**Nuclear Energy Agency (NEA)**
NEA/WKP(2025)3
October 2025
www.oecd-nea.org

# NEA WORKING PAPER

# Summary Report of the Workshop on Future Research for Accident Management Enhancement (FRAME) in Operating and Future Reactors, Informed by Fukushima Daiichi Insights

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NEA
NUCLEAR ENERGY AGENCY

Nuclear Energy Agency

NEA/WKP(2025)3

Unclassified

English text only

9 October 2025

OECD Nuclear Energy Agency
STEERING COMMITTEE FOR NUCLEAR ENERGY

# Summary Report of the Workshop on Future Research for Accident Management Enhancement (FRAME) in Operating and Future Reactors, Informed by Fukushima Daiichi Insights



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JT03572870

Please cite this working paper as:

NEA (2025), "Summary Report of the Workshop on Future Research for Accident Management Enhancement (FRAME) in Operating and Future Reactors, Informed by Fukushima Daiichi Insights", OECD Publishing, Paris, https://doi.org/10.82155/g8hr-7x07.

# *Foreword*

The OECD Nuclear Energy Agency (NEA), in partnership with Argonne National Laboratory, the United States Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the United States Nuclear Regulatory Commission (NRC), convened the Workshop on Future Research for Accident Management Enhancement (FRAME) on 26–27 September 2024 at Argonne National Laboratory in Lemont, Illinois, United States.

FRAME was held as several NEA joint nuclear safety research projects that had been initiated after the Fukushima Daiichi accident approached completion in 2025. It underscored the need to sustain key experimental capabilities, tackle emerging safety challenges, and ensure long-term stakeholder engagement in support of both current and future reactor systems.

Reaffirming the Fukushima Daiichi accident as a fundamental reference point for ongoing learning, the workshop offered a collaborative forum for dialogue among regulators, utilities, research organisations, and industry representatives. Discussions highlighted progress made in accident management over the past decade, while also exploring shifting priorities aimed at strengthening nuclear safety and resilience for the next generation of reactors.

FRAME played a central role in identifying research needs and priorities relevant to accident management — an area of strategic importance to the NEA Committee on the Safety of Nuclear Installations (CSNI), particularly through the activities of the Working Group on the Analysis and Management of Accidents (WGAMA) and various joint projects related to thermal-hydraulics and severe accidents. This report is intended to inform and support these ongoing efforts by capturing and conveying the key outcomes of the workshop.

# *Acknowledgements*

The Nuclear Energy Agency (NEA) and its Committee on the Safety of Nuclear Installations (CSNI) gratefully acknowledge the valuable contributions of all individuals who played a key role in the preparation of this summary report. Special appreciation is extended to those, particularly the members of the Organising Committee, who provided leadership in organising and ensuring the success of the Workshop on Future Research for Accident Management Enhancement (FRAME), which was focused on both operating and future reactors and informed by insights from the Fukushima Daiichi accident. Appreciation is also extended to all participants for their active engagement and meaningful input throughout the event.

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## Lecturers and panellists

The lecturers and panellists listed in the workshop programme (Appendix 1) are sincerely thanked for their invaluable contributions. Their insightful presentations and expert perspectives greatly enriched the discussions throughout the event.

## Sponsors

Financial support from the United States Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the United States Nuclear Regulatory Commission (NRC) is gratefully acknowledged. Special thanks are extended to Argonne National Laboratory for their flawless organisation, which was instrumental in the success of the event.

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# *List of abbreviations and acronyms*

| | |
|---|---|
| AC | Alternating current |
| AI | Artificial intelligence |
| AMT | Additive manufacturing technologies |
| ANL | Argonne National Laboratory (United States) |
| ASNR | Autorité de sûreté nucléaire et de radioprotection (France) |
| ASTRID | Advanced Sodium Technological Reactor for Industrial Demonstration |
| ATF | Accident-tolerant fuels |
| BEPU | Best-estimate plus uncertainty |
| BWR | Boiling water reactors |
| BWROG | Boiling Water Reactors Owner's Group |
| CEA | Commissariat à l'énergie atomique et aux énergies alternatives (France) |
| CFD | Computational fluid dynamics |
| CNL | Canadian Nuclear Laboratories |
| CNSC | Canadian Nuclear Safety Commission |
| CSNI | Committee on the Safety of Nuclear Installations (NEA) |
| D&D | Decommissioning and dismantling |
| DEC | Design extension condition |
| DOE | Department of Energy (United States) |
| EC | European Commission |
| ECCS | Emergency core cooling systems |
| EDF | Électricité de France |
| EPRI | Electric Power Research Institute (United States) |
| FP | Fission product |
| FRAME | Future Research for Accident Management Enhancement |
| GFR | Gas-cooled fast reactor |
| HALEU | High-assay low-enriched uranium |
| HTGR | High-temperature gas-cooled reactor |
| HTTR | High-temperature engineering test reactor |
| IAEA | International Atomic Energy Agency |
| INL | Idaho National Laboratory |
| IRSN | Institut de Radioprotection et de Sûreté Nucléaire (ASNR since January 2025, France) |
| ISP | International standard problem |

| | |
|---|---|
| JAEA | Japan Atomic Energy Agency |
| KAERI | Korea Atomic Energy Research Institute |
| KIT | Karlsruhe Institute of Technology (Germany) |
| LOCA | Loss of coolant accident |
| LSTF | Large Scale Test Facility (Japan) |
| LUT | Lappeenranta-Lahti University of Technology (Finland) |
| LWR | Light-water reactor |
| MCCI | Molten core-concrete interaction |
| MSR | Molten salt reactor |
| NEA | Nuclear Energy Agency |
| NRC | Nuclear Regulatory Commission (United States) |
| OECD | Organisation for Economic Co-operation and Development |
| PAFS | Passive auxiliary feedwater system |
| PAR | Passive autocatalytic recombiner |
| PCCS | Passive containment cooling systems |
| PCV | Pressure containment vessel |
| PECCS | Passive emergency core cooling system |
| PIRT | Phenomena identification and ranking tables |
| PRA | Probabilistic risk assessment |
| PSI | Paul Scherrer Institute (Switzerland) |
| PWR | Pressurised water reactors |
| RCIC | Reactor core isolation cooling |
| RCS | Reactor coolant system |
| RPV | Reactor pressure vessel |
| SA | Severe accident |
| SDAA | Standard design approval application |
| SFP | Spent fuel pool |
| SFR | Sodium-cooled fast reactor |
| SMR | Small modular reactor |
| SRV | Safety relief valve |
| SSC | Structures, systems and components |
| STUK | Radiation and Nuclear Safety Authority (Finland) |
| TEPCO | Tokyo Electric Power Company Holdings |
| TH | Thermal-hydraulics |
| TSO | Technical support organisation |

| | |
|---|---|
| VVER | Vodo-Vodianoï Energuetitcheski Reaktor (Russia) |
| WGAMA | Working Group on the Analysis and Management of Accidents (NEA) |
| WCR | Water-cooled reactor |

# *Executive summary*

The Nuclear Energy Agency (NEA), in partnership with US organisations including Argonne National Laboratory, the DOE, EPRI and NRC, held the Workshop on Future Research for Accident Management Enhancement (FRAME) on 26–27 September 2024 at Argonne National Laboratory.

As several NEA research projects that began after the Fukushima Daiichi accident neared completion in 2025, FRAME aimed to define priorities for sustaining key experimental infrastructure, addressing emerging safety challenges, and guiding future research. The workshop brought together regulators, industry, and research experts to identify practical needs and shape a strategic path forward for research to continue enhancing accident management in both current and advanced reactor systems.

## Key insights from the Fukushima Daiichi accident

**Post-Fukushima Daiichi safety enhancements**: Worldwide upgrades — such as improved resistance to natural hazards, mobile emergency equipment, enhanced procedures and training, more reliable depressurisation systems, better instrumentation use, hydrogen risk mitigation, and containment of radioactive releases — have strengthened accident management capabilities.

**Global insights for accident management**: FRAME emphasised the need to apply nuclear safety knowledge globally, focusing on SSC performance under severe conditions, ECCS resilience, complex accident phenomena (e.g. debris relocation, gas behaviour, fission product transport), and reducing modelling uncertainties to enhance predictive tools.

**Research contributions**: International projects, including NEA-led efforts, have advanced understanding of accident progression, fuel debris distribution, and safety system performance. These findings support new safety measures, such as revised procedures and alternative corium management strategies.

**Remaining knowledge gaps**: Knowledge gaps remain in areas such as RPV failure modes, melt relocation effects, combustible gas dynamics, containment failure mechanisms, and long-term fission product behaviour — underscoring the need for continued targeted research.

## Key nuclear safety research topics

FRAME identified key research priorities for both current and future reactor technologies:

### *Operating reactors*

- **Fuel and materials**: Experimental validation with irradiated materials is needed to assess high-burnup fuels, HALEU, and ATFs.
- **Long-term irradiation**: Extended testing is required to understand material behaviour over prolonged lifespans, in co-ordination with vendors and laboratories.
- **Accident behaviour**: Further study is needed on how advanced fuels impact severe accident scenarios, including fission product chemistry.

- **Thermal-hydraulics**: Updated models and data are essential to address challenges under extended operations.

***Emerging technologies***

- **Licensing and risk**: Event selection and risk assessment methods must be adapted for designs lacking operational data.
- **Uncertainty**: Uncertainties must be explicitly addressed in new reactor design and licensing.
- **Validation**: New experiments are needed, as existing data may not apply to advanced designs.
- **Accident management**: A solid technical basis is needed for preventing and managing severe accidents and ensuring passive system reliability.
- **Confinement and emergency response**: Research should improve source term modelling and emergency planning strategies.
- **Instrumentation and codes**: Advanced monitoring tools and modernised analytical codes are required.
- **Disruptive technologies**: AI, AMT, and digital twins offer benefits but require thorough risk understanding for safe adoption.

