

Overview of Experiments and Code Validation Efforts for Molten Salt Reactors Development within International Organizations

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Introduction

Molten Salt Reactors (MSRs) represent one of the most distinctive and forward-looking nuclear reactor concepts, with origins that trace back to pioneering experiments in the mid-20th century. The molten salt reactor is one of the six reactor technologies selected by the Generation IV International Forum (GIF) for further research and development. The technology is appropriate for small modular reactor, and molten salt reactors are expected to have advantages over light water reactors in terms of safety, environment, economics and non-proliferation. High operating temperatures leading to increased efficiencies in electricity generation, passive decay heat removal and flexible fuel cycles are some of the additional benefits of this reactor technology.

Today, multiple MSR concepts are under development worldwide, differing in fuel state, neutron spectrum, salt composition, and moderator choice. In China, a 2 MW experimental thorium MSR “TMSR-LF1” has been built and achieved full power operation in October 2024, aiming to gain operational insights that could inform a future commercial rollout. In the United States, there are some companies pursuing MSR deployment in the 2020s and early 2030s. Some demonstration projects jointly funded by the government and the industry are currently underway. In Europe, EURATOM has played a significant role in advancing the MSR research, primarily through funded international collaborative projects under its research frameworks, like SAMOSAFER, MIMOSA, and ENDURANCE. Other countries, including Canada, Russia, Switzerland, Korea, etc, also have some ongoing MSR research projects.

However, the lack of dedicated experimental facilities capable for MSR's special operating conditions is one of the major challenges for MSR development. In parallel, there is an urgent need for developing and validating codes for MSR reactor design and safety assessment that can accurately simulate multi-physics process of fluid flow, fluid and structural dynamics, neutron kinetics, salt chemistry, and thermal feedback. Addressing these challenges will be critical for progressing MSRs to advancing MSRs from concept to commercial reality.

To better share knowledge on these challenges and align efforts, this paper summarizes the current status of the related activities within several International Organizations, including the International Atomic Energy Agency (IAEA), Gen-IV Forum (GIF), the European Commission (EC) Research and Technological Development (RTD) Euratom Research and the Nuclear Energy Agency (NEA).

IAEA Activities

In accordance with its statute, the IAEA is authorized to foster the exchange of scientific and technical information on peaceful uses of atomic energy [1]. Though the MSR technology has not been the magistral line of the global nuclear power development, the IAEA has been monitoring progress in this field since flexibility of MSRs in various applications continues to attract interest of R&D groups world-wide since the early days of the nuclear era dated to the middle of the last century.

It is instructive to refer to the IAEA publication "Challenges related to the use of liquid metal and molten salt coolants in advanced reactors" issued in 2013 that positions MSR in the domain of advanced reactors and categorized them either as breeders or burners [2]. This categorization well reflects the mainstream of the R&D in the first decade of 2000s focused on advanced fuel cycles supported by breeding of fissile isotopes $^{233}\text{U}/^{239}\text{Pu}$ (in thermal and fast spectrum, respectively) to reach fuel abundance or to burn excess plutonium and minor actinides to lift the burden of proliferation resistance and long-term radiotoxicity associated with these transuranic. The driving characteristic behind was the possibility of on-line refuelling and extraction of either neutron poisoning fission products or valuable fissile materials – that might be treated as a closing the fuel cycle within one particular facility. This very prominently illustrates flexibility of MSR technology and its high potential in resolving the tasks facing global nuclear power development.

During the second decade of 21 century when the climate change and requirements for reduction of GHG emissions fixed in Paris agreements manifested themselves as global issues, two more advantageous features of MSR technology appears as the main drivers of its development – high temperature and low pressure. Combination of these two features gives an opportunity to localize the SMRs close to the industrial heat consumers thus contributing to reduction of GHG footprint from industrial sector (about 20% of the total footprint). This is shifting the paradigm of MSR deployment from being a fuel cycle facility (that usually is envisioned as of large capacity) to power producer in the vicinity of industrial partner (that focuses on small power capacity). The paradigm shift brings MSR in the format of SMRs as

the mainstream development line. In SMR catalogue published by the IAEA in 2024 there are over 70 designs presented with brief descriptions of their technical features, within this list 11 belonging to MSR-SMR family [3].

Reflecting the growing interest towards MSRs, the Agency in 2023 published a comprehensive status of molten salt reactor technology that includes a history of MSR development, MSR taxonomy in terms of class, family and type with description of dozens of SMR designs as well as notes on current challenges in their deployment [4]. In the same year, the IAEA also published an assessment of the applicability of its safety standards to non-water-cooled reactors and small modular reactors (SMRs) [5], with the aim of identifying potential applicability issues and gaps. The publication includes considerations related to the interfaces between safety, security and safeguards.

An IAEA technical document on ‘Considerations on the Safety of Molten Salt Reactors’ is currently under development. The TECDOC is intended to address applicability issues and gaps in design safety and safety assessment standards identified in the report [5]. In particular, it focuses on the fulfilment of the fundamental safety functions, the implementation of defence in depth and the notion of design extension conditions, including severe accidents. In addition, a safety guide (DS537: Safety Demonstration of Innovative Technology in Nuclear Power Plants) and several technical documents related to design safety and safety assessment cross-cutting topics are also under development, covering both existing and advanced technologies, including MSRs. In particular, Safety Guide DS537 addresses the use of computer codes for safety analysis.

Keeping in mind maturing the MSR technology, in 2025, the IAEA conducted several events like Technical Meeting on Reactor Physics, Thermal Hydraulics, and Plant Design of Molten Salt Reactors (22-25 April), Workshop on Molten Salt Reactors Fuels: Recent Development and Future Challenges (21-25 July), Workshop on MSR Fuel Cycle Taxonomy and Related Terminology (3-7 November) that served as fora for the exchange of information and receive feedback from Member States on different aspects of MSR technological developments. Under planning is the launching of the coordinated research project on Experimental Testing for Verification and Validation of Design Tools for Molten Salt Reactor Technology Development that will help to resolve some particular issues of MSR engineering development.

Information Sharing on Experimental Facilities and Code Validation

To reduce costs and increase schedule certainty associated with experiments and code validation needed for the design and licensing of SMRs and advanced reactors, the IAEA has established the Network for Experiment and code validation sharing (NEXSHARE) [6] since 2024. NEXSHARE is a technical forum of global cooperation and resource sharing for experiments and code validation among design organizations, experimental facilities, international organizations, Technical Support Organizations (TSOs) and code developers. The Network provides a database of experimental facilities applicable to SMRs and advanced

reactors, including MSRs. Under the cooperation with International Organizations and Members States, this database is continuously being expanded and updated. Integration with other existing IAEA experimental databases and extension to simulation codes are also planned.

The IAEA is committed to organizing regular activities that further support and strengthen NEXSHARE. The first workshop in support of NEXSHARE was jointly organized by the IAEA, the NEA and GIF during 18-21 June 2025 [7]. More than 70 participants from 29 countries and 3 international organizations attended this event. This workshop marked the official launch of NEXSHARE and featured presentations on topics such as experimental testing and code validation programmes, including similarities, gaps and potential for collaborations, as well as common approaches and best practices in testing and code validation.

In 2025, under the framework of NEXSHARE, four reactor technology Focus Groups (FGs) have been established, including Water Cooled Reactors, High Temperature Gas Cooled Reactors, Liquid Metal Fast Reactors and Molten Salt Reactors. The NEXSHARE FGs are short-term groups to work on experiments and code validation on a specific focus area. For the MSR FG, they plan to map the existing MSR experimental facilities and populate the database, issue working papers and organize webinars on topics of interest to the industry. All outcomes and activities will be shared through the NEXSHARE platform.

Fuels and Fuel Cycle

MSRs are gaining renewed global attention due to their potential benefits in fuel efficiency, inherent safety, and versatile fuel cycle capabilities. The recent launch of China's thorium MSR and growing R&D worldwide have underscored the urgency for international coordination, particularly in developing MSR fuel technologies.

To address this, the IAEA formed a Task Force on MSR Fuels and hosted its first workshop on Molten Salt Reactors Fuels in 2025: Recent Development and Future Challenges to identify the specific needs of IAEA Member States in areas such as salt synthesis, purification, and fuel qualification.

The IAEA workshop on Molten Salt Reactor (MSR) fuel technologies brought together experts to address key technical and operational challenges in developing MSR fuel salts. Topics included salt synthesis and packaging, fuel salt characterization, purification methods, and advanced modelling tools. A recurring issue was the lack of standardized purity and qualification criteria for MSR salts, as well as inconsistencies in synthesis techniques across laboratories. These gaps, combined with limited availability of anhydrous commercial salts, hinder reproducibility and scale-up of MSR fuels production. Furthermore, data on thermophysical properties and the effects of impurities and radiolysis—especially in chloride-based systems—remain incomplete, underlining the need for further experimental research and advanced diagnostic tools.

Modelling and simulation play a critical role in advancing MSR technology. Tools such as CALPHAD and other open-source platforms are being employed to bridge data gaps and support integrated analyses. However, coupling simulation codes across neutronics, thermal-hydraulics, and chemistry domains is still a significant hurdle, requiring systematic validation. Integrated fuel cycle modelling offers a promising avenue for optimizing salt selection and MSR core design, but computational and convergence challenges must be addressed to enable broader adoption.

Operationally, MSR fuel salt development is advancing at the laboratory scale but faces infrastructure and technical barriers to industrial-scale production. Key bottlenecks include limited enrichment capacity for critical isotopes like ^7Li and ^{37}Cl , and the absence of scalable purification systems. Monitoring technologies, such as redox probes, LIBS, and off-gas detection, are being explored for real-time system control but remain in early development stages. Additionally, complex regulatory frameworks and unresolved questions around transport, waste handling, and final disposal present long-term challenges.

To overcome these issues, workshop participants emphasized the importance of sustained international collaboration and coordination through the IAEA.

IAEA maintains IAEA Nuclear Fuel Cycle Simulation System (NFCSS) is a web-based tool that estimates material and service requirements for various nuclear fuel cycles over up to 200 years [8]. It supports multiple reactor types (e.g., PWR, BWR, PHWR, FR, MSR) and fuels (UOX, MOX, ThOX). Recent updates included MSRs with thorium-based fuels and reprocessing (assuming fuel in & out in a year). The cross-section library for U233-Th in MSR is given in IAEA-TECDOC –1319 [9]. MSR Case Studies included into NFCSS: Case-1 U-233/Th epi-thermal spectrum (lower graphite, better Th-232 conversion), Case-2, Pu/Th epi-thermal spectrum lower graphite, better Th-232 conversion, Case-3 (LEU/Th) thermal spectrum (high graphite), Case-4 (Fast MSFR, U-233/Th). ORIGEN was verified with SRAC 1-group cross-sections. Errors were generally within a few percent.

Generation-IV International Forum Activities

The founding document of the Generation IV International Forum (GIF), the first framework agreement for international cooperation in research and development for the next generation of nuclear energy systems was signed in July 2001. Since the agreement duration was limited, it was renewed once in 2015 and again in 2025. The recent renewal is also the reason, why not all countries have yet signed the new framework agreement and the system arrangements, project arrangements and Memorandums of Understandings (MoUs). Whereas 4 of the 6 GIF systems: Very High Temperature Reactor (VHTR), Sodium-cooled Fast Reactor (SFR), SuperCritical Water Reactor (SCWR) