of MELCOR and ASTEC Codes with TRACE Thermal-Hydraulic Reference	UNIBO	Italy
Manuel Venditto	Preliminary fuel Thermal Design of DESIGN 1 LW-SMR	UNIROMA1	Italy
Marcello Principato	DEC-B MELCOR transient analyses in an integral Pressurized Water Reactor	UNIROMA1	Italy
Marcello Savini	Analyses of DBA and several BDBA sequences in a generic iPWR	UNIBO	Italy
Marco Barbieri	OFFBEAT simulation and validation in a Generic iPWR rod under LOCA conditions	UNIBO	Italy
Sara Calistri	Production of radioisotopes of medical interest by 14 MeV neutron beam and radiochemical processes	UNIBO	Italy
Valentina Patitucci	Small modular reactors: a key solution for low-carbon energy transition and enhanced safety through passive systems.	UNIPI	Italy
Federica Vespucci	Application of the beta distribution in probability estimation: comparison between data simulations and REPAS results	UNIPA	Italy
Rainer Kelk	Application of machine-learning methods for condensation in severe accident analysis	PSI	Switzerland

1.3 ATTENDANCE

The workshop attracted a diverse group of participants, highlighting the international collaboration and expertise gathered to address the safety of LW-SMRs. A total of over 60 participants from 14 countries attended the event, representing a broad spectrum of stakeholders, including:

- **Regulatory organizations:** international regulatory bodies focusing on nuclear safety.
- **Reactor designers and operators:** Industrial stakeholders engaged in SMR development and deployment.

- **TSOs:** Independent organizations providing expertise and services to regulatory authorities.
- **Consultancies and Senior Engineers:** Experts providing guidance on design, safety analysis, and strategic implementation.
- **Academic and Research Institutions:** Researchers and analysts contributing to the development of safety methodologies and tools.

The geographical diversity of the participants emphasized the global importance of SMR safety, with representatives from Europe, North America, Asia, and other regions actively contributing to discussions.

In addition to the plenary and technical sessions, the poster session provided a platform for young researchers and project teams to showcase ongoing work, fostering an environment of collaboration and innovation. The strong attendance underlines the commitment of the nuclear community to advancing SMR technologies for a sustainable and safe future.

1.4 Organization of the report

The report was structured to systematically present the outcomes of the International Workshop on SMR Safety for a Sustainable Short-term Deployment. Its organization reflects the workshop's objectives and sessions, ensuring a logical flow from introductory remarks to detailed technical analyses and final recommendations. The key sections include:

Introduction: Providing technical background, scope, and workshop objectives, with emphasis on the importance of SMRs in achieving decarbonization goals.

Summary of Sessions: Detailed accounts of each session, highlighting key presentations, discussions, and findings, categorized under themes like European project achievements and international initiatives.

Technical Presentations: Summarizing contributions on experimental, modeling, and safety advancements specific to SMRs, along with identified R&D needs.

Conclusions and Recommendations: Drawing cross-cutting insights and proposing short-term R&D priorities to address identified gaps in SMR safety and deployment.

References and Appendices: Listing cited projects, documents, and supplementary materials such as experimental data and project-specific details.

This structure facilitates easy navigation while ensuring a comprehensive understanding of the workshop's contributions and outcomes.

2 SUMMARY OF THE WORKSHOP SESSION/TOPICS

2.1 OPENING REMARKS AND WELCOME

Session Chairs: F. Mascari (ENEA, Italy) and Ahmed Bentaib (IRSN, France)

The Opening Remarks and Introduction session provided a foundational overview of the meeting. **A. Bentaib (IRSN)** and **F. Mascari (ENEA)** welcomed participants and outlined the agenda. **P. Giordano (IRSN)** highlighted the importance of SMR safety for sustainable deployment, highlighting nuclear energy's role in decarbonization, the evolving global nuclear ecosystem, TSOs' critical role, and public trust. **A. Iorizzo (European Commission)** highlighted the European Commission's role and commitment to supporting nuclear safety and innovation.

Table 6: Lectures list

09:00 - 09:10	Welcome and Introduction	A. BENTAIB (IRSN), F. MASCARI (ENEA)
09:10 - 09:20	IRSN Introduction	P. GIORDANO (IRSN) – Director of Research in Safety
09:20 - 09:30	Introduction from European Commission	A. IORIZZO (European Commission)

2.1.1 09:00 - 09:10 | Welcome and Introduction - A. BENTAIB (IRSN), F. MASCARI (ENEA)

A. Bentaib (IRSN) and **F. Mascari (ENEA)** delivered the welcome address, setting a collaborative frame for the workshop, and introduced its objectives, emphasizing the importance of SMR safety for sustainable deployment.

2.1.2 09:10 - 09:20 | IRSN Introduction – P. GIORDANO (IRSN) – Director of Research in Safety

P. Giordano (IRSN) highlighted the importance of SMR safety for sustainable deployment, emphasizing nuclear energy's role in decarbonization. Key points included the evolving global nuclear ecosystem, the critical role of TSOs in independent research, and the need to address public trust and human-organizational factors. He also shared insights on the upcoming ASNR merger, ensuring continuity in nuclear safety research and international collaboration. Gratitude was expressed to the European Commission and ENEN2plus for their support, with hopes for productive discussions during the workshop.

2.1.3 09:20 - 09:30 | Introduction from European Commission - A. IORIZZO (European Commission)

A. Iorizzo (European Commission) provided updates on Euratom's research on SMR safety, highlighting its alignment with EU policy for decarbonization and sustainable energy. Key projects funded under Horizon Euratom were discussed, focusing on Light Water and Advanced Modular Reactors. The role of international partnerships, including collaborations with IAEA and NEA-OECD, was emphasized to enhance safety standards. Additionally, the evolving European SMR ecosystem, such as European Industrial Alliance on SMRs, was explored. The session concluded by outlining future plans for fostering innovation and safety in SMR deployment.

2.2 OVERVIEW OF THE SASPAM-SA PROGRESS

Session Chairs: Ahmed Bentaib (IRSN, France) and F. Giannetti (UNIROMA1, Italy)

The session provided a comprehensive update on the SASPAM-SA project. **F. Mascari (ENEA)** gave an overview of the project's objectives and current results, followed by **F. Gabrielli (KIT)** presenting analyses of DBA and SA scenarios for iPWR. **T. Lind (PSI)** discussed the relevance and applicability of existing experimental databases to iPWR designs. **F. Fichot (IRSN)** discussed the assessment of code capabilities to simulate and evaluate corium retention in iPWRs. **N. Reinke (GRS)** the current status of the assessment of the code capabilities to simulate IPWR containment and characterize mitigation measures efficiency. Finally, under WP6 **M. Ilvonen (VTT)** presented preliminary conservative (partly even extremely conservative) assessments of EPZ extent and more generally, testing the applicability of the appropriate dispersion and dose codes, rounding off the session's discussions.

Table 7: Lectures list

09:30 - 10:00	SASPAM-SA overview and current results	F. MASCARI (ENEA)
10:00 - 10:30	Analysis of postulated DBA and SA Scenarios in Generic Integral PWR Small Modular Reactor in the frame of the Horizon Euratom SASPAM-SA Projects	F. GABRIELLI (KIT)
10:30 - 11:00	Assessment of the relevance and applicability of existing experimental databases to iPWR	T. LIND (PSI)
11:50 - 12:20	WP4 Major Insights	F. FICHOT (IRSN)
12:20 - 12:50	WP5 Current Activity	N. REINKE (GRS)
12:50 - 13:20	Preliminary assessments of EPZ extent in SASPAM-SA WP6	M. ILVONEN (VTT)

2.2.1 09:30 - 10:00 | SASPAM-SA overview and current results - F. MASCARI (ENEA)

Summary: Fulvio Mascari (ENEA) presented the current status of the Horizon Euratom SASPAM-SA project[2], which focuses on the safety analysis of SMRs with passive mitigation strategies in SA scenarios. The presentation emphasized the project's key objectives: investigate the applicability and transfer of the operating large-LWR reactor knowledge and know-how to the near-term deployment of iPWR, in the view of SA and EPZ, considering the European licensing analyses needs. Key outcomes include to be supportive for the iPWR licensing process by bringing up key elements of the safety demonstration needed; and speed up the licensing and siting process of iPWRs in Europe. The project is structured into seven WPs addressing diverse areas such as scenario modeling (WP2), experimental

[2] Mascari, F. et al., HORIZON EURATOM SASPAM-SA Project: Main ideas and first outcomes International Conference on Small Modular Reactors and their Applications, Vienna, Austria, 21- 25 October 2024, IAEA, Vienna, Austria.
https://zenodo.org/communities/saspam-sa/about
https://www.saspam-sa.eu
https://cordis.europa.eu/project/id/101059853

database applicability (WP3), in-vessel melt retention modeling (WP4), containment behavior analysis (WP5), and EPZ characterization (WP6). Emphasis was placed on integrating advanced computational tools and experimental data to address identified knowledge gaps. Progress was highlighted for tasks including input-deck development, scenarios simulation, and SA code capability analyses, with collaborative efforts spanning European institutions. Future goals involve refining safety frameworks and enhancing international cooperation to ensure robust safety standards for SMR deployment.

Key R&D needs investigated

- Identification of plausible SA scenarios for iPWR and address potential impact on the environment.
- Identify the conditions in the vessel and in the containment that take place in the identified iPWR SA scenarios and differ from L-LWR.
- Investigation of the applicability and transfer of the operating L-LWR reactor SA knowledge & knowhow (codes, experiments, methodologies, etc.) to the near-term deployment of iPWR.
- Identification of SA experimental and code development needs.
- Test the current best estimate safety analyses methodologies for iPWR SA analyses.
- Start to address challenges of SA mitigation measures in iPWR including EPZ assessment.

Key words

SMR, iPWR, Severe accident, IVMR, Containment integrity, Source Term, Emergency planning zone.