***New applications***

As nuclear energy expands into non-electric sectors, new hazards emerge. Safety research must address these, along with external challenges like climate change, security threats, and geopolitical tensions.

## Key nuclear safety research capabilities

The workshop highlighted the vital role of experimental facilities and the need for co-ordinated international collaboration. NEA members outlined progress and remaining gaps in accident management research.

**Infrastructure strengths:** NEA-backed facilities have advanced thermal-hydraulics and severe accident studies and show promise for future work on ATFs, passive systems, and SMRs. New NEA projects are planned for 2025–2030, including upgrades to current infrastructures.

**Integrating new capabilities:** Facilities like METERO, PRIUS-2, NIST-2, NSTF, PASTIS, and i-SMR could support broader NEA frameworks, with some adaptable beyond water-cooled reactors.

**Non-WCR research needs:** Despite strong WCR support, infrastructure for HTGRs, SFRs, and MSRs remains limited. Existing facilities such as HANC, HTTF, and SAFeTY address some needs but fall short, highlighting the need for expanded capabilities.

## Key takeaways and strategic recommendations

**Continued learning from the Fukushima Daiichi accident remains essential** — not only for decommissioning but for improving safety across all reactor types. As decommissioning progresses, applying these lessons broadly should remain a global priority.

**Preserving and upgrading experimental infrastructure is critical.** Modernisation efforts must include integrating advanced demonstration systems and ensuring knowledge transfer to the next generation. For non-water-cooled reactors, a collective, strategic approach is needed to identify and develop essential capabilities.

**A phased experimental strategy is recommended** for advanced reactor development — starting with small-scale tests of key phenomena and progressing to larger-scale or full-system demonstrations (e.g. JAEA's HTTR). This ensures efficient use of resources and progressive validation under realistic conditions.

To increase research efficiency and impact, **co-ordinated frameworks are needed**. Broad stakeholder involvement — including regulators, industry, and academia — should guide international collaboration through cost-sharing, cross-platform validation, and clustering of capabilities by thematic areas. Aligning global facility use with structured, stakeholder-informed agendas will maximise value.

**Developing a long-term, globally co-ordinated research roadmap,** supported by tools like PIRTs and stakeholder input, will help prioritise investments and ensure alignment with licensing and safety goals.

**FRAME reaffirmed the importance of international co-operation to meet evolving challenges from advanced systems, fuels, and disruptive technologies.** The NEA is well positioned to lead the next phase by promoting cross-sector engagement, shared funding models, and sustained investment. These actions will keep nuclear safety research aligned with a changing energy landscape and maintain public trust in the future of nuclear energy.

# 1. Introduction

Since its inception, the Nuclear Energy Agency (NEA) has served as a platform for multinational research co-operation, particularly in nuclear safety. For decades, NEA-led projects have enabled nuclear safety regulators, industry leaders, and research organisations to share costs and findings, ultimately strengthening safety regulations, harmonising practices worldwide, and advancing knowledge in the field.

To review the accomplishments of the joint nuclear safety research projects over the past four decades[1] and explore future directions, the NEA hosted the Nuclear Safety Research Joint Projects Week: Success Stories and Opportunities for Future Development in January 2023 [1]. A key focus of the discussions was on the challenges ahead, particularly in accident management research for both operating and future reactors. Key issues highlighted included:

- **Sustaining international momentum**: Fourteen years after the Fukushima Daiichi accident, continued global interest and both public and private support are essential to addressing remaining knowledge gaps and maximising insights from accident analyses for improved management strategies.
- **Impending project closures**: Seven NEA collaborative projects (ATLAS-3, ETHARINUS, QUENCH-ATF, THEMIS, ESTER, PANDA, and ROSAU) are set to conclude by 2025 and 2026 [2]. These projects have addressed key issues stemming from Fukushima Daiichi accident investigations, and their closure poses a risk of losing unique, long-standing experimental facilities and expertise built through significant investments. Given their potential to fill remaining research gaps, particularly for advanced fuels (ATFs, high burnups, increased enrichment) and emerging reactor safety challenges, their discontinuation could be a considerable setback.
- **Strategic research focus**: Moving forward, research efforts must prioritise outstanding safety concerns from the perspectives of industry, regulators, and researchers. A structured approach should be developed to optimise the use of complementary experimental facilities, ensuring that both operating and next-generation reactors benefit from targeted research initiatives.

To address these challenges, it was recommended that continued dialogue take place within forums that bring together regulators, industry representatives, and operators of research infrastructures. These discussions should focus on identifying and preserving the core capabilities needed, both in the near and long term, to effectively tackle nuclear safety challenges for current and future reactor technologies.

[1] Appendix 2 provides a summary description of joint NEA nuclear safety research projects in the thermal-hydraulic and severe accident domains.

# 2. FRAME workshop objectives

The FRAME workshop was organised in response to the above recommendation, providing a platform for nuclear safety regulators, industry representatives, and research organisations to exchange insights on how lessons from the Fukushima Daiichi accident have shaped accident management strategies for both operating and future reactors. It also explored opportunities for further improvements.

Additionally, the workshop offered a chance to review existing research capabilities and the opportunities provided by research facilities and their operating agents.

Serving as a collaborative forum, the event brought together regulators, industry leaders, and research institutions to discuss potential avenues for future co-operative research. The discussions aimed to establish recommendations on key research priorities, necessary capabilities, and stakeholder engagement to advance the development of optimised accident management strategies.

These recommendations, in turn, are expected to support operating agents in maintaining and enhancing core research capabilities while facilitating the design of collaborative project proposals that address stakeholders' evolving research needs.

# 3. FRAME workshop organisation and participation

The workshop was held on 26-27 September 2024 at Argonne National Laboratory in Lemont, Illinois, United States. It was structured into three key sessions (programme provided in Appendix 1):

- **Session 1:** Presentations reviewing safety knowledge gaps and emerging challenges in accident management for both operating reactors and advanced designs, including small modular reactors (SMRs), with a focus on insights gained from the Fukushima Daiichi accident.
- **Session 2:** Presentations highlighting collaborative research programmes, existing capabilities, and future research opportunities offered by operating agents for both current and next-generation reactors.
- **Session 3:** A panel discussion on the further dissemination and integration of Fukushima Daiichi insights, the essential research capabilities required, relevant frameworks, and the necessary stakeholder involvement moving forward.

The workshop organising committee and co-sponsors are listed in the acknowledgements section.

The workshop brought together 110 participants from 15 countries, representing 45 national organisations and three international organisations. Attendees included experts from industry, regulatory bodies, research institutions, technical support organisations, and academia.

High-level representatives from these sectors were invited to share their perspectives on key insights gained from Fukushima Daiichi accident management and analysis, existing knowledge gaps, and emerging challenges in accident management for both operating and advanced reactors. Discussions also covered research capability needs, stakeholder engagement, and strategies for securing sustainable research funding.

The event fostered valuable exchanges between decision makers and operating agents of various NEA projects, exploring opportunities for future collaborative research initiatives.

# 4. Session 1 - Summary and key takeaways: Insights from Fukushima Daiichi and emerging challenges in accident management

Session 1 was co-chaired by Didier Jacquemain (NEA) and Joy Rempe (Rempe and Associates, LLC, United States). It featured key speakers from various stakeholder groups, Marrissa Bailey (United States NRC), Randy Bunt (Southern Nuclear, United States), Myriam Clayes (Électricité de France [EDF], France), Toyoshi Fuketa (NDF, Japan), Robert Hill (Argonne National Laboratory [ANL], United States), Shinya Mizokami (Tokyo Electric Power Company Holdings [TEPCO], Japan), Jean-Christophe Niel (IRSN, France), Tomi Routamo (STUK, Finland), who shared their insights on safety knowledge gaps and emerging challenges in accident management, drawing from lessons learnt from the Fukushima Daiichi accident.

Presentations provided an overview of how nuclear safety research, including NEA collaborative projects, has contributed to improving accident management strategies for the existing reactor fleet, addressing knowledge gaps identified through operational experience and unexpected events like the Fukushima Daiichi accident.

## 4.1. Key discussion topics

Speakers from industry, regulatory bodies, and research organisations addressed the following:

- major insights from Fukushima Daiichi accident for accident management and analysis;
- knowledge gaps and emerging issues in accident management for both operating and advanced reactors;
- research capabilities needed to support safety improvements; and
- stakeholder engagement and sustainable research funding.

## 4.2. Safety enhancements implemented after Fukushima Daiichi

Presenters highlighted that, in response to evaluations of the Fukushima Daiichi accident, many countries undertook substantial safety enhancements for their existing reactor fleets. These upgrades, grounded in proven technologies, vary depending on the specific plant or national context; they include the following measures:

- **Reinforced protection against external and internal hazards:** Measures such as the installation of physical flood barriers and bunkered safety systems strengthen resilience against both external and internal hazards. To ensure their effectiveness, comprehensive assessments of site-specific extreme events, including correlated hazards, are essential. Furthermore, protective measures should be adapted for multi-unit configurations when several reactors are present on the same site.
- **Deployment of additional on-site and off-site emergency equipment to strengthen defences against complete loss of AC power or heat sinks.** This includes mobile backup power units, heat sinks, water supply systems, communication tools, debris-clearing machinery, and emergency control centres.

National response centres have also been established to airlift critical equipment and supplies to affected sites when necessary. Furthermore, additional standardised connection points have been implemented to facilitate the rapid deployment of mobile equipment.

- **Modernised symptom-based operational guidance**, offering plant operators a robust defence-in-depth framework with multiple strategies to manage severe accident scenarios effectively.
- **Improved reliability of depressurisation systems** coupled with strengthened preventive and mitigative measures to reduce the risk of core damage and containment failure.
- **Enhanced utilisation of existing instrumentation for accident diagnostics**, with diverse methodologies for monitoring water levels in both the reactor core and the spent fuel pool (SFP), thereby improving real-time response and decision making during critical events.
- **Installation of additional diagnostic instrumentation**, such as thermocouples designed to detect molten material arrival in reactor cavities and instrumentation rooms, an approach notably implemented in French PWRs.
- **Expanded safeguards against hydrogen explosion risks**, including the use of natural circulation in interconnected structures, hydrogen sensors in BWR reactor buildings, and thermocouples within hydrogen recombiner units in PWRs.
- **Strengthened measures to minimise radioactive dispersion**, through the deployment of advanced hardened filtered containment venting systems and the integration of spray systems to wash down radioactive plumes.

Furthermore, the analysis of the Fukushima Daiichi accident yielded valuable insights into the performance and resilience of steam-driven water injection systems, including ECCS such as the reactor core isolation cooling (RCIC) system and the high-pressure coolant injection system. These insights have been instrumental in extending the operational boundaries of these systems under off normal and severe accident conditions.

Several of these enhancements are technology-neutral, improving the safety of boiling water reactors (BWRs), pressurised water reactors (PWRs), CANDU reactors, and some non-water-cooled reactor (non-WCR) designs.

In addition, the Fukushima Daiichi accident led to significant advancements in both physical and digital technologies for post-accident damage assessment. Notable innovations include the use of muon tomography for internal structural imaging, deployment of specialised robots and drones for exploring high-radiation or physically hazardous areas, and the development of high-fidelity three-dimensional virtual models of the damaged reactor units to support detailed analysis and decommissioning efforts.

## 4.3. Fukushima Daiichi triggered several international research initiatives

Presenters emphasised that the Fukushima Daiichi accident served as a catalyst for international collaboration, leading to several post-Fukushima NEA joint nuclear safety

research projects[2], including BSAF [3,4], Pre-ADES [5], ARC-F [6,7], TCOFF [8] and FACE [9]. These projects have driven significant research progress, including:

- A shared understanding of the accident's progression and the distribution of fuel debris within the damaged units.
- Enhanced knowledge of severe accident phenomena, including in-vessel and ex-vessel debris formation and relocation, combustible gas dynamics, and the release and transport of fission products.
- Enhanced insights into the performance of structures, systems, and components (SSC) under severe accident conditions, such as reactor core isolation cooling (RCIC), isolation condensers, safety relief valves (SRV) and pressure containment vessel (PCV) pressurisation and induced leakages.

These findings have been achieved through instrumentation data analyses, post-accident examinations, and advanced simulations.

International collaboration continues with the NEA FACE [9] and TCOFF-2 [10] projects which are further enhancing safety while supporting preparation of fuel debris retrieval and decommissioning and dismantling (D&D) efforts.

Beyond immediate accident analysis, the Fukushima Daiichi accident has also accelerated research in key nuclear safety areas, including:

- Accident-tolerant fuels (ATFs) for improved resilience under extreme conditions[3], as explored in the NEA FIDES-II, QUENCH-ATF, SCIP and TCOFF-2 projects.
- Thermal-hydraulics research, particularly related to design extension condition (DEC) scenarios related to the Fukushima Daichi accident, supported by the NEA ATLAS and ETHARINUS projects.
- Passive safety system performance assessments, investigated through the NEA ATLAS, ETHARINUS and PANDA projects.
- Severe accident modelling, including:
  - Core material degradation, studied in the NEA QUENCH-ATF and TCOFF-2 projects.
  - Corium stabilisation, both in-vessel and ex-vessel, as explored in the NEA COPS and ROSAU projects.
  - Hydrogen combustion risk management, as addressed in the NEA THEMIS project.
  - Radioactive release mitigation, studied in the NEA ESTER project.

Findings from thermal-hydraulics (TH) and severe accident (SA) research projects have already translated into practical industry applications, including improved procedures for DEC [11] and the development of an alternative corium stabilisation strategy for French nuclear power plants[4]. Additionally, project results have contributed to the development

[2] Appendix 2 provides a summary description of joint NEA nuclear safety research projects in the thermal-hydraulic and severe accident domains.

[3] This also encompasses other critical core components, such as fuel cladding and control rod drives, which are manufactured from materials with greater resistance to accident conditions.

[4] Drawing on the results of the NEA MACE, MCCI, and ROSAU projects, EDF plans to implement modifications in its operating plants for a new ex-vessel corium stabilisation strategy. This strategy involves dry spreading of corium into the cavity and instrumentation room, followed by top-flooding with water to achieve stabilisation.

and validation of advanced simulation codes, such as 3D system codes and computational fluid dynamics (CFD) codes within the TH domain.

These high-fidelity modelling capabilities are expected to play an increasingly important role in future nuclear safety assessments and operational planning [13,14]. Severe accident research has also increased understanding in several key areas, including the effects of material interactions on in-vessel and ex-vessel accident progression, the risks associated with combustible gas explosion during accidents, the remobilisation behaviour of iodine and caesium from surface deposits, and the uncertainties inherent in modelling these complex phenomena.

## 4.4. Remaining knowledge gaps from the Fukushima Daiichi accident

Despite significant advancements in analysing the Fukushima Daiichi accident, uncertainties remain in several areas, including:

- the impact of a dry-core scenario on reactor pressure vessel (RPV) failure mode and timing;
- the effects of the forest of BWR lower head penetrations on RPV failure and ex-vessel melt progression;
- the extent of ex-vessel melt relocation and underlying concrete degradation mechanisms;
- combustible gas generation and transport dynamics, influencing explosion risks;
- mechanisms leading to containment integrity failure and potential leakage paths;
- fission product behaviour, including release, retention, and transport through gas and liquid pathways, particularly over the long term.

These knowledge gaps are relevant not only to several reactor types but also to the ongoing and future D&D activities at Fukushima Daiichi.

Presenters underscored the importance of maintaining a strong commitment to continuous learning from the Fukushima Daiichi accident, particularly as decommissioning efforts are still in their early stages. This commitment should extend beyond the current FACE project, which is expected to conclude in 2026, ensuring that research continues to address these uncertainties and strengthen global nuclear safety. They emphasised that insights gained from Fukushima Daiichi investigations should be expanded and made more universally applicable through research, enabling their integration into a broader range of reactor designs. Ensuring that Fukushima Daiichi findings contribute meaningfully to nuclear safety remains a key priority.

## 4.5. Key safety research topics for operating plants and advanced reactors

Presenters emphasised that safety research plays a big role in developing the technical basis for improving risk assessment and safety margin evaluations while supporting both regulatory and industrial applications across all nuclear technologies. Research efforts should:

- identify emerging safety challenges and validate existing safety demonstrations;
- drive safety innovations, enhancing the resilience of current and future reactors;
- integrate advanced and disruptive technologies — such as artificial intelligence (AI), additive manufacturing technologies (AMT), and digital twins — which offer

significant potential to enhance reactor design, operation, and safety assessment. A thorough understanding of their associated risks and challenges is essential for their safe implementation. Equally important is the development of robust data ecosystems to enable advanced analytics and ensure reliable, data-driven decision making.

Safety research should incorporate all these technologies, alongside evolving external factors such as climate change, security threats, and geopolitical conflicts (e.g. the Russia-Ukraine war).

A science-based approach remains essential across all nuclear technologies, ensuring the continued advancement of state-of-the-art practices and computational models in neutronics, fuel performance, thermal-hydraulics, severe accident progression, source term evaluation, and consequence analysis. The best-estimate plus uncertainty (BEPU) methodology [15] is also a key tool for improving safety evaluations.

### *International research priorities for operating plants*

Lessons learnt from the Fukushima Daiichi accident and operational experience — including related to long-term and flexible operation driven by economic considerations — should be incorporated when identifying research gaps for existing reactors. In particular, the long-term operation of nuclear plants raises key safety questions regarding the ageing and degradation of structures, systems, components and materials.

Specific areas requiring further research include:

**Fuel performance and advanced fuel validation**

- The benefits and challenges of operating with high-burnup (HBU) fuels, high-assay low-enriched uranium (HALEU) fuels, and near-term ATFs (e.g. Cr-coated claddings and doped fuels) must be validated through experimental studies on irradiated materials.
- Long-term irradiation (LTR) programmes are needed to assess material behaviour over extended periods, requiring close collaboration with fuel vendors to source representative materials.
- The impact of advanced fuels on severe accident progression and consequences must be characterised, including aspects such as eutectic formation and fission product chemistry.

**Thermal-hydraulics (TH) and severe accident (SA) research, including effects of advanced fuels**

- Outstanding issues in TH safety analysis under extended operation conditions.
- Combustible gas generation, transport, and ignition phenomena and effectiveness of accident management strategies.
- Corium retention capabilities for improved severe accident management.
- Atmospheric and liquid source term evaluations under extended operation conditions and with advanced fuels.

By addressing these key areas, safety research will support the continued safe operation of existing reactors while also informing the development of next-generation nuclear technologies.

### *International research priorities for emerging reactor technologies*

Globally, research efforts for emerging reactor technologies are focused on addressing key safety challenges and regulatory considerations, particularly given the unique designs and operational characteristics of advanced reactors. Priority areas include:

**Licensing basis event selection & probabilistic risk assessment (PRA)**

- Ensuring completeness and uncertainty management in PRA methodologies, especially as SA scenarios and phenomenology may differ significantly from traditional WCRs.

**Limited operating experience and validation data**

- New reactor designs lack long-term operational data, which increases uncertainty and raises concerns about the completeness of traditional PRA approaches.
- Uncertainty quantification and scaling effects need to be carefully considered.

**Legacy testing data limitations**

- Many safety claims for advanced reactors rely on historical experimental data that may not be fully applicable.
- New experimental programmes are required to validate safety performance and inform licensing.

**Technical basis for "practical elimination" of severe accidents**

- Some advanced reactors aim to eliminate severe accident scenarios, but the technical basis for achieving this goal must be robust and well-documented.

**Long-term performance of passive safety systems**

- Research is needed to assess the ageing effects of passive safety systems and the long-term reliability of monitoring instrumentation.

**Source term modelling & emergency planning considerations**

- Advanced reactors feature diverse fuels and plant designs, leading to significantly different radionuclide behaviours compared to light-water reactors (LWRs).
- Functional containment strategies and novel radionuclide barriers require unique safety considerations.
- Monitoring the performance of containment barriers during an accident is more challenging compared to traditional leak-tight containments.
- Non-core radionuclide sources (e.g. off-gas systems, molten salt purification systems) may be significant contributors to overall plant risk.

**Advanced instrumentation for accident monitoring & management**

- Instrumentation for advanced reactors should be qualified for plausible accident scenarios with several technical challenges, including harsh environments (high temperatures, radiation, and corrosion), material compatibility, data integrity and security, real-time monitoring, miniaturisation, integration, and long-term reliability.

**Modernisation of analytical codes**

- Current safety codes must be updated to account for advanced fuels, and non-WCR designs.

**Application of emerging technologies**

- AI, additive manufacturing technologies (AMT), and digital twins offer opportunities to enhance reactor design, operation, and safety assessment.

Given the diversity of fuels and reactor configurations, further safety research is needed in thermal-hydraulics (TH) and severe accident (SA) domains. For instance, safety concerns in small modular reactor (SMR) WCRs include:

- thermal-hydraulics for compact reactor designs;
- passive safety system long-term performance;
- hydrogen risk mitigation;
- in-vessel retention strategies for externally flooded reactor vessels;
- source term assessments, considering novel containment strategies and non-traditional radionuclide release pathways.

By addressing these research priorities, international efforts will help bridge knowledge gaps, support regulatory frameworks, and enhance the safety of both operating and next-generation nuclear technologies.

### *Research topics for new industrial applications*

The expansion of nuclear energy beyond traditional electricity generation into areas such as hydrogen production, industrial processing, powering data centres and district heating introduces new operational hazards that must be thoroughly evaluated and mitigated.

Key research areas include:

- Identification and assessment of new hazard pathways associated with these applications, including thermal, chemical, and radiological risks.
- Development and validation of modelling and simulation tools to ensure accurate prediction of system behaviour under novel operating conditions.
- Integration of nuclear systems with external industrial processes, ensuring safety, reliability, and regulatory compliance.
- Risk-informed safety strategies to address process coupling complexities and potential accident scenarios unique to these applications.

A robust research framework is essential to ensure that these new industrial uses of nuclear energy meet the highest safety and performance standards, while maximising their potential benefits.

## 4.6. Ensuring research infrastructure and expertise for nuclear safety

As nuclear energy applications expand, both in new reactor designs and broader industrial uses, it is crucial to maintain and strengthen key research infrastructures and technical competencies [15]. While past projects have significantly advanced nuclear safety research, additional efforts are needed to extend their applicability to both existing reactors and next-generation designs. Additionally, new capabilities must be developed to support future advancements in nuclear safety.

### *Sustaining and expanding experimental & analytical capabilities*

Robust experimental and computational capabilities are essential to support ongoing and future safety research in several domains:

- Thermal-hydraulics and severe accidents: Ensuring continued access to key experimental facilities and datasets is essential.
- Advanced modelling and simulation:
  - Greater use of 3-D system codes and CFD models to better capture phenomena found in complex reactor simulations.
  - Expanded uncertainty and sensitivity analyses to better quantify safety margins and improve predictive capabilities.
  - Development of severe accident (SA) simulators and AI-enhanced SA modelling tools, as done in ASSAS [17] (AI for SA simulation), can significantly improve severe accident response guidance by enabling real-time simulation and decision support.
- Simulation tools for reactor safety: It is essential to maintain qualified simulation tools to quantify coping times, decay heat removal capacity, and reactivity control effectiveness in various operational and accident scenarios.

### *Maintaining technical expertise and knowledge transfer*

The preservation of skilled personnel with multidisciplinary expertise is just as vital as maintaining research infrastructure. In particular:

- Cross-disciplinary expertise in neutronics, fuel performance, thermal-hydraulics, severe accidents, and source term evaluations must be sustained.
- Emerging technologies such as AI, advanced manufacturing, and digital tools hold transformative potential for nuclear safety and efficiency. However, their safe implementation requires a thorough understanding of associated risks and the development of robust data ecosystems to support new analytical approaches.
- Knowledge retention programmes should be implemented to avoid losing decades of expertise, as rebuilding technical competence is extremely challenging.
- Public confidence in nuclear safety relies on maintaining a strong technical foundation; a loss of expertise could lead to diminished trust in nuclear energy.

### *Strategic priorities for the future*

- Ensure continued access to key research infrastructures by securing long-term funding and international collaboration.
- Develop new simulation and modelling capabilities to enhance severe accident analysis and safety assessments.
- Expand the applicability of past research findings to new reactor designs and operational conditions.
- Invest in workforce development to sustain nuclear safety expertise and foster innovation in reactor safety research.

By prioritising these efforts, the nuclear industry can strengthen its safety framework, support innovation, and ensure long-term sustainability in an evolving energy landscape.

## 4.7. Challenges and recommendations for future research

Maintaining deep technical expertise in reactor safety that spans the existing nuclear fleet and advanced reactor technologies presents a significant challenge, particularly given limited financial and human resources. To address this, stronger stakeholder engagement and sustainable funding models are essential.

### *Advantages of international collaborative research*

International collaboration in nuclear safety research provides important benefits, including:

- Leveraging collective expertise, enabling a broader, more robust understanding of nuclear safety challenges.
- Optimising resources through cost-sharing, knowledge exchange, and joint research initiatives.
- Supporting near-term operational improvements, including life extensions, power uprates, reactor restarts, as well as new reactor design deployment.
- Enhancing international safety standards by integrating diverse experiences and best practices.
- Safeguarding at-risk experimental facilities by pooling resources to maintain existing infrastructure and develop new test capabilities.
- Ensuring next-generation workforce development by providing researchers with access to world-class experimental facilities and training opportunities.
- Strengthening analytical capabilities through comparative simulations, improving modelling tools and methodologies.

### *Strengthening stakeholder awareness and long-term planning*

To enhance support for NEA research initiatives, governments, industry leaders, and the public must recognise the tangible benefits of international collaboration. A long-term research roadmap is essential to align diverse stakeholder priorities and secure sustained funding. Key strategies include:

- Incorporating stakeholder input — including industry, government, and regulators — to prioritise research needs and develop test matrices that are aligned with practical safety concerns.
- Ensuring financial sustainability by integrating research planning with long-term funding commitments.
- Defining clear research objectives to improve project selection and stakeholder engagement.
- Encouraging industry involvement to increase the likelihood that research findings have near-term applications in real-world nuclear operations.

Experimental programmes and test campaigns should be designed with clear industrial objectives, delivering usable results and actionable conclusions that address specific safety challenges. This approach will help maintain industry participation and ensure the continued operation of key testing facilities.

### *Adapting to emerging challenges*

The research roadmap and strategic priorities must be regularly updated to:

- Balance support for existing nuclear reactors while advancing next-generation technologies.
- Address emerging global challenges, including climate change, security risks, and disruptive technologies such as AI and additive manufacturing.
- Factor in geopolitical risks, such as the impact of conflicts, exemplified by the Russian-Ukraine's war.

By maintaining a forward-looking research agenda, nuclear safety organisations can enhance preparedness, drive innovation, and ensure long-term sustainability in a rapidly evolving energy landscape.

# 5. Session 2 - Summary and key takeaways: Key safety research capabilities and perspectives in the TH and SA domains

Session 2 was co-chaired by Mitch Farmer (ANL, United States), Terttaliisa Lind (Paul Scherrer Institute [PSI], Switzerland), Shinya Mizokami (TEPCO, Japan), and Andrew Morreale (Canadian Nuclear Laboratories [CNL], Canada). The session featured presentations from key experimental infrastructure operating agents and researchers actively involved in NEA projects in the thermal-hydraulic and severe accident domains and from the International Atomic Energy Agency. The speakers included:

- Satoshi Abe (JAEA, Japan)
- Steve Bajorek (NRC, United States)
- Marc Barrachin (IRSN, France)
- Sanjeev Gupta (Becker Technologies, Germany)
- Christophe Journeau (Commissariat à l'énergie atomique et aux énergies alternatives [CEA], France)
- Kyoung-Ho Kang (KAERI, Korea)
- Jeremy Licht (ANL, United States)
- Yu Maruyama (JAEA, Japan)
- Andrew Morreale (CNL, Canada)
- Domenico Palladino (PSI, Switzerland)
- Vesa Riikonen (Lappeenranta-Lahti University of Technology [LUT] University, Finland)
- Martin Steinbrück (Karlsruhe Institute of Technology [KIT], Germany)
- Eve-Lyne Pelletier (IAEA)

These experts shared their insights on the benefits of collaborative research programmes, the core research capabilities that need to be developed or maintained, and opportunities for future collaborative research initiatives in the thermal-hydraulic and severe accident domains.

## 5.1. Key discussion topics

Speakers provided valuable input on:

- existing and planned research capabilities across various countries and organisations;
- nuclear safety issues that these capabilities can address in the near future for both existing and advanced reactors;
- opportunities for future collaborative programmes and research frameworks;
- the importance of stakeholder engagement to sustain key research platforms in thermal-hydraulics and severe accident research.

The session emphasised the need for continued investment in international research collaboration to ensure that experimental facilities remain available, technical expertise is retained, and safety advancements continue to be made for both current and next-generation nuclear reactors.

## 5.2. Research infrastructures supporting ongoing and planned NEA projects on accident management in current and advanced reactor designs

Presentations showed that ongoing and planned NEA projects are leveraging existing research infrastructures, open to international collaboration, to support both current and next-generation reactor designs. These collaborative research efforts are increasingly focused on integrating design features and operational scenarios relevant to advanced technologies. At this stage, particular emphasis is placed on water-cooled SMRs, more advanced fuels including ATFs, and passive safety systems [18]. While the feasibility of facilities upgrades for non-WCR designs is being considered, no new NEA projects are currently planned to address non-WCR safety. The Loss of Force Cooling project is addressing the safety of high-temperature gas-cooled reactor (HTGR) designs through tests conducted in the JAEA HTTR large-scale demonstration reactor [2]. However, as testing is now complete, there are no plans for a follow-up international project in the HTTR.

In the domain of thermal-hydraulics, research capabilities are being enhanced to accommodate the specific boundary conditions, safety systems, and circuit and containment characteristics of more integrated water-cooled SMR designs. Experimental facilities are being equipped with advanced instrumentation to generate qualified data for evaluating accident management strategies, assessing the performance of innovative safety systems, and supporting the development and validation of next-generation thermal-hydraulic codes [19]. Certain instrumentation advancements developed for thermal-hydraulic experiments can serve as valuable references for instrumentation development in reactors.

The following research infrastructures are currently used or planned for use in NEA thermal-hydraulic projects:

- ASPIC and MIDI (operated by Autorité de sûreté nucléaire et de radioprotection [ASNR], France): Utilised in the POLCA project (2024-2028) to examine the behaviour of spent fuel pools (SFPs) under loss of cooling scenarios, ASPIC supports assembly-scale investigations while MIDI enables experiments at pool scale.
- ATLAS (operated by KAERI, Korea): Based on the APR1400 reactor design, this integral test facility features mock-ups of the Reactor Coolant System (RCS) and containment. The facility has been used in NEA projects since 2014. It has undergone continuous upgrades to support investigations of passive systems such as passive auxiliary feedwater system (PAFS), passive emergency core cooling system (PECCS), and passive containment cooling systems (PCCS), and instrumentation to generate 3D-grade and CFD-grade data. A new PCCS module was recently added. ATLAS Phase 3 concluded in 2024, and phase 4 (2025-2028) explores RCS–containment coupling, performance of passive systems, design extension condition (DEC) procedures, and scaling resolution [20] — relevant to both large reactors and water-cooled SMRs.
- CIGMA (operated by JAEA, Japan): This facility supports containment investigations for both large reactors and SMRs. JAEA envisages providing

counterpart tests for THEMIS-2 and PANDA-2 as in-kind contributions, using CIGMA alongside the PANDA and THAI+ facilities.

- LSTF (operated by JAEA, Japan): Based upon the design of the Tsuruga Unit-2 PWR, this facility supported the ROSA projects (2005–2012). It has since provided counterpart tests for ATLAS and PKL. With PKL now decommissioned, the LSTF is expected to partially compensate as a large-scale thermal-hydraulic test facility. Counterpart tests are planned within ATLAS-4 and SYSTHER (2025-2028).
- MOTEL (operated by LUT University, Finland): Focused on SMR thermal-hydraulics, this facility resembles the NuScale SMR design, including helical coil steam generators. Studies include SB-LOCA and cooldown procedures following SGTR events. MOTEL is included in SYSTHER and the European Commission (EC) MsSAFER projects.
- MISTRA (operated by CEA, France): Designed for containment studies in large PWRs, MISTRA was used in SETH-2 and HYMERES (2007–2016). It is proposed for use in SYSTHER (2025–2028) for SMR-relevant studies on passive heat removal and containment pressurisation.
- PANDA (operated by PSI, Switzerland): Based on the ESBWR containment concept, the PANDA multi-compartment facility supports investigations on both active and passive containment cooling systems (PCCS), including natural circulation, condensation, and thermal stratification in pools, relevant for designs with large containments and for SMRs. The facility has been used in NEA projects since 2001 (SETH, HYMERES and PANDA projects). PANDA is currently active in a project set to conclude in 2025. A new phase (2025-2029) will address containment thermal-hydraulics with tests on flow interactions and radiative heat transfer with complex containment internal structures, passive (PCCS) and active spray safety systems and BWR suppression pool behaviour.
- PASI (operated by LUT University, Finland): Based on the AES-2006 Vodo-Vodianoï Energuetitcheski Reaktor (VVER) design, PASI includes a PCCS and is scheduled for use in the SYSTHER and the EC PASTEL project.
- PWR-PACTEL (operated by LUT University, Finland): Based upon the EPR design, PWR-PACTEL was used in the ETHARINUS project (concluded in 2024). It will be further utilised in SYSTHER (2025–2028) for SB-LOCA and natural circulation studies.
- RBHT (operated by Pennsylvania State University, United States): Focuses on core reflooding and ECCS performance under low and variable inlet flow conditions, the ongoing RBHT Phase 2 (2023–2026) project is generating 3D and CFD-grade data for advanced modelling validation. Looking ahead, the facility holds strong potential for future testing involving modern fuel assembly designs and SMR configurations.
- THAI+ (operated by Becker Technologies, Germany): A two-compartment facility supporting containment studies related to hydrogen risk, aerosols, and iodine behaviour. Active in NEA projects since 2007, THAI+ recently completed the THEMIS project (2024). A follow-up phase (2025–2028) will explore SMR-related heat transfer in water pools, stratification, hydrogen combustion, iodine remobilisation, and passive autocatalytic recombiner (PAR) performance in obstructed containments.

The PKL facility, operated by Framatome GmbH, Germany, and long active in NEA research since 2001, was decommissioned in 2024. It played a key role in the ETHARINUS project and in previous SETH and PKL project series. Data from 15 tests performed prior to closure are planned to be incorporated into the SYSTHER project. JAEA's LSTF facility is expected to partially fill the resulting capability gap for large-scale PWR thermal-hydraulic testing.

In the field of severe accidents, NEA-supported research is underpinned by advanced experimental capabilities designed to investigate key phenomena relevant to core meltdown scenarios. These include facilities for rod bundle testing to evaluate the resilience of fuel cladding materials in accidents, corium melt and fuel debris behaviour, and fission product chemistry affecting source term assessments. Research efforts increasingly incorporate the study of advanced fuels, including ATFs, to evaluate their impact on accident progression, source term behaviour, and accident management strategies.

The following research infrastructures are currently used or planned for use in NEA severe accident projects:

- AMIX (operated by INL, United States): This facility supports detailed investigations of fission product release from irradiated fuel samples, with a particular focus on advanced fuels, including ATFs. As part of the NEA FORESEEN project (2026–2029), AMIX will be used to conduct targeted experiments on the fission product release behaviour of irradiated chromium-doped $UO_2$ fuel.
- CHROMIA Platform (operated by ASNR, France): Comprising the CHIP facility for fission product transport studies in the reactor coolant system (RCS) and EPICUR for radiochemistry investigations in the containment, CHROMIA has supported NEA research since 2011 through the STEM and ESTER projects. The ESTER project, set to conclude in 2025, focuses on fission product remobilisation from RCS deposits and organic iodide formation in the containment. A follow-up project, FORESEEN (2026–2029), will explore source term behaviour in scenarios involving ATFs.
- DCAM and MST (operated by ANL, United States): These facilities enable experiments with depleted $UO_2$. DCAM supports research on in-vessel and ex-vessel debris coolability, while MST investigates ex-vessel melt spreading and cooling phenomena. The ROSAU project was completed in 2024. A continuation, ROSAU-2 (2025–2029), is planned to address remaining uncertainties in modelling coolability and underwater melt spreading, particularly for melt compositions with high-metallic content and for ATF-based core debris.
- QUENCH (operated by KIT, Germany): This facility conducts rod bundle tests to assess the performance of cladding materials under severe accident conditions. The ongoing QUENCH-ATF project (running through 2026) focuses on Cr-coated claddings. Discussions have started for a new phase beyond 2026.
- PLINIUS platform (operated by CEA, in Cadarache, France) and ATTILHA (operated by CEA, in Saclay, France): These facilities enable testing with depleted $UO_2$ to study thermophysical properties of corium melts. Such measurements are essential for improving the accuracy of severe accident modelling. They are currently used in the ongoing COPS project (2024–2029).
- THAI+ (operated by Becker Technologies, Germany): As described in the thermal-hydraulics section, THAI+ also supports source term investigations related to aerosols, iodine chemistry, and containment phenomena. It continues to contribute

to NEA projects with relevance to both traditional and advanced reactor designs, including SMRs.

Stakeholders must actively support the preservation and continuous upgrading of these world-class facilities, along with their associated experimental and analytical expertise. Such support is essential to effectively accompany the evolving needs of the nuclear sector, enabling modernisation, fostering innovation, and enhancing the economic performance of existing plants. These capabilities are also key to the successful implementation of advanced reactor designs, including water-cooled SMRs.

In the source term area, the LESSAC project related to liquid source term-related to corium leaching has been proposed by CEA under the NEA umbrella, making use of the PLINIUS platform for generating prototypic corium samples and of the ATALANTE facilities for leaching tests and chemical analysis. The project plans to be complementary to the EC SOCRATES (2025-2029) project addressing the same topic. At this point, limited interest beyond the EC makes the project's development uncertain.

## 5.3. New opportunities for future NEA collaborative projects and associated research infrastructure

Presentations also emphasised emerging opportunities for NEA projects to leverage both existing and upcoming research infrastructures — many of which are open or will soon be opened to international collaboration — to support the development and safety assessment of advanced reactors. Several facilities have already contributed to demonstrating specific SMR concepts. Notable examples include:

- METERO (operated by CEA) and PRIUS-II (operated by KAERI): Discussions are currently underway to propose a joint NEA project in 2025 aimed at generating high-quality experimental data at these two facilities. The focus would be on improving core-mixing models and enhancing the assessment of core safety margins, including those relevant to modern reactor designs.
- i-SMR (operated by KAERI): Now in the commissioning phase, this facility is expected to play a pivotal role in future joint projects related to SMRs, particularly micro-reactors and offshore floating nuclear power plant designs. Testing plans include separate effect tests in 2025-2026, followed by integral system tests in 2027. Upon completion, the facility could be opened to international collaboration. Key research topics include natural circulation, condensation, helical-type steam generator behaviour, and the long-term cooling capacity of passive safety systems.
- NIST-2 (operated by Oregon State University): This facility previously supported NuScale's standard design approval application (SDAA) and was placed on standby in 2023. It remains a strong candidate for reactivation under a potential NEA joint project focused on experimental research for SMRs.
- NSTF (operated by ANL): Originally developed to support U.S. DOE programmes and U.S. vendors, NSTF has been utilised to evaluate ex-vessel passive decay heat removal strategies. Its flexible infrastructure, including adaptable reactor vessel and containment configurations, makes it suitable for experiments across a wide range of reactor types, including LWRs, SFRs, gas- cooled fast reactors (GFRs), MSRs, and SMRs.
- PASTIS platform (operated by ASNR): This platform leverages the ALCINA and KOKOMO facilities to conduct testing of passive safety systems.

NEA has been encouraged to explore, in close co-ordination with the operating organisations of these facilities, the feasibility of launching joint international projects in the near future to fully capitalise on their unique experimental capabilities.

In addition, several other "historical" experimental capacities in the thermal-hydraulic and severe accident domains were presented. While many still possess valuable test capabilities with potential adaptations to advanced designs, no current plans for international collaborative use were reported. Similarly, some facilities developed for the demonstration of specific designs of water-cooled SMRs were introduced though their accessibility for international collaboration remains unclear.

While water-cooled reactors, both conventional and SMR designs, benefit from decades of research infrastructure development, capabilities supporting accident management strategies for non-water-cooled designs remain limited. Relevant infrastructures presented include both legacy and new developments:

- HANC (operated by CNL): Designed to study air ingress scenario in HTGRs, HANC is expected to begin experimental operations in 2025. Its design builds on experience from Oregon State University's HTTF.
- HTTF (operated by the Oregon State University): An integral test facility simulating MHTGR behaviour during depressurised conduction cooldown events.
- SAFeTY platform (operated by CEA): Focused on severe accident testing for sodium and water-based technologies, this platform draws on France's extensive SFR expertise, particularly from the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) project. It is currently in detailed design and is expected to be operational by the end of 2029.

Other organisations, including Becker Technologies and PSI, noted the potential for adapting existing facilities to study a wide range of non-water-cooled reactor concepts. Interest was expressed in using these facilities to investigate several topics, such as loss of coolant accident (LOCA) and air/steam ingress scenarios, dust transport and capture in HTGR containment, fission product behaviour and retention in molten salt reactors, and hydrogen/dust transport in fusion systems.

To better address these needs, it would be beneficial to develop a collective approach for identifying and prioritising critical research infrastructure requirements.

In addition to opportunities for experimental programmes, several organisations have expressed interest in co-ordinating an international standard problem (ISP) or a benchmark exercise, drawing on data generated from testing across various facilities, including domestic research initiatives. Notably, selected results from tests conducted at KAERI's SMART-ITL facility — developed for the SMART reactor design — could be made available for use in an international benchmarking effort.

## 5.4. Key trends in research collaboration frameworks

Clustering experimental facilities with similar capabilities can significantly enhance co-ordination, optimise resources, and enable more efficient planning. For instance, key containment performance and thermal-hydraulics facilities include ATLAS-CUBE (KAERI), THAI+ (Becker Technologies), PANDA (PSI), CIGMA (JAEA), MISTRA (CEA), TOSCAN (ASNR), etc. The diversity of available facilities presents strong opportunities for scaling analyses and complementary testing across different platforms. Given the varying sizes and capabilities of these facilities, collaborative efforts can:

- support scaling analysis through co-ordinated testing programmes;
- reduce uncertainties in large-scale reactor behaviour via targeted experiments; and
- address safety concerns more effectively through integrated, multi-facility validation initiatives.

To ensure the long-term sustainability of research capabilities in thermal-hydraulics and severe accident analysis, a more integrated and strategic approach is needed—one that links experimental platforms across multiple facilities and operating organisations. The NEA could play a pivotal role in shaping such collaborative frameworks, which would bring together a broad range of stakeholders including designers, vendors, utilities, regulators, technical support organisations (TSOs), research institutions, and academia. These frameworks would help identify key safety research gaps and required infrastructure, enabling co-funded projects that reflect shared stakeholders' priorities. They would also strengthen safety analysis methodologies, promote knowledge transfer and training, and ensure the long-term preservation of valuable research data.

However, challenges remain, particularly in expanding current capabilities beyond water-cooled systems. Advanced reactor designs require new experimental setups. A phased development strategy is recommended, starting with small-scale bench experiments and progressing to medium- and large-scale facilities as needed. Large prototype or demonstration units, such as JAEA's HTTR for high-temperature gas reactors (HTGRs), could be leveraged for integral testing.

While commercially developed facilities for advanced reactors are beginning to emerge, integrating them into NEA-supported projects continues to pose co-ordination challenges.

## 5.5. Stakeholder engagement to support research capabilities

To sustain and expand key experimental research capabilities, stronger collaboration among vendors, operators, regulators, and R&D organisations is essential. Strategic focus should be placed on the following priorities:

- Activating regulators and industry participation: engaging regulators and industry leaders is vital to align international research with real-world needs and accelerate progress.
- Targeting key research gaps: prioritising the most pressing safety and technology gaps ensures that limited resources are allocated effectively.
- Leveraging workshops and integrated research frameworks for strategic alignment: workshops and inclusive research frameworks are essential platforms for identifying priorities, fostering stakeholder dialogue, and shaping collaborative agendas.

Building more integrated and inclusive frameworks will be key to expanding stakeholder engagement and broadening the funding base. Such frameworks not only provide stable, long-term support for essential facilities but also help anticipate and respond to emerging challenges in nuclear safety and technology development. Moreover, structured tools such as phenomena identification and ranking tables (PIRTs) and stakeholder surveys, conducted within these frameworks, should play a vital role in prioritising research needs. These mechanisms would ensure active stakeholder input and foster stronger commitment to shared research agendas.

Continued experimental research must be recognised as indispensable for vendors and operators, particularly for the licensing and validation of advanced reactor designs,

including SMRs. Without sustained investment in testing infrastructure, innovation and deployment timelines for next-generation nuclear systems may face significant delays.

## 5.6. Key findings and recommendations

- A number of world-class thermal-hydraulics and severe accident test facilities exist to support safety research for WCRs.
- There is growing momentum in SMR and passive system testing, reflecting the shift toward advanced reactor designs.
- Several existing facilities could be adapted to support testing for next-generation technologies.
- Building more integrated and inclusive frameworks will be key to expanding stakeholder engagement and broadening the funding base.
- Joint research projects clustering experimental facilities with similar capabilities enable shared use of infrastructure and expertise.
- These collaborative efforts help address scaling challenges and promote complementary testing across facilities, enhancing the overall effectiveness of experimental programmes.
- Synergies with initiatives like the IAEA NEXSHARE, the EC OFFER and EC SEAKNOT provide valuable pathways for integrating and optimising research infrastructures.

The expansion and integration of experimental capabilities are essential for advancing nuclear safety research. Sustained collaboration, reliable funding mechanisms, and active international engagement will be key to developing robust accident management strategies for both current and future reactor technologies.

# 6. Session 3 - Panel discussion on research insights, capabilities, and future frameworks

Session 3 was chaired by the general workshop Chair, Toyoshi Fuketa (NDF, Japan). Session 3 featured a high-level panel discussion focused on:

- lessons from the Fukushima Daiichi accident: insights, knowledge dissemination, and code development needs;
- key research capabilities: preparing for future challenges;
- research frameworks and stakeholder involvement.

Panellists: Shinya Mizokami (TEPCO), Myriam Claeys (EDF), Matthew Nudi (EPRI), Jean-Christophe Niel (IRSN (now ASNR)), Thambiayah Nitheanandan (Canadian Nuclear Safety Commission (CNSC)), Hossein Esmaili (United States NRC), Tomi Routamo (STUK), Won-Pil Baek (KAERI).

## 6.1. Key discussion points

### *Insights from the Fukushima Daiichi accident and knowledge dissemination*

Implemented actions:

- Post-accident analyses have significantly strengthened accident management strategies and informed D&D practices.
- Enhanced training protocols, including revised training and drills, along with deployment of additional on-site and mobile emergency equipment, have improved operational preparedness for unforeseen events.

Remaining knowledge gaps and future needs:

- Despite progress, industry-wide adoption of improved accident analysis codes has been limited and remains a challenge.
- Continued validation and refinement of existing severe accident models, especially for bounding and best-estimate scenarios, is necessary.
- Reactor pressure vessel failure models should be improved to increase the accuracy of predictions regarding both the mode and timing of failure.
- Additional testing on molten core-concrete interaction (MCCI) is needed, focusing on:
  - corium composition and thermophysical properties;
  - effect of high-metallic debris content;
  - impacts on structural integrity and containment performance.
- Ongoing monitoring of Fukushima Daiichi accident findings is essential to anticipate future challenges in severe accident management.
- Greater deployment of advanced instrumentation and monitoring should be pursued for both current and next-generation reactors.

### *Future research priorities & capabilities*

A forward-looking research roadmap should be developed to:

- prioritise research based on evolving nuclear safety needs;
- incorporate stakeholder input through mechanisms such as surveys and PIRTs;
- define needed experiments on passive safety systems and advanced non-LWRs;
- reinforce experimental infrastructure to deliver high-quality data for advanced code validation;
- address persistent knowledge gaps in severe accident behaviour and source term characterisation;
- advance understanding of ex-vessel melt behaviour (MCCI), debris stabilisation, and containment system performance;
- support continuous enhancement of safety analysis codes, ensuring responsiveness to newly identified limitations.

### *Research frameworks and stakeholder engagement*

To ensure long-term success in nuclear safety research, a robust international research framework should:

- engage a wide array of stakeholders including regulators, vendors, operators, research laboratories, universities;
- use structured tools such as PIRTs and stakeholder consultations to align priorities with industry and regulatory needs;
- emphasise short-term applicability and measurable impact to drive industry participation;
- attract vendors, plant operators, and the next generation of nuclear professionals.

Increase visibility of NEA-supported research by highlighting:

- cost-sharing benefits for participants;
- training and mentorship programmes for early-career researchers;
- access to cutting-edge facilities and global expertise.

## 6.2. Key takeaways and proposed directions

- Sustained international collaboration is crucial to integrate lessons learnt from the Fukushima Daiichi accident and advance safety for both current and next-generation reactors.
- Launch new collaborative projects targeting key knowledge gaps in:
  - passive safety systems performance;
  - source term behaviour and implications for emergency planning zones;
  - material behaviour in advanced non-LWR designs.
- Improve co-ordination of thermal-hydraulics and severe accident research to optimise use of new and existing experimental infrastructure.

- Establish a strategic, long-term research roadmap that balances diverse stakeholder priorities while securing stable funding and engagement.
- Continue developing and upgrading state-of-the-art thermal-hydraulics and severe accident analysis codes to support licensing and operation of both conventional and advanced reactor designs.
- Develop a comprehensive understanding of the risks associated with implementing emerging technologies — such as AI, advanced manufacturing, and digital tools — that hold significant transformative potential for enhancing nuclear safety, efficiency, and performance. Equally important is the establishment of robust, interoperable data ecosystems to support advanced analytical methods and ensure reliable, data-driven decision-making approaches.

# 7. Conclusion and strategic path forward

The key findings of the FRAME workshop, both regarding nuclear safety research needs and the development of research collaboration frameworks, will be central to shaping the NEA Strategic Nuclear Reactor Safety Research Roadmap, currently in development.

Building on these insights, the NEA will lead efforts to establish broad, inclusive, and forward-looking collaborative research frameworks in the areas of thermal-hydraulics and severe accidents. These frameworks will be designed to address both immediate accident management needs and long-term safety objectives for operating reactors and emerging advanced designs.

To ensure meaningful progress, the NEA will pursue the following actions:

- Foster cross-sector collaboration by engaging a wide range of stakeholders, including industry (operators, vendors), regulators, R&D institutions, and academia, in the co-development of high-priority research initiatives.
- Align funding and research efforts by supporting the creation of co-funded projects that target shared safety challenges and optimise the use of complementary research infrastructure.
- Strengthen stakeholder participation in developing future research capabilities and safety projects, particularly those supporting the safe and timely deployment of innovative technologies, including SMRs and non-water-cooled reactors.

In doing so, the NEA will help ensure that the global nuclear community remains equipped to address evolving safety challenges, preserve key expertise and infrastructure, and maintain public confidence in the safety of nuclear energy.

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# Appendix 1: Programme

## *Day 1 – Thursday, 26 September 2024*

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|---|---|
| **08:30-08:50** | **Welcoming address**<br>**Paul KEARNS, Argonne National Laboratory Director**<br>**Véronique ROUYER, Nuclear Energy Agency, Head of the Nuclear Safety Technology and Regulation Division** |

### Session 1: Safety knowledge gaps and emerging issues for accident management in reactors, Fukushima Daiichi's insights

**Chairs: Didier JACQUEMAIN (NEA), Joy REMPE (REMPE and Associates, LLC)**

**08:50-09:25** ► **How we failed and what we now expect from research**

**Toyoshi FUKETA**, Senior Technical Adviser, Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), Senior Researcher, University of Tokyo, Japan

**09:25-10:00** ► **Fukushima Daiichi insights**

**Shinya MIZOKAMI**, Research Director, Fukushima Daiichi Accident Specialist, TEPCO, Japan

**10:00-10:25** **Morning Break**

► **Regulator views**

**10:25-11:00** **Marissa G. BAILEY**, Deputy Director of the Office of Nuclear Regulatory Research, United States NRC

**11:00-11:35** **Tomi ROUTAMO**, Deputy Director for New Nuclear Power Plant Regulation, Radiation and Nuclear Safety Authority (STUK), Finland

► **Industry views**

**11:35-12:10** **Randy BUNT**, Manager of Severe Accident Management, Southern Nuclear, Boiling Water Reactors Owner's Group (BWROG), United States

**12:10-13:30** **Lunch**

**13:30-14:05** **Myriam CLAEYS**, Deputy Director of the Design and Technology Branch of Nuclear Engineering and Supply Chain Directorate, Électricité de France S.A. (EdF), France

► **Technical Support Organisation and Research Laboratory views**

**14-05-14:40** **Jean-Christophe NIEL**, Director-General, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France

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|---|---|
| **14-40-15:15** | **Robert HILL**, Programme Manager, Advanced Nuclear Energy Research and Development, Argonne National Laboratory (ANL), Generation IV International Forum Technical Director, United States |

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| **15:15-15:40** | **Afternoon Break** |

## Session 2: Collaborative research programmes, capabilities and future potential

**Chairs: Andrew MORREALE (CNL), Terttaliisa LIND (PSI)**

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|---|---|
| **15-40-16:10** | **Kyoung-Ho KANG**, Korea Atomic Energy Research Institute (KAERI), Korea |
| **16:10-16:40** | **Vesa RIIKONEN**, Lappeenranta-Lahti University of Technology (LUT University), Finland |
| **16:40-17:10** | **Sanjeev GUPTA**, Becker Technologies, Germany |
| **17:10-17:40** | **Domenico PALADINO**, Paul Scherrer Institute (PSI), Switzerland |

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| **17:40** | **End of Day 1** |

## *Day 2 – Friday, 27 September 2024*

## Session 2 (continued): Collaborative research programmes, capabilities and future potential

**Chairs: Andrew MORREALE (CNL), Terttaliisa LIND (PSI)**

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|---|---|
| **8:30** | **Opening** |
| **8:30-9:00** | **Steve BAJOREK**, United States Nuclear Regulatory Commission, United States |
| **9:00-09:30** | **Martin STEINBRÜCK**, Karlsruhe Institute of Technology (KIT), Germany |
| **09:30-10:00** | **Jeremy LICHT**, Argonne National Laboratory (ANL), United States |
| **10:00-10:20** | **Morning Break** |

**Chairs: Mitch FARMER (ANL), Shinya MIZOKAMI (TEPCO)**

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|---|---|
| **10:20-10:50** | **Christophe JOURNEAU**, Commissariat à l'Energie Atomique et aux Énergies Alternatives (CEA), France |
| **10:50-11:20** | **Marc BARRACHIN**, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France |
| **11:20-11:50** | **Satoshi ABE and Yu MARUYAMA**, Japan Atomic Energy Agency (JAEA), Japan |
| **11:50-13:00** | **Lunch** |

**Chairs: Mitch FARMER (ANL), Shinya MIZOKAMI (TEPCO)**

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|---|---|
| **13:00-13:30** | **Andrew MORREALE**, CNL, Canada |
| **13:30-14:00** | **Eve-Lyne PELLETIER**, International Atomic Energy Agency (IAEA), International Organisation |
| **14:00-15:30** | **Panel Discussion** |

**Chair and Moderator: Toyoshi FUKETA (NDF, University of Tokyo)**

**Panellists:**
**Shinya MIZOKAMI (TEPCO)**

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|---|---|
| | **Myriam CLAEYS (EdF)**<br>**Matthew NUDI (EPRI), Senior Technical Leader, Risk & Safety Management**<br>**Jean-Christophe NIEL (IRSN)**<br>**Thambiayah NITHEANANDAN (CNSC), Director, Reactor Behaviour Division**<br>**Hossein ESMAILI (United States NRC), Chief of Fuel and Source Term Code Development Branch, Office of Nuclear Regulatory Research**<br>**Tomi ROUTAMO (STUK)**<br>**Won-Pil BAEK (KAERI), Senior Researcher and President of the Korean Nuclear Society**<br><br>**Topics**<br>- **Insights from Fukushima Daiichi, dissemination, and meeting code data needs**<br>- **Key research capabilities to prepare for the future**<br>- **Research frameworks and stakeholder's involvement** |
| **15:30-15:50** | **Afternoon Break** |
| **15:50-16:10** | **Concluding Session**<br><br>**Summary of workshop sessions by Session Chairs**<br>**General chair final message, Toyoshi FUKETA, (NDF, University of Tokyo)** |
| **16:10** | **End of Day 2** |

# Appendix 2: List of completed, ongoing and planned NEA projects in the thermal-hydraulic and severe accident domains

## Circuit, containment and spent fuel pools thermal-hydraulics projects

| Project name | Subject | Host country | Status mandate |
|---|---|---|---|
| LOFT | LOCA integral tests | United States | Completed 1983-1989 |
| SETH | LOCA, boron dilution, shutdown state tests | Germany | Completed 2001-2006 |
| PSB-VVER | LOCA in VVER, natural circulation, scaling tests | Russia | Completed 2003-2008 |
| ROSA<br>ROSA-2 | LOCA, SGTR, natural circulation, 1-ϕ and 2-ϕ flows, mixing, stratification, complex flows, scaling (ROSA/PKL) | Japan | Completed 2005-2009<br>2009-2012 |
| PKL<br>PKL-2<br>PKL-3<br>PKL-4 | LOCA including DEC, cool down and late SAM procedures, boron dilution and precipitation, shutdown states, MSLB, MSGTR, scaling (ATLAS/PKL/ROSA) | Germany<br>Hungary<br>Finland | Completed 2004-2007<br>2008-2011<br>2012-2016<br>2016-2020 |
| ETHARINUS | LOCA including DEC, passive systems, cool down and late SAM procedures, cooling with core blockage, MSGTR, scaling | Germany<br>Finland | Completed 2021-2024 |
| ***SYSTHER*** | ***PKL: LOCA including DEC, parametric studies from last 15 tests performed before the facility's shutdown***<br>***PWR-PACTEL: SB-LOCA, natural circulation***<br>***MOTEL: SB-LOCA, cooldown procedures, referencing NuScale design***<br>***PASI: Passive Containment Cooling System***<br>***MISTRA: SMR-related containment passive system and pressurisation scenarios*** | ***Germany<br>Finland<br>France*** | ***Planned 2025-2028*** |
| ATLAS<br>ATLAS-2 | LOCA including DEC, SGTR, natural circulation, 1-ϕ and 2-ϕ flows, mixing, stratification, complex flows, scaling | Korea | Completed 2014-2017<br>2017-2020 |
| ATLAS-3 | LOCA including DEC, integral tests with RCS/containment interactions, natural circulation, passive systems, scaling | Korea | 2021-2024 |
| **ATLAS-4** | **Integral tests with RCS/containment coupling, DEC scenarios, natural circulation, passive safety systems, scaling resolution, with focus on SMRs** | **Korea** | **Ongoing 2025-2028** |
| RBHT | High-quality data for core reflooding models, uncertainty analysis | United States | Completed 2019-2022 |
| **RBHT-2** | **High-quality data for core reflooding models, uncertainty analysis, very low and variable inlet flows** | **United States** | **Ongoing 2023-2026** |

| **Project name** | **Subject** | **Host country** | **Status mandate** |
|---|---|---|---|
| BUBCON | VVER bubbler condenser, containment pressure suppression system | Russia | Completed 2001-2002 |
| SETH | Gas stratification and mixing in containment (in relation to $H_2$ combustion) | Switzerland | Completed 2001-2006 |
| SETH-2<br>HYMERES | Gas stratification and mixing in containment, effects of safety systems (sprays, coolers, $H_2$ recombiners, rupture discs), scaling (PANDA/MISTRA), high-quality data for CFD modelling | Switzerland<br>France | Completed 2007-2010<br>2013-2016 |
| HYMERES-2 | Effect of internal structures on flows, effects of combination of safety systems, BWR pressure suppression pools | Switzerland | Completed 2017-2020 |
| **PANDA** | **Effect of internal structures on flows, BWR pressure suppression pools, SMRs systems** | **Switzerland** | **Ongoing 2021-2025** |
| ***PANDA-2*** | ***Effect of containment internal structures on flows, heat radiation, spray system activation, BWR pressure suppression pools, PWR IRWST, SMRs systems*** | ***Switzerland*** | ***Planned 2026-2029*** |
| THAI<br>THAI-2<br>THAI-3 | $H_2$ mixing including effects of spray systems, $H_2$ recombiners performance, $H_2$ combustion | Germany | Completed<br>2007-2009<br>2011-2014<br>2016-2019 |
| THEMIS | Recombiners performance and combustion in late phases of a severe accident ($H_2$/CO mixes) | Germany | Completed 2020-2024 |
| ***THEMIS-2*** | ***SMR-related heat transfer in water pools, stratification, hydrogen combustion, iodine remobilisation, and Passive Autocatalytic Recombiner (PAR) performance in obstructed containments.*** | ***Germany*** | ***Planned 2025-2028*** |
| **POLCA** | **Thermal-hydraulics of spent fuel pools during situations of loss of cooling** | **France** | **Ongoing 2024-2028** |

## Severe accident projects

### *Accident progression and melt coolability in-vessel and ex-vessel*

| Project name | Subject | Host country | Status mandate |
|---|---|---|---|
| RASPLAV | In-vessel melt coolability with and without external cooling, melt chemical composition effects on stratification and thermal loads on RPV | Russia | Completed 1994-2000 |
| OLHF | RPV deformation and failure, mechanical analysis | United States | Completed 1998-2002 |
| MASCA<br>MASCA-2 | In-vessel melt coolability, melt chemical composition effects on stratification and thermal loads on RPV, fission products partitioning, scaling to reactor applications | Russia | Completed 2000-2003<br>2003-2007 |
| SERENA | Molten fuel coolant interaction, steam explosion, scaling to reactor applications | France<br>Korea | Completed 2007-2012 |
| MCCI<br>MCCI-2 | Ex-vessel melt coolability and long-term containment basemat concrete erosion by melt, scaling to reactor applications | United States | Completed 2002-2005<br>2006-2010 |
| ROSAU | Ex-vessel melt coolability by top flooding and underwater spreading, scaling to reactor applications | United States | Completed 2019-2024 |
| ***ROSAU-2*** | ***Melt/debris coolability in-vessel and ex-vessel, melt spreading ex-vessel, effect of high metal content and ATFs-based melt and debris*** | ***United States*** | ***Planned 2025-2029*** |
| **COPS** | **Corium thermophysical properties for coolability analyses** | **France** | **Ongoing 2024-2029** |
| **QUENCH-ATF** | **DBA and BDBA rod bundle tests with Cr-coated Zircaloy claddings** | **Germany** | **Ongoing 2021-2026** |

### *Source term-related projects*

| Project name | Subject | Host country | Status mandate |
|---|---|---|---|
| LOFT | Gap fission product (FP) release in LOCA, FP release in severe accident | United States | Completed 1983-1989 |
| BIP<br>BIP-2<br>BIP-3 | Iodine (I) source term in containment<br>I chemistry in sumps and in gas phase incl. effects of contaminants Interactions with surfaces<br>Organic iodides (RI) formation) | Canada | Completed 2007-2011<br>2011-2014<br>2016-2018 |
| THAI<br>THAI-2<br>THAI-3 | PARs poisoning and iodine formation by aerosols interacting with PARs<br>Wash down of soluble aerosols<br>I reaction with aerosols<br>FP re-entrainment from boiling pools<br>FP resuspension by $H_2$ deflagration | Germany | Completed 2007-2009<br>2011-2014<br>2016-2019 |
| THEMIS | Interaction of IOx with aerosols<br>FP retention by pool scrubbing<br>Aerosol interactions with PARs | Germany | Completed 2020-2024 |
| ***THEMIS-2*** | ***SMR-related heat transfer in water pools, stratification, hydrogen combustion, iodine remobilisation, and Passive Autocatalytic Recombiner (PAR) performance in obstructed containments.*** | ***Germany*** | ***Planned 2025-2028*** |
| STEM<br>STEM-2 | I and ruthenium (Ru) source terms (Ru transport in RCS, irradiation of iodine-bearing aerosols, $IO_x$ formation, I interaction with aged paints and RI formation) | France | Completed 2011-2015<br>2016-2019 |
| ESTER | Fission product (Cs, I, Mo, Te) remobilisation from deposits (differed releases)<br>RI formation | France | Completed 2020-2025 |
| ***FORESEEN*** | ***Release and transport of fission products from ATFs*** | ***France<br>United States*** | ***Planned 2025-2029*** |

### *Major accidents projects (TMI-2, Fukushima Daiichi)*

| Project name | Subject | Host country | Status mandate |
|---|---|---|---|
| TMI-VIP | TMI-2 accident analysis with a focus on RPV integrity, analysis of material from RPV lower head | United States | Completed 1988-1993 |
| BSAF | Fukushima Daiichi accident analyses with a focus on thermal-hydraulic response of RPV and PCV over six days | Japan | Completed 2012-2015 |
| BSAF-2 | Fukushima Daiichi accident analyses extended to three weeks and including radioactive release | Japan | Completed 2016-2018 |
| PreADES | Preparatory studies for fuel debris retrieval in damaged units at Fukushima Daiichi | Japan | Completed 2017-2021 |
| ARC-F | Compilation and analysis of data and information from damaged units at Fukushima Daiichi<br>Accident analyses with a focus on in-vessel and ex-vessel accident development, hydrogen explosion events and radioactive release | Japan | Completed 2019-2022 |
| **FACE** | **Continue supporting preparation of fuel debris retrieval from damaged units at Fukushima Daiichi**<br>**Refine accident analyses with a focus on effects of accident measures** | **Japan** | **Ongoing 2022-2026** |
| TCOFF | Enhancement of thermodynamic databases for Fukushima Daiichi accident analysis | Japan | Completed 2017-2020 |
| **TCOFF-2** | **Enhancement of thermodynamic databases for severe accident analysis including for ATF material** | **Japan** | **Ongoing 2022-2025** |