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CSNI Technical Opinion Paper No. 21

Research Recommendations to Support the Safe Deployment of Small Modular Reactors

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Nuclear Safety

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Foreword

There is growing interest worldwide in nuclear energy, including in small, modular systems that can generate energy efficiently and reliably while minimising the impact on the climate. In order to support the safe deployment of these technologies, the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) convened the Expert Group on Small Modular Reactors (EGSMR). The EGSMR's mandate is to evaluate the needs of NEA member countries for SMR safety research. The group is tasked with recommending CSNI actions that can help countries address the identified knowledge gaps and safety challenges.

The EGSMR assessment of the needs of NEA member countries identified four major areas of interest related to SMR safety: 1) regulatory harmonisation, 2) cross-cutting safety issues, 3) experimental campaigns, and 4) benchmarking for computer code validation and verification. Several actions were suggested for the CSNI to investigate the technical knowledge gaps identified in these areas as well as in new research areas that warrant further study. The actions were prioritised based on their safety significance and relevance to the CSNI mandate and on whether they can be addressed through CSNI working/expert group efforts, task force initiatives, activity proposals and joint projects.

The EGSMR suggested actions to co-ordinate efforts by the CSNI and other NEA committees and international organisations pursuing similar initiatives related to SMRs. These efforts support and develop the scientific and technical knowledge base needed for the sound safety demonstration of SMRs, thereby helping to pave the way for the deployment of SMRs as a promising source of clean energy that is much needed to meet the net zero CO_2 emissions targets.

This report was approved by the CSNI at its 73rd meeting on 6 June 2023 and prepared for publication by the NEA Secretariat.

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List of abbreviations and acronyms

AECL	Atomic Energy of Canada Limited
ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator
ANVS	Autoriteit Nucleaire Veiligheid en Stralingsbescherming (Netherlands)
AOI	Area of interest
ATR	Advanced Test Reactor
AT-SMR	Advanced Technology Small Modular Reactor
BWR	Boiling water reactor
CAPS	CSNI Activity Proposal Sheet
CEA	French Alternative Energies and Atomic Energy Commission
CFD	Computational fluid dynamics
CHF	Critical Heat Flux
CIEMAT	Centro de Investigaciones Energeticas Medioambientales y Tecnologicas (Spain)
CNL	Canadian Nuclear Laboratories
CNRA	Committee on Nuclear Regulatory Activities (NEA)
CNSC	Canadian Nuclear Safety Commission
CORDEL	Cooperation in reactor Design Evaluation and Licensing (WNA)
CRP	Co-ordinated research project
CRPPH	Committee on Radiological Protection and Public Health (NEA)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
DiD	Defence in depth
EGSMR	Expert Group on Small Modular Reactors (NEA)
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
EPZ	Emergency planning zone
ETSON	European Technical Safety Organisations Network
FOAK	First-of-a-kind
GIF	Generation IV International Forum
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HTGR	High-temperature gas-cooled reactors
HTO	Human Technology Organisation
HTTF	High-temperature test facility
HTTR	High-temperature engineering test reactor
IAEA	International Atomic Energy Agency
IKE	Institut für Kernenergetik und Energiesysteme (Germany)
IRSN	Institut de Radioprotection et de Sureté Nucléaire (France)
JAEA	Japan Atomic Energy Agency

KAERI	Korea Atomic Energy Research Institute
KIT	Karlsruhe Institute of Technology (Germany)
LFR	Lead fast reactor
LOCA	Loss-of-coolant accident
LOFC	Loss of forced cooling
LW	Light water
LWR	Light water reactor
LW-SMR	Light water small modular reactor
MASLWR	Multi-application small light water reactor
MMR	Micro Modular Reactor
MSR	Molten salt reactor
MWe	Megawatt electric
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
NEA	Nuclear Energy Agency
NHSI	Nuclear Harmonization and Standardization Initiative (IAEA)
NIST	NuScale Integral System Test
PIRT	Phenomena Identification and Ranking Table
PSA	Probabilistic safety analysis
PSI	Paul Scherrer Institute (Switzerland)
PWR	Pressurised water reactor
RCS	Reactor coolant system
RSWG	Risk and Safety Working Group (Generation IV International Forum)
SCWR	Supercritical water reactor
SDA	Standard design approval
SEGPD	Senior Expert Group on Preservation of Key Experimental Datasets (NEA)
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SSM	Swedish Radiation Safety Authority
THYR	Thorium and Hybrid Reactor
TRL	Technological readiness level
TSO	Technical safety organisation
USNRC	United States Nuclear Regulatory Commission
V&V	Validation and verification
WC-SMR	Water-cooled small modular reactor
WGAMA	Working Group on Analysis and Management of Accidents (NEA)
WGEV	Working Group on External Events (NEA)
WGFCS	Working Group on Fuel Cycle Safety (NEA)
WGFS	Working Group on Fuel Safety (NEA)
WGHOF	Working Group on Human and Organisational Factors (NEA)
WGNT	Working Group on New Technologies (NEA)
WGPL	Working Group on Policy and Licensing (NEA)
WGRISK	Working Group on Risk Assessment (NEA)
WNA	World Nuclear Association

Executive summary

The NEA Committee on the Safety of Nuclear Installations (CSNI) convened an Expert Group on Small Modular Reactors (EGSMR) to help evaluate the safety impacts of small modular reactors (SMRs). A growing number of NEA member countries are investigating the potential deployment of SMRs to efficiently and reliably increase energy generation while minimising the impacts on the climate. A range of technologies are employed in SMR designs with a variety of coolants (water-cooled and non-water-cooled) and reactor sizes. SMRs are envisaged for multiple applications (electricity, hydrogen production, process heat, etc.) and locations (grid-scale generation, remote operations, floating power stations, mining/industrial operations). They also utilise a modular design, which should grant efficient construction through serial production of multiple identical units. Therefore, SMRs require supporting research and new safety evaluations.

The EGSMR is comprised of CSNI participants (23 organisations from 15 countries) with an interest in SMRs along with international bodies (the International Atomic Energy Agency [IAEA], and the European Commission [Euratom]). It is mandated firstly to evaluate NEA member needs for SMR safety research and assessments, and secondly to recommend CSNI efforts to be conducted to address them. The EGSMR co-ordinates with other NEA committees (e.g. the Committee on Nuclear Regulatory Activities [CNRA]; and the Committee on Nuclear Science [NSC]) and with international organisations pursuing similar efforts related to SMRs in order to promote co-operation, complement efforts and avoid duplication. In this way, the CSNI ensures that it can properly support understanding of SMR safety to assist with their deployment.

A survey of EGSMR participants identified interest in both evolutionary water-cooled SMRs (WC-SMRs) and innovative advanced technology SMRs (AT-SMRs; i.e. Generation IV). Given the high technological readiness level (TRL) and close deployment horizon of WC-SMRs, nearly all respondents are interested in this technology, which can be well supported considering extensive CSNI experience in large water-cooled reactor safety. There is also interest in AT-SMRs due to their unique features (e.g. high-temperature process heat, fast neutron spectra, and fuel cycle impacts), specifically high-temperature gas-cooled reactors (HTGRs). Sodium/lead fast reactors and molten salt designs are of interest, though with a slightly longer deployment horizon. Micro-reactors (< 10 MWe) and their potential applications are also drawing attention. The survey also highlighted the desire for international collaboration and consideration of the knowledge base needed to support new designs, as well as the importance of a graded approach.

The EGSMR has identified four major areas of interest (AOIs), and provides suggested actions (“a”), to address them:

1. Regulatory harmonisation
   a. While regulatory issues are primarily handled by the CNRA, the CSNI can provide technical support for the regulatory safety assessments of SMRs. Thus, the CSNI needs to maintain awareness of regulatory efforts underway, and be ready to respond to requests for assistance from partners and other international organisations.
2. Cross-cutting safety issues
   – application of defence in depth (DiD) levels when passive safety is applied at multiple levels;
   – probabilistic safety analysis (PSA) for innovative/first-of-a-kind designs;
   – emergency planning zones (EPZ) and emergency response requirements for SMRs;
   – fuel safety of SMRs (both WC-SMR and AT-SMR);

- human factors (including remote operations and multi-unit/multi-module plants);
- multi-unit/multi-module design aspects and impacts on safety;
- transport of pre-fuelled/spent nuclear modules and transportable/floating SMRs;
- associated process applications: H_2 production, process heat (e.g. chemical, mining, district heating).

   a. The eight prioritised cross-cutting issues above should each be reviewed by a relevant CSNI working/expert group to assess the issue, understand the work underway, and identify gaps and research needs. The output of this effort should be a status report for the CSNI.

3. Experimental campaigns

   a. Experiments form the basis of evidence to demonstrate safety, and it is therefore suggested that support be provided to the determination of knowledge gaps, the leveraging of existing experimental data, the identification of existing facilities, and the recommendation of new experiments.

4. Benchmarking for code validation and verification (V&V)

   a. Qualified modelling/analysis tools are an essential part of modern safety assessments, which can be facilitated with the following activities: Developing V&V guidance, extending validation matrices to include SMR safety, encouraging benchmarking activities, and capturing modelling best practices.

Overall, the suggested key, short-term actions prioritised based on safety significance and relevance to the CSNI mandate are:

1. Gathering SMR phenomena identification and ranking tables (PIRTs) to identify SMR safety phenomena and prioritise future efforts.
2. Starting work on the high-priority cross-cutting issues (identified above).
3. Reviewing and updating the CSNI code validation matrix for SMR safety, and producing a guidance report on V&V needs for code qualification.
4. Collecting and generating data through joint research projects to support SMR safety.

The EGSMR identified new research areas that warrant further study, including the impact of "external" events from associated processes connected to SMRs, and materials concerns for AT-SMRs. The EGSMR has also conducted information collection efforts focused on SMR safety, including data on experimental facilities, national and multi-national projects, and PIRTs.

The suggested actions and the areas for further study can be addressed through a combination of efforts by relevant CSNI working/expert groups, and co-ordination with other NEA committees and external organisations. Activities should be initiated within the relevant groups to address the actions and produce the desired outcomes. These include internal working/expert group efforts, co-ordinated task force initiatives between multiple groups (with a suitable leading group), CAPS (CSNI Activity Proposal Sheets) or NEA joint projects. While regulatory issues are primarily handled by the CNRA, the EGSMR concluded that in many cases the CSNI could provide technical support to regulatory licensing activities.

Following the CSNI request to assist in co-ordinating efforts in the area of SMR safety, the EGSMR will consider revising and expanding its mandate in order to ensure that future activities of the group are captured in a way that is consistent with CSNI expectations, and propose a draft mandate for approval to the CSNI. The EGSMR could provide support to the other CSNI working/expert groups to initiate and organise activities through the assignment of EGSMR participants as "action champions", providing background information and additional resources during the start-up of activities.

A forum for exchange will be proposed (e.g. a periodic “SMR Safety Review” event) to track progress and disseminate results of internal CSNI efforts on SMR safety, and to connect with related external efforts by other international organisations. This can help to align common pursuits, promote co-operation and avoid redundancy.

Through the efforts listed and discussed herein, the CSNI will be able to properly support and advance the scientific and technical knowledge base for the safe deployment of SMRs.

Chapter 1. Introduction and background

The NEA Committee on the Safety of Nuclear Installations (CSNI) is responsible for NEA programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations. Recently, there has been increased interest among several NEA member countries in small modular reactors (SMRs), which are being investigated for potential deployment to address challenges related to climate change and the increased electrification of infrastructure and transportation. These SMRs are typically smaller than large power reactors, with a modular design and the potential to realise the economies of serial production. They also include a wide variety of technologies, with both water-cooled and advanced (i.e. non-water-cooled) options. SMR designs are being proposed for differing roles (grid-scale, remote operations, floating power stations, and mining/industrial process operations) and power levels (generally < 300 MWe). Many of these SMR designs are quite different from currently operating reactors and require new safety evaluations for both classical reactor issues and potential new issues that may arise out of these designs.

Considering this move towards SMR deployment, the CSNI organised an Expert Group on Small Modular Reactors (EGSMR) with the mandate to assess potential CSNI activities in the area of SMR safety. The focus is on technologies close to deployment and activities relevant to CSNI capabilities and experience. The EGSMR is charged with formulating an approach to identify recommended activities/actions to be conducted/taken and determining any new technical areas where the CSNI should develop expertise, including:

- identifying important issues and phenomena;
- identifying and understanding knowledge gaps;
- determining how CSNI activities can best be used to fill those gaps.

The EGSMR also supports information exchange between participating organisations and countries on related SMR safety activities. Several international organisations, including the International Atomic Energy Agency (IAEA), the Generation IV International Forum (GIF) and the European Commission Euratom (European Atomic Energy Community), are also conducting work in the area of SMR safety. The EGSMR, therefore, aims to co-ordinate with these international organisations and, as appropriate, to make the activities complementary.

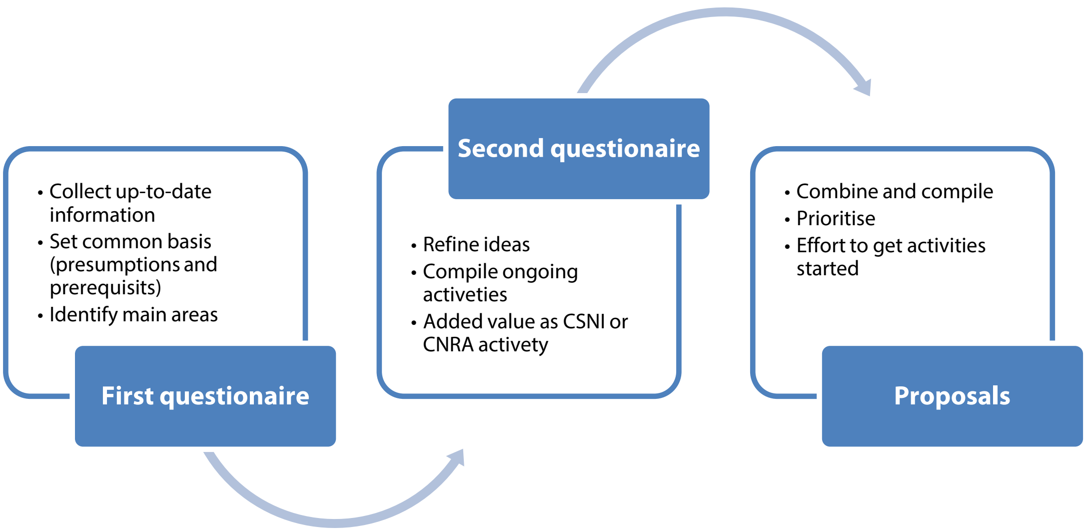
The EGSMR is comprised of representatives from 15 NEA countries (Belgium, Canada, the Czech Republic, France, Germany, Italy, Japan, Korea, the Netherlands, Norway, Spain, Sweden, Switzerland, Türkiye and the United States) along with international bodies (IAEA and Euratom) with an interest in SMRs, and involves 23 organisations, including nuclear regulators, research institutes and national laboratories, technical safety organisations (TSOs), and utilities. A list of the EGSMR organisations and participants is provided in the "Acknowledgements" section of this report.

Chapter 2. EGSMR assessment process

The NEA Expert Group on Small Modular Reactors (EGSMR) executed its assigned mandate through a process of collecting and evaluating information and generating recommendations. The information collection effort was in the form of questionnaires, which utilised the diversity of the EGSMR participants and allowed the identification of issues relevant to NEA members. The participants of the EGSMR also overlap with those of the NEA Committee on the Safety of Nuclear Installations (CSNI) and its constituent working groups, allowing for input on the relevance of the generated information to CSNI capabilities and interests.

The process, illustrated in Figure 2.1, collected information to determine the areas of interest (AOIs) in SMR safety, which were then refined in a subsequent process that sought to propose actions that the CSNI could take to address the AOIs.

Figure 2.1. **EGSMR assessment process**



The first questionnaire gathered a variety of information (detailed in Annex A) to generate a picture of SMR safety analysis, research and deployment plans in NEA member countries. Additionally, parallel international efforts related to SMR safety under the International Atomic Energy Agency (IAEA), Euratom and the Generation IV International Forum (GIF) were identified. The detailed results, discussed in Chapter 3, were then aggregated to determine specific AOIs related to SMR safety where the CSNI could contribute. These AOIs were referred back to the EGSMR in a second questionnaire, which sought to:

- refine the AOIs (e.g. narrowing or broadening, identifying concerns or challenges, and any missing areas);
- develop suggested actions for the CSNI to address these AOIs.

The suggested actions include: i) specific activities to address the AOIs; ii) adjustments to current CSNI efforts already in progress; and iii) review of and potential collaboration with ongoing efforts in other international organisations. These actions focus on the unique added value of CSNI involvement and on activities beneficial to the NEA Committee on Nuclear Regulatory Activities (CNRA) and regulators facing licensing of SMRs. They are linked to the standing working or expert groups of the CSNI (see Annex B) or to those in other NEA committees (e.g. CNRA), and some could be developed into potential international joint safety research projects. The identified AOIs and suggested actions comprise the primary results of the EGSMR effort and are discussed in detail in Chapter 4, which outlines the four major AOIs, their breakdown and the related suggested actions for the CSNI.

These results summarise the EGSMR assessment of CSNI activities of relevance to SMRs which have a high technology-readiness level (TRL) and are anticipated to see near-term deployment. In determining the priority of different proposals, the EGSMR evaluated each proposal's safety significance and the available CSNI capabilities. Experimental programmes, key facilities and efforts conducted at other international organisations were also considered. There are several areas and actions that focus on safety issues that cross a number of designs and the EGSMR has identified new technical areas where the CSNI should develop knowledge.

Chapter 3. Analysis of SMR deployment survey

3.1. Prerequisites – Technologies

The term "small modular reactor (SMR)" can encompass a wide variety of technologies, sizes (power/thermal output) and aspects (e.g. modularity, multi-module operations, risk minimisation, remote operation). To frame and delimit the work of the NEA Expert Group on Small Modular Reactors (EGSMR), the NEA definition was adopted:

> "SMRs are defined today as nuclear reactors with a power output between 10 megawatts electric (MWe) and 300 MWe. They integrate by design higher modularisation, standardisation and factory-based construction in order to maximise economies of series (or the "series effect"). The different modules can then be transported and assembled on site, leading to predictability and savings in construction times" (NEA, 2021a).