2.2.2 10:00 - 10:30 | Analysis of postulated DBA and SA Scenarios in Generic Integral PWR Small Modular Reactor in the frame of the Horizon Euratom SASPAM-SA Project – F. GABRIELLI (KIT)

Summary: F. Gabrielli (KIT) presented the analysis of Design Basis Accident (DBA) and SA scenarios for generic iPWR designs under the SASPAM-SA project. The study explored two generic iPWR configurations: Design-1 (submerged containment, ~60 MWe) and Design-2 (dry containment, passive systems, ~300 MWe). The project assessed state-of-the-art safety codes (ASTEC, MELCOR, MAAP, AC2 etc.) and Computational Fluid Dynamics (CFD) models for their ability to simulate key thermal-hydraulic, core degradation, and containment behavior phenomena. Key outcomes included the identification of SA scenarios, applicability of SA codes, and the investigation of Accident Tolerant Fuel (ATF) materials[3].

Major progress:

- Two generic iPWR design concepts were selected:
  - Design 1: Submerged containment with ~60 MWe electric power.
  - Design 2: Dry containment with passive systems and ~300 MWe electric power.

[3] Gabrielli, F. (2024). ANALYSIS OF POSTULATED SEVERE ACCIDENTS IN GENERIC INTEGRAL PWR SMALL MODULAR REACTORS IN THE FRAME OF THE HORIZON EURATOM SASPAM-SA PROJECT. The 11th European Review Meeting on Severe Accident Research (ERMSAR2024), KTH, Stockholm, Sweden. Zenodo. https://doi.org/10.5281/zenodo.12594257

- A shared database for the two generic designs was developed using open literature and engineering judgment, including detailed fuel inventory and decay heat analysis conducted with CASMO5.
- Input decks for state-of-the-art European and non-European integral SA codes (ASTEC, MELCOR, MAAP, etc.) and CFD tools have been developed, assessed, and shared for both designs.
- DBA and BDBA scenarios were identified and analyzed. SA progressions have been identified.
- Applicability of the computational tool:
  - SA codes demonstrated the capability to predict key thermal-hydraulic and degradation phenomena in iPWRs.
  - No lower head vessel failures were observed in simulations for both designs.
  - Differences among the SA code results were analyzed.
  - Code development needs have been identified.
- A comprehensive database of postulated SA scenarios was created, identifying in-vessel, containment, and source term phenomena specific of iPWRs.
- Preliminary CFD results confirmed stable simulations and good qualitative representation of expected phenomena, and further validation activity have been identified.

2.2.3 10:30 - 11:00 | Assessment of the relevance and applicability of existing experimental databases to iPWR – T. LIND (PSI)

Summary: Terttaliisa Lind (PSI) presented WP3 which focuses on assessing the relevance and applicability of existing experimental databases to iPWRs. WP3 is directly linked to WP2 because it is fed with the SA phenomena and SA conditions needed to characterize the experimental data applicability to iPWR. She outlined the methodology developed to systematically review, apply, and propose extensions for experimental data, ensuring it meets the unique needs of iPWR safety assessments. Additionally, she discussed the database currently under analysis, which includes data from experiments, emphasizing their role in validating iPWR models and identifying gaps for future research[4].

Major progress:

- The experimental data evaluated spans the entire SA domain including thermal hydraulic aspects related to natural circulation and passive safety systems.
- The datasets analyzed include natural circulation, passive systems, debris bed formation, liquid melt spreading, in-vessel steam explosion, core reflooding, melt pool formation, corium cooling under water, hydrogen distribution, combustion, mitigation, wall condensation, aerosol transport, iodine behavior, pool scrubbing, and fission product composition.

[4] Lind, T. (2024). SASPAM-SA: ASSESSMENT OF THE RELEVANCE AND APPLICABILITY OF EXISTING EXPERIMENTAL DATABASES TO IPWR. The 11th European Review Meeting on Severe Accident Research (ERMSAR2024), KTH, Stockholm, Sweden. https://doi.org/10.5281/zenodo.12645051

- A methodology was developed to assess the applicability of existing data to iPWRs, using dimensionless numbers and governing equations for each phenomenon.
- Experimental data and calculated data for iPWRs are compared based on key parameters and dimensionless analysis.
- Experimental data are categorized into:
  - Data directly applicable to iPWR.
  - Data usable with extrapolation methods.
  - Data not applicable to iPWR.
- The first results of this categorization have been discussed, with ongoing assessments.
- No lower head failures were identified in simulations, so no new ex-vessel experimental data needs have been identified.

2.2.4 11:50 - 12:20 | WP4 Major Insights on IVMR - F. FICHOT (IRSN)

Summary: F. Fichot (IRSN) presented WP4 focusing on the IVMR strategies for iPWRs. The primary goal was to analyze molten pool formation, stratification, and heat transfer phenomena in the lower plenum using SA codes and a 0D corium model. Preliminary results demonstrated have been discussed and specific iPWR features has been presented. Model improvements were suggested to address these unique aspects and enhance prediction accuracy. Coupled vessel and containment simulations were emphasized as crucial next steps to provide deeper insights into stabilized plant configurations and to validate mechanical safety margins under transient conditions[5].

Major progress:

- A 0D Corium Model has been developed to preliminarily study the IVMR phenomenology for iPWRs:
  - Initial results indicate the feasibility of the IVR strategy with sufficient safety margins.
  - Maximum heat flux is small enough to be extracted by pool boiling, and the vessel retains enough thickness to ensure mechanical resistance.
- Key iPWR-specific IVMR features identified include:
  - Larger fraction of power transferred to the oxide pool's top due to the shallow pool geometry.
  - Presence of a thick oxide crust.
  - Occurrence of a thin metal layer with limited focusing effects due to significant radiative heat losses.
- Further detailed data and integral SA code calculations are needed for comprehensive analysis.

[5] Principato, M. (2024). IN VESSEL MELT RETENTION 0D MODEL FOR INTEGRAL PRESSURIZED WATER REACTORS. The 11th European Review Meeting on Severe Accident Research (ERMSAR2024), KTH, Stockholm, Sweden. Zenodo. https://doi.org/10.5281/zenodo.12594268

- Initial integral SA code applications provide results consistent with the 0D model, requiring minor modeling refinements for enhanced accuracy.
- Coupled vessel/containment calculations are anticipated to offer deeper insights into the plant's stabilized configuration during severe accidents.

2.2.5 12:20 - 12:50 | WP5 Current Activity on Containment - N. REINKE (GRS)

Summary: Nils Reinke (GRS) presented WP5 which focusing on assessment of the code capabilities to simulate IPWR containment and characterize mitigation measures efficiency. The objectives include developing input decks, performing best-estimate analyses, and refining ST predictions to provide data for WP6. Two phases were outlined: an initial phase evaluating SA code performance and developing ST data, and a refined phase addressing detailed SA progression and mitigation efficiency.

Major progress:

- Identification of differences in SA sequence progression, such as containment leakage in Design 1 and potential containment failure in Design 2.
- Integrating results from CFD and SA codes, addressing validation gaps and providing a robust framework for future safety evaluations.
- First results have been shared, and further refinement of methodologies is underway.

2.2.6 12:50 - 13:20 | Preliminary assessments of EPZ extent in SASPAM-SA WP6 - M. ILVONEN (VTT)

Summary: Mikko Ilvonen (VTT) presented WP6 focusing on EPZ for iPWRs. The primary objectives include evaluating the size of EPZs under SA scenarios using both conservative and best-estimate (BE) approaches. The presentation highlighted the integration of ST assessments, weather data, and site-specific parameters to calculate radiological consequences and EPZ distances. A critical review of existing EPZ methodologies and dose assessment criteria was conducted, along with testing of code capabilities and also some preliminary conservative assessments of EPZ size using simplified assumptions. The work also explored the hypothesized potential for reduced EPZs for iPWRs due to their lower radioactive inventory and advanced safety features, emphasizing the importance of quantitative justification for siting SMRs near populated areas. Recommendations were provided on robust methodologies for determining EPZ sizes, considering uncertainties and regional regulatory differences. Future work will focus on using BE source terms from WP5, refining BE models and validating results with advanced simulation tools.

Major progress:

- WP6 represents the final step in assessing hypothetical SA for iPWRs, transitioning from atmospheric releases to evaluating potential off-site health impacts.
- Radiological risks are quantified through predicted effective or organ-specific doses, compared with dose limits to define EPZ distances.
- Dose limits are derived from sources like IAEA GSR Part 7, national protective action thresholds, or direct EPZ-setting regulations (e.g., STUK Y/2/2024 in Finland).

- iPWRs are considered inherently safer than large NPPs due to smaller radioactive inventories and advanced passive safety systems, suggesting that they may have lower radiological impacts and smaller EPZs.
- EPZ sizes are not universal even for one certain plant design, but varying by country due to technical and non-technical factors; a review of existing methodologies and regulations was conducted in WP6:
  - The review covered international standards (e.g., IAEA, EU) and national regulations in countries like Bulgaria, Finland, Lithuania, Ukraine, and the USA, focusing on dose projection, protective measures, and atmospheric dispersion models.
- Practical WP6 work proceeds in two phases:
  - Conservative phase: Dispersion, dose, and EPZ calculations using simplified and cautious methods to account for high doses under extreme assumptions.
  - BE phase: Mechanistic calculations with SA codes to refine source terms and EPZ sizes.
- Conservative results incorporate conservativeness on many levels in factors like ST nuclides, release parameters, weather conditions, and dispersion modeling assumptions, with recognized variability in results due to site characteristics and national dose criteria.

2.2.7 Session Chair Conclusions with R&D Focus:

The SASPAM-SA session highlighted the project's significant progress in advancing safety analysis practices for iPWRs, emphasizing the integration of computational tools, experimental data, and licensing needs:

1. **Severe Accident Scenario Identification:** DBA and BDBA scenarios to evaluate the capabilities of state-of-the-art SA and CFD codes have been identified. The conditions in the containment and in the vessel that characterize iPWR scenarios have been identified, and a dedicated database has been fully developed.
2. **Advanced SA Analysis Tools:** State-of-the-art SA codes were tested for their ability to predict degradation phenomena, containment conditions, and vessel behavior in postulated iPWR scenarios. The need for code refinement and validation was identified to address iPWR-specific features like shallow molten pools and heat transfer.
3. **Experimental Database Applicability:** WP3 developed a comprehensive database to evaluate the relevance of existing experimental data to iPWR scenarios, identifying gaps and guiding future experimental efforts.
4. **In-Vessel Melt Retention (IVMR):** WP4 analyses confirmed the feasibility of IVMR strategies for iPWRs, showing sufficient safety margins in managing heat flux and vessel integrity. These findings enhance understanding of IVMR phenomena and guide near-term code development needs. Coupled vessel/containment calculations are anticipated to offer deeper insights into the plant's stabilized configuration during SAs.
5. **Emergency Planning Zones (EPZ):** WP6 evaluated SA scenarios and radiological impacts caused by SA scenarios, some of the work suggesting preliminarily that iPWRs may require smaller EPZs than large NPPs due to lower radioactive

inventories and passive safety features. This finding supports siting iPWRs near populated areas.

6. **Building Expertise and Training:** The project has fostered expertise among code users, including training new generations, to advance SA analysis capabilities and ensure robust licensing support for iPWRs in Europe.

Cross-Cutting Priorities:

SASPAM-SA underscores the importance of validated safety analysis methodologies and collaborative international efforts. These initiatives aim to enhance iPWR safety, streamline licensing processes, and support the deployment of SMRs in diverse European contexts.

2.3 INTERNATIONAL INITIATIVES

Session Chairs: M. Ilvonen (VTT, Finland), N. Reinke (GRS, Germany)

The session explored global and regional efforts to advance SMR deployment. **M. Berdai (CNSC)** outlined Canadian safety considerations for SMR reviews, while **S. Campbell (USNRC)** shared insights on U.S. initiatives. **H. Nakamura (JAEA)** and **M. Adorni (NEA)** highlighted WGAMA activities to accelerate SMR deployment through reliable safety assessments. **F. Stephani (IAEA)** provided updates on emergency preparedness for SMRs, emphasizing international collaboration. **S. Takenouti (EDF)** discussed the European SMR Pre-Partnership, and **A. Al Mazouzi (SNETP)** concluded with insights into the Industrial SMR Alliance, showcasing industry-driven progress.

Table 8: Lectures list

14:50 - 15:15	CNSC Safety Considerations for the Review of Small Modular Reactors	M. BERDAI (CNSC)
15:15 - 15:40	Initiatives in USA	S. CAMPBELL (USNRC)
15:40 - 16:05	Accelerating Deployment of SMRs with WGAMA Activities for Reliable Safety Assessment	H. NAKAMURA (JAEA); M. ADORNI (NEA)
16:05 - 16:30	Updates on IAEA activities on Emergency Preparedness and Response for Small Modular Reactors	F. STEPHANI (IAEA)
16:30 - 16:55	European SMR Pre-Partnership	S. TAKENOUTI (EDF)
16:55 - 17:20	Industrial SMR Alliance	A. AL MAZOUZI (SNETP)

2.3.1 14:50 - 15:15 | CNSC Safety Considerations for the Review of Small Modular Reactors – M. BERDAI (CNSC)

Summary: M. Berdai (CNSC) outlined key safety considerations for SMRs, focusing on deterministic and probabilistic safety analyses within the Canadian framework. It highlighted accident management strategies and the graded approach to licensing and compliance, tailored to SMR specific risks. Key insights from Vendor Design Reviews (VDRs) emphasized the need for improved validation of computational codes and long-term performance of safety systems. Challenges specific to advanced reactor designs, such as TRISO fuel and passive safety systems, were addressed. M. Berdai concluded by reaffirming CNSC commitment to rigorous safety evaluations and collaboration with international stakeholders.

Key R&D Needs

- Validation of safety analysis codes, with experimental support from both integral and separate effects, to address limitations in available computational tools.
- Investigation of uncertainties in thermophysical properties of advanced coolants (e.g., salt compositions) and their implications on system performance.
- Study of passive safety features, including natural circulation and inherent reactivity feedback mechanisms, with validation against experimental data.

- Long-term performance analysis of SSCs, focusing on corrosion, operational environments, and material reliability.
- Development of effective tritium management strategies, particularly for MSR designs.
- Exploration of advanced containment strategies using TRISO fuel and assessment of its effectiveness as a barrier.
- Evaluation of SAM strategies, including improvements to guidelines and mitigation techniques.

Key Words

Safety analysis codes, experiments, validation, passive safety, thermophysical properties, molten salt reactors, TRISO fuel, severe accident management, SSC reliability, tritium management, containment strategies.

2.3.2 15:15 - 15:40 | Initiatives in USA - S. CAMPBELL (USNRC)

Summary: Shawn Campbell (USNRC) outlined recent U.S. NRC initiatives for SMRs. It discussed ongoing reviews of designs like BWRX-300, SMR, LLC (Holtec), Westinghouse AP300, Deep Fission, and NuScale's US600 (50MWe/module) and US460 (77MWe/module), emphasizing regulatory processes. The use of MELCOR for SA analysis and ST modeling was highlighted, along with international collaborations through programs like CSARP. Advanced reactor projects and innovative fuel technologies, including ATFs, were addressed. The USNRC continues to focus on refining regulatory frameworks to support the safe and efficient deployment of SMRs.

Key R&D Needs

- Modernization and adaptation of MELCOR for ATF, high-burnup (HBU), and non-LWR applications.
- Expansion of international experimental programs for SMR designs.
- Revision of regulatory STs (e.g., RG 1.183) to account for advanced fuels and high-burnup conditions.
- Validation of safety codes through separate and integral effect experimental data;
- Evaluation of SA scenarios, including in-vessel retention and ex-vessel steam explosion risks.
- Licensing support for non-LWR demonstrations.
- Research on advanced fuel technologies, focusing on SA behavior (e.g., Cr-coated cladding).

Key Words

MELCOR, SMRs, ATF, HBU, non-LWR, severe accidents, source terms, safety codes, experimental programs, licensing, advanced fuels.

2.3.3 15:40 - 16:05 | Accelerating Deployment of SMRs with WGAMA Activities for Reliable Safety Assessment - H. NAKAMURA (JAEA); M. ADORNI (NEA)

Summary: Mr H. Nakamura (JAEA) emphasized enhancing safety assessments for SMRs through the analysis and management of accidents. It highlighted advancements in thermal-hydraulics, SA management, and CFD to improve safety models and tools. Collaborative efforts such as CSNI Code Validation Matrices (CCVMs) and international benchmarks were discussed to ensure reliable safety evaluations. Knowledge transfer initiatives like the THICKET seminars were presented as crucial for building expertise in emerging reactor technologies. He concluded by identifying future challenges and the importance of rigorous methodologies for SMR deployment.

Key R&D Needs

- Validation of the thermal-hydraulic of passive systems for SMRs using experimental data and best-estimate methodologies with uncertainty quantification.
- Enhancement of CFD for nuclear safety and integration of uncertainty analysis.
- Development of advanced SAM strategies and guidelines tailored to SMRs, incorporating recent findings and instrumentation advancements.
- Update and extension of the CCVM to ensure comprehensive safety assessments for emerging reactor designs.
- Improvement of reliability assessments for equipment in long-term SA conditions.
- Knowledge transfer initiatives, such as THICKET seminars, to train future experts in safety-relevant areas, including SMRs.

Key Words

Thermal-hydraulics, passive systems, CFD, uncertainty quantification, SAM guidelines, CSNI Code Validation Matrix, long-term reliability, experimental data, SMRs, knowledge transfer.

2.3.4 16:05 - 16:30 | Updates on IAEA activities on Emergency Preparedness and Response for Small Modular Reactors- F. STEPHANI (IAEA)

Summary: Mr. F. Stephani (IAEA) provided updates on EPR for SMRs. He emphasized the development of a TECDOC and new EPR Series guidance for SMRs, focusing on methodologies for determining EPZs and addressing unique SMR challenges. He highlighted international collaboration through consultancy meetings and workshops, involving experts from multiple countries. The revision of General Safety Requirements (GSR Part 7) was discussed, aiming to enhance global EPR standards. The presentation underscored the importance of integrating deterministic and probabilistic approaches for SMR safety.

Key R&D Needs

- Development of methodologies and criteria for determining EPZs specific to SMRs, integrating deterministic and probabilistic approaches.
- Assessment of accident scenarios, atmospheric dispersion, and dose projections to establish EPZ sizes for SMRs.
- Evaluation of uncertainties in ST calculations and safety margins for SMR designs.
- Revision and alignment of EPR standards to address unique challenges of SMRs.
- Advancement of technical guidance through new EPR Series documents tailored for SMRs, building on existing IAEA Safety Standards.
- Exploration of compact SMR designs' impact on defense-in-depth independence and the multipurpose use of safety systems.

Key Words

Emergency Planning Zones, SMRs, accident scenarios, source term, dose projection, EPR standards, deterministic approaches, probabilistic approaches, safety margins, defense-in-depth.

2.3.5 16:30 - 16:55 | European SMR Pre-Partnership – S. TAKENOUTI (EDF)

Summary: S. Takenouti (EDF) presented the EU SMR Pre-Partnership, focusing on enabling the deployment of SMRs in Europe by the early 2030s. The initiative promotes collaboration among industry, R&D organizations, policymakers, and regulators to address market integration, licensing harmonization, supply chain adaptation, and innovation. A key highlight was the R&D&I roadmap, targeting passive safety systems, advanced fuels, SA management, modularization, and human factors. The presentation stressed the importance of pooling European resources for experimental data and infrastructure. This collective effort aims to establish the base for a safe SMR deployment across Europe.

Key R&D Needs

- Validation safety analyses code for passive safety systems analyses through experimental data.
- Reliability: adapt safety assessment methodology.
- Advanced core and fuel designs, including boron-free cores, ATFs, and critical heat flux evaluation.
- Improvement of reactor internals, focusing on hydraulics, in-service inspection, and advanced manufacturing of components.
- Addressing SA scenarios, emphasizing RPV and containment integrity, and dose calculations for EPZs.
- Development of modular construction techniques and effective interface management to optimize SMR deployment.
- Exploration of human factors, including multi-unit operations, hybrid processes, and human reliability analysis methodologies.
- Expansion of non-electricity applications such as hybridization, co-location, and public acceptance strategies.

Key Words

Passive safety systems, boron-free cores, accident-tolerant fuels, reactor thermal-hydraulics, reliability, in-service inspection, severe accidents, modularization, human factors, hybridization, public acceptance, EPZs.

2.3.6 16:55 - 17:20 | Industrial SMR Alliance - A. AL MAZOUZI (SNETP)

Summary: A. Al Mazouzi (SNETP) presented the role of the European Industrial Alliance for SMRs in facilitating the development, demonstration, and deployment of SMRs in Europe by the early 2030s. The presentation emphasized collaborative efforts through working groups focusing on technology R&D&I, licensing, financing, supply chain, and safety. Key objectives included addressing technological gaps, fostering innovation, and ensuring compliance with EU legislative frameworks. Al Mazouzi highlighted several pilot projects as key examples of ongoing initiatives. The presentation stressed the importance of partnerships among stakeholders to accelerate SMR deployment in diverse applications.

Key R&D Needs

- Identification of major technology R&D&I gaps for SMRs and AMRs to ensure safety, competitiveness, and strategic independence.
- Development of test facilities and demonstrators to validate SMR in diverse industrial applications.
- Exploration of materials compatibility, advanced fuels, and digitalization to enhance SMR designs.

- Verification and validation (V&V) of safety analysis codes using experimental data.
- Modularization of SMRs, focusing on efficient manufacturing, components, and transportability.
- Support for non-electric applications, including hybrid energy systems and public acceptance strategies.
- Strengthening collaborations across EU R&D facilities to share resources and accelerate technology development.

Key Words
R&D gaps, SMRs, AMRs, safety analysis, V&V, modularization, materials compatibility, advanced fuels, digitalization, test facilities, hybrid systems, public acceptance, EU collaboration.

2.3.7 Session Chair Conclusions with R&D Focus:

This session underscored the critical importance of aligning global efforts to advance SMR deployment while addressing R&D needs to ensure safety and innovation. Several key areas of focus for R&D have been highlighted:

1. **Global Harmonization for Safety:** The presentations highlighted the need for harmonized safety frameworks and methodologies, emphasizing the development of deterministic and probabilistic safety analysis tools applicable to SMRs. International collaboration, is essential to standardize safety demonstration.

2. **Emergency Preparedness and Planning:** Work on EPZs identified gaps in existing models, particularly for new reactor types. R&D should focus on robust hazard assessments, atmospheric modeling, and advanced computational tools to refine emergency preparedness guidelines.

3. **Experimental Data and Code Validation:** Qualified experimental databases and validated computational models need to be stressed. There is the need to expand these experimental databases for SA analysis in SMR, passive safety systems characterization, material performance under different scenarios conditions, etc.

4. **Innovative Designs and Materials:** Several emphasized the importance of new materials, advanced manufacturing techniques, and innovative core and fuel designs. Research must prioritize ATFs, modular components, and long-term operational reliability.

5. **R&D Collaboration and Infrastructure:** The session reinforced the value of shared R&D infrastructure and collaborative networks. Leveraging pooled resources across regions, particularly in Europe, can accelerate the validation of safety systems and support the demonstration of SMR designs.

Cross-Cutting
Advancing SMR deployment requires a dual focus:

- Rigorous safety assurance through cutting-edge R&D and
- Fostering global partnerships to address shared challenges.

Building robust experimental and analytical frameworks, supported by innovative technologies, will be pivotal in achieving the safety and efficiency goals of SMRs.

2.4 EUROPEAN PROJECT ACHIEVEMENTS

Session Chairs: T. Lind (PSI, Swizerland), F. Gabrielli (KIT, Germany)

This session provided a comprehensive exploration of R&D initiatives and regulatory frameworks supporting SMR safety and deployment. **L.E. Herranz (CIEMAT)** emphasized SA roadmaps through the SEAKNOT project, focusing on preserving expertise and addressing research gaps for SMRs. **M. Montout (EDF)** showcased the integration of experimental data and numerical tools through the PASTELS project, emphasizing the validation of passive safety systems. **N. Sobecki (EDF)** discussed SMR-specific innovations and advanced safety methodologies through the EASI-SMR project, highlighting passive systems and regulatory challenges. **G. Pavel (ENEN)** highlighted educational programs and knowledge dissemination efforts through ENEN, stressing the importance of workforce development for the nuclear sector. **G. Jimenez (UPM)** presented advancements in accident management and mitigation strategies for hydrogen and CO risks via the AMHYCO project. **V. Sanchez (KIT)** provided insights into multi-scale safety evaluations and thermal-hydraulic experiments conducted under the McSAFER project. **C. Vaglio-Gaudard (CEA)** addressed the safe integration of SMRs into hybrid energy systems through the TANDEM project. **E. Urbonavičius (LEI)** presented efforts to harmonize safety standards for SMR licensing via the HARMONISE project. **L. Chailan (IRSN)** discussed the development of AI-driven tools for safety assessments in the ASSAS project, emphasizing collaboration and innovation for sustainable SMR deployment.

Table 9: Lectures list

09:00 - 09:25	SEAKNOT: Building a Roadmap on Severe Accidents	L.E. HERRANZ (CIEMAT)
09:25 - 09:50	PASTELS: From Experimental to Numerical, Main Results of the Project	M. MONTOUT (EDF)
09:50 - 10:15	EASI-SMR project overview	S. SOBECKI (EDF)
10:15 - 10:40	ENEN SMR initiative overview	G. PAVEL (ENEN)
11:10 - 11:35	AMHYCO Project Overview and First Outcome	G. JIMENEZ (UPM)
11:35 - 12:00	McSAFER Project: Main Outcomes and Highlights	V. SANCHEZ (KIT)
12:00 - 12:25	The TANDEM Euratom Project to Support the Safe Integration of SMRs into Low-Carbon Hybrid Energy Systems -	C. VAGLIO-GAUDARD (CEA)
12:25 - 12:50	Review of IAEA Safety Standards in Respect to SMRs Licensing	E. URBONAVIČIUS (LEI)
12:50 - 13:15	ASSAS Project: Overview and Key Findings	L. CHAILAN (IRSN)

2.4.1 09:00 - 09:25 | SEAKNOT: Building a Roadmap on Severe Accidents - L.E. HERRANZ (CIEMAT)

Summary: L. E. Herranz (CIEMAT) presented the Horizon Euratom SEAKNOT project, which aims to build a comprehensive roadmap for SA research and knowledge management for large LWRs and SMRs. Key objectives include preserving expertise, addressing research gaps, and integrating innovative technologies like AI and ATFs. The project focuses on critical tasks such as developing a Phenomena Identification Ranking Table (PIRT), creating a validation database, and establishing an experimental infrastructure network. Training and knowledge dissemination are supported through updated textbooks, mobility programs, and international workshops. SEAKNOT ultimately seeks to strengthen Europe's leadership in SA research and education[6].

Key R&D Needs

- Development and application of the PIRT methodology to identify key SA phenomena and prioritize future R&D needs, including in-vessel, ex-vessel, containment, and ST aspects.
- Creation of a Validation Database Directory (VADD) to consolidate and assess experimental data for SA modeling and code validation, focusing on LWRs, SMRs, and ATFs.
- Mapping and enhancement of EU experimental facilities to establish the Severe Accident Infrastructure Network (SAINET) for coordinated testing and research.
- Updates to the SARNET SA Textbook to reflect the latest R&D findings and provide comprehensive educational materials for SA phenomenology.
- Strengthening knowledge dissemination through mobility programs, training initiatives, and events like SAP and ERMSAR to foster a skilled workforce.
- Advancement of new modeling approaches, including uncertainty quantification and AI, for SA applications.

Key Words

PIRT, severe accidents, VADD, SAINET, experimental facilities, SMRs, ATFs, source term, SARNET, uncertainty quantification, AI, mobility programs, SA modeling.

2.4.2 09:25 - 09:50 | PASTELS: From Experimental to Numerical, Main Results of the Project – M. MONTOUT (EDF)

Summary: M. Montout (EDF) presented the H2020 PASTELS project, focused on advancing the understanding and development of innovative passive safety systems for nuclear reactors, specifically the Containment Wall Condenser (CWC) and Safety Condenser (SACO). The project combined experimental tests and numerical simulations to evaluate system performance, identify key parameters, and validate safety models. Key findings included the role of non-condensable gases and thermal stratification in system, the importance of relying on the most accurate experimental data to limit uncertainties in the calculation/measurement comparisons and the necessity of improving scaling validation. Numerical activities demonstrated the key role of the system codes and the potential of CFD for localized phenomena analysis. The project established a comprehensive experimental database and disseminated its findings to support future R&D initiative[7].

Key R&D Needs

- Development and validation, against experimental data, of innovative passive safety systems, focusing on Containment Wall Condenser (CWC) and Safety Condenser (SACO).
- Enhanced numerical modeling capabilities for passive systems using system codes, CFD, and SA codes, emphasizing boundary conditions accuracy and address scaling.

[6] https://cordis.europa.eu/project/id/101060327
[7] https://cordis.europa.eu/project/id/945275

- Investigation of critical physical phenomena such as non-condensable gases, thermal stratification, and oscillations in passive systems.
- Creation of an extensive experimental database for validation of safety codes and to support industrial applications.
- Improvement of scaling methodologies and experimental designs to ensure reliable data for system validation.
- Development of analytical models to describe the dynamic behavior of passive systems under varying conditions.
- Dissemination of results and skills development through collaborations, training initiatives, and public deliverables.

Key Words
Passive safety systems, CWC, SACO, numerical modeling, CFD, experimental database, non-condensable gases, thermal stratification, scaling validation, analytical models, training initiatives.

2.4.3 09:50 - 10:15 | EASI-SMR project overview - S. SOBECKI (EDF)

Summary: N. Sobecki (EDF) presented the Horizon Euratom EASI-SMR project, focusing on advancing the safety of LW-SMRs through passive systems and addressing regulatory, technological, and societal challenges. The project includes experimental testing, code validation, and reliability assessments to improve safety models and methodologies. Key innovations include advanced core physics studies for boron-free designs and additive manufacturing for large-scale SMR components. The project also emphasizes public acceptance, stakeholder engagement, and human and organizational factors in SMR operation. EASI-SMR aims to create a comprehensive roadmap for safe and sustainable SMR deployment in Europe[8].

Key R&D Needs
- Validation and benchmarking of safety analysis codes for passive safety systems through experimental data.
- Development of advanced modeling techniques for boron-free cores, including multiphysics and multiscale approaches for innovative fuel and cladding designs.
- Investigation of SA scenarios, focusing on RPV integrity, containment integrity, and dose calculations for EPZs.
- Reliability assessments for passive systems using probabilistic and deterministic methodologies, with a focus on multi-unit operations and human reliability.
- Exploration of additive manufacturing for specific SMR components, including fabrication, validation, and qualification of mock-ups.
- Enhancement of human and HOF understanding for LW-SMR operations, including the impact of modularity and cybersecurity on safety.
- Support for non-electric applications such as hybrid systems, co-location, and public acceptance strategies to facilitate SMR deployment.

Key Words
Passive safety systems, boron-free cores, safety codes, thermal-hydraulics, severe accidents, additive manufacturing, reliability assessment, human factors, modularity, hybrid systems, public acceptance.

[8] https://cordis.europa.eu/project/id/101164810

2.4.4 10:15 - 10:40 | ENEN SMR initiative overview - G. PAVEL (ENEN)

Summary: G. Pavel (ENEN) presented the European Nuclear Education Network's (ENEN) initiatives to advance education and training in the nuclear sector. The focus included fostering collaboration between universities, industry, and regulatory bodies to ensure high-quality training and career development, with emphasis on SMR/AMR technologies. ENEN's SMR-specific programs, like the European SMR/AMR Training Academy (ESTA), aim to address human resources needs and promote global networking. Key achievements include mobility programs, workshops, and summer schools to support professionals and students in nuclear fields. The ENEN2plus project was highlighted for its mobility fund and efforts to strengthen nuclear expertise across Europe.

Key R&D Needs

- Development of tailored education and training programs to meet human resource needs for SMR/AMR technologies, including technical, societal, and regulatory aspects.
- Creation of the European SMR/AMR Training Academy (ESTA) to foster skills development for operators, regulators, and other stakeholders.
- Strengthening global and regional collaborations to support nuclear education and training through shared infrastructure and knowledge hubs.
- Implementation of mobility programs and internships to promote knowledge exchange and career development in nuclear fields.
- Identification and addressing of safety compliance challenges for integrating SMRs and AMRs into hybrid energy systems.

Key Words

SMR, AMR, nuclear education, training academy, mobility programs, hybrid energy systems, safety compliance, global collaboration.

2.4.5 11:10 - 11:35 | AMHYCO Project Overview and First Outcome - G. JIMENEZ (UPM)

Summary: G. Jiménez (UPM) presented the H2020 AMHYCO project, which focuses on improving AM strategies for hydrogen and carbon monoxide combustion risks in nuclear reactors. The project combines experimental research, including PAR performance and combustion behavior under SA conditions, with advanced simulation tools like CFD to enhance safety assessments. Key outcomes include refined SAMGs and innovative engineering criteria for mitigating combustion risks. The project has also developed a Generic Containment Database (GC database) and validated engineering correlations for improved safety tool accuracy. Dissemination efforts include workshops, publications, and student mobility programs to foster knowledge sharing and training[9].

Key R&D Needs

- Experimental investigation of H2/CO combustion and Passive Autocatalytic Recombiners (PARs) performance under SA conditions, considering interactions with sprays and venting systems.
- Development and validation of engineering correlations and numerical codes (LP, 3D, CFD) for combustion risk evaluation in reactor containments.
- Establishment of a GC database to support detailed modeling of PWR designs, including KONVOI and VVER reactors.

[9] https://cordis.europa.eu/project/id/945057

- Enhancement of SAMGs for both in-vessel and ex-vessel phases, incorporating findings from experimental and simulation data.
- Transfer of experimental results into practical accident management measures, minimizing human error and ensuring equipment reliability.
- Dissemination and communication of project findings through workshops, mobility programs, and open-access publications to support stakeholder engagement and training.

Key Words
H2/CO combustion, PARs, severe accidents, LP codes, CFD, containment database, SAMGs, accident management, experimental validation, stakeholder engagement.

2.4.6 11:35 - 12:00 | McSAFER Project: Main Outcomes and Highlights - V. SANCHEZ (KIT)

Summary: V. H. Sanchez-Espinoza (KIT) presented the H2020 McSAFER project, focusing on experimental investigations and high-performance simulation tools for the safety evaluation of LW-SMRs. The project conducted thermal-hydraulic experiments at facilities like MOTEL, HWAT, and COSMOS-H, addressing phenomena such as CHF, natural circulation, and passive heat removal. Multiscale, multiphysics methods were developed to improve core and plant transient analysis, with tools like Serpent2 and OpenFOAM enhancing predictive capabilities. McSAFER provided new experimental data for code validation and demonstrated the advantages of advanced methods over traditional industry tools. The project aims to pave the way for safer SMR deployment through comprehensive safety evaluations and training initiatives[10].

Key R&D Needs
- Experimental investigations of key thermal-hydraulic phenomena for SMRs, including CHF, cross-flow, natural circulation, and transitions between forced and natural circulation.
- Validation of thermal-hydraulic codes (CFD, subchannel, and system codes) using experimental data from facilities like MOTEL, HWAT, and COSMOS-H.
- Development of high-fidelity multiphysics tools for core and plant transient analyses, integrating neutronics, thermal-hydraulics, and advanced materials modeling.
- Enhancement of passive residual heat removal system (PRHR) designs, focusing on decay heat removal effectiveness under various conditions.
- Application of multiscale and multiphysics methods to improve accuracy in safety evaluations for SMRs.
- Investigation of innovative core designs and materials, such as ATF, to enhance performance and safety.
- Establishment of standardized experimental programs and data sharing to support code validation and cross-partner collaboration.

Key Words
Thermal-hydraulics, SMRs, CHF, natural circulation, code validation, multiphysics tools, PRHR, ATF, core design, experimental data, multiscale analysis, safety evaluations.

[10] https://cordis.europa.eu/project/id/945063

2.4.7 12:00 - 12:25 | The TANDEM Euratom Project to Support the Safe Integration of SMRs into Low-Carbon Hybrid Energy Systems - C. VAGLIO-GAUDARD (CEA)

Summary: C. Vaglio-Gaudard (CEA) presented the Horizon Euratom TANDEM[11] project, which aims at integrating SMRs into hybrid energy systems for a decarbonized energy mix in Europe. The project focuses on safety compliance, techno-economic assessments, and environmental impacts of coupling SMRs with non-nuclear components like district heating networks, hydrogen production and energy storage. It has required the development and the use of a new simulation tool[12] and the coupling of already existing tools[13] to size the components and to evaluate their dynamic interactions within hybrid systems. Safety outcomes include first guidelines to address hazards from coupling nuclear and non-nuclear systems. TANDEM targets to establish a pioneering framework for the safe deployment of SMR-based hybrid energy systems across Europe[14].

Key R&D Needs

- Development of safety analysis guidelines tailored for SMRs integrated into hybrid energy systems (HES), addressing coupling with non-nuclear components like hydrogen production plants.
- Investigation of hybridization transients, including dynamic interactions between nuclear and non-nuclear subsystems, and their implications for operational safety.
- Enhancement of modeling and simulation tools for SMRs in HES, integrating nuclear steam supply systems with non-nuclear applications such as heat, hydrogen, and desalination.
- Validation of passive safety features and operational flexibility of SMRs under varying load demands and thermal storage conditions.
- Assessment of the techno-economic feasibility and environmental impact of SMR deployment in low-carbon HES configurations.
- Development of stakeholder engagement strategies to promote public acceptance and address societal concerns about SMRs and HES integration.

Key Words

SMRs, hybrid energy systems, safety guidelines, hybridization transients, modeling tools, passive safety, operational flexibility, techno-economic analysis, public acceptance, hydrogen production.

2.4.8 12:25 - 12:50 | Review of IAEA Safety Standards in Respect to SMRs Licensing – E. URBONAVIČIUS (LEI)

Summary: E. Urbonavičius (LEI) presented the Horizon Euratom HARMONISE project, aimed at harmonizing safety standards for SMR licensing in Europe. The project reviews IAEA safety documents to identify gaps and ensure applicability to advanced reactor designs, including SMRs and fusion technologies. Key objectives include addressing risk-

[11] C. Vaglio-Gaudard et al, THE TANDEM EURATOM PROJECT: CONTEXT, OBJECTIVES AND WORKPLAN, Nuclear Engineering and Technology, 56, 993-1001 (2024). https://doi.org/10.1016/j.net.2023.12.015

[12] An open-source modelica-based library (https://gitlab.pam-retd.fr/tandem/tandem).

[13] The coupling of CATHARE3, ATHLET, PERSEE with modelica models.

[14] https://cordis.europa.eu/project/id/101059479

informed, performance-based approaches and standardizing component assessments and methodologies. Recommendations highlight the need for updates in existing safety requirements to account for modular and innovative reactor technologies. The project emphasizes international collaboration to align regulatory practices and facilitate SMR deployment[15].

Key R&D Needs

- Analysis of preliminary safety assessments for innovative fission and fusion installations, emphasizing SMR and multi-module reactor designs.
- Examination of risk-informed, performance-based (RIPB) approaches to improve licensing reviews and regulatory decision-making for advanced reactors.
- Harmonization and standardization of component assessments, methodologies, codes, and standards to support the deployment of SMRs and Gen-IV concepts.
- Evaluation of IAEA safety standards and documents, identifying gaps and proposing amendments to address non-water-cooled technologies and multi-module designs.
- Development of collaborative frameworks for international regulatory cooperation, ensuring effective oversight and shared responsibilities for SMR deployment.
- Inclusion of new safety considerations for mobile or transportable nuclear facilities, addressing challenges in decommissioning and transport.

Key Words

Safety assessments, RIPB, licensing, SMRs, Gen-IV, IAEA standards, harmonization, standardization, regulatory cooperation, transportable nuclear facilities

2.4.9 12:50 - 13:15 | ASSAS Project: Overview and Key Findings – L. CHAILAN (IRSN)

Summary: L. Chailan (IRSN) [16]presented the Horizon Euratom ASSAS project, which aims to develop AI-driven simulators for SA scenarios in nuclear reactors. The project integrates legacy codes like ASTEC with AI models to enable real-time simulations, improving speed and without significantly impacting accuracy. Key innovations include hybrid AI approaches, data-driven surrogate models, and a large-scale database for training.. ASSAS seeks to improve safety assessments by combining traditional physics-based methods with cutting-edge AI technologies[17].

Key R&D Needs

- Development of AI-driven SA simulators for SMRs, integrating machine learning with physical models to optimize real-time performance.
- Evaluate SAMGs in the specific context of some SMR designs relying on multi-reactor control rooms or remote operation, and train operator on them.
- Acceleration of ASTEC calculations through model simplification, parallelization, and hybrid AI approaches for critical SA phases.

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[15] https://cordis.europa.eu/project/id/101061643

[16] Bastien Poubeau, Yann Richet, Lionel Chailan, Fulvio Mascari, Mattia Massone, et al.. HORIZON EURATOM ASSAS PROJECT: CAN MACHINE-LEARNING MAKE FAST AND ACCURATE SEVERE ACCIDENT SIMULATORS A REALITY? Proceedings of the 11th European Review Meeting on Severe Accident Research (ERMSAR2024), Kungliga Tekniska Högskolan, May 2024, Stockholm, Sweden. pp.1-12, ⟨10.5445/IR/1000174165⟩. ⟨irsn-04588965⟩

Blacketta, C., Eitrheima, M. H. R., McDonalda, R., & Blocha, M. (2022, June). HUMAN PERFORMANCE IN OPERATION OF SMALL MODULAR REACTORS. In Proceedings of the 16th International Conference on Probabilistic Safety Assessment and Management (PSAM 16), Honolulu, Hawaii (Vol. 26).

[17] https://cordis.europa.eu/project/id/101059682

- Creation of a large-scale database for SA sequences, supporting AI training and improving uncertainty quantification and prediction accuracy.
- Design and validation of hybrid AI models to replace or augment computationally intensive SA code modules for SMR applications.
- Adaptation of existing SA simulation tools (e.g., ASTEC and TEAM_SUITE®) to SMR-specific designs and innovative systems.
- Exploration of multi-fidelity learning techniques combining experimental data and high-fidelity simulations for enhanced model accuracy without compromising computational efficientcy
- Development of diagnostic and prognostic tools for emergency response, leveraging pre-calculated SA data to improve decision-making.

Key Words
AI, severe accident, SMRs, ASTEC, hybrid models, machine learning, real-time simulation, database, emergency response.

2.4.10 Session Chair Conclusions: Cross-Cutting R&D Needs

This session provided an in-depth overview of ongoing Euratom projects addressing safety, integration, and innovation for SMRs, highlighting several key areas of focus for R&D:

1. **SA Research and Roadmaps**
   Some projects emphasized the critical need for robust SA research frameworks. Developing comprehensive experimental databases and advanced modeling tools is essential to address complex phenomena, e.g. thermal-hydraulic coupling specific to SMRs.

2. **Experimental and Numerical Synergies**
   The importance of combining experimental data with high-fidelity numerical simulations have ben underlined. Continued investment in scalable experimental facilities and multiscale simulation tools will be pivotal for validating safety models and improving predictive accuracy.

3. **SMR-Specific Safety and Integration**
   The need for tailored methodologies to assess the safety of SMRs within hybrid energy systems have been underlined. Research should address the unique dynamics of SMR deployment, such as modularity, small containment designs, and coupling with non-nuclear systems like hydrogen production.

4. **Education and Knowledge Dissemination**
   There are initiatives that underscored the importance of fostering nuclear expertise through mobility programs, training academies, and international collaboration. Building a skilled workforce is a critical enabler for SMR deployment.

5. **Artificial Intelligence and Advanced Tools**
   The potential of AI-driven tools for SA simulation, combining physics-based methods with machine learning for real-time safety analysis have been discussed. R&D must further explore hybrid AI models, database expansion, and validation to enhance emergency preparedness and risk assessment.

6. **Regulatory Harmonization**
   The need for harmonized regulatory frameworks to accommodate advanced reactor designs have been discussed. Addressing gaps in existing safety standards and promoting international collaboration are essential for streamlined SMR licensing and deployment.

Cross-Cutting Recommendation:
The presentations revealed a shared R&D need for integrating advanced methodologies, cross-disciplinary collaboration, and resource pooling across the European and global SMR ecosystem. These efforts will drive innovation, ensure safety, and open the way for sustainable SMR deployment.

2.5 TECHNICAL PRESENTATIONS

Session Chairs: F. Fichot (IRSN, France), F. Mascari (ENEA, Italy)

This session highlighted cutting-edge experimental, modeling, and analytical advancements supporting SMR safety. **S. Gupta (BT)** presented THAI experimental research outcomes, emphasizing the development of a validation database for SMR safety assessments. **J. Ham (KAERI)** discussed SA analyses using the CINEMA code for i-SMR designs, providing insights into core degradation and source term behavior. **D. Luxat (SNL)** showcased enhancements in MELCOR capabilities, addressing SMR-specific thermal-hydraulic and safety phenomena. **L. Lebel (CNL)** explored strategies for the 4th and 5th levels of Defence-in-Depth, focusing on containment performance and emergency response. **S.J. Ormiston (Manitoba)** demonstrated advancements in CFD modeling for containment flows and aerosol transport, offering precise tools for SMR safety evaluations.

Table 10: Lectures list

14:45 – 15:10	Validation Database and Future Directions of the THAI Experimental Research for Assessing the Safety of Water-Cooled Small Modular Reactors -	S. GUPTA (BT)
15:10 - 15:35	Overview of i-SMR design and severe accident analysis using CINEMA code	J. HAM (KAERI)
15:35 - 16:00	Advances in MELCOR Modelling Capabilities for Characterizing Small Modular Reactor Safety	D. LUXAT (SNL)
16:00 - 16:25	Informing the 4th and 5th Levels of Defence-in-Depth for Water-Cooled SMRs	L. LEBEL (CNL)
16:25 - 16:50	Development and Benchmarking of CFD Models of SMR Containment Flow and Aerosol Transport	S.J. ORMISTON (MANITOBA)

2.5.1 14:45 - 15:10 | Validation Database and Future Directions of the THAI Experimental Research for Assessing the Safety of Water-Cooled Small Modular Reactors - S. GUPTA (BT)

Summary: S. Gupta (BT) presented the THAI experimental research program, focusing on containment safety for LW-SMRs. Key topics included hydrogen distribution, combustion behavior, and mitigation strategies using PARs. The extension of the THAI+ facility enables testing of SMR-specific safety systems, including passive designs and containment dynamics under SA conditions. The research emphasized data generation for validating CFD and lumped-parameter codes, supporting accurate safety models. Future directions involve expanding the database and infrastructure to address advanced SMR technologies and SA scenarios.

Key R&D Needs

- Expansion and adaptation of the THAI experimental infrastructure to support LW-SMR safety research, including hydrogen distribution, combustion, and mitigation studies.
- Validation of safety codes (CFD and LP) using experimental data from THAI and THEMIS programs for SMR-specific conditions, including high Rayleigh number flows and passive systems.
- Investigation of hydrogen behavior under SA scenarios, focusing on stratification, deflagration, and recombiner performance in SMR containments.

- Study of water pool dynamics in SMRs, including stratification, bubble hydrodynamics, and FP retention to support pool scrubbing efficiency.
- Integration of thermal-hydraulic data into benchmarks and validation databases, ensuring accurate code prediction capabilities for advanced SMR designs.
- Evaluation of passive safety systems performance in SMRs under accident conditions, with specific focus on thermal stratification and heat transfer in large water bodies.

Key Words
THAI facility, LW-SMRs, hydrogen safety, deflagration, passive safety systems, CFD validation, water pool dynamics, fission product retention, thermal stratification, THEMIS project.

2.5.2 15:10 - 15:35 | Overview of i-SMR design and severe accident analysis using CINEMA code - J. HAM (KAERI)

Summary: J. Ham (KAERI) presented the design and SA analysis of the i-SMR using the CINEMA code. The focus was on key safety features, including the Passive Emergency Core Cooling System (PECCS) and Passive Containment Cooling System (PCCS), which ensure long-term stability under severe conditions. The analysis highlighted core damage mitigation, hydrogen combustion control, and containment vessel performance, emphasizing the prevention of early containment vessel failure. Results demonstrated effective management of FP release and thermal-hydraulic phenomena under various scenarios. The presentation reinforced the i-SMR's safety capabilities, aligning with stringent safety criteria for advanced reactors.

Key R&D Needs
- Development and validation of PECCS and PCCS for i-SMRs, focusing on long-term safety without operator intervention.
- Investigation of SA phenomena, including corium coolability via External Reactor Vessel Cooling (ERVC) and prevention of early containment vessel failure.
- Analysis of hydrogen behavior in small containment volumes, addressing high hydrogen concentration and combustion risks under vacuum operation.
- Optimization of containment vessel design, including high-pressuremetal containment vessels and passive cooling efficiency.
- Reduction of FP release and transport within reactor buildings, emphasizing containment leakage rate minimization.
- Examination of ex-vessel steam explosions and molten core fragmentation to ensure integrity under SA scenarios.

Key Words
i-SMR, PECCS, PCCS, hydrogen combustion, corium coolability, ERVC, containment vessel, fission product reduction, passive safety systems, steam explosion

2.5.3 15:35 - 16:00 | Advances in MELCOR Modelling Capabilities for Characterizing Small Modular Reactor Safety - D. LUXAT (SNL)

Summary: D. Luxat (SNL) presented advancements in the MELCOR code for modeling and simulating SA scenarios in SMRs and advanced reactors. The focus was on modernizing MELCOR's architecture to improve its adaptability for diverse reactor types and passive safety systems. Key developments include enhanced radionuclide transport modeling, integration with ORIGEN for dynamic decay analysis, and advanced physics-based models for hydrogen behavior and FP dynamics. These updates aim to provide more accurate safety assessments and support regulatory needs, including risk-informed decision-making. The modernization efforts also emphasized user-friendly interfaces and modularity to accelerate model development.

Key R&D Needs

- Modernization of MELCOR architecture to improve scalability, modularity, and applicability for advanced reactor designs, including SMRs and non-LWRs.
- Integration of ORIGEN with MELCOR for comprehensive radionuclide tracking, decay, and transport analysis across multiple reactor components.
- Development of generalized transport and aerosol dynamics models to enhance SA predictions for diverse reactor technologies.
- Implementation of advanced modeling for passive safety systems and non-electrical applications in nuclear energy systems.
- Expansion of MELCOR capabilities to include molten salt and gas-cooled reactors, with detailed ST and FP behavior analyses.
- Application of graph theory for improved component modeling, enabling accurate simulations for innovative reactor designs.
- Incorporation of CORQUENCH as an alternative framework for ex-vessel debris modeling, improving accuracy for SA scenarios.

Key Words

MELCOR, advanced reactors, SMRs, non-LWRs, radionuclide transport, passive safety systems, severe accidents, ORIGEN, CORQUENCH, aerosol dynamics

2.5.4 16:00 - 16:25 | Informing the 4th and 5th Levels of Defence-in-Depth for Water-Cooled SMRs- L. LEBEL (CNL)

Summary: L. Lebel (CNL) presented advancements in modeling and experimental approaches for SMR safety, focusing on Level 4 and 5 Defense-in-Depth. MELCOR simulations explored passive cooling system failures and their impact on radionuclide release, with scenarios highlighting hydrogen production and containment performance. The Strong Condensation Containment Apparatus (SCCA) experimental setup investigated containment thermal-hydraulics and aerosol transport, revealing key phenomena such as helium stratification and diffusiophoretic aerosol trapping. CFD tools for near-field atmospheric dispersion modeling were developed to address complex topologies and urban settings, surpassing the capabilities of Gaussian plume models. These efforts aim to refine emergency response strategies and inform safety standards for SMRs.

Key R&D Needs

- Enhance passive safety systems for SMRs and advanced reactors to ensure resilience in critical scenarios.
- Improve defense-in-depth strategies with a focus on accident mitigation and radiological consequence reduction.
- Develop advanced modeling tools like MELCOR and CFD for accurate simulation of accident progression and dispersion.
- Conduct experimental validation to understand thermal-hydraulics and aerosol dynamics under prototypical conditions.
- Optimize emergency preparedness methodologies for effective near-field dispersion and response planning.

Key Words
Passive Safety Systems, SMRs, Defense-in-Depth, Accident Mitigation, Radiological Consequences, MELCOR Modeling, CFD, Experimental Validation, Thermal-Hydraulics, Aerosol Dynamics, Emergency Preparedness, Near-Field Dispersion, Severe Accident Management, Safety Features, Containment Systems.

2.5.5 16:25 - 16:50 | Development and Benchmarking of CFD Models of SMR Containment Flow and Aerosol Transport - S.J. ORMISTON (MANITOBA)

Summary: S. J. Ormiston (MANITOBA) presented the development and benchmarking of CFD models for SMR containment flow and aerosol transport. The models, implemented in STAR-CCM+ and Fluent, simulate turbulent gas flow, wall condensation, and aerosol deposition using advanced techniques like the Drift-Flux model. Validation was conducted against SCCA experimental data, with findings showing over-prediction of wall condensation and aerosol deposition compared to experiments. Results revealed the impact of phoretic forces and turbulent diffusion on aerosol behavior within containment. Future work focuses on integrating droplet evaporation, improved radiation modeling, and utilizing containmentFOAM for enhanced accuracy.

Key R&D Needs
- Development and benchmarking of CFD models for SMR containment, focusing on aerosol transport and wall condensation.
- Validation of sub-models for turbulent flow, condensation phenomena, and aerosol deposition using experimental data (e.g., SCCA).
- Improvement of aerosol transport models, incorporating droplet evaporation, thermal radiation, and particle group interactions.
- Integration of Lagrangian multiphase modeling for enhanced prediction of droplet behavior and evaporation effects.
- Application of Drift-Flux models for accurate particle size distribution and steady-state aerosol simulations in SMR environments.
- Exploration of thermal radiation effects on droplet behavior using surface-to-surface and participating medium models.
- Development of containmentFOAM to model SCCA experiments with advanced computational techniques.

Key Words
CFD models, SMR containment, aerosol transport, wall condensation, SCCA experiments, Drift-Flux, Lagrangian multiphase, thermal radiation, droplet evaporation, containmentFOAM

2.5.6 Session Chair Conclusions: Cross-Cutting R&D Needs

This session highlighted diverse approaches to advancing SMR safety, emphasizing the need for robust experimental data, advanced modeling capabilities, and innovative methodologies. Several key areas of focus for R&D have been highlighted:

1. **Experimental Data and Validation**
   It has been emphasized the importance of the experimental facilities for providing validation data crucial for assessing SMR specific phenomena such as hydrogen

behavior and containment performance. Expanding such experimental databases is essential to support model accuracy and ensure confidence in safety predictions.

2. **Advanced Modeling Tools**
   It has been demonstrated the significance of state-of-the-art modeling tools for SA analysis and safety assessment. Further R&D should focus on integrating passive safety features modeling addressing the unique characteristics of SMRs.

3. **Defence-in-Depth Strategies**
   It has been provided insights into how advanced simulations can inform the 4th and 5th levels of Defence-in-Depth. Developing methodologies to assess containment integrity and radionuclide releases under severe scenarios remains a high-priority area for R&D, particularly for emergency preparedness and response.

4. **CFD and Aerosol Transport**
   It has been highlighted the role of CFD in modeling containment flows and aerosol transport. R&D efforts should focus on improving the accuracy of CFD simulations, particularly for multi-phase flow and particle behavior, to better predict SMR containment performance under accident conditions.

5. **Future Directions**
   This session underscored the interconnectedness of experimental, computational, and methodological approaches to SMR safety. Future R&D must prioritize integrating these elements into comprehensive frameworks that address passive systems, multi-physics phenomena, and complex accident scenarios. Collaboration between experimental facilities, modeling experts, and regulatory stakeholders will be key to achieving this goal.

Cross-Cutting Recommendation:
Advancing SMR safety requires a balanced effort to bridge experimental data with cutting-edge modeling tools, ensuring alignment with evolving regulatory and operational needs. A continued emphasis on multi-disciplinary collaboration and validation remains vital for the successful deployment of SMRs.

3 CONCLUSIONS AND RECOMMENDATIONS SHORT TERM NEEDS

3.1 CONCLUSIONS

The *International Workshop on SMR Safety for Short-Term Sustainable Deployment* provided a platform for discussing the latest advancements and best practices in LW-SMR safety. Experts from the global nuclear community shared insights into recent research developments and practical experiences in the SMR licensing process, while also emphasizing the broader role of nuclear energy in sustainable development and decarbonization.

The workshop underscored the importance of SMR safety for sustainable nuclear technology deployment and European competitiveness, highlighting nuclear energy contribution to the Net Zero Goal by 2050 in Europe. Key discussions focused on the evolution of global nuclear ecosystem, the key role of TSOs in providing independent safety assessments and research, the necessity of public trust and engagement, integrating human-organizational factors into SMR safety and deployment strategies.

Key Research Topics discussed are the following:

- Validation of safety analysis codes, with a focus on new representative experimental data to improve the knowledge of advanced reactor features (e.g. passive safety systems) and code accuracy.
- Performance of passive safety systems, reliability assessment, and how their operation impacts the accident progression.
- Identification and characterization of accident scenario for DBA, BDBA and SA conditions.
- Assessment of uncertainties, particularly in SA modeling.
- 4th and 5th levels of DiD, with a focus on containment integrity and emergency preparedness.
- Advanced multi-physics and multi-scale modeling techniques, integrating high-fidelity thermal-hydraulic, neutronics, and structural analysis.
- Harmonization of safety frameworks and methodologies, essential for streamlining European licensing processes.
- Potential of AI in accident analysis, particularly for real-time safety assessments and decision making.
- Integration of SMRs into hybrid energy systems, including hydrogen production, district heating, and industrial applications.

By addressing both technical safety challenges and deployment considerations, the workshop reinforced the need for international collaboration, regulatory modernization, and structured public engagement strategies to ensure the safe and efficient adoption of SMRs.

Advancing SMR Safety Research and Addressing Gaps
Over the past decade, significant progress has been made in SMR safety research through Euratom-funded projects and broader international initiatives. These efforts have led to

enhanced expertise in advanced SMR designs, improved modeling capabilities, and strengthened safety assessment frameworks. However, some gaps still remain and must be addressed from both phenomenological deterministic perspective (e.g., thermal-hydraulics, severe accident progression including uncertainty) and probabilistic perspective. Specific attention should be done on the SMR reactor type that can be deployed in Europe (e.g. integral PWR, loop type PWR, BWR, etc).

Licensing and Safety Framework Challenges

Regarding SMR licensing, the workshop emphasized the importance of accident management strategies and the need for a graded approach to licensing and compliance, tailored to SMR-specific features. Given these distinct features of LW-SMR designs, such as increased reliance on passive safety systems and the introduction of innovative materials like ATF, participants highlighted the urgent need to advance the validation and benchmarking of computational safety analysis codes. This is particularly relevant for both DSA and PSA. Furthermore, the need for harmonizing regulatory frameworks across different European countries was emphasized to streamline international licensing efforts and facilitate cross-border deployment of SMRs.

Safety Analysis Codes and Experimental Data Needs

The workshop also underscored the importance of experimental data in validating and further develop advanced best estimate models for safety analysis codes. Updated experimental datasets are essential for ensuring the accuracy of code validation, particularly in the context of uncertainty quantification and multi-physics coupling for transient scenarios, including SA. Additionally, the development of advanced modeling tools is necessary to enhance predictive capabilities and improve the assessment of SMR-specific safety phenomena, such as passive system performance, hydrogen distribution and mitigation, small containment behavior, and IVMR efficiency. To achieve these objectives, a more extensive and harmonized use of experimental facilities is required to generate qualified high-quality data that can support both DSA and PSA. Expanding and consolidating experimental databases through international collaboration is critical for improving the understanding of reactor phenomenology, enhancing model accuracy, and ensuring reliable safety predictions.

Deployment Challenges: Densely populated Areas, Industrial Integration, and EPZs

The potential deployment of SMRs in densely populated areas requires refined safety assessment methodologies, particularly in evaluating containment integrity, radionuclide retention, and source-term releases under SA conditions. Current regulatory frameworks, originally designed for large-scale nuclear reactors, may require adaptations to accommodate SMR-specific features (e.g., smaller source terms, passive safety features, and modular deployment). Additionally, further research is needed to define and optimize EPZs by balancing safety, public acceptance, and operational feasibility. Developing advanced modeling tools and integrating PRA techniques will be essential for risk-informed EPZ determination, ensuring a tailored regulatory framework that enables the safe and effective deployment of SMRs in densely populated areas.

Another emerging challenge is the integration of SMRs into industrial applications, such as heat production, hydrogen generation, and desalination, which introduces new safety considerations. The interactions between SMRs and industrial processes can impact nuclear safety margins, requiring careful evaluation of process-plant interfaces. Additionally, the establishment of shared emergency planning and coordinated response strategies will be necessary to address potential cascading failure risks, where industrial incidents could compromise SMR safety performance. Addressing these challenges will require the development of enhanced safety models, incorporating dynamic risk assessments to evaluate complex interactions between SMRs and external systems. Regulatory frameworks must evolve to ensure compatibility with hybrid energy systems, while international collaboration will be crucial in establishing best practices for multi-use SMR deployment and fostering harmonized safety standards.

Advancing International Collaboration and Safety Analysis Tools

The workshop also reinforced the importance of international collaboration in advancing SMR safety innovation. The modernization of safety analysis tools is essential to support the regulatory approval process, optimize SA modeling, and ensure compliance with evolving safety standards. In this context, leveraging both European and non-European safety codes is critical to improving the accuracy and reliability of safety assessments for advanced fuels and SMR-specific designs. European safety codes, such as ASTEC and AC2, and non-European codes, such as MELCOR and MAAP, play a fundamental role in this effort. The continuous validation and enhancement of these tools will be key to ensuring regulatory harmonization and fostering technological innovation for the safe and sustainable deployment of SMRs.

INTERNATIONAL WORKSHOP ON SMR SAFETY FOR A SUSTAINABLE SHORT-TERM DEPLOYMENT

Hosted by Institut de Radioprotection et de Sûreté Nucléaire (IRSN)

Final Agenda

WORKSHOP AGENDA - DAY 1 – 17th October

SESSION 1: OPENING REMARKS AND INTRODUCTION
- 09:00 - 09:10 | Welcome and Introduction - **A. BENTAIB (IRSN), F. MASCARI (ENEA)**
- 09:10 - 09:20 | IRSN Introduction – **P. GIORDANO (IRSN) – Director of Research in Safety**
- 09:20 - 09:30 | Introduction from European Commission - **A. IORIZZO (European Commission)**

SESSION 2: OVERVIEW OF SASPAM-SA PROGRESS
Chair: A. BENTAIB, F. GIANNETTI
- 09:30 - 10:00 | SASPAM-SA overview and current results - **F. MASCARI (ENEA)**
- 10:00 - 10:30 | Analysis of postulated DBA and SA Scenarios in Generic Integral PWR Small Modular Reactor in the frame of the Horizon Euratom SASPAM-SA Projects – **F. GABRIELLI (KIT)**
- 10:30 - 11:00 | Assessment of the relevance and applicability of existing experimental databases to iPWR – **T. LIND (PSI)**

11:00 - 11:50 | Coffee Break + Poster Session
- 11:50 - 12:20 | WP4 Major Insights - **F. FICHOT (IRSN)**
- 12:20 - 12:50 | WP5 Current Activity - **N. REINKE (GRS)**
- 12:50 - 13:20 | Preliminary assessments of EPZ extent in SASPAM-SA WP6 - **M. ILVONEN (VTT)**

13:20 - 14:50 | Lunch and Group photo

SESSION 3: INTERNATIONAL INITIATIVES

Chair: M. ILVONEN, N. REINKE
- 14:50 - 15:15 | CNSC Safety Considerations for the Review of Small Modular Reactors – **M. BERDAI (CNSC)**
- 15:15 - 15:40 | Initiatives in USA - **S. CAMPBELL (USNRC)**
- 15:40 - 16:05 | Accelerating Deployment of SMRs with WGAMA Activities for Reliable Safety Assessment - **H. NAKAMURA (JAEA); M. ADORNI (NEA)**
- 16:05 - 16:30 | Updates on IAEA activities on Emergency Preparedness and Response for Small Modular Reactors- **F. STEPHANI (IAEA)**
- 16:30 - 16:55 | European SMR Pre-Partnership – **S. TAKENOUTI (EDF)**
- 16:55 - 17:20 | Industrial SMR Alliance - **A. AL MAZOUZI (SNETP)**

17:20 - 18:10 | Coffee Break + Poster Session

SESSION 4: DISCUSSION OF DAY 1 AND CLOSING REMARKS
- 18:10 - 18:30 | Discussion and Closing Remarks – **A. BENTAIB (IRSN), F. MASCARI (ENEA)**

WORKSHOP AGENDA - DAY 2 – 18th October

SESSION 5: EUROPEAN PROJECT ACHIEVEMENTS

Chair: T. LIND, F. GABRIELLI

- 09:00 - 09:25 | SEAKNOT: Building a Roadmap on Severe Accidents - **L.E. HERRANZ (CIEMAT)**
- 09:25 - 09:50 | PASTELS: From Experimental to Numerical, Main Results of the Project – **M. MONTOUT (EDF)**
- 09:50 - 10:15 | EASI-SMR project overview - **S. SOBECKI (EDF)**
- 10:15 - 10:40 | ENEN SMR initiative overview - **G. PAVEL (ENEN)**

10:40 - 11:10 | Coffee Break + Poster Session

- 11:10 - 11:35 | AMHYCO Project Overview and First Outcome - **G. JIMENEZ (UPM)**
- 11:35 - 12:00 | McSAFER Project: Main Outcomes and Highlights - **V. SANCHEZ (KIT)**
- 12:00 - 12:25 | The TANDEM Euratom Project to Support the Safe Integration of SMRs into Low-Carbon Hybrid Energy Systems - **C. VAGLIO-GAUDARD (CEA)**
- 12:25 - 12:50 | Review of IAEA Safety Standards in Respect to SMRs Licensing – **E. URBONAVIČIUS (LEI)**
- 12:50 - 13:15 | ASSAS Project: Overview and Key Findings – **L. CHAILAN** (IRSN)

13:15 - 14:45 | Lunch

SESSION 6: TECHNICAL PRESENTATIONS

Chair: F. FICHOT, F. MASCARI

- 14:45 - 15:10 | Validation Database and Future Directions of the THAI Experimental Research for Assessing the Safety of Water-Cooled Small Modular Reactors - **S. GUPTA (BT)**
- 15:10 - 15:35 | Overview of i-SMR design and severe accident analysis using CINEMA code - **J. HAM (KAERI)**
- 15:35 - 16:00 | Advances in MELCOR Modelling Capabilities for Characterizing Small Modular Reactor Safety - **D. LUXAT (SNL)**
- 16:00 - 16:25 | Informing the 4th and 5th Levels of Defence-in-Depth for Water-Cooled SMRs- **L. LEBEL (CNL)**
- 16:25 - 16:50 | Development and Benchmarking of CFD Models of SMR Containment Flow and Aerosol Transport - **S.J. ORMISTON (MANITOBA)**

16:50- 17:10 | Coffee Break + Poster Session

SESSION 7: DISCUSSION AND CLOSING REMARKS

- 17:10 - 18:30 | Discussion and Closing Remarks - **A. BENTAIB (IRSN), F. MASCARI (ENEA)**