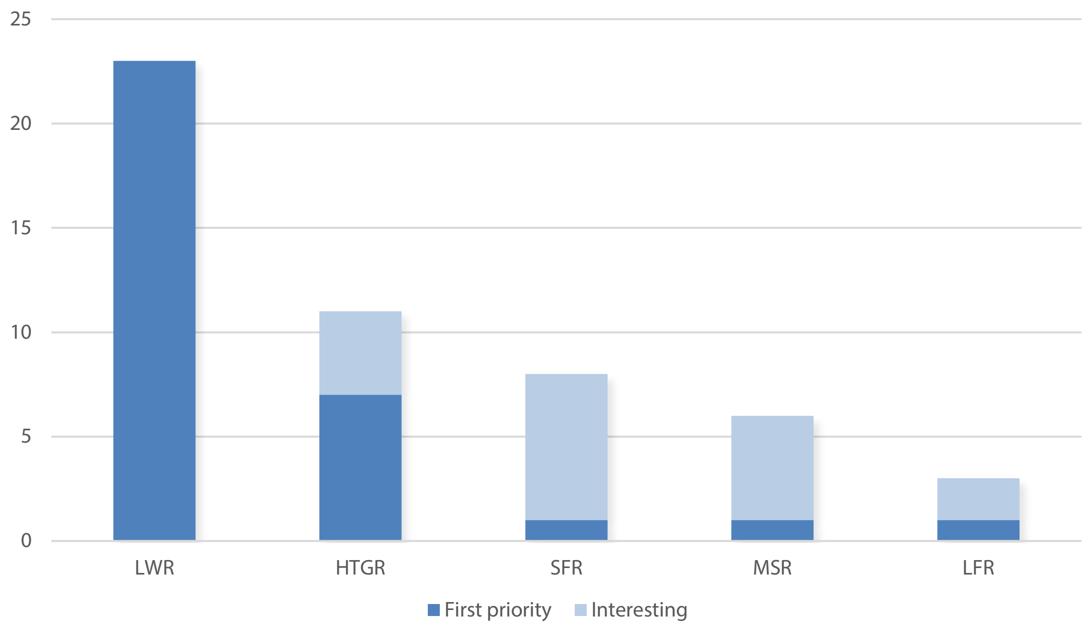
SMRs include a variety of reactor technologies in terms of coolants (water, gas, liquid metal, molten salt, heat pipes, etc.) and fuels (UO_2, TRISO, molten salt, etc.). The above definition aligns with previous efforts of other organisations to come to a common understanding of the term "SMR". The EGSMR does maintain flexibility related to power output and technology, however, and considers in addition that SMR design features also offer potential increases in safety.

Within the EGSMR mandate is also an expectation to initially focus on SMR designs that have a high technology-readiness level (TRL) and that are anticipated to see near-term deployment. The first questionnaire explored the interest in new reactor technologies among the respondents to understand plans for deployment (or not) in their countries, and find which technologies are of interest in the near term and/or in a longer time frame. This helps to focus the areas of interest (AOIs) and suggested actions to support NEA member needs and identify common issues that could be addressed through international co-operation (potentially led by the NEA or other organisations if better suited to the future task).

It is clear from Figure 3.1 that the technologies close to near-term deployment are primarily water-cooled designs. These are also the technologies where the NEA Committee on the Safety of Nuclear Installations (CSNI) is currently best able to provide support. Advanced technologies can offer advantages that the current light water reactor (LWR) designs cannot. For example, a fast neutron spectrum can burn actinides or provide very high temperatures for industrial processes. These technologies, while potentially farther from deployment, are also important to advance, and the CSNI is well positioned to support this given the large resources and capabilities of the participating countries. It is for this reason that the EGSMR supports two tracks: 1) water-cooled SMRs (WC-SMRs) and 2) advanced technology SMRs (AT-SMRs; i.e. Generation IV).

In terms of the prioritisation of AT-SMR designs, Figure 3.1 indicates that possible co-operation could be beneficial in studying safety issues related to high-temperature gas-cooled reactors (HTGRs), sodium-cooled fast reactors (SFR), molten salt reactors (MSR), and lead fast reactors (LFR).

Figure 3.1. **Responses regarding which SMR technologies should be covered**



Source: The EGSMR first questionnaire results (CSNI EGSMR).

3.2. Prerequisites – International co-operation

The interest in new reactor technologies and SMRs has increased and resulted in initiatives in several countries and between several countries. Often the same experts and organisations participate in different initiatives covering similar topics, but it is recognised that international co-operation is valuable. It promotes the exchange of knowledge and development of competences and allows issues to be analysed from different perspectives. When formulating proposals for new efforts within the NEA, it is necessary to be informed about other ongoing work, which can be considered for co-operation. Alternatively, the scope of the new efforts can be limited to ensure they are complementary.

The EGSMR has identified the following avenues of co-operation and to a large extent suggests collaborating with them:

- the International Atomic Energy Agency (IAEA), with initiatives like the Nuclear Harmonization and Standardization Initiative (NHSI) (IAEA, n.d.) and the SMR Regulators Forum (SMR RF) (NEA, 2022);
- the World Nuclear Association (WNA) CORDEL (Cooperation in reactor Design Evaluation and Licensing) working group, and other international industry associations/groups;
- the EU SMR Pre-Partnership effort (notably Work Stream WS2 on Licensing and WS5 on R&D needs);
- Euratom Research Projects;
- the Generation IV International Forum (GIF);
- within the NEA, the Committee on Nuclear Regulatory Activities (CNRA) (especially the Working Group on New Technologies [WGNT], and the Working Group on Policy and Licensing [WGPL]).

3.3. Knowledge base requirements for SMRs

Many proposed SMR designs rely on technologies different from those of established large water-cooled reactors. The latter benefit from an extensive knowledge base built over decades of research and operational experience in many countries. This foundation has been an essential element supporting the safe operation of such reactors. There is the potential to apply this knowledge to WC-SMRs, but there are still phenomena requiring further investigation (e.g. natural circulation and passive cooling). For AT-SMRs, this water-cooled operating knowledge is less applicable. Given these challenges, it may not be realistic to expect a knowledge base of a similar extent to be developed for AT-SMRs such as gas-cooled, molten salt, or liquid metal cooled (e.g. sodium, lead) designs.

New designs, both WC-SMRs and AT-SMRs, also promise safer operations than the existing fleet of reactors, but the safety case has yet to be fully demonstrated to regulatory authorities. Evidence of these claims needs to be built upon experimental support, experience and sound safety assessments.

Delving deeper into the issue of gaining knowledge about new systems has revealed a few important principles that the EGSMR recommends to apply in future development work and tasks.

- It will be necessary to develop new analytical tools or validate current tools for new applications to support investigations of new reactor technologies with new phenomena. New tests and experiments will be necessary not only to demonstrate the phenomena for the application in the design, but also to develop appropriate models for those phenomena (over a full range of conditions from normal operations to design-basis accidents, design extension conditions, severe accidents and long-term recovery) to justify the safety analysis methods.
- The safety case needs to be robust. However, systems and models for some new reactor technologies are currently in a developing stage and their accuracy and precision may not be fully realised. In developing stages, it is necessary to balance the level of imprecision with appropriate safety margins.
- Demonstration and first-of-a-kind (FOAK) SMRs need to be suitably equipped with instrumentation and probes to collect comprehensive measurements. This could allow high quality data generation, the identification of potential improvements, and future reductions in margins.

An overarching goal for the EGSMR and the CSNI is to advance the scientific and technical knowledge base for the safety of nuclear installations. Hence, it is well in line with CSNI goals to develop the knowledge base regarding SMRs over the whole chain of safety justifications from tests, through models and methods development, to the exchange of experience with actual systems, as well as harmonisation between nations in these steps.

3.4. Graded approach

A graded approach for both WC-SMR and AT-SMR designs includes these main components:

- The level of analysis, verification, documentation, regulation, activities and procedures used to comply with a safety requirement should be commensurate with the associated radiation risks.
  - Determine which elements are considered important and novel (or less mature; maturity relates to the use of proven practices and calculation codes, proven design features, operating experience from similar facilities, etc.) and prioritise these in a pre-licensing process with safety authorities.
- Appropriate consideration of the knowledge base and uncertainties must be taken to a level that meets national regulatory standards and, as appropriate, the IAEA safety standards.

  - The knowledge base must be sufficient to prove the safety claims that the vendor is making.
  - Sufficient accuracy and precision should be demonstrated to meet regulatory standards, and when accuracy and precision are not high, larger safety margins may be necessary. The level of accuracy should support a robust safety case.
- Providing high-level, non-prescriptive, and objective-oriented regulations based on the revision of current LWR regulations could be an efficient way to quickly establish a regulatory base for novel reactors.
  - This should be aligned with risk-informed design/regulation and keep risk as low as reasonably achievable (ALARA).

Chapter 4. Areas of interest and suggested actions

The NEA Expert Group on Small Modular Reactors (EGSMR) surveys have explored current knowledge and ongoing programmes in order to determine areas of interest (AOIs) for further work and especially to find topics for small modular reactor (SMR) safety that require attention. The EGSMR analysis has resulted in a handful of suggested actions that would advance the scientific and technical knowledge base for the safety of nuclear installations. These suggestions all include several parts that each can be expanded to specific tasks, activities or projects. In some cases, similar actions are being performed in other international organisations (e.g. International Atomic Energy Agency [IAEA], Euratom, and Generation IV International Forum [GIF]) and the NEA should actively seek information exchange with these efforts.

The identified AOIs for further consideration by the NEA Committee on the Safety of Nuclear Installations (CSNI) and suggested actions focus on four categories:

1. **Regulatory harmonisation**: Foster international regulatory harmonisation regarding SMR licensing.
2. **Cross-cutting safety issues**: Support understanding of broad cross-cutting SMR safety issues that impact many different designs (detailed in Section 4.2).
3. **Experimental campaigns**: Organise reviews of international experimental campaigns and define new campaigns to improve phenomenological understanding and experimental validation of SMR designs.
4. **Benchmarking for code V&V**: Support international benchmark activities for computer modelling V&V for SMR designs.

For all AOIs, the EGSMR recommends efforts into two parallel tracks: 1) WC-SMRs, and 2) AT-SMRs, with further prioritisation to support technologies/designs nearest to deployment. These AOI are important areas for co-operation in the NEA, and most of the broad cross-cutting SMR issues would be suitable for tasks in the respective CSNI working or expert groups. The suggested actions to address these AOI are further elaborated on in the following sections.

4.1. AOI #1: Regulatory harmonisation

The first AOI identified by the EGSMR relates to the harmonisation at an international level of regulatory requirements and practices for SMR licensing.

Clearly, this topic is not new and is already being explored in initiatives outside of the NEA like the IAEA NHSI, the World Nuclear Association (WNA) CORDEL or the WS2 on Licensing of the EU SMR Pre-Partnership.

The EGSMR, although organised within the CSNI, is also conscious that this AOI would be primarily handled by the NEA Committee on Nuclear Regulatory Activities (CNRA), and that this might already be the case to some extent within its working groups WGNT and/or WGPL.

Nonetheless, the EGSMR wants to emphasise that regulatory harmonisation remains a fundamental AOI to enable the timely deployment of SMRs in the near term and for which international collaboration must be fostered.

Safety demonstration requirements are clearly important to the CSNI, its working groups, and their specific participants, who are stakeholders in their formulation and implementation. Therefore, the CSNI needs to maintain awareness of regulatory and associated safety demonstration efforts currently underway, and be ready to respond to requests for assistance from partners and other international organisations.

Consequently, to contribute to this collaboration, the EGSMR wanted to provide its view on the main topics where CSNI efforts could support regulatory safety assessment and licensing activities:

- Development and application of regulation and guidance on simulation code qualification verification, validation, and simulation model qualification; notably:
  - Establishing guidelines on necessary V&V for new modelling and simulation tools (or enhancements of established codes to apply to SMRs).
  - Finding balance between preciseness and predictiveness of the codes and the acceptance of uncertainties for simulation tool results against safety margins.
  - Addressing existing model gaps or validation gaps in a safety demonstration, and the expectations on simulation code user qualification.
  - Assessing the potential for reduced validation data (single validation per phenomena) and the potential of licensing a first "prototype" unit within a conservative envelope.
- The application of graded approaches in establishing safety provisions (regulations) for SMRs; notably:
  - Paying specific attention to codes and standards, and to simulation code qualification.
  - Considering implementing risk-informed approaches to regulation.
- The collection of information on phenomena to inform regulation, as well as the identification of knowledge gaps and related research needs from a regulatory perspective.

As a result, in terms of overwhelming action for this first AOI, the CSNI should, possibly through the EGSMR, maintain relationships and information transfers with other parties exploring SMR safety. From the EGSMR's perspective, these actions can be divided between "outside NEA initiatives" and "inside NEA initiatives", in the following sub-actions:

- On the side of outside initiatives, this would mainly be to build and/or maintain relationships with the following parties:
  - IAEA (NHSI and the SMR Regulators Forum);
  - WNA (CORDEL);
  - Western European Nuclear Regulators Association (WENRA);
  - Euratom Research Projects;
  - EU SMR Pre-partnership, notably WS2 (Licensing), WS4 (Supply chain) and WS5 (R&D needs);
  - ETSON (European Technical Safety Organisations Network);
  - GIF (Risk and Safety Working Group).

In particular, the EGSMR notes that the CSNI, its working groups and their specific participants should be aware of the differences in rules and responsibilities between the different parties and notably between the NEA and IAEA working groups and committees. This is noted as a key element to avoid, or at least reduce, duplication of efforts through proper information exchange.

These relationships should also allow building a better understanding from the different stakeholders' points of view, for instance from the regulatory or industry sides, of the harmonisation efforts, the possible challenges and the gaps to be filled.

Understanding the points of view of the different stakeholders is important as "harmonisation" may present (at least) two different viewpoints: i) regulators aligning regulations, and ii) industry aligning interpretations of safety and licensing requirements to harmonise, for instance, the safety demonstration methodologies. Overall, the EGSMR thinks that an open dialogue between all stakeholders is beneficial to support harmonisation and that the CSNI could be one of the relevant and credible facilitators between regulators, research centres and industry stakeholders through its activities generating research results and expert consensus to support harmonisation.

As one example, more interaction with the IAEA NHSI's industry track would be beneficial for NEA members as it could bring more co-operation and resource sharing for experiments and code validation between experimental facilities, technology holders/developers and potentially TSOs.

- On the side of internal efforts, the EGSMR sees two tracks that could be activated or to which attention should be paid:
  - The possibility of applying the NEA Multi-national Design Evaluation Programme (MDEP) mechanisms to SMR designs.
  - The maintenance of good information exchange with the CNRA and its working groups (e.g. WGNT and WGPL) regarding ongoing efforts in the regulatory space related to SMR safety.

In summary, the suggested actions are for the CSNI (perhaps through the EGSMR) to maintain relationships and information transfer with other parties exploring SMR regulatory and industry harmonisation (both external and internal to NEA), including close information exchange with the CNRA regarding ongoing efforts in the regulatory space.

4.2. AOI #2: Cross-cutting safety issues

The second AOI identified by the EGSMR covers the understanding of broad cross-cutting SMR safety issues. These issues are more general safety concerns that impact a range of designs (both WC-SMR and AT-SMR) and may pertain to the design, construction/assembly, operation and applications of SMRs. In this section, these cross-cutting safety issues are described in detail along with the suggested actions to address them.

Before delving deeper into the cross-cutting issues identified by the EGSMR, it should be acknowledged that most of the EGSMR participants have background expertise within the areas of nuclear fuel, thermal-hydraulics and severe accidents, which may therefore lead to some bias in the identification of these cross-cutting safety issues. Thus, while an effort was made to include a variety of issues, the list provided should not be considered exhaustive and could expand in the future, especially considering that international collaborations could be a source for additional elements.

The EGSMR has identified the following eight cross-cutting SMR safety issues and ranked them by priority according to their safety significance, timeline for resolution and relevance to the CSNI mandate and capabilities, the first issue being of the highest priority:

- **Application of defence in depth (DiD) (NEA, 2016; IAEA, 2005) when safety features (e.g. passive safety systems/features) are used on multiple DiD levels.**

  A common feature of the majority of SMR designs is the use of passive safety systems/features, frequently spanning multiple levels of DiD. Generally, the requirements on current large reactors aim for independence between the DiD levels as much as practicable (IAEA, 2016). Thus, it is prudent to assess the extent of independence of DiD levels that is practicable for designs with passive safety systems/features and the impacts of such reliance on these systems on SMR safety. The reliability of these passive systems is a key component of this assessment. It is suggested that reviews be undertaken involving the Working Groups on Analysis and Management of Accidents (WGAMA), and Risk Assessment (WGRISK) to understand the evaluation of the reliability of passive systems and their integration in probabilistic safety analysis (PSA) as well as deterministic and risk-informed decision making approaches. The EGSMR also suggests that the CSNI continue to exchange information and collaborate with the IAEA and others on the development of methodologies for safety assessment and the regulation of designs with passive safety systems/features. Recommendations on reliability requirements for passive systems would be of particular benefit.

- **PSA for innovative/FOAK designs.**

  SMRs might well employ innovative and FOAK components, systems and overall design that are not fully explored in terms of reliability or probability of failure. This may include module factory sites, fuel fabrication and processing facilities, which are quite different from facilities employed for large water-cooled reactors. As a result, efforts should be made to develop methods to apply the PSA to SMRs taking into account this issue. In addition, the relative advantages of the PSA compared to both deterministic approaches of safety assessment and to risk-informed decision making should be considered. The EGSMR therefore suggests that the CSNI review PSA methods and their application to innovative systems and FOAK designs. This is likely best led by WGRISK, with input from other WGs as needed.

- **Investigation of emergency planning zones (EPZs) and emergency response requirements for SMRs.**

  This cross-cutting safety issue was identified as many SMR designs expect to reach an accident robustness level sufficient to demonstrate that EPZs would be limited to the site boundary and no off-site emergency response requirements would be needed. This is a rather challenging position to attain and further actions are needed to address emergency preparedness and response issues for SMRs. The EGSMR is aware that this issue is covered by the ongoing efforts of many regulators and by the IAEA, including a Coordinated Research Project (CRP) specifically focused on the EPZ (IAEA, 2017). In addition, there are efforts under the NEA Committee on Radiological Protection and Health (CRPPH) that are focused on the EPZ. It is therefore recommended that the CSNI consider the output of these actions before determining if any further CSNI action is needed.

- **Fuel safety of SMRs (both WC-SMR and AT-SMR).**

  Reactor safety is never assumed but demonstrated by proper analysis with verified and validated tools. It terms of fuel safety, the EGSMR assumes that near-term deployable WC-SMR designs will rely on proven fuel design technologies that have been demonstrated through irradiation in conventional LWRs. Therefore, there will be fewer open questions related to fuel performance and safety than for SMR designs that utilise novel fuel concepts. The AT-SMR designs may rely on more novel fuel design concepts that require further research on fuel performance topics. This area of research is suggested to be explored by the Working Groups on Fuel Safety (WGFS), Fuel Cycle Safety (WGFCS) and WGAMA and there are connected efforts being conducted by the NEA Committee on Nuclear Science and the McSAFER Euratom Research project. The topical areas fall in a few categories, with specific issues, as follows:

  - Reactor physics:
    - **WC-SMR**: Fuel designs; V&V of fuel behaviour/neutronics codes for SMRs; fuel radionuclide inventory for source term prediction.
    - **AT-SMRs**: Use of more detailed neutronics simulations (multi-group, detailed cross-sections); novel fuel designs (e.g. liquid fuels); fuel burnup/transmutation.
  - Fuel performance (both materials and burnup):
    - **All SMRs**: Efficiencies in SMR cores and generation of actinides; in-reactor fuel behaviour in normal operations and accident conditions; fuel safety criteria.
    - **AT-SMRs**: Core lifetime limits related to material concerns; impact of fuel/coolant chemistry and corrosion issues.
  - SMR fuel cycles:
    - **WC-SMR**: Potential impacts to spent-fuel management and final repositories (including burnup and fuel volume).
    - **AT-SMRs**: impact of novel designs on fuel cycle back end (long-term management).

- **Human factors (including remote operations and multi-unit/multi-module plants).**

  The differences in the design, applications and operational states of SMRs compared to conventional large reactors also present challenges related to human factors. This is specifically evident for remote operations, maintenance and emergency preparedness (potentially with significantly reduced or no on-site operations staff), and for the control of multi-unit/multi-module plants by a team of operators. In the case of remote operations or multi-unit/multi-module plants, the impacts of shared control rooms may be of interest. Additionally, from a technology point of view, aspects related to operator interaction/control of passive safety systems/features are of interest. The EGSMR suggests a review of efforts in this area, most suitably by the WG on Human Factors (WGHOF), whose participants are particularly skilled and are already beginning some research in this area. Such a review could also form a suitable foundation for the development of guidance on addressing these aforementioned human factor challenges to mitigate issues that may arise. In this area there are important connections to the following:

  - Activities being conducted at the Halden HTO (Human Technology Organisation). The CSNI can exchange information and provide support to ongoing and newly planned efforts related to SMR remote operation.
  - Regulators investigating these human factor issues, which warrants consultation with the CNRA and a review of ongoing work.

- **Exploration of multi-unit/multi-module design aspects to determine the impacts on safety (including shared systems, adjacent unit/module accidents and common mode failures).**

  This topic was identified because several SMR designs include a multi-unit/multi-module configuration and/or a potentially closer link with adjacent plants compared to the majority of currently operating large nuclear reactors. This issue is therefore focused on gathering information on these aspects to provide sound recommendations that could be addressed through updates to PSA (or other deterministic or risk-informed) methods. This gathering of information would primarily concern:

  - Information on the safety assessment of multi-unit facilities in operation (including the Fukushima Daiichi accident, other LWR stations, and CANDU multi-unit plants with shared containment).
  - Information on multi-module SMR designs and the differences from traditional multi-unit stations (e.g. licensing experience for PRISM, NuScale and HTR-PM).
  - Information on specific design measures based on the design characteristics of SMRs, including PSA methodology development for multi-module applications.

- **Safety and security aspects related to the transport of fuelled nuclear modules and transportable/floating nuclear power plants (SMRs).**

  This safety issue relates to some SMR designs exhibiting either transportable fuelled nuclear cores (for delivery to, or the return of a spent core from, a plant site; e.g. the USNC Micro Modular Reactor, or Westinghouse eVinci) or floating vessel configurations (multiple possible sites e.g. KLT-40S, OFPU RITM-200, and Seaborg Power Barge). For this issue, the EGSMR provided the following two recommendations:

  - To consult with the IAEA initiative on the design safety of transportable nuclear power plants; it is recommended that the CSNI review the output of this effort before determining if further action is needed.
  - A joint assessment of this cross-cutting issue by multiple CSNI WGs (led by one WG) may be beneficial with potential input from the WGFS, WGRISK and WGAMA.

- **Understanding of safety implications related to interconnections between SMRs and associated process applications (hydrogen production, process heat for chemicals, mining, etc.).**

  This issue was identified because SMRs are generally advertised as disruptive means of electricity and/or heat production (e.g. district heating) that could support the decarbonisation of industrial process applications (hydrogen generation, desalinisation, mining, etc.). However, the impact on SMR safety of such closely connected processes has so far, to the knowledge of the EGSMR, not been sufficiently investigated. This is understandable as it needs to bring together the two different worlds of nuclear reactor developers/operators, who are less knowledgeable of industrial constraints, and industrial developers/operators, who are less knowledgeable of nuclear safety requirements. The EGSMR is advocating for building and maintaining, within the CSNI and its working groups, greater understanding and an assessment of the safety implications related to interconnections between SMRs and associated process applications through the following concrete actions:

  - A consultation with the CNRA and the Euratom Research TANDEM Project, with the suggested involvement of the CSNI Working Group on External Events (WGEV).
  - A review of JAEA work on the coupling of the HTTR (High-Temperature Engineering Test Reactor) to a hydrogen production facility (Shibata, 2022), as this could provide insight into the safety impacts and connections challenges, which are applicable to interconnections with process applications for HTGR-SMR.
  - An investigation of the following topics in priority:
    - decoupling possibilities between the nuclear island and balance of plant/ connected infrastructure/associated process applications to enhance safety;
    - the impact on credible "external events" of different "load losses" related to processes;
    - the level of detail and validation of numerical tools needed for the safety demonstration of an SMR within an energy hub (e.g. high-level complex systems modelling). For this point, consultation with national laboratories working on Energy Hubs is recommended (e.g. Idaho National Laboratory [INL], US; National Renewable Energy Laboratory [NREL], US; Canadian Nuclear Laboratories [CNL]; the French Alternative Energies and Atomic Energy Commission [CEA]; the Institute of Energy Economics of Japan [IEEJ]; Japan Atomic Energy Agency [JAEA]; Energy Systems Catapult, UK; National Nuclear Laboratory [NNL], UK [NNL, n.d.]).

The overall suggested action is that for each of the seven cross-cutting SMR safety issues, a relevant CSNI working or expert group be assigned to conduct a review and assessment of the issue (including understanding work underway, gaps and research needs) and generate a status report for the CSNI. In some cases, it may be best to have one WG lead a joint assessment by multiple WGs.

4.3. AOI #3: Experimental campaigns

Experimental campaigns are necessary to improve the understanding of important phenomena affecting SMR safety and to form the basis for evaluation model development and assessment. The EGSMR recognises conducting large-scale experiments for a variety of different SMR design concepts is resource intensive and therefore proposes a series of activities aimed at prioritising research resources towards phenomena with a high safety significance and low current knowledge level. To this end, the EGSMR proposes conducting the following next steps:

1. determining knowledge gaps of the highest safety significance;
2. leveraging existing experimental data to address knowledge gaps;
3. identifying existing experimental facilities that may be suitable for addressing gaps;
4. recommending new experiments, for any remaining gaps, and providing guidance for those experiments.

As mentioned earlier, for all AOIs the EGSMR recommends efforts into two parallel tracks: 1) WC-SMRs, and 2) AT-SMR, with further prioritisation to support technologies/designs closest to deployment.

4.3.1. *Determining knowledge gaps*

To prioritise limited resources for experimental campaigns, the EGSMR recommends collecting phenomena identification and ranking tables (PIRTs) for relevant WC-SMR and AT-SMR designs. PIRTs are formulated with the purpose of identifying, for a specific design and event, the phenomena that have the most important influence on the consequences (USNRC, 2005). PIRTs are routinely produced during the development of evaluation models for performing safety analysis and the EGSMR plans to leverage the insights captured in existing PIRTs where possible.

First, the EGSMR will collect existing WC-SMR and AT-SMRs PIRTs (e.g. from international or national projects). Second, as needed, the EGSMR can co-ordinate with the CSNI to generate further PIRTs for different SMR designs and events (e.g. design-basis accidents, anticipated transients, severe accidents), which would be led by a relevant working group. By examining the near-term deployable SMR designs in concert with the PIRTs for the highest safety significant events, a relevant CSNI WG(s) can identify and prioritise those phenomena most significant to SMR safety. An initial PIRT collection effort by the EGSMR is currently underway (see Section 4.6, and Annex E). PIRTs routinely categorise the knowledge level associated with the phenomena (USNRC, 2005), but even if the PIRTs lack this information, the WGs can look to relevant, historical experimental data to determine if the highly important phenomena have been well studied or if there are gaps in the experimental assessment.

The EGSMR would co-ordinate the grouping of different PIRTs with the WGs that will conduct the assessments. The culmination of these combined efforts would be to produce a report that summarises the phenomena with high safety significance and low knowledge level, first for WC-SMRs and then for AT-SMRs. This will help to identify gaps that can be addressed through future international efforts, including those within the CSNI.

4.3.2. *Leveraging existing experimental data*

In evaluating the PIRT insights, consideration will need to be given to both the importance of the phenomena and the current level of knowledge of those phenomena. The current knowledge is dictated by the existing body of experimental data. The EGSMR, therefore, recommends leveraging existing experimental data that may be relevant to support SMR safety to address the identified knowledge gaps.

The EGSMR recognises the effort of the Senior Expert Group on Preservation of Key Experimental Datasets (SEGPD) to produce high-level guidance on best practices and strategies in data collection and preservation. As this guidance will be technology-neutral, it will be applicable to the collection of data pertaining to SMR safety. The guidance should be applied to the different areas of safety-related experimental data such as fuel performance, thermal-hydraulics and containment (including, as appropriate, design-basis accidents, design extension conditions, severe accidents and long-term events). The SEGPD guidance will be valuable to collecting and managing data related to SMR safety in the future.

In addition to the organisation of future data collection, efforts must be made to collect and evaluate existing experimental databases, details of the test facilities, and scaling impacts. As a future activity, the EGSMR (and/or other CSNI WGs) can correlate the documented data to the phenomena of interest (as identified in the collection of PIRTs).The review of existing data should consider historical data sets collected for large-scale LWRs that may be applicable to WC-SMRs and data from joint experimental programmes organised through the NEA. Examples include data on containment behaviour, source term, etc. from projects such as Halden (NEA, n.d. a), THEMIS (NEA, n.d. b), PANDA (PSI, n.d.), and HYMERES (NEA, n.d. c). Data should also be available from experiments, prototypes and operations of non-light water-cooled reactor technologies that could be applicable to AT-SMRs. Data suitable for the qualification of passive systems and their reliability should be included. This data collection i) may include the recovery of data from closed facilities (from their parent organisations or archives), ii) should document the findings generated along with the raw data, and iii) may require furnishing databases to store the information. There is also the potential to share existing data between different organisations (OECD, IAEA, Euratom, etc.), which should be explored.

The EGSMR proposes that an effort be organised to collect these databases and document the test facility details, including any known scaling distortions, and to correlate these existing data sets with the previously identified, highly important phenomena. This will be an extensive effort and will need commitment and resources from NEA members (and their associated organisations) to share data from databases they own, and support the data collection, as well as conduct the documentation and correlation efforts.

4.3.3. ***Identifying existing facilities***

The EGSMR has initiated an effort to collect preliminary information about participating countries' experimental facilities/capabilities (see Section 4.6 and Annex C). This initial effort should be expanded to produce a report that provides a standardised set of information about the countries' experimental facilities. This information should include test facility descriptions, testing capabilities and scaling information. The EGSMR can consult with the upcoming WGAMA Specialists Workshop on Advanced Instrumentation and Measurement Techniques for Nuclear Reactor Thermal Hydraulics and Severe Accidents (SWINTH; next meeting in 2024) regarding current large facilities involved in NEA joint experimental projects and other facilities with applications to SMR safety. The resulting report can be used in future efforts by the CSNI to match knowledge gaps in high importance phenomena with existing facilities that are well suited to study those phenomena, providing a list of key facilities to support SMR safety.

4.3.4. ***Recommending new experiments***

Having identified the highly important phenomena, correlated those phenomena with existing data sets and collected information about existing experimental capabilities, the EGSMR will propose a path forward. This path will identify SMR safety research topics (including, as appropriate, design-basis accidents, design extension conditions, severe accidents and long-term events) based on gaps in the existing data relative to the important phenomena and will estimate the resources needed to close those gaps. In formulating this path forward, the EGSMR (supported by other CSNI working groups) will consider whether a single set of validation data is sufficient to close any given gap, and if licensing a FOAK prototype within a conservative operating envelope would be a viable option.

In this manner, the CSNI can push for new experimental campaigns to close knowledge/data gaps, using both new and existing facilities, with a focus on the concerns and data needs for code qualification/validation. This push should support both WC-SMR and AT-SMR designs and can utilise NEA joint projects, CAPS (CSNI Activity Proposal Sheets) and dedicated efforts by working groups to facilitate the efforts.

For existing facilities, the efforts in PIRT collection and facility identification can be leveraged to correlate important phenomena gaps (from PIRTs) to current experimental facilities. This effort can also highlight experimental gaps that may require new facilities or refurbishments to existing facilities.

In order to support new experimental campaigns and new or refurbished facilities, the EGSMR proposes that the CSNI develop guidance for those campaigns, which will support validation activities for SMR safety. This guidance should include best practices for instrumentation of full-scale experiments, demonstrator test facilities, or FOAK prototypes and associated documentation requirements. The instrumentation should consider SMR safety specific issues (e.g. passive safety systems, natural circulation). The documentation should include information about the experiment/test-facility/FOAK-prototype (e.g. geometry, scaling, available conditions), and on the instrumentation used and measurement data collected (e.g. data channel descriptions, data format). This effort can borrow from the report on existing facilities, as it will provide a partial platform for standardising test facility descriptions.

4.4. AOI #4: Benchmarking for code V&V

Safety conclusions for new WC-SMRs and AT-SMRs will rely on safety analyses performed using qualified evaluation models. These must be validated against relevant experimental data to cover important phenomena over the range of conditions encountered during risk significant events, be they design-basis accidents, severe accidents or anticipated transients. In addition to the recommended path forward of collecting the necessary experimental data to cover the most important phenomena, as discussed in Section 4.3, the EGSMR also recommends efforts to facilitate code validation, evaluation model development and benchmarking. These efforts should prioritise design types and activities to ensure that targeted studies, focused on safety significant issues and with timely added value, can be implemented with the limited resources of the CSNI's participating countries.

The EGSMR recommends reviewing and updating the CSNI code validation matrix to cover the important safety phenomena for typical near-term deployable WC-SMR and AT-SMR designs. In addition, the EGSMR recommends that the CSNI (via relevant WGs) prepare a guidance report on V&V needs for code qualification, including:

- Suggestions on a minimum set of validation cases to provide coverage of the full scope of the key phenomena. Currently, AT-SMRs are relying on modelling and simulation more than experimental tests compared to previous LWR development, so recommendations on data needs and margins are important.
- Reaching consensus and providing guidance on the reliance of integral effects testing compared to separate effects testing. It may be that adequate qualification can be achieved with a heavier reliance on integral tests than separate effect tests.
- Guidance on how many assessment cases constitute a sufficient validation basis for code qualification. For example, a single high quality validation assessment case may be sufficient to provide the necessary coverage for certain key phenomena. Validation case resolution must be sufficient to ensure it is properly captured by the simulation code system.
- Consideration of the recommended path forward on experimental data discussed in Section 4.3.

An experienced systems analyst will understand that a code alone does not constitute an evaluation model appropriate for safety analysis. The evaluation model also incorporates modelling practices, such as nodalisation choices, that are required to achieve the necessary degree of accuracy. Favourable comparisons of the code results to experimental data are insufficient alone to qualify an evaluation model. The modelling practices required to achieve that agreement must be part of the evaluation model. Therefore, the EGSMR recognises the importance of not only reviewing the agreement between codes and experimental results, but also understands the importance of best modelling practices. The EGSMR recommends capturing the important modelling practices that are discovered through the benchmarking process, including the development of best practice guidelines for modelling and simulation.

International standard problems and other cross-walk comparisons are an ideal platform for developing and disseminating best modelling practices. In these kinds of international activities, participating nations perform calculations or validation assessments using their own codes and methods and the results are compared between the participants. Those approaches yielding the most accurate results can be captured in these cross-walks and shared as findings in the final reports.

Models and documentation from benchmarking activities or even standard problems for WC-SMRs and AT-SMRs could be saved and shared by the NEA through technology-specific virtual test beds. In these test beds, the participants of each country can share their codes, input decks, models and documentation. This forum would allow for easier sharing of successful modelling practices and other lessons learnt.

The EGSMR recommends that the CSNI take a stance and encourage these benchmarking activities as part of joint projects and in working groups. Specifically, the EGSMR recommends that the CSNI:

- Create WC-SMR and AT-SMR validation matrices for near-term deployable technologies, and, as applicable, reference aggregated test facility information and experimental databases.
- Organise participating countries' efforts to validate existing analysis codes against key phenomena based on existing data or potential future experiments in existing facilities.
- Develop technology-specific virtual test beds to facilitate sharing code decks, evaluation models and best modelling practices.
- Encourage benchmarking of passive safety systems, like the PERSEO test and cross-walk (NEA, 2021b) (NEA, 2021c), and encourage assessment of modern capabilities (e.g. computational fluid dynamics, CFD) for passive systems.
- Provide guidance and criteria for benchmarking activities such as cross-walks and international standard problems. This guidance should include how to document lessons learnt, especially in terms of best modelling practices.
- Maintain cognisance of ongoing international benchmarks through other fora (e.g. IAEA, Euratom, GIF) and review this work to avoid redundant efforts.

The EGSMR's recommendations are intended to facilitate the assessment and qualification of SMR evaluation models so these can be used by designers and regulators alike to determine safety findings for the proposed near-term deployable designs.

4.5. Conclusion and key suggested actions

The detailed AOIs and suggested actions were reviewed and initial key actions were prioritised based on their safety significance and relevance to the CSNI mandate. The EGSMR presents the following key suggested actions for the CSNI:

- Gather SMR PIRTs to identify unique SMR safety phenomena and prioritise future efforts (discussed in Section 4.3.1 and 4.6).
- Start working on the high-priority cross-cutting issues (identified in Section 4.2).
- Engage in V&V activities (detailed in Section 4.4) including:
  - Reviewing and updating the CSNI code validation matrix for SMR safety.
  - Producing a guidance report on V&V needs for code qualification.
- Initiate new efforts or promote ongoing efforts to collect and generate experimental data through joint projects to support SMR safety (detailed in Section 4.4).

Within the EGSMR efforts, new areas have been identified that warrant further studies by the CSNI to support SMR safety, such as:

- The impact of "external" events from associated processes on safety.
- Materials concerns for AT-SMRs.

These initial key suggested actions, as well as all the suggested actions discussed in detail in Sections 4.1 to 4.4, and the areas for further study can be addressed through a combination of efforts by the EGSMR and relevant CSNI working groups/expert groups, and co-ordination with other NEA and external organisations.

4.6. EGSMR information collection

In support of the AOIs and suggested actions discussed in the earlier sections, the EGSMR has embarked on information collection efforts to help set a foundation for future efforts in SMR safety. These were conducted through surveys of the EGSMR participants, which comprise a significant portion of the NEA member countries and include many of the countries actively deploying or expressing interest in deploying SMRs. It should be noted that these information collection efforts, while yielding good results, are by no means exhaustive and are meant as a basis to jump start future dedicated information collection and tracking efforts related to SMR safety. The information collections have the following focus (the results are presented in Annexes to this report):

- Experimental facilities to support SMR safety research (discussed in Section 4.3.3), working from a baseline of previous NEA efforts (NEA, 2021d) (NEA, 2016b); presented in Annex C.
- National and multi-national projects related to SMR safety, and relevant projects underway at international organisations (Euratom, IAEA and GIF); presented in Annex D.
- PIRTs related to SMR safety (discussed in Section 4.3.1); presented in Annex E.

Chapter 5. EGSMR future efforts

The mandate of the Expert Group on Small Modular Reactors (EGSMR) from the Committee on the Safety of Nuclear Installations (CSNI) identifies specific outputs, including:

- Summarising the assessment of CSNI activities of relevance to small modular reactors (SMRs) with a high technology-readiness level (TRL) that are anticipated to see near-term deployment.
- Providing a prioritised ranking of the safety knowledge gaps and recommendations to address the gaps, with a focus on safety issues that cross a number of designs.
- Identifying any new technical areas the CSNI needs to develop, the experimental programmes that are required and some of the key facilities.
- Considering what is being done in other international organisations (e.g. the International Atomic Energy Agency, IAEA).

This technical opinion paper details the areas of importance (AOIs) for SMR safety, presents suggested actions for the CSNI to address them, and provides initial summaries of experimental facilities and projects related to SMR safety. Therefore, this effort addresses the mandated EGSMR outputs directly or suggests specific actions to complete them through future efforts of the EGSMR and/or other relevant CSNI working/expert groups.

The AOIs and suggested actions identified by the EGSMR must be followed up with further efforts to complete these actions and produce the desired outcomes in order to ensure the CSNI is able to properly support safe SMR deployment. These suggested actions, described in Chapter 4, are in some cases best accomplished directly by the EGSMR, and in others are more suitably led by standing CSNI working/expert groups. The suggested actions need support to be initiated and stood up as activities to accomplish the desired objectives. Given that the EGSMR has relevant background knowledge and directly formulated these suggested actions, it is logical for it to provide such support. Thus, the EGSMR's future efforts would be conducting activities to accomplish the suggested actions assigned to the EGSMR and providing support to the other CSNI working/expert groups in the initiation of activities to accomplish suggested actions relevant to their specific areas of expertise. To facilitate this support of other WG/EGs in the organisation and launching of initiatives, specific EGSMR participant(s) will champion each of the recommended actions. These action champions will provide background information and resources to the relevant CSNI working/expert groups to help initiate activities.

Part of the current EGSMR mandate is to assist in co-ordinating CSNI efforts related to SMR safety, including supporting information exchange between CSNI participating organisations/countries as well as interactions with the SMR-related activities of other NEA committees and external international organisations to avoid duplication and promote complementary efforts. It is envisaged that the EGSMR would support the CSNI Programme Review Group (PRG) to follow the progress and outcomes of the various CSNI efforts regarding SMR safety and provide reporting back to the CSNI (and possibly the Committee on Nuclear Regulatory Activities, CNRA). In addition, the EGSMR would provide a forum for the exchange of information on SMR safety from internal (CSNI, CNRA) and external (International Atomic Energy Agency, Generation IV International Forum, Euratom) efforts. These could take the form of a "SMR Safety Review" event organised periodically by the EGSMR to discuss the progress on SMR safety-related activities both inside and outside the CSNI.

Therefore, the EGSMR's proposed future efforts are two-pronged: i) conducting/supporting activities to follow through on the suggested actions, and ii) supporting the co-ordination of CSNI efforts in the area of SMR safety and interacting with internal NEA and external international organisations conducting similar pursuits.

Conclusions

The Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) formed the Expert Group on Small Modular Reactors (EGSMR) at the end of 2021 to ensure its capabilities to support the safety of SMRs. Throughout 2022 and into 2023, the EGSMR conducted an assessment process to evaluate the SMR safety landscape. This included: i) collecting information related to SMR safety and deployment in participating countries (results presented in Chapter 3), ii) determining areas of interest (AOIs) related to SMR safety (Chapter 4), and iii) suggesting actions for the CSNI to address these areas and support safe SMR deployment (Sections 4.1 to 4.5). In addition, the EGSMR began information collection efforts (Section 4.6) focused on experimental facilities, projects, and phenomena identification and ranking tables (PIRTs) related to SMR safety through surveys of the EGSMR participating countries and international organisations (International Atomic Energy Agency, Generation IV International Forum, Euratom) also working to support safe deployment and operation of SMRs.

The suggested actions (presented in Sections 4.1 to 4.5) require follow-on efforts by CSNI working and expert groups to produce the desired outcomes. It is suggested that some of these activities be conducted directly by the EGSMR, while others are better suited to be executed by one or more of the other standing CSNI working or expert groups whose areas of focus are relevant to the specific actions (a lead group will be identified for co-ordinated efforts).

Following a CSNI request to the group to assist in co-ordinating CSNI efforts in the area of SMR safety, the EGSMR will consider revising and expanding the group mandate in order to ensure that future activities of the group are captured in a way that is consistent with CSNI expectations. It will propose a draft mandate for approval by the CSNI.

The EGSMR proposes to define its future role by co-ordinating CSNI efforts in the area of SMR safety (presented in Chapter 5). This can include interacting with both internal NEA and external international organisations also supporting SMR safety, providing a forum (e.g. an "SMR Activities Review" event) to exchange information on these internal and external efforts, and then informing the CSNI about progress and providing advice on future priority activities. Such information sharing makes it possible to co-ordinate efforts and promote complementary efforts.

The EGSMR, in addition to conducting its own activities, could provide support to the other CSNI groups to initiate and organise activities to address the suggested actions. The support could be facilitated by EGSMR participants assigned to be "action champions", which would see them providing background information and insight on the suggested actions as well as resources to assist in getting associated activities up and running. The activities could take the form of internal working or expert group efforts, co-ordinated task force initiatives between multiple working/ expert groups, CAPS, or NEA joint projects.

The suggested CSNI actions and associated efforts will allow the CSNI to properly support and advance the scientific and technical knowledge base needed for the safe deployment of SMRs as part of the portfolio of nuclear energy installations.

References

IAEA (n.d.), "Small Modular Reactor (SMR) Forum", web page (last consulted in July 2023), IAEA, Vienna, www.iaea.org/topics/small-modular-reactors/smr-regulators-forum.

IAEA (2022), "IAEA Initiative Sets Ambitious Goals to Support the Safe and Secure Deployment of SMRs", web page (last consulted in July 2023), IAEA, Vienna, www.iaea.org/newscenter/news/iaea-initiative-sets-ambitious-goals-to-support-the-safe-and-secure-deployment-of-smrs.

IAEA (2017), *Cooperative Research Project (CRP-I31029): Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for Emergency Planning Zone for Small Modular Reactor Deployment*, IAEA, Vienna, www.iaea.org/projects/crp/i31029.

IAEA (2016), *Safety of Nuclear Power Plants: Design*, IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), IAEA, Vienna, www-pub.iaea.org/MTCD/Publications/PDF/Pub1715web-46541668.pdf.

IAEA (2005), *Assessment of Defence in Depth for Nuclear Power Plants*, Safety Reports Series No. 46, IAEA, Vienna, www-pub.iaea.org/MTCD/Publications/PDF/Pub1218_web.pdf.

NEA (n.d. a), "Halden Reactor Project – Fuels and Materials", web page (last consulted in July 2023), NEA, www.oecd-nea.org/jcms/pl_24970/halden-reactor-project-fuels-and-material.

NEA (n.d. b), "THAI Experiments on Mitigation measures, and source term issues to support analysis and further Improvement of Severe accident management measures (THEMIS) Project", web page (last consulted in July 2023), NEA, www.oecd-nea.org/jcms/pl_58863.

NEA (n.d. c), "Hydrogen Mitigation Experiments for Reactor Safety (HYMERES) Project", web page (last consulted in July 2023), NEA, www.oecd-nea.org/jcms/pl_24982/hydrogen-mitigation-experiments-for-reactor-safety-hymeres-project.

NEA (2021a), *Small Modular Reactors: Challenges and Opportunities*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_57979.

NEA (2021b), *Status Report on Reliability of Thermal-Hydraulic Passive Systems (Addendum: PERSEO Benchmark Report)*, NEA/CSNI/R(2021b)2, OECD Publishing, Paris.

NEA (2021c), *WGAMA PERSEO Benchmark Results Report*, NEA/CSNI/R(2021c)2/ADD, OECD Publishing, Paris.

NEA (2021d), *Nuclear Safety Research Support Facilities for Existing and Advanced Reactors: 2021 Update*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_60542.

NEA (2017), *A State-of-the-Art Report on Scaling in System Thermal-hydraulics Applications to Nuclear Reactor Safety and Design*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19744.

NEA (2016), *Implementation of Defence in Depth at Nuclear Power Plants*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_14950.

Shibata, T. et al. (2022), "Present status of JAEA's R&D toward HTGR deployment", *Nuclear Engineering and Design*, Vol. 398, Article ID 111964, Elsevier, Amsterdam, https://doi.org/10.1016/j.nucengdes.2022.111964.

Annex A. First questionnaire on SMR deployment and research status

The initial information collection effort by means of the EGSMR's first questionnaire sought to understand the "Current Status of SMR Deployment/Research" in the participating countries and organisations. The information gathered included:

- The specific definition of SMR used in the organisation/country.
- The SMR deployment landscape such as designs planned/constructed/operating, technological readiness levels (TRL) for the proposed technologies, and major knowledge gaps.
- Specific SMR technologies of interest (high TRL and near-term deployment).
- Important safety impacts of SMRs based on: application of the SMR, the operating location, or the potential for multi-module configurations.
- Planned research activities related to SMR safety (including international efforts) and the availability of experimental facilities/data to support code validation to benefit SMR safety.
- The knowledge base needed for SMRs including:
  - Applicability of current knowledge base and required extensions to support the safety of water-cooled SMR designs.
  - Extent of the knowledge base needed to support confidence in the safety case of novel/advanced (non-water-cooled) SMRs.
  - SMR issues/topics requiring specific attention (or which are potentially less important) compared to the safety cases of conventional currently operating designs.
- Balancing analysis accuracy with the urgency for deployment.
- Valuable areas for CSNI to contribute to SMR safety to support deployment.

The above areas not only yielded information on activities in the individual countries, but also identified parallel international efforts related to SMR safety under the IAEA, Euratom, and GIF.

Annex B. CSNI and CNRA working and expert groups

The list of CSNI working and expert groups is provided below:

- Working Group on Risk (WGRISK)
- Working Group on Analysis and Management of Accidents (WGAMA)
- Working Group on Fuel Safety (WGFS)
- Working Group on Human and Organisational Factors (WGHOF)
- Working Group on Integrity and Ageing of Components and Structures (WGIAGE)
- Working Group on Fuel Cycle Safety (WGFCS)
- Working Group on External Events (WGEV)
- Working Group on Electrical Power Systems (WGELEC)
- Senior Expert Group on Preservation of Key Experimental Datasets (SEGPD)
- Expert Group on Small Modular Reactors (EGSMR)

The list of CNRA working and expert groups is provided below:

- Working Group on Policy and Licensing (WGPL)
- Working Group on New Technology (WGNT)
- Working Group on Supply Chain (WGSUP)
- Working Group on Leadership and Safety Culture (WGLSC)
- Working Group on Reactor Oversight (WGRO)
- Expert Group on Operating Experience (EGOE)

Many of the suggested actions presented by the EGSMR connect to one or more of the CSNI and/or CNRA working/expert groups mentioned above. The EGSMR, through the suggested action champions, will be supporting the initiation of activities in these groups to address them.

Annex C. Experimental facilities related to SMR safety

Provided below are the results of the EGSMR information collection effort on SMR safety-related experimental facilities. The responses are provided in alphabetical order and include contributions from the following:

- 16 organisations (ANVS, CEA, CNL, CIEMAT, ENEA, GRS, IKE, IRSN, JAEA, KAERI, PSI, SEABORG, SIET, SSM, Tractebel, USNRC)

from

- 12 countries (Belgium, Denmark, France, Germany, Italy, Japan, Netherlands, Korea, Spain, Sweden, Switzerland and the United States)

The collection herein builds on previous NEA facility collection efforts described in the following NEA reports:

- NEA (2021), *Nuclear Safety Research, Support Facilities for Existing and Advanced Reactors: 2021 Update*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_60542.
- NEA (2017), *A State-of-the-Art Report on Scaling in System Thermal-hydraulics Applications to Nuclear Reactor Safety and Design*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19744.

For the sake of clarity, the test facilities were sorted according to technologies (WC-SMRs and AT-SMRs) and countries (both in an alphabetical order). The list includes information on test facilities specifically for SMRs, and test facilities originally designed for other reactors, research reactors and/or hot cells, in which certain SMR safety-related phenomena can be investigated.

Some of these facilities are designed for LWR safety support so the applications to SMRs may be limited, though potentially impactful for WC-SMRs. Many of these experimental activities are devoted to developing/designing high (CFD-grade) resolution set-ups or material investigations.

Three tables are presented: i) SMR safety-related experimental facilities for WC-SMRs, ii) SMR safety-related experimental facilities for AT-SMRs, and iii) information on experimental facilities, in which SMR issues can be investigated in principle. In addition, selected literature references (if provided) are included after each table.

Table C.1. **SMR safety-related experimental facilities for WC-SMRs**

Facility name ***STATUS***	**Operator**	**Type of SMR(s) covered**	**Brief description of facility and test programme**
CAPCN (High Pressure Natural Convection Loop) *OPERATING*	INVAP for CNEA	CAREM	CAPCN is used to verify dynamic thermal-hydraulic response and critical heat flux for the CAREM nuclear power plant by producing validation data for modelling codes covering the CAREM operating states. CAPCN replicates the CAREM primary loop and the boundary conditions for the steam generator. Operational parameters are reproduced approximately for intensive magnitudes (pressures, temperatures, void fractions, heat flux, etc.) and scaled for extensive magnitudes (flow, heating power, size, etc.), while height is 1:1. The CAPCN primary loop (150 bar: 340°C) can operate in saturated (self-pressurised), or subcooled (dome pressure increased by nitrogen injection) regime, with heating power up to 300 kW and different hydraulic resistance. The secondary side is 60 bar 340°C (Boado, 1998; Delmastro, 2018).
Coupled Loop Passive Safety Facility (**CPSF**) *DESIGNED*	CNL/Atomic Energy of Canada Limited (AECL)	WC-SMR	Study direct reactor auxiliary cooling systems (DRACS) and reactor cavity cooling systems (RCCS). In particular, behaviour of coupled natural circulation loops and instability modes that may be evident. Potential extension to study ICS behaviour.
SCCA *iPWR – OPERATING* *BWR – IN MODIFICATION*	CNL/AECL	iPWR and small BWR	The SCCA is a rectangular vessel (3.66 m tall) with one heated wall and one chilled wall, as well as steam, helium and aerosol injection capability. It is designed to study aerosol transport behaviour and gas mixing phenomena (including thermal stratification and strong steam condensation against a cooled surface; i.e. a vertical wall, ceiling, or passive containment cooling system). The SCCA also simulates radionuclide transport in water-cooled SMR containments, with large windows enabling detailed optical particle measurements. Initial experiments for iPWR containment configuration and concepts are being explored for modifications to represent small BWR containment volumes.
Motel *OPERATING*	LUT University	Several SMR	Investigation of heat exchanger performance and crossflow (Sanchez-Espinoza, 2021; Sanchez-Espinoza, 2022) power: < 1 MW pressure: < 2.5 MPa loop height: 8.8 m test section height: 3.7 m
ALCINA (NAtural CIrculation AnaLysis) *OPERATING*	IRSN (Institut de Radioprotection et de Sureté Nucléaire)	Several SMR	Thermal-hydraulic loop dedicated to the analysis of parameters influencing the natural two-phase circulation and the evaluation of the pressure drops.
EVEREST *IN CONSTRUCTION*	CEA (no data available)	iSMR	SMR Nuward, dedicated to Safety Condenser.
KoKoMo (COndensation in a Containment MOdel facility) *OPERATING*	IRSN	Several SMR	Containment cooled by a condensation wall dedicated to the study of convective flow and effects of coupled condensation-stratification.

Table C.1. **SMR safety-related experimental facilities for WC-SMRs** *(cont'd)*

Facility name *STATUS*	**Operator**	**Type of SMR(s) covered**	**Brief description of facility and test programme**
PASTIS *IN CONSTRUCTION*	IRSN (no data available)	PWR and iSMR	Dedicated to Safety Condenser.
ATHOS *OPERATING*	Universität Stuttgart IKE (Institut für Kernenergetik und Energiesysteme)	iPWR in general	Passive cooling of large water pools (SMR water wall) to avoid evaporation (Krüssenberg et al., 2019; Grass et al., 2022). pressure: ambient no. tubes: < 2 x 9 height/diameter: 10 m/0.032 m
COSMOS-H *OPERATING*	Karlsruhe Institute of Technology (KIT) (access to selected data for members of the McSafer user group)	iPWR (e.g. CAREM, NUWARD, NuScale and SMART)	Designed for investigation of boiling phenomena (e.g. boiling crisis) and complex flow regimes, e.g. in FA test bundles for development and validation of high-performance, advanced analytical methods for the safety evaluation of generic SMRs (Sanchez-Espinoza, 2021; Sanchez-Espinoza, 2022) power: < 2 MW pressure: 5 – 17 MPa height/diameter: 3.5 m/0.08 m no. heated rods / tubes: 1-5
THAI+ (Thermal-hydraulic, Aerosol, Iodine) – SMR containment test section *OPERATING*	Becker Technologies (free access for German project partners, for international partners via GRS)	iPWR in general	Heat transfer at containment inner walls at presence of non-condensables, heat transfer at the other containment wall to water pools at high Ra numbers power: < 1 MW pressure: < 2 MPa height: 9 m Ra: < 10^{15}
ELSMOR *STAND BY*	ELSMOR consortium	iPWR	Tests of an Emergency Heat Removal System (EHRS) based on a natural circulation loop including a type-plate heat exchanger (as SG) and an in-Pool heat exchanger with vertical tubes. Scaling: 1/50-power, 1/1 height to the E-SMR.
NuScale SGFIV *OPERATING*	NuScale Power (proprietary data)	NuScale Power VOYGR	Investigate modal frequencies and flow induced vibration of VOYGR steam generator. Full scale (reduced tube banks).
NuScale TF2 *OPERATING*	NuScale Power (proprietary data)	NuScale Power VOYGR	Investigate heat transfer and density wave oscillations (DWO) of VOYGR steam generator. Full scale (reduced tube banks).
SIET *CLOSED*	ENEA	iSMR	PERSEO (not SMR) and ELSMOR (SMR), dedicated to Safety Condenser.
HUSTLE (Hitachi Utility Steam Test LEading facility) *OPERATING*	Hitachi-GE Nuclear Energy (part of test data is public via papers)	BWRX-300	One of world's largest test facilities owned by plant manufactures. HUSTLE was used to evaluate detailed two-phase flow behaviour around fuel of BWR temperature and pressure conditions and characteristics of in-core components of BWR (Ishihama et al., 2013; Katono et al., 2015; Marquino et al., 2014; Nishi-da et al., 1994; Takahashi et al., 2013). Apply the scaling methodology in some experiments.

Table C.1. **SMR safety-related experimental facilities for WC-SMRs** *(cont'd)*

Facility name *STATUS*	**Operator**	**Type of SMR(s) covered**	**Brief description of facility and test programme**
EOS (Establishment of Safety) loop *OPERATING*	MHI (part of test data is public via papers)	PWR	EOS loop provides a model with full height but reduced power and volume of PWR to simulate high pressure and temperature conditions of primary and secondary systems for PWR.
SF6 (sulfar hexa-fluoride) ethanol test facility *OPERATING*	MHI (part of test data is public via papers)	PWR	Visualise gas-liquid two-phase flow under low temperature and pressure conditions using alternative fluid against PWR under high temperature and pressure conditions.
FESTA (ITF) *OPERATING*	KAERI	iPWR	FESTA (otherwise known as SMART-ITL) supports the SMART design (110 MWe) and is used to investigate integral thermal-hydraulic characteristics during major design-basis accidents, to validate the simulation capability of safety analysis codes, and the system performance of SMART-specific design features. Scaling = 1:1 height, 1:7 diameter and 1:49 volume of SMART.
FINCLS **(SETF)** *OPERATING*	KAERI	iPWR	FINCLS supports the SMART and is used to investigate single- and two-phase natural circulation phenomena in SMART and to validate the simulation capability of safety analysis codes. Scaling: 1:1 height and 1:750 volume of SMART.
SISTA-2 (SETF) *OPERATING*	KAERI	iPWR	SISTA-2 supports the SMART. It has 1/1-height and 1/750-volume of SMART and is used to validate TH characteristics of SMART CPRSS design and to simulate its long-term cooling performance. Scaling: 1:1 height and 1:750 volume of SMART.
VISTA-ITL *OPERATING*	KAERI	SMART	Passive residual heat removal sys-tem (NEA, 2020; Park, 2023). Scaling: 1:2.77 length scale; 1:473 area scale; 1:1310 volume scale; 1:1.664 time scale; 1:2.77 pressure drop.
HWAT *UNDER UPGRADE*	KTH (access to selected data for members of the McSafer user group)	iPWR, BWR	Transient heat transfer in natural circulation (transition from forced to natural circulation) including Departure from nucleate boiling (DNB) and CHF in conditions typical for LWR SMRs. Measurement of flow local parameters including void fraction. Representative for SMRs height, heat fluxes, pressure and temperatures.
ATR (Advanced Test Reactor) *OPERATING*	Idaho National Laboratory	SMR	At 250 MW, the ATR is the world's largest, most powerful and versatile test reactor. Its unique design and thermal spectrum capabilities serve a wide range of vital missions for the Department of Energy's Office of Nuclear Energy, the US Navy, universities in the United States and overseas, as well as for the nuclear industry. ATR's distinctive cloverleaf core design creates nine high flux traps, six of which currently have independently controlled pressurised loops that allow irradiations to occur using different coolant types under a wide range of prototypic conditions. In addition to the 9 flux traps, 66 other test locations can accommodate drop-in capsule tests, and work is under way to add two additional pressurised loops in the next few years.

Table C.1. **SMR safety-related experimental facilities for WC-SMRs** *(cont'd)*

Facility name *STATUS*	Operator	Type of SMR(s) covered	Brief description of facility and test programme
IST *OPERATING*	Centre for Advanced Engineering and Research (CAER)	SMR	Passive residual heat removal system (NEA, 2020) Scaling: 1:1 length scale, volume and mass flow rates are scaled with power
MARBLE *OPERATING*	University of Michigan – Ann Arbor	WC-SMR	8x8 water/air bundle with gamma tomography for high resolution two-phase distributions.
MASLWR/NIST (MASLWR = **M**ulti-**A**pplication **S**mall **L**ight **W**ater **R**eactor; NIST = **N**uScale **I**ntegral **S**ystem **T**est) *OPERATING*	Oregon State University (OSU) (selected test data is public via books, papers)	iPWR	MASLWR was an integral systems thermal-hydraulic testing facility at OSU and included a scaled-down reactor primary system, containment, cooling pool, and the secondary system venting to atmosphere. It was designed as a proof-of-concept system for natural circulation driven reactors. In 2008, MASLWR was modified into NIST, which is a 1:3 height, 1/254 volume, 1:1 time scaled, electrically heated (rods), full pressure and temperature (1 650 psia, 610°F), NuScale reactor model. It also consists of a primary reactor system, containment, cooling pool, and pressurised secondary system. NIST is designed to produce experimental data in support of verification and validation of thermal-hydraulic codes for safety and operational analyses. It can perform loss-of-coolant accident, flow stability, long-term cooling, decay heat removal system, and separate effect tests.
PUMA (Purdue University Multi-dimensional Test Assembly) *OPERATING*	Purdue (selected test data is public via books, papers)	WC-SMR	PUMA is a scaled replica of an Advanced Boiling Water Reactor (ABWR) which uses an electric heated core simulator. It is equipped with 400 advanced instruments. PUMA is unique in that it is designed so that the facility can be used to simulate other advanced light water reactors, including LWR-based SMRs (Kim, 2017) Scaling: 1:400 volume scale, 1:4 height scale.
RBHT (Rod Bundle Heat Transfer test facility) *OPERATING*	Penn State	WC-SMR	The test section consists of a 7x7 array of simulated fuel rods that are 9.5 mm outer diameter x 3.66 m long with a pitch spacing of 12.6 mm. These rod dimensions are prototypical of a commercial PWR fuel rod assembly. Power for the rods is provided by a 750 kW DC power supply. The facility is capable of operating from 137-412 kPa, with rod temperatures up to 1 204°C. Reflood water can be delivered at constant or oscillatory rates up to 20.3 cm/s and up to 127°C.
TREAT (Transient Reactor Test Facility) *OPERATING*	Idaho National Laboratory	various SMR	The Transient Reactor Test Facility uses uranium oxide dispersed in graphite blocks to yield a core that affords strong negative temperature feedback. Automatically controlled, fast-acting transient control rods enable TREAT to safely perform extreme power manoeuvres – ranging from prompt bursts to longer power ramps – to broadly support research on postulated accidents for many reactor types.
UM Helical Coil Facility *OPERATING*	University of Michigan – Ann Arbor	iPWR	Helical coil facility for two-phase flow behaviour in a helical coil tube (with very high resolution instrumentation). It is water/air, but the instrumentation (high-speed X-ray) would work also for water/steam at high pressure.

Table C.1. **SMR safety-related experimental facilities for WC-SMRs** *(cont'd)*

Facility name *STATUS*	**Operator**	**Type of SMR(s) covered**	**Brief description of facility and test programme**
UIUC MTDL (Multiphase Thermo-fluid Dynamics Laboratory) *OPERATING*	University of Illinois – Urbana Champaign (UIUC)	WC-SMR	The MTDL Loop is a closed steam-water loop (pressure under 0.1-1 MPa) capable of capturing various two-phase phenomena. The phasic density ratio changes by one order of magnitude over the pressure range allowing the flexibility to highlight or suppress low pressure phenomena such as flashing. A wide flow rate range (1-20 GPM) is available, driven by natural circulation or forced convection. The modular test section is 5 m in height with previous experiments using a 3 m internally heated annulus followed by a 2 m adiabatic chimney. The channels are 1.5″ outer diameter and can contain a 0.75″ or 1″ diameter heater rod (up to 54 kW; uniform heat flux up to 300 kW/m^2). Instrumentation measures flow rate, pressure, temperature and two-phase parameters including radial profile. Transparent view ports allow for high-speed visualisation, and steady-state and periodic flows can be captured with dedicated techniques. Data has been generated for phenomena (boiling, flashing, condensation, and flow area transition) and systematic dynamics (single-phase natural circulation, two-phase natural circulation, and flashing instability), which has supported modelling, validation, and general experimental investigation.
UM Post-CHF Facility *OPERATING*	University of Michigan – Ann Arbor	iPWR	75 bar water/steam facility for high resolution measurements of two-phase flows from bubbly flow regimes all the way to post-CHF flow regimes.
UWM-HPCHF **(University of Wisconsin, Madison Thermal Hydraulics Laboratory; THL)** *OPERATING*	University of Wisconsin	iPWR	The CHF test facility is comprised of two interconnected loops. The low pressure loop is for Departure from nucleate boiling (DNB) and LOCA experiments in an annular flow channel geometry under atmospheric conditions with high-speed flow visualisation and a direct heated test section (40 cm in length). The high pressure loop allows DNB experiments under PWR and BWR prototypical conditions of temperature, pressure, and heat flux profiles (i.e. cosine shape); it is indirectly heated and can accommodate full length fuel pins. Experiments can be conducted for an annular flow channel with a single simulated pin (140 kW max power) or a 4 x 4 bundle (560 kW max power; 140 kW each). This loop is also capable of performing heat transfer experiments with supercritical water up to 25 MPa and 500°C. Fibre-Optic Distributed Temperature Sensors (FO-DTS) provide high-spatial and high-temporal resolution wall temperature measurements throughout the simulated fuel pin length detailing the DNB phenomenon This is valuable in the assessment of CHF location, peak cladding temperature, post-CHF heat transfer, rewetting characteristics, quenching etc. THL also has X-ray imaging to analyse simulated fuel pin integrity before/after testing to assess any damage to the rod (due to high temperatures during DNB).
VQSEC (Validation and Qualification Sciences Experimental Complex) *OPERATING*	Sandia National Laboratories	Applicable to both WC- and AT-SMRs	VQSEC in New Mexico is a unique group of experimental and computational capabilities that create and/or simulate a broad range of extreme operational or abnormal environments. The facilities are secure and remote, and are routinely used to perform tests with energetic and hazardous materials including: - detonation of large explosive charges - high velocity, high gas or rocket-assisted mechanical events - high heat flux fire tests, across a spectrum of fuel types.

References for SMR Safety-related experimental facilities for WC-SMRs:

Boado, H.J. et al. (1998), *Carem project: 1995 Status of Engineering and Development*, IAEA-TECDOC-999, 1 February 1998.

Delmastro, D. (2018), *Design and Technology Development of CAREM for Near-Term deployment, and the Status of the construction of CAREM25 prototype*, First Meeting of the Technical Working Group for Small Modular Reactors (TWG-SMR), April 2018, Vienna.

Grass, C. et al. (2022), *Experimental Investigation on Atmospheric Passive Spent-Fuel Pool Cooling by Two-Phase Closed Thermosyphons*, Proceedings of the NURETH 19, virtual meeting, 6-11 March 2022.

Ishihama, K. et al. (2013), "Development of a Plate Heat Exchanger for High-Temperature and High-Pressure", *Proceedings of the ASME 2013 Power Conference*, POWER2013-98061, Boston, 29 July to 1 August 2013.

Katono, K. et al. (2015), "Three-Dimensional Time-Averaged Void Fraction Distribution Measurement Technique for BWR Thermal Hydraulic Conditions Using an X-ray CT system", *Journal of Nuclear Science and Technology*, Vol. 52 (3), pp. 388-395, https://doi.org/10.1080/00223131.2014.952699.

Kim, S., Ishii, M. (2017), *Purdue University Thermal Hydraulic Experiment Facility – LWR & SMR Group*, Nuclear Thermal-hydraulics Capabilities Workshop, 13 July 2017, Idaho Falls.

Krüssenberg, A. et al. (2019), *Passive Lagerbeckenkühlung durch Wärmerohre - Verbesserung und Validierung numerischer Modelle*, Report GRS-564, September 2019.

Marquino, W. et al. (2014), "Analysis of HUSTLE test data and ESBWR application", *Proceedings of 2014 International Congress on Advances in Nuclear Power Plants* (ICAPP 2014), 6-9 April 2014, Charlotte.

NEA (2020), *Status Report on Reliability of Thermal-Hydraulic Passive Systems*, Draft – rev. 12, Status 31 July 2020.

Nishida, K. et al. (1994), "Spacer Effect on Liquid Film Flow and Critical Power in BWR Fuel Bundles", *Journal of Nuclear Science and Technology*, Vol. 31 (3), pp. 213-221.

Park, H.-S. (2023), *Korean SMART Design and Its Technical*, EG-SMR Meeting, 27 March 2023, Copenhagen.

Sanchez-Espinoza, V.H. et al. (2022), *The H2020 McSafer Project*, ETSON conference 2022: TSO Challenges for SMR Topics, 12 October 2022, Garching.

Sanchez-Espinoza, V.H. et al. (2021), "The H2020 McSafer Project: Main Goals, Technical Work Program, and Status", *Energies 2021*, Vol. 14, 6348, https://doi.org/10.3390/en14196348.

Takahashi, S. et al. (2013), "Development of BWR Steam Dryer Loading Evaluation Methods Through Scale Model Tests Under Actual Steam Conditions", *Proceedings of ASME 2013 Pressure Vessels and Piping Conference*, PVP2013-97564, 14-18 July 2013, Paris.

Table C.2. **SMR Safety-related experimental facilities for AT-SMRs**

Facility name ***STATUS***	**Operator**	**Type of SMR(s) covered**	**Brief description of facility and test programme**
Air ingress experimental apparatus (to be named) *IN PLANNING*	CNL/AECL	HTGR	An apparatus is being designed to study the onset of natural circulation of air through the core region in a postulated HTGR primary circuit break. Scaling down of the previous High-Temperature Air Ingress Facility (HTAIF) concept is in progress. Construction of the new apparatus is planned to start in 2024.
Advanced Fuels TRISO Facilities *IN DEVELOPMENT*	CNL/AECL	HTGR	TRISO analysis and manufacturing facilities. This includes development of TRISO particle manufacturing, production of fuel compacts/pellets, irradiation testing, and post irradiation examination.
Emissivity Bell-Jar Apparatus *UNDER CONSTRUCTION*	CNL/AECL	HTGR/MSR	Measurement of emisivity of non-metalic components at high temperature (up to 1 400°C)
HTTR *OPERATING*	JAEA (part of test data is public via papers)	HTGR	Demonstrate inherent safety features of HTGR under OECD/NEA/CSNI Loss of Forced Cooling (LOFC) project (see NEA (2011)) as a multilateral international co-operation.
HAIRE (Helium Air Ingress gas Reactor Experimental) *OPERATING*	University of Michigan – Ann Arbor	HTGR	The HAIRE facility provides insight into the flow phenomena associated with small and medium sized break air ingress accident scenarios of HTGRs. It is a scaled separate effect test facility (1/20 scaling of the general atomics GT-MHR). HAIRE provides high resolution experimental data (including pressure, temperature, oxygen concentration, and 2-D velocimetry) for both CFD and system code validation of the depressurisation and air ingress phases of the air ingress accident scenario. HAIRE also provided valuable insight about the additional variables that help to determine the depressurisation behaviour over time, as well as showing additional variables that determine the air ingress rate for small and medium sized breaks that were not previously discussed in nuclear literature. While the HAIRE facility is quite mature, it continues to provide meaningful data for CFD, system level codes, and even HTGR cavity design consideration.
RIMPLE (Refractive Index Matched PebbLe Bed facility) *OPERATING*	University of Michigan – Ann Arbor	HTGR	The RIMPLE facility is a new experimental facility to study the flow phenomena in HTGR pebble bed reactors during accident and steady-state conditions. Flow measurements take advantage of the refractive index matching technique where the spheres in the pebble bed are matched to the fluid's index of refraction. With a matched index of refraction the pebbles visually disappear during the experiment. The RIMPLE facility is unique to other pebble bed fluid dynamic experiments because of its scale. The facility takes advantage of quarter core symmetry, but retains the diameter ratio between the pebble and core diameter (1:50). Therefore over 15 000 spheres are present for the flow experiment in RIMPLE.
UWTHL (University of Wisconsin Thermal Hydraulics Laboratory) sCO_2 Loop *OPERATING*	University of Wisconsin	HTGR, GFR	UWTHL operates a Supercritical carbon dioxide pump cart that is capable of flow rates to 0.6 kg/s pressures to 4 000 psi and depending on configuration sCO_2 temperatures up to 800°C. The loop consist of a triplex pump with a series of recuperates to capture lost heat. The system can conduct heat exchanger tests and can be coupled to either the salt or sodium loops which are part of the THL suite of flow loops. The system can also be used to test valves, seals and other components that would be used in sCO_2 power cycles.

Table C.2. **SMR Safety-related experimental facilities for AT-SMRs** *(cont'd)*

Facility name *STATUS*	Operator	Type of SMR(s) covered	Brief description of facility and test programme
ATHENA *IN CONSTRUCTION*	RATEN-ICN	LFR	Lead large pool for integral tests, 10 m height, 3.2 m diameter, 800 tons coolant, components testing for LFR applications, 2.21 MW multi-assemblies core simulator.
BID-1 *OPERATING*	ENEA	LFR	Lead pool facility, coolant chemistry and oxygen control, coolant conditioning.
CHEM-LAB *IN CONSTRUCTION*	RATEN-ICN	LFR	Study of the coolant chemistry and lead conditioning.
CIRCE *OPERATING*	ENEA	LFR	Lead bismuth eutectic large pool, 10 m height, 1.2 I.D., 90 tons coolant. Pool Thermal-hydraulics, components testing, transient analysis, SGTR, coolant chemistry.
CORE *IN CONSTRUCTION*	newcleo	LFR	Loop facility, lead-cooled, coolant and oxygen control, material testing, flowing corrosion up to 650°C.
HELENA *OPERATING*	ENEA	LFR	Loop, 4 tons of lead, component testing, FIV study, pump characterisation, instrumentation qualification.
LIFUS-5 *OPERATING*	ENEA	LFR	Separated effect test facility, 100 litres pool, interaction between heavy liquid metals and water, coolant chemistry, pressure wave propagation study.
NACIE-UP *OPERATING*	ENEA	LFR	Lead bismuth eutectic loop, 250 kW wire wrapped FPS test section. heavy liquid metals thermal-hydraulics under gas enhanced and natural circulation regimes.
PERFORMANCE *OPERATING*	newcleo	LFR	Multipurpose loop-type facility, lead-cooled, component testing, mechanical pump. 2.5 MW installed.
PRECURSOR *PLANNED*	newcleo	LFR	Pool facility representative of the new-cleo LFR design, integral tests, proof of concept. 10 MW installed.
RACHEL *OPERATING*	ENEA	LFR	Heavy liquid metal laboratory, coolant chemistry and oxygen control, sensor testing, stagnant corrosion in lead.
SIRIO *OPERATING*	SIET	LFR (ALFRED)	Testing of a passive decay heat removal system with non-condensable gases, 20 m height, power-to-volume scaling approach with respect to the ALFRED DHR.
SEFACE *IN CONSTRUCTION*	KTH (no)	LFR	Experimental investigation of flow accelerated corrosion/ erosion of structural materials under different flow and temperature condition in molten lead.
CTF *IN CONSTRUCTION*	KTH (no)	LFR	Experimental facility for study of pump duty and impeller erosion and corrosion in molten lead.

Table C.2. **SMR Safety-related experimental facilities for AT-SMRs** *(cont'd)*

Facility name *STATUS*	Operator	Type of SMR(s) covered	Brief description of facility and test programme
COSTA *OPERATING*	KTH (no)	LFR	Experimental facility testing corrosion in stagnant liquid lead and lead bismuth eutectic. Includes small strain rate testing and connects to materials characterisation laboratories (SEM, XRD, EDX, XPS, etc.)
Heat Pipe Apparatuses *OPERATING*	CNL/AECL	Heat Pipe Reactors	A 5x5 array of sodium heat pipe in a steel monolith for testing of heat pipes during off-normal scenarios. Single heat pipes (sodium and potassium) to produce data for model development.
PHIRE (Potas-sium **H**eat p**I**pe expe**R**imental d**E**vice) *IN CONSTRUCTION*	Universität Stuttgart (Institut für Kernenergetik und Energiesysteme) IKE	MMRs like eVinci, Kilopower, and Megapower	High-Temperature Heat Pipe Test facility (test heat pipe < 4 m, operation temperature up to 700°C, heating and cooling power < 15 kW_{th})
SCARLETT – (Super-critical **Car**bon Dioxide Test Loop**)** *OPERATING*	Universität Stuttgart (Institut für Kernenergetik und Energiesysteme) IKE	SMRs, where CO_2 power cycles could be attached	CO_2-test loop for components of innovative power cycles attached to MicroSMR (<10 MW_{th}). The test section inlet conditions are: mass flow < 100 g/s, pressure < 14 MPa, temperature < 150°C, installed heating power = 36 kW, and cooling power (total) = 48 kW
Advanced Fuels Molten Salt Analysis Faci-lities *OPERATING + EXPANDING CAPABILITIES*	CNL/AECL	MSR	Capabilites for molten salt characterisation and verification of thermodynamic properties (Differential Scanning Calorimeter for melting points; Laser Flash for thermal diffusivity; Dilatometer for liquid density; and thermoconductivity). Corrosion of materials in contact with salts. Development of facilities for the synthesis of actinide flourides and chlorides. Molten salt fission product behaviour experiments in hot cell (flouride and flouride-cloride salts with UF and dissolved fission products; conducted in 2018). Simsalt production and experiments on fission product behaviour and retention in development including studies of conversion of UO_2 to UF. Initial testing with stable sim-salts and then potential irradiation of simsalts in later phases.
Molten Salt Natural Con-vection – Heat Transfer (MSNC-HT) loop. *IN COMMISSIONING*	CNL/AECL	MSR	Natural circulation loop for studying salt compatible R&D instumentation, and effects of small geometrical changes on natural convection flow. Generate data to benchmark codes.
Microwave self-heating fluid apparatus *IN DESIGN*	CNL/AECL	MSR	Study intrinsic differences between heat transfer behaviour under natural circulation for externally heated fluid and fluid with internal heat generation.
Amager Facilities *OPERATING*	Seaborg Technologies	MSR	• Large-scale salt component testing • Prototyping
Symbion Facilities *OPERATING*	Seaborg Technologies	MSR	• Fluoride salt laboratories • Thermal analysis • Microprep • Radiolab (under commissioning)
Titanhus Facilities *OPERATING*	Seaborg Technologies	MSR	• Hydroxide laboratories • Molten salt loop facilities • New loop platform (under commissioning)

Table C.2. **SMR Safety-related experimental facilities for AT-SMRs** *(cont'd)*

Facility name *STATUS*	Operator	Type of SMR(s) covered	Brief description of facility and test programme
UWTHL (University of Wisconsin Thermal Hydraulics Laboratory) **Chloride Salt Loop** *OPERATING*	University of Wisconsin	MSR	UWTHL operates a few molten chloride test loops. This loop operates with a MgCl2:KCL:NaCL salt but could be used with a variety of molten chlorides. The first loop is mainly designed for pump testing and is fabricated out of 2-inch pipe. It is equipped with a salt holding tank, a molten salt valve and venturi flow metre all capable of operation up to 750°C. This loop allows development of pump flow/head curves. There are ports for insertion and testing of probes. The second loop is constructed of 1-inch in 625 piping and is a simple rectangular loop able to do materials testing and diagnostic testing of different instruments. It has a hermetically sealed magnetic coupled pump and can gene-rate velocities in the test section up to 10 m/s. It is equipped with a calibrated venturi flow metre to measure flow rate. Chloride purification, the UW Thermal Hydraulics Laboratory also has chloride salt chemical purification facilities to purify up to 70 kg at a time.
UWTHL Flibe Loop *OPERATING*	University of Wisconsin	MSR	UWTHL operates a molten flibe (lithium fluoride Beryllium fluoride mixture) loop and flibe purification facilities. The loop is primarily designed for materials testing and is configured with two legs that can operate at different temperatures such as 750°C and 700°C. Velocities in the test sections range from 0-5 m/s approx., and 50 kW of heat can be added with cartridge heaters and are subsequently removed with an air cooler. The loop is designed to enable insertion and removal of samples during operation and without coming into contact with the atmosphere. This is achieved through a double ball valves sample retrieval system. The loop is also hermetically sealed (verified with helium leak detection) with a magnetic coupled custom molten salt pump. The system can accommodate long runs and insertion of test probes or samples.
UWTHL Nitrate Salt Loop *OPERATING*	University of Wisconsin	MSR	UWTHL operates a two story (20 feet tall) molten nitrate salt loop used for testing instrumentation, heat exchangers, heaters, coolers etc. The primary loop is constructed out of 2-inch pipe, the loop utilises on the order of 1 000 lb of molten salt and is pump at flow rates up to 120 GPM. The temperature limit is dictated by the salt decomposition of around 580°C and the loop currently has heat input and removal of about 30 kW. This loop can be coupled to a sCO_2 flow loop through a heat exchanger to test the performance of advanced heat exchangers.
JOYO *COMMISSIONING UNDER REGULATORY REVIEW*	JAEA (part of test data is public via papers)	SFR	Obtain irradiation test data for materials and fuels for SFR (Takamatsu et al., 2013).
PLANDTL (Plant Dynamics Test Loop) *OPERATING*	JAEA (part of test data is public via papers)	SFR	Investigate thermal-hydraulic behaviours of sodium by simulating core, primary main cooling system, secondary main cooling system, and decay heat removal system for SFR (Ono, et al., 2020). Natural circulation decay heat removal test programme under birateral SFR development collaboration.

Table C.2. **SMR Safety-related experimental facilities for AT-SMRs** *(cont'd)*

Facility name *STATUS*	**Operator**	**Type of SMR(s) covered**	**Brief description of facility and test programme**
CCTL (Core Component Thermal-hydraulic Test Loop) *OPERATING*	JAEA (part of test data is public via papers)	SFR	Thermal-hydraulic characteristics of fuel subassemblies and components in the thermal transportation system have been tested in the sodium loop (Kamide et al., 1998).
AtheNa (Advanced Technlogy Experiment Sodium (Na) Facility) *OPERATING*	JAEA (part of test data is public via papers)	SFR	Investigate sodium behaviour for enhancing the safety of SFR and demonstrating technology for the development of large-scale sodium components and systems (Imamura et al., 2019).
MELT *OPERATING*	JAEA (part of test data is public via papers)	SFR	Out-of-pile test facility to investigate the molten core material behaviour in SFR severe accidents. Molten material sodium interaction test and its data analysis under Japan-France SFR development collaboration (Journeau et al., 2022).
SWAT (Sodi-um-water Reactor Test Rig) *OPERATING*	JAEA (part of test data is public via papers)	SFR	Test facility to evaluate the tube failure / pressure propagation caused by water leak from heat transfer tube in steam generator of SFR (Beauchamp et al., 2013).
STELLA-2(ITF) *OPERATING*	KAERI	SFR	STELLA-2 supports the PGSFR (150 MW_e) and SALUS (100 MW_e). It has 1/5-height and 1/125-volume of PGSFR and can simulate the trasients to evaluate plant dynamic behaviours and to demonstrate its decay heat removal performance. Scaling: 1:5-height and 1:125-volume of PGSFR.
MISOH1 & 2 *OPERATING*	University of Michigan – Ann Arbor	SFR	Experimental facilities to investigate the behaviour of sodium heat pipes with high resolution instrumentation. #1 facility is for an individual heat pipe. #2 facility is for a mini core to investigate the effect of a heat pipe failure on the heat redistribution and potential occurrence of cascade failure effects for multiple heat pipes.
NaSCoRD *HISTORICAL DATABASE*	Sandia National Laboratories	SFR	NaSCoRD (Sodium System and Component Reliability Database) mission is to re-create the capabilities of the legacy Centralized Reliability Database Organization (CREDO) database. The CREDO database provided a record of component design and performance documentation across various systems that used sodium as a working fluid but was lost by its US custodian in the 1990s. Raw data of US origin was only recently recovered from JAEA with whom the US had established a joint database. This NaSCoRD database uses reconstructed CREDO data (CREDO-I) with reliability information sourced from operational documents, unusual occurrence reports, and design documents, called CREDO-II.

Table C.2. **SMR Safety-related experimental facilities for AT-SMRs** *(cont'd)*

Facility name *STATUS*	Operator	Type of SMR(s) covered	Brief description of facility and test programme
UWTHL (University of Wisconsin Thermal Hydraulics Laboratory) Sodium loops *OPERATING*	University of Wisconsin	SFR	The UWTHL operates several liquid sodium loops, which are located in an underground building with reactive metal fire suppression and a 3 000 SCFM water cyclone exhaust system and stack to handle any potential planed or unplaned sodium fires or burns. The facility currently has approximately 400 gallons of sodium inventory and five different loops designed to look at different thermal-hydraulic phenomena. Two of the loops of similar flow rate and configurations (rectangular flow loop geometry with 1.315 OD pipe) are used for heat transfer measurements and instrument testing. Each of these loops uses a moving magnet pump capable of 30 GPM and 20 ft of head and can be operated at temperatures from 150-700°C.

References for SMR safety-related experimental facilities for AT-SMRs:

Beauchamp, F. et al. (2013), "Cooperation on impingement wastage experiment of Mod. 9Cr-1Mo steel using SWAT-1R sodium-water reaction test facility", *Proceedings of International Conference on Fast Reactors and Related Fuel Cycles*; Safe Technologies and Sustainable Scenarios (FR13), 4-7 March 2013, Paris.

Imamura, H. et al. (2019), *Construction of the sodium test loop in advanced technology experiment sodium facility (AtheNa)*, JAEA-Technology 2019-005, 163 pages (in Japanese).

Journeau, C. et al. (2022), "French-Japanese experimental collaboration on fuel-coolant interactions in sodium-cooled fast reactors", *Proceedings of International Conference on Fast Reactors and Related Fuel Cycles*; Sustainable Clean Energy for the Future (FR22), IAEA, Paper CN291-302, 19-22 April 2022, Vienna.

Kamide, H. et al. (1998), "An Experimental study of inter-subassembly heat transfer during natural circulation decay heat removal in fast breeder reactors", *Nuclear Engineering and Design*, Vol. 183, pp. 97-106.

NEA (2011), *Loss of Forced Coolant (LOFC) Project*, https://oecd-nea.org/jcms/pl_25168/loss-of-forced-coolant-lofc-project.

Ono, A. et al. (2020), "Preliminary Analysis of Sodium Experimental Apparatus PLANDTL-2 for Development of Evaluation Method for Thermal-Hydraulics in Reactor Vessel of Sodium Fast Reactor Under Decay Heat Removal System Operation Condition", *Mechanical Engineering Journal*, Vol. 7 (3), pp. 19-00546.

Takamatsu, M. et al. (2013), *Restoration work for obstacle and upper core structure in reactor vessel of experimental fast reactor Joyo (2)*, 4-7 March 2013, Fast reactors and Related Fuel Cycles: Safe technologies and Sustainable Scenarios (FR13), Paris.

Table C.3. **Existing experimental facilities for possible use in investigation of SMR safety issues**

Facility name *STATUS*	Operator	Type of SMR(s) covered	Brief description of facility and test programme
ZED-2 (Zero Energy Deuterium) Reactor	CNL/AECL	Various	ZED-2 is a versatile tank type, heavy water moderated low power research reactor. It has the flexibility to accept large experimental assemblies with few restrictions, and It is primarily used for performing reactor physics measurements and fuel studies in the development of neutron cross-section data and for instrumentation development. This facility has been utilised extensively over many decades in support of CANDU reactors, and today supports the development of new reactor designs and advanced fuel cycles. ZED-2 is currently being assessed in terms of its abilities to support various proposed SMR designs.
NOKO *CLOSED*	FZJ (part of test data is public via papers)	BWR	Not dedicated to SMR but passive systems (emergency condenser, building condenser, plate condenser, passive pressure pulse transmitters) (Fethke et al., 1998; Schaffrath et al., 1999).
PKL (Primärkreislauf) *CLOSED*	Framatome	PWR	Not dedicated to SMR but relative to passive systems (safety condensers).
LSTF (Large-Scale Test Facility) (ROSA/AP600) *OPERATING (AP600 COMPONENTS CLOSED)*	JAEA/USNRC (part of test data is public via papers)	PWR/ Westinghouse AP600	Modified LSTF provides a 1/30.5 volumetric-scaled full height model of AP600 based on power-to-volume scaling (Kukita et al., 1996). Contribute to certificate of conformity for AP600 through confirmation of effectiveness of passive safety systems (Yonomoto et al., 1997; and Yonomoto et al., 1998).
HFR *OPERATING*	NRG	All	The High Flux Reactor is a material test reactor which can be used for fuel and material R&D for all types of nuclear reactors, including all types of SMRs.
PALLAS *IN CONSTRUCTION*	NRG	All	The PALLAS reactor is aimed at replacing the HFR. Apart from production of medical isotopes, also R&D for fuel and material will be accommodated www.pallasreactor.com).
HOR *OPERATING*	TUD	All	The Hoger Onderwijs Reactor is a research reactor at the TU Delft which is available for fuel and material R&D for all types of nuclear reactors.
LASS *OPERATING*	CIEMAT	Non-specific	LASS is designed for aerosol & thermal-hydraulics investigation and safety systems performance testing. LASS houses the PECA facility, which was designed to withstand temperatures and pressures around 140°C and almost 3 bar, respectively. With an 8 m^3 vessel, so far experimental campaigns on pool scrubbing; aerosol agglomeration; gas submerged injection; SGTR-secondary system filtering effect; etc. have been experimentally addressed in the frame of national and international projects (CIEMAT, 2018).

Table C.3. **Existing experimental facilities for possible use in investigation of SMR safety issues** *(cont'd)*

Facility name *STATUS*	**Operator**	**Type of SMR(s) covered**	**Brief description of facility and test programme**
Studsvik Hot cells *OPERATING*	Studsvik	non-specific	In addition to LOCA and Fuel integrity during interim storage also have capabilities for out-of-pile RIA, new materials properties verifications. Advanced characterisation capabilities for both fuel and materials studies, e.g.: OM with hardness measurements, SEM/FIB/EDS/WDS/EBSD/in-situ heating/mechanical testing, XRD (crystal structure, phase composition, residual stress measurements), ICP-MS, ICP-OES, Gas-MS, Laser ablation coupled with ICP-MS, STA (TGA, DSC, online gas mass spectrometry), thermal hot bridge (thermal diffusivity), carbon and sulphur analysis, ferritescope measurements, residual stress measurements, oxygen and nitrogen analysis.
Chalmers – Fuel laboratory *OPERATING*	Chalmers University of Technology	All	Fabrication facility for full actinide fuels.
Chalmers – Alpha laboratory *OPERATING*	Chalmers University of Technology	All	Fully licenced for handling of substantial amounts of alpha active material.
Chalmers – Gamma laboratory *IN RENOVATION*	Chalmers University of Technology	All	Hot cell with manipulators.
Chalmers – Gamma irradiation source *OPERATING*	Chalmers University of Technology	All	Co-60 source with max dose rate of 5 kGy/h.
Chalmers – Interaction lab *OPERATING*	Chalmers University of Technology		Facilities for investigating fuel/coolant/cladding interactions. Tested with MOX, nitrides and molten sodium and molten lead (and lead/bismuth).
Odqvist laboratory *OPERATING*	KTH	All	The KTH engineering mechanics laboratory. Mechanical testing of materials and components, fluid mechanical testing, high-speed imaging, etc. Not for active materials.
Hultgren laboratory *OPERATING*	KTH	All	The KTH central materials science laboratory. Wide range of advanced micro-structural characterisation techniques available. Not for active materials.
BETTAN *OPERATING*	Uppsala University	All reactor types using defined fuel geometries	Test facility for developing tomographic methodologies for use on irradiated fuel assemblies. The goal is to supply the industry and regulator with instruments for PIE and safeguards.
NESSA *IN CONSTRUCTION*	Uppsala University	General purposes	High-intensity neutron source for supporting activities in development of e.g. new structural materials and education.

Table C.3. **Existing experimental facilities for possible use in investigation of SMR safety issues** *(cont'd)*

Facility name *STATUS*	Operator	Type of SMR(s) covered	Brief description of facility and test programme
PANDA *OPERATING*	PSI	Water-cooled (PWR/iPWR/BWR, e.g. Rolls-Royce SMR, SMART, NuScale, Holtec-160, NUWARD, BWRX-300)	PANDA is a large-scale, multi-compartment facility dedicated to containment cooling, suppression pool phenomena, passive safety systems, heat transfer from immersed containment to water pool, condensation, and natural circulation Pressure: 0.2-10 bar Power: 1.5 MWe Loop height: 25 m (possible up to 30 m)

References for existing experimental facilities for possible use in investigation of SMR safety issues:

CIEMAT (2018), *LASS: Laboratory for Analysis of Safety Systems – Facility and Experiments*, Madrid.

Fethke, M., A. Schaffrath et al. (1998), "Experimental investigation of the operation mode of passive safety systems", *Proceedings of ENC '98 World Nuclear Congress*, 25-28 October 1998, Nice.

Kukita, Y. et al. (1996), "ROSA/AP600 testing: Facility modifications and initial test results", *Journal of Nuclear Science and Technology*, Vol. 33 (3), pp. 259-265.

Schaffrath, A. et al. (1999), "Experimental and analytical investigations of the operation of the emergency condenser of the SWR1000", *Nuclear Technology*, Vol. 126(5), pp. 123-142.

Yonomoto, T. et al. (1997), "Core makeup tank behaviour observed during the ROSA-AP600 experiments", *Nuclear Technology*, Vol. 119, pp. 112-122.

Yonomoto, T. et al. (1998), "Heat transfer analysis of the passive residual heat removal system in ROSA/AP600 experiments", *Nuclear Technology*, Vol. 124 (1), pp. 18-30.

Annex D. Projects focused on SMR safety

Provided below are the results of the EGSMR information collection on national and multi-national projects focused on SMR safety. The collection also includes lists of Euratom projects and other activities underway at the IAEA, GIF, and NEA.

The responses are provided in alphabetical order by country (with each country presented in a separate table), followed by the Euratom project summary at the end. Note that some countries reported on the international (Euratom, IAEA, GIF, and NEA) projects, which they are involved resulting in some duplication across this collection. The organisations and countries that contributed to this collection are as follows:

- 18 organisations (ANVS, Bel V, CEA, CNL, CNSC, Euratom, GRS, GIF, Hitachi-GE, IAEA, IFE, JAEA, KAERI, KIT, MHI, NEA, NRG, SSM, Tractebel, TU Delft, USNRC)

from

- 10 countries (Belgium, Canada, France, Germany, Japan, Netherlands, Norway, Korea, Sweden and the United States)

Table D.1. **National and multi-national projects (Belgium: Bel V and Tractebel)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
Bel V				
ETSON SMR Report	IRSN	PWR	Ongoing	Challenges and opportunities for licensing process and safety assessment of light water small modular reactors (LW-SMRs).
Tractebel				
EU, NEA, and IAEA projects	various	various	Ongoing	Tractebel co-operates in EU, NEA and IAEA projects related to SMR safety.

Table D.2. **National and multi-national projects (Canada: CNL and CNSC)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
CNSC				
NSERC-CNSC SMR Grant	Canada – NSERC-CNSC	All	Upcoming (Grant programme and research to begin in 2023)	This is a five-year SMR Research Programme that CNSC is administering through the Natural Sciences and Engineering Research Council (NSERC). The NSERC-CNSC SMR Grant Initiative is a CAD 15 million programme and research will begin later this calendar year. Research AOIs include: • Chemistry and materials (consequences of high temperature on reactor components, chemistry control for various materials and fuel types) • Environmental and radiological protection (source term characterisation, geotechnical and effect of the environment on SMR design and operation, emergency planning) • Human and organisational factors (interface design, digital I&C) • Safeguards and security (cybersecurity, safeguards inspection methods) • Novel fuel compositions
CNL				
AECL-FNST Work Plan	Canada – AECL/ CNL	All	Ongoing	This national programme administered by the AECL includes science and technology work related to SMRs (both water-cooled and advanced designs) including safety. Safety-related projects include modelling/analysis and experiments covering a variety of topics including safety analysis, materials, chemistry, fuel performance and manufacturing (including molten salt and TRISO fuel types), thermal-hydraulics, containment physics, hybrid energy systems, and severe accidents.
CNRI	Canada – CNL	All	Ongoing	The Canadian Nuclear Research Initiative is a collaborative research programme with an annual intake of proposals for commercial projects with clean energy technology and SMR vendors/developers, as well as academia, to pursue collaborative work in key focus areas, including specific issues/phenomena related to design, development, and safety of advanced reactors.
CEDIR	Canada – CNL	All	Ongoing	The Clean Energy, Demonstration, Innovation, and Research (CEDIR) Initiative was developed to support the research, development and demonstration of the clean energy technologies needed to help the Government of Canada achieve its national target of net zero by 2050. The initiative has two phases: 1) CEDIR Labs focusing on modelling, simulation and benchtop experiments of various aspects of low-carbon technologies and hybrid energy systems. 2) CEDIR Park, is a future vision of a collaborative research park where clean energy technologies can be developed and demonstrated within a hybrid energy system.

Table D.2. **National and multi-national projects (Canada: CNL and CNSC)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
EGSMR (NEA)	NEA	All	Ongoing	The CSNI organised EGSMR seeks to assess the SMR safety landscape, identify important AOIs and suggest specific actions for CSNI to take in support of SMR safety. CNL is participating in and chairing this expert group.
SASPAM-SA (EU Project)	Euratom	Water-cooled SMRs (iPWR primary; small BWR secondary)	Ongoing	The SASPAM-SA EU project is focused on severe accident behaviour of water-cooled SMRs including passive safety systems (see full description in Euratom projects list). CNL is participating with integrated severe accident analysis, experimental data/benchmarking on iPWR containment behaviour, and evaluations of EPZs and emergency response for SMR.
IAEA CRP on EPZ (I31029)	IAEA	All		Participation in IAEA CRP I31029 Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for Emergency Planning Zone for SMR Deployment. IAEA TECDOC summarising the CRP work and outcomes is currently in preparation.
GIF RSWG	GIF	All (especially advanced technology/ Generation IV designs)		Membership in the GIF Risk and Safety Working Group (RSWG). The RSWG advises the GIF Experts Group and Policy Group on matters related to the safety of Gen-IV systems and leads GIF interaction with the IAEA and the NEA WGSAR (now WGNT).
ECC-SMART Project	Euratom, Canada, China	Supercritical Water Reactor (SCWR)	Ongoing	Oriented towards assessing the feasibility and identification of safety features of an intrinsically and passively safe small modular reactor cooled by supercritical water (SCW-SMR), taking into account specific knowledge gaps related to the future licensing process and implementation of this technology. ECC-Smart (ecc-smart.eu)

Table D.3. **National and multi-national projects (France: CEA)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
CEA				
ELSMOR	Lead -VTT	iSMR	Ongoing	Dedicated to assessing the feasibility of a European SMR licensing
TANDEM	Lead – CEA	iSMR	Ongoing	Dedicated to the integration of SMR plant in a global cogeneration or hybrid electricity smart grid (with renewables)
PASTELS	Lead – EDF	PWR	Closed	Dedicated to the passive systems reliability assessment and validation code (safety condensers)
SASPAM	Lead – ENEA	iSMR	Ongoing	Dedicated to the severe accident mitigation demonstration for a European SMR

Table D.4. **National and multi-national projects (Germany: GRS, KIT)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
GRS				
SMR Study	GRS	All types of SMR	Completed	This report documents the work and results of the project RS1521 *Study of Safety and International Development of Small Modular Reactors (SMR)*. The aims of this study are • setting-up of a sound overview on SMR • identification of essential issues of reactor safety research and future R&D projects • identification of needs for adaption of system codes of GRS used in reactor safety research.
THYR Study	GRS	Several Thorium and Hybrid Reactors (THYR)	Completed	This report documents the work and results of the project RS1578 *Study of Safety and International Development of THYRs*. The aims of this study are • setting-up of a sound overview on THYRs • identification of essential issues of reactor safety research and future R&D projects • identification of needs for adaption of system codes of GRS used in reactor safety research.
FENNECS	GRS	Several types of SMRs	Completed	The objective of this research project is the further development of the 3-d few-group neutron kinetic code FENNECS for the safety assessment of (v)SMR – (very) Small and Medium size Reactors – and advanced and innovative reactor systems with complex and irregular geometries. The peculiarities of the cores of such systems or concepts are, e.g., their compactness, which can have large neutron flux gradients and increased leakage, long cycle times, their complex geometries that deviate from regular grids and their heterogeneous material composition with special fuels, absorbers and cooling media.
AC^2 Development and Validation	GRS	Several types of SMRs	Completed and ongoing	There are multiple challenges for the AC^2 system code package regarding model improvements and validation for SMRs, which GRS is in the process of resolving. Consequently, GRS' new nationally funded projects for the development and validation of AC^2 put a specific focus on issues related to advanced LWR and integral PWR SMR reactor designs. This is accompanied by collaborations with national and international partners on specific topics. There is ongoing work in AC^2 module COCOSYS development and validation to improve models for passive containment cooling systems, covering both heat exchangers with natural circulation heat transfer to external water pools and condensation heat transfer at large containment structures.
VASIL	GRS	Several types of SMRs	Ongoing	GRS initiated the national research alliance VASIL. One objective is the implementation and validation of dedicated models for innovative heat exchangers of the compact plate, bayonet and helically coiled type. Also, improved models for evaporation from water pools will be implemented. Finally, AC^2/ATHLET is validated by performing test calculations for generic input decks of extant SMR designs and assessing their quality against available information in the literature.

Table D.4. **National and multi-national projects (Germany: GRS, KIT)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
PALAWERO	GRS	SMRs using heat pipe e.g. for cooling of water pools	Completed	Within a joint national R&D project, GRS has improved ATHLET models for water-filled wickless heat pipes (thermosiphons) proposed for cooling of water pools (e.g. in which SMR containments are submerged) and validated them against dedicated experiments at the University of Stuttgart. This work continues with the PALAWERO-II project, where further improvements for ATHLET models will be derived, implemented and tested against experiments at the ATHOS test facility in Stuttgart.
MISHA	GRS and IKE	Liquid potassium heat cooled MMRs	Ongoing	Extension of the national computational simulation chain for MMRs and validation against experimental and analytical results (e.g. the special purpose reactors designs A and b). This includes inter alia • creation of a 3D neutronics model for analyses using the GRS code FENNECS and validation • further development of AC^2 module ATHLET for MMR with potassium-filled heat pipes, validation and qualification against published reference data • experiments on potassium-filled HPs to support model development • further development of ATHLET for CO_2 and air-based Joule cycles as operational heat rejection for power generation • specification of a consistent MMR model and qualification of the computational chain through integral simulations of MMR operational and accident behaviour.
SiFeKo	MPA Stuttgart	Several types of SMRs	Ongoing	The aim of the research cluster is to build up wide-ranging competencies for the safety assessment of the new reactor types in connection with SMR. The focus is on manufacturing, damage developments and effects, and to be able to evaluate the safety of such plants accordingly.
NukSiFutur	Universität der Bundeswehr München	Several types of SMRs	Ongoing	The NukSiFutur junior research group con-tributes to the completion of the analysis chain for nuclear safety. The aim is to improve CFD simulations for multi-physics problems with pronounced multi-scale, i.e. generally turbulent, multiphase, non-isothermal and reactive flows.
KIT				
InnoPool SMR	Germany	LW-SMR	Ongoing	BMBF funded strategic initiative to study the safety of SMRs in the HGF-centres (KIT, HZDR and FZJ) devoted to core physics, transient analysis, containment issues.

Table D.4. **National and multi-national projects (Germany: GRS, KIT)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
McSAFER H2020	Germany (COOR), Belgium, Sweden, Finland, Czech, Spain, Argentina, UK, France	LW-SMR (natural circulation, forced convection, boron /no boron free concepts, HEX and SQUARE FAs)	Ongoing, started in 2020 and will end in February 2024	KIT is co-ordinator of McSAFER. The goal is to improve the safety analysis methods for design-basis accident and it includes multi-physics/multi-scale methods. Investigations are complemented by an experimental programme at 3 EU Facilities located at KIT (COSMOS-H), LUT (MOTEL) and KTH (HWAT), where safety-relevant experiments for the core, helical HX representative for different SMR designs (F-SMR, CAREM, SMART, NuScale) are being performed. The different safety analysis methodologies will be applied to investigate accidents like REA (SMART, NuScale), cold water injection (F-SMR, CAREM), boron dilution (NuScale), ATWS (SMART) and SLB (NuScale, SMART) and they will be benchmarked to each other. The experimental data generated in McSAFER will be used to validate different kind of thermal-hydraulic codes e.g. CFD, sub-channel, and system thermal-hydraulic codes.
EU Horizon Europe project SASPAM-SA	Italy (COOR), Germany, Switzerland, Belgium, France, Czech, Finland, Spain, Lithuania, Romania, Ukraine, Bulgaria,	LW-SMR (two designs; see description)	Started in October 2022 and will last for 4 years	The focus is on investigations of severe accidents of two generic SMR designs with different severe accident codes, assess the experimental data base for IVMR-phenomena, accident management, radiological dispersion and impact around the site. Containment issues is also an important goal of the investigations using different kind of tools including CFD. **Design 1:** Generic iPWR characterised by a submerged containment and electric power of about 60 MWe. **Design 2:** generic iPWR characterised by the use of several passive systems, a dry containment and an electric power of about 300 MWe.

Table D.5. **National and multi-national projects (Japan: Hitachi-GE, JAEA, MHI)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
Hitachi-GE				
OPG's Darlington new nuclear project	OPG in Canada, GE Hitachi Nuclear Energy (Hitachi-GE Nuclear Energy will support this project)	BWRX-300	Ongoing	Deploy a BWRX-300 SMR at the Darlington new nuclear site that could be completed as early as 2028.
PRISM	GE Hitachi Nuclear Energy/Hitachi-GE Nuclear Energy	PRISM	Ongoing	Introduce PRISM to Japan.
RBWR	Hitachi-GE Nuclear Energy /US and UK academia	RBWR	Ongoing	Conduct benchmarking for nuclear analysis codes for RBWR in collaboration with US (i.e. UCB and UM) and UK academia (i.e. University of Cambridge).

Table D.5. **National and multi-national projects (Japan: Hitachi-GE, JAEA, MHI)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
JAEA				
NEA/CSNI LOFC project	JAEA (Czech Republic, France, Germany, Hungary, Japan, Korea and the United States)	HTGR	Ongoing	Demonstrate inherent safety features of HTGR to validate code predictive capability and accuracy of models, through LOFC tests and loss-of-coolant flow test by the HTTR.
Mitsubishi Heavy Industries (MHI)				
Mitsubishi Small PWR	MHI	iPWR	Ongoing	Develop plant conceptual design by using Japanese government (Ministry of Economy, Trade and Industry) subsidies.
Mitsubishi HTGR	MHI	HTGR	Ongoing	Develop plant conceptual design by using Japanese government (Ministry of Economy, Trade and Industry) subsidies.
Mitsubishi Micro-Reactor	MHI	Micro Reactor	Ongoing	Develop plant conceptual design by using Japanese government (Ministry of Economy, Trade and Industry) subsidies.
MCR (Mitsubishi Compact Reactor)	MHI/MFBR	SFR	Ongoing	Develop plant conceptual design by using Japanese government (Ministry of Economy, Trade and Industry) subsidies.

Table D.6. **National and multi-national projects (Netherlands: AVNS, NRG, TU Delft)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
AVNS and NRG				
WSMR	NRG (Netherlands)	iPWR	Completed	Safety analyses for the Westinghouse SMR.
SMR	NRG (Netherlands)	All	Ongoing	Drafting of a white-paper on SMR for Dutch government and public.
GEMINI4.0	NCBJ (Poland)	HTGR	Ongoing	Safety analyses for the GEMINI HTGR prismatic block reactor design.
FALCON	Ansaldo Nucleare (Italy)	LFR	Ongoing	Safety analyses for the ALFRED reactor design.
SEALER	LeadCold (Sweden)	LFR	Completed	Safety analyses for the SEALER reactor design and its electric mock-up SEALER-E.

Table D.6. **National and multi-national projects (Netherlands: AVNS, NRG, TU Delft)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
HTTF	OECD/NEA	HTGR	Starting	Preparation for participation to the future OECD/NEA benchmark on the US High-Temperature Test Facility (HTTF) safety analyses.
RMV	NRG (Netherlands)	iPWR	Completed	Implementation of reflood models in the SPECTRA system thermal-hydraulics code.
Thorizon	Thorizon (Netherlands)	MSR	Ongoing	Design of a modular MSR (www.thorizon.com/)
TU Delft				
Ubattery	TUD (Netherlands)	HTR	Ongoing	Design of a micro reactor.
MIMOSA	TUD (Netherlands)	MSR	Ongoing	Plutonium burning in small MSR.

Table D.7. **National and multi-national projects (Norway: IFE)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
IFE				
Halden HTO Project	Institute for Energy Technology, Norway	Studies are not limited to a particular SMR design	Ongoing	The focus and scope of these efforts include: • Staffing • Human-machine interface • Organisational factors • Human performance • Management of unplanned/unanticipated events • Safety management • Automation • Evolving concepts of operation • Human factors • Teamwork, crew roles, conduct of operations

Table D.8. **National and multi-national projects (Korea: KAERI)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
KAERI				
SMART	Korea, KSA	iPWR	Completed	SMART is an integral PWR with a rated electrical power of 110 MWe from 365 MWt. The first standard design approval (SDA) is issued in July 2012 but with further modification it is in the last phase for the second SDA of SMART100 expected to be issued within 2023.
iSMR	Korea	iPWR	Ongoing	The "iSMR" is an innovative small modular PWR producing 540 MWt with an electrical power of 170 MWe. It has fully passive safety systems and is in the conceptual design phase with the target of SDA in 2028.
PGSFR	Korea	SFR	Pending	The PGSFR is a pool-type SFR with a rated electrical power of 150 MWe from 392.2 MWe. After the specific design safety analysis report (SDSAR) was issued in 2017, the project has been suspended and waiting for determining the national nuclear spent management policy.
SALUS	Korea	SFR	Ongoing	SALUS is a pool-type SFR with a rated electrical power of 100 MWe with 268 MW thermal power. It is a long-term sustainable SMR with a cycle length of 20 years and is exploring its licensability.

Table D.9. **National and multi-national projects (Sweden: SSM)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
SSM				
McSAFER (Euratom)	KIT	iPWR	Ongoing	Development, improvement, validation, and application of numerical simulation tools (traditional, advanced low-order and high-fidelity) validated with experimental data generated in European facilities (COSMOS-H, MOTEL, HWAT) that are relevant for the majority of SMR designs.
SUNRISE	KTH	LFR	Ongoing	Development of R&D platform for materials and components' testing in support of design and safety analysis of a Swedish lead-cooled research reactor (SUNRISE-LFR) and an electrical mock-up prototype (Solstice).
FREDMANS (Euratom)	Chalmers	LFR	Ongoing	Nuclear fuel design and manufacturing methods for lead-cooled SMRs.
PASCAL (Euratom)	ENEA	LFR	Ongoing	To pave the way to the future licensing of LFRs and ADSs by supporting the further advancement of the pre-licensing of the ALFRED and MYRRHA demonstrators in line with the priorities identified by the European Sustainable Nuclear Industrial Initiative (ESNII). Safety of the fuel, reactor coolant systems and containment.

Table D.9. **National and multi-national projects (Sweden: SSM)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
SASPAM (Euratom)	ENEA	iPWR	Ongoing	A sound demonstration of iPWR ability to address the challenges posed by SA with particular emphasis on specific accident management aspects, for example: In Vessel Melt Retention (IVMR), Ex-vessel phenomena and fission products release to the environment. Two reference generic iPWR designs with forced and natural primary coolant circulation
Solstice	SMR AB	LFR	Ongoing	An electrically powered non-nuclear prototype for the SUNRISE-LFR and the SEALER-55 reactors is under construction at Oskarshamn. The facility will be used for testing and verifying materials and technology in an environment of molten lead at high temperatures
ANItA	Sweden (Uppsala University)	LWR SMRs and AMRs	Ongoing	Gather the Swedish academic and industrial nuclear technology competence onto one platform. The mission is through multidisciplinary research and development work, supply the political sphere and policy makers with knowledge-based information to be able to implement SMRs as fast as possible in Sweden. ANIta – Uppsala University, Sweden (uu.se)

Table D.10. **National and multi-national projects (United States, US: USNRC)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
USNRC				
ETHARINUS	NEA	Non-specific, but relevant to SMRs with straight-tubed, decay heat removal heat exchangers	Ongoing	One of the objectives of ETHARINUS is to investigate the performance of passive heat removal systems. The project scope also facilitates a common database to contribute to the experimental verification of cool down procedures, operation modes and systems (including passive ones) for different transients.
ATLAS	NEA (operated by KAERI)	Non-specific, but relevant to SMRs that use natural circulation and passive safety systems	Ongoing	Full pressure integral effects test facility scaled to APR1400 with additional systems beyond those in APR1400. A large focus on beyond design-basis events or design extension conditions, natural circulation, and passive safety systems yields large applicability to SMRs.

Table D.11. **Multi-national projects (Euratom)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
Euratom				
ELSMOR	Co-ordinated by VTT - Teknologian Tutkimuskeskus Oy (Finland) (15 participants, 8 countries)	Light Water (LW)	Duration 42 months, Start date 1 September 2019, End date 28 February 2023	Towards European Licensing of Small MOdular Reactors https://cordis.europa.eu/project/id/847553 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
McSAFER	Co-ordinated by KIT – Karlsruher Institut fuer Technologie (Germany) (12 participants, 9 countries)	LW	Duration 36 months, Start date 1 September 2020, End date 31 August 2023	High-Performance Advanced Methods and Experimental Investigations for the Safety Evaluation of Generic SMRs https://cordis.europa.eu/project/id/945063 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
SASPAM-SA	Co-ordinated by ENEA (Italy) (21 participants, 13 countries)	LW	Duration 48 months, Start date 1 October 2022, End date 30 September 2026.	Safety Analysis of SMR with PAssive Mitigation strategies – Severe Accident https://cordis.europa.eu/project/id/101059853 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
GEMINI+	Co-ordinated by Narodwe Centrum Badan Jadrowych (Poland) (26 participants, 12 countries)	HTGR	Duration 42 months, Start date 1 September 2017, End date 28 February 2021	Conceptual design for a HTGR for supply of process steam to industry, a framework forthe licensing of such system and a business plan for a full-scale demonstration https://cordis.europa.eu/project/id/755478 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
ECC-SMART	Co-ordinated by Centrum Vyzkumu Rez Sro (Czech Republic) (19 participants, 16 countries)	SCWR	Duration 48 months, Start date 1 September 2020, End date 31 August 2024	Joint European-Canadian-Chinese Development of Small Modular Supercritical Water-cooled Reactor Technology https://cordis.europa.eu/project/id/945234/reporting https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
GEMINI For Zero Emission	Co-ordinator: Framatome (France) (26 participants, 14 countries)	HTGR	Duration 36 months, Start date 1 June 2022, End date 31 May 2025	Nuclear cogeneration, polygeneration, decarbonisation, high emperature reactor https://cordis.europa.eu/project/id/755478/reporting https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf

Table D.11. **Multi-national projects (Euratom)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
ANSELMUS	Co-ordinator: SCK-CEN (Belgium) (15 participants, 9 countries)	Liquid Metal	Duration 48 months, Start date 1 September 2022, End date 31 August 2026	Advanced Nuclear Safety Evaluation of Liquid Metal Using Systems https://cordis.europa.eu/project/id/101061185 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
ESFR-SIMPLE	Co-ordinator: CEA (France) (11 participants, 9 countries)	Sodium Fast Reactor	Duration 48 months, Start date 1 October 2022, End date 30 September 2026	European Sodium Fast Reactor - Safety by Innovative Monitoring, Power Level flexibility and Experimental research https://cordis.europa.eu/project/id/101059543 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
MIMOSA	Co-ordinator: ORANO (France) (12 participants, 4 countries)	Molten Salt reactors	Duration 48 months, Start date 1 June 2022, End date 31 May 2026	Multi-recycling strategies of LWR SNF focusing on Molten Salt technology https://cordis.europa.eu/project/id/101061142 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
TANDEM	Co-ordinator: CEA (France) (17 participants, 9 countries)	LW and GEN-IV	Duration 36 months, Start date 1 September 2022, End date 31 August 2025	SMR for a European safe and Decarbonised Energy Mix https://cordis.europa.eu/project/id/101059479 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf
HARMONISE	Co-ordinator: Lietuvos Energetikos Institutas (Lithuania) (22 participants, 11 countries)	Licensing of fusion and fission installations	Duration 36 months, Start date 1 June 2022, End date 31 May 2025	Towards harmonisation in licensing of future nuclear power technologies in Europe https://cordis.europa.eu/project/id/101061643 https://research-and-innovation.ec.europa.eu/system/files/2023-02/ec_rtd_smr-project.pdf

Table D.12. **Multi-national projects (GIF)**

Project name	Nation(s) involved/ lead	Type of Gen. IV reactors covered	Status	Brief description of project focus and scope
GIF Research Projects/WGs				
Risk and Safety Working Group (RSWG)	GIF members and IAEA	All six GIF Generation IV systems (VHTR, SCWR, SFR, MSR,	Active since 2005	Development and maintenance of Integrated Safety Assessment Methodology (ISAM) as a technology-neutral toolkit to support a design and evaluate risk and safety. Development of Safety Design Criteria and Guidelines to establish basic requirements for design, fabrication, construction, inspection, and operation of Gen IV plants. www.gen-4.org/gif/jcms/c_9366/risk-safety
Proliferation Resistance and Physical Protection Working Group (PRPPWG)	GIF members and IAEA	All six GIF Generation IV systems	Active since 2004	PRPPWG develops, implements and fosters the use of an evaluation methodology to assess Gen IV systems with respect to GIF PRPP Goa; and to provide the designers and policymakers a technology-neutral framework and a formal comprehensive approach to evaluate PRPP characteristics of advanced nuclear systems. www.gen-4.org/gif/jcms/c_9365/pr-pp
Gas Fast Reactor (GFR) Conceptual Design and Safety Project	Euratom, France	GFR	Active since 2009	R&D in support of safety – mainly focused on ALLEGRO, benchmarking and experimental activities, development of safety design criteria. www.gen-4.org/gif/jcms/c_42148/gas-cooled-fast-reactor-gfr
Supercritical Water-Cooled Reactor (SCWR) Thermal hydraulics and Safety Project	Canada, China, Euratom	SCWR	Active since 2009	Safety requirements and evaluation, heat transfer, hydraulic characteristics, stability, development of system codes and methodologies, safety analysis. www.gen-4.org/gif/jcms/c_42151/supercritical-water-cooled-reactor-scwr
Sodium Fast Reactor (SFR) Safety and Operation Project	France, Japan, Korea and the United States	SFR	Active since 2009	Methods, models and codes for safety evaluation, experimental programmes, operational experience, and benchmark analyses.
Very High-Temperature Reactor (VHTR) Computational Methods Validation and Benchmarks Project	China, Euratom, Japan, Korea, the United States	VHTR	Active since 2022	Validation of new computational methods and codes in the areas HTR thermal hydraulics, thermal mechanics, core physics and chemical transport for licensing assessment of reactor performance in normal, upset and accident conditions. Benchmark tests and code-to-code comparisons.
Advanced Manufacturing and Materials Engineering Task Force	GIF Members	All six GIF Generation IV Systems	Active since 2020	The overarching main objective of the AMMETF is to promote the use of Advanced Manufacturing and Materials Engineering technology to reduce the time to deployment of advanced reactor systems. The specific recommended focus areas and potential activities include qualifications (including codes and standards development), demonstration and deployment, and design and modelling.

Table D.13. **Multi-national projects (IAEA)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
IAEA Cooperative Research Projects				
I12007	IAEA (countries in weblink)	Various	Ongoing (ends December 2024)	Economic Appraisal of Small Modular Reactors Projects: Methodologies and Applications www.iaea.org/projects/crp/i12007
I31020	IAEA (countries in weblink)	HTGR	Completed (ended February 2023)	HTGR Reactor Physics, Thermal-Hydraulics and Depletion Uncertainty Analysis www.iaea.org/projects/crp/i31020
I31021	IAEA (countries in weblink)	Sodium Fast Reactor	Completed (ended May 2016)	Benchmark Analysis of an EBR-II Shutdown Heat Removal Test www.iaea.org/projects/crp/i31021
I31022	IAEA (countries in weblink)	Various	Completed (ended October 2019)	Application of CFD Codes for Nuclear Power Plant Design www.iaea.org/projects/crp/i31022
I31026	IAEA (countries in weblink)	HTGR	Completed (ended February 2023)	Modular HTGRs Safety Design www.iaea.org/projects/crp/i31026
I31029	IAEA (countries in weblink)	Various	Ongoing (expected end was August 2021)	Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for Emergency Planning Zone for SMR Deployment www.iaea.org/projects/crp/i31029
I31031	IAEA (countries in weblink)	Various	Ongoing (expected end was February 2022)	PSA Benchmark for Multi-Unit/Multi-Reactor Sites www.iaea.org/projects/crp/i31031
I31032	IAEA (countries in weblink)	Sodium Fast Reactor	Ongoing (ends December 2024)	Neutronics Benchmark of CEFR Start-Up Tests www.iaea.org/projects/crp/i31032
I31033	IAEA (countries in weblink)	Water-cooled Reactor	Ongoing (ends June 2024)	Advancing the State-of-Practice in Uncertainty and Sensitivity Methodologies for Severe Accident Analysis in Water-Cooled Reactors www.iaea.org/projects/crp/i31033
I31034	IAEA (countries in weblink)	SCWR	Ongoing (ends April 2026)	Advancing Thermal-Hydraulic Models and Predictive Tools for Design of SCWR Prototypes www.iaea.org/projects/crp/i31034
I31038	IAEA (countries in weblink)	Liquid Metal Cooled	Ongoing (ends August 2026)	Benchmark of Transition from Forced to Natural Circulation Experiment with Heavy Liquid Metal Loop www.iaea.org/projects/crp/i31038

Table D.13. **Multi-national projects (IAEA)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
I32009	IAEA (countries in weblink)	Sodium Fast Reactor	Completed (Ended March 2021)	Radioactive Release from the Prototype Fast Breeder Reactor under Severe Accident Conditions www.iaea.org/projects/crp/i32009
I32010	IAEA (countries in weblink)	Various	Ongoing (expected end was December 2021)	Design and Performance Assessment of Passive Engineered Safety Features in Advanced SMRs www.iaea.org/projects/crp/i32010
I32012	IAEA (countries in weblink)	Various	Ongoing (ends April 2026)	Technical Evaluation and Optimisation of Nuclear-Renewable Hybrid Energy Systems www.iaea.org/projects/crp/i32012
T12031	IAEA (countries in weblink)	Fast Reactors	Ongoing (ends June 2023)	Fuel Materials for Fast Reactors www.iaea.org/projects/crp/t12031
T12032	IAEA (countries in weblink)	Water-cooled Reactor	Ongoing (ends August 2024)	Testing and Simulation for Advanced Technology and Accident Tolerant Fuels (ATF-TS) www.iaea.org/projects/crp/t12032

Table D.14. **Multi-national projects (NEA)**

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
NEA Joint Projects				
EGSMR (Expert Group on Small Modular Reactors)	NEA (Chair – Canada)	All	Ongoing	EGSMR seeks to assess the SMR safety landscape, identify important areas of interest and suggest specific actions and research projects for CSNI to take in support of SMR safety. www.oecd-nea.org/jcms/pl_79842/expert-group-on-small-modular-reactors-egsmr
Nuclear Safety Research Joint Projects	NEA	LWR and advanced technologies	Ongoing	NEA Joint Safety Research Projects support the safe operation of nuclear installations. Typical safety research projects include the conduction of a set of experiments that address a safety issue and closes a safety knowledge gap; or the exchange of experimental information and modelling results to better understand safety-related phenomenology. www.oecd-nea.org/jcms/pl_72332/nuclear-safety-research-joint-projects
NEA Data Bank	NEA	LWR and advanced technologies	Ongoing	The NEA Data Bank is an international reference centre for computer codes, nuclear and thermochemical data. You can learn more about us and our three services below. www.oecd-nea.org/jcms/rni_6525/data-bank

Table D.14. **Multi-national projects (NEA)** *(cont'd)*

Project name	Nation(s) involved/lead	Type of SMR(s) covered	Status	Brief description of project focus and scope
LOFC (Loss of Forced Coolant)	Lead – Japan and Czech Republic, France, Germany, Hungary, Korea and the United States	HTR	Current mandate 2011-2027	The LOFC experiments plan to study effects of reactor cavity cooling system (RCCS) performance reduction are highly relevant for safety assessments of advanced reactors such as high-temperature reactor (HTR). www.oecd-nea.org/jcms/pl_25168/loss-of-forced-coolant-lofc-project
FIDES-II	Belgium, Czech Republic, Finland, France, Germany, Hungary, Japan, Netherlands, Spain, Sweden, Switzerland, the United States, European Commission (EC)	LWR and advanced technologies	Current mandate 2022-2024	The NEA Second Framework for Irradiation Experiments (FIDES-II) supports the fuel and material experimental needs of nuclear safety regulators, technical support organisations, research institutions and industry and safeguards experimental knowledge for future generations. FIDES-II connects a global network of research facilities to perform high-priority experiments through joint experimental programmes (JEEPs).
DRAGON, HTGR Reactor Project		HTR	(1958-1975), completed	Dragon was the first experimental HTGR built in the 1960s. A very high-temperature reactor is one of the Generation IV concepts and several countries are considering HTR technology as one of the promising concepts to be utilised for SMRs. Projects on construction and operation of modular pebble-bed reactors (PBR) are also under way. www.oecd-nea.org/jcms/pl_51567/dragon-project
HALDEN HTO, Human, Technology Organization Project	Canada, China, France, Germany, Japan, Korea, Netherlands, Norway, Sweden, UAE, the United Kingdom, the United States	LWR and advanced technologies	Current mandate 2021-2023	Halden HTO's 2021-2023 goal is to advance in the HTO field by working on aspects of human performance, reliability and organisation in various stages of the plant life, including during accident situations. www.oecd-nea.org/jcms/pl_61937/halden-human-technology-organisation-hto-project
QUENCH-ATF	Czech Republic, France, Germany, Japan, Sweden, Switzerland, the United Kingdom, the United States	LWR and advanced technologies	Current mandate 2021-2025	The purpose of the QUENCH-ATF project is to investigate the chemical, mechanical and thermal-hydraulics behaviour of ATF claddings in design-basis accidents and beyond design-basis accidents scenarios.
Joint project on Waste intergration for Small and Advanced Reactor Designs (WISARD)	NEA – ongoing preparation	Advanced technologies	To be started	The project focuses on the development of a set of waste acceptance criteria for different types of waste produced by the next generation SMRs and ARs.

Annex E. PIRTs related to SMR safety

Provided below are the results of the EGSMR information collection on PIRTs related to SMR safety. This represents an initial effort in PIRT collection for the EGSMR and will be expanded upon.

The responses for national PIRTs are provided in alphabetical order by country (with each country presented in a separate table) followed by a single table for the Euratom project related PIRTs. The countries that contributed to this collection are:

- Canada, France, Italy, Japan, Netherlands, Korea, Switzerland and the United States

Table E.1. **Canada – PIRTs relevant to SMR safety**

PIRT title	Nation(s) involved (owner)	Type of SMR(s) covered	Status	Brief description of PIRT focus and availability
HTGR limiting accident PIRT	Canada	HTGR	Completed	Executed for a hypothetical limiting accident (with significant radionuclide releases) in a generic small HTGR. The intent was to envelope and evaluate most or all phenomena that could occur in a beyond design-basis accident. Summary published in open-literature: https://pubs.cnl.ca/doi/full/10.12943/CNR.2019.00006
Molten Salt limiting accident PIRT	Canada	MSR	Completed	Executed for a hypothetical limiting accident (with significant radinuclide releases) for two small MSR concepts. The intent was to envelope and evaluate most or all phenomena that could occur in a beyond design-basis accident. Summary was presented at the Fourth International Conference on Generation IV and Small Reactors (G4SR-4) and is included in the conference proceedings.
Design extension condition	Canada	BWR	To be started	Development of a PIRT for Design Extension Conditions in a BWRX-300 to explore potential accident progression and source terms.

Table E.2. **France – PIRTs relevant to SMR safety**

PIRT title	Nation(s) involved (owner)	Type of SMR(s) covered	Status	Brief description of PIRT focus and availability
Validation Code Task Force	French Consortium	IPWR Nuward	Completed	Physical phenomenon and code validation requirements for the licensing of Nuward (confidential data)

Table E.3. Japan – PIRTs relevant to SMR safety

PIRT title	Nation(s) involved (owner)	Type of SMR(s) covered	Status	Brief description of PIRT focus and availability
PIRT under NC decay heat removal operation	Japan (JAEA)	JSFR (Japan SFR)	Completed	Develop PIRT for JSFR (Japan SFR) under NC decay heat removal operation (Doda et al., 2012).
PIRT for sodium fire	Japan (JAEA)	SFR	Ongoing	Develop PIRT for sodium fire event in SFR to validate sodium fire analysis codes (Ohno et al., 2012; Aoyagi et al., 2019).
PIRT for unprotected loss of flow	Japan (JAEA)	SFR	Ongoing	Develop PIRT for unprotectd loss of flow in SFR to validate code for simulation of initiating phase of core disruptive accident (Ishida et al., 2020; Kawada and Suzuki, 2021).

References

N. Doda, et al. (2012), “Development of PIRT for Fast Reactor under Natural Circulation Decay Heat Removal Operations”, *Transactions of the Japan Society of Mechanical Engineers*, B, 78 (787), 465-467 (in Japanese).

S. Ohno, et al. (2012), “Development of PIRT and Assessment Matrix for Verification and Validation of Sodium Fire Analysis Codes”, *Journal of Power and Energy Systems*, Vol. 6 (2), pp. 241-254.

M. Aoyagi, et al. (2019), “Identification of important phenomena through the PIRT process for development of sodium fire analysis codes”, *Nuclear Engineering and Design*, Vol. 353, Article ID 110240.

S. Ishida, et al. (2020), “Validation study of SAS4A code for the unprotected loss-of-flow accident in an SFR”, *Mechanical Engineering Journal*, Vol. 7 (3), 19-00523.

K. Kawada and T. Suzuki (2021), “Study on dominant aspects of unprotected loss-of-flow to be evaluated in the initiating phase for a sodium-cooled fast reactor”, *Journal of Nuclear Science and Technology*, Vol. 58 (3), pp. 347-360.

Table E.4. Korea – PIRTs relevant to SMR safety

PIRT title	Nation(s) involved (owner)	Type of SMR(s) covered	Status	Brief description of PIRT focus and availability
SMART PIRT (2009)	Korea (KAERI)	iPWR	Completed	Developed for SMART with passive residual heat removal system (PRHRS) focusing on 9 safety-related design-basis accidents in 2009. It was used for the multipurpose (test programmes establishment, facility scaling and analysis model development) of the design certification (in Korean, publically unavailable).
SMART PSS PIRT (2013)	Korea (KAERI)	iPWR	Completed	Developed for thermal-hydraulic phenomena of SMART with full passive safety system focusing on SBLOCA and MSLB in 2013. In this report, the reactor coolant system (RCS) of SMART was reviewed as well as PRHRS, passive safety injection system (PSIS) and automatic depressurisation system (ADS) (in Korean, publically available).
iSMR PIRT (2023)	Korea (KHNP, KAERI)	iPWR	Preparing	The PIRT process is expected to start during 2023 (in Korean, publically unavailable).
PGSFR PIRT (2016)	Korea (KAERI)	SFR	Pending	Developed to evaluate suitability of the MARS-LMR code for safety analysis and determine physical phenomena during transients in the PGSFR (150 MWe). It is for DEC (design extension condition) scenarios such as UTOP (unprotected transient over-power), ULOF (unprotected loss of flow), and ULOHS (unprotected loss of heat sink) (in Korean, publically available).

Table E.5. **United States – PIRTs relevant to SMR safety**

PIRT title	Nation(s) involved (owner)	Type of SMR(s) covered	Status	Brief description of PIRT focus and availability
Pre-PIRT Report for NuScale-like (iPWRs)	United States (USNRC)	iPWR	Completed	PIRT applies to LOCA and Rod Withdrawal. Redacted version will be publicly available.
PIRT Report for NuScale Stability	United States (USNRC)	iPWR	Completed	PIRT applies to thermal-hydraulic stability of the NuScale RCS. Redacted version will be publicly available.

Table E.6. **Euratom Projects – PIRTs relevant to SMR safety**

PIRT title	Nation(s) involved (owner)	Type of SMR(s) covered	Status	Brief description of PIRT focus and availability
PIRTs developed within ELSMOR Project Including WP3.1	Various including France and Switzerland	Various	Complete	The PIRTs developed within the ELSMOR project are of high quality and may be referenced to many LW-SMRs (iPWRs), e.g. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cdaebbb7&appId=PPGMS and https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5dc79c953&appId=PPGMS Analysis of simplified PIRTs VOYGR, SMART, IRIS (open data) SBO & LOCA.
ANSELMUS	Italy, Belgium, Germany, Romania, Netherlands, European Commission, (Ansaldo Nucleare, Italy)	LFR	Ongoing	Within the frame of the EU Horizon Europe collaborative project ANSELMUS, PIRTs will be developed for the ALFRED and MYRRHA reactor based SMRs. Work will start early 2023. The focus is on the impact/uncertainties of relevant phenomena in the safety demonstration of the ALFRED and MYRRHA reactors. The objective is to drive future R&D need, both experimental and numerical, to bring licensing forward. PIRT results will be publicly available.

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CSNI Technical Opinion Paper No. 21

While there is a growing interest in the deployment of small modular reactors (SMRs) as a promising option to help mitigate climate change, further international efforts are needed to accelerate the development and safety demonstration of the innovative technologies that are being considered for many of these SMRs. This publication presents the actions taken by the NEA Committee on the Safety of Nuclear Installations (CSNI) and its expert group on SMRs to define the areas of future CSNI research and safety assessment work needed to support sound safety demonstrations for SMRs. The proposed activities address four areas: support for regulatory harmonisation, common safety issues of interest for different designs, experimental campaigns, and benchmarking for computer code validation and verification.

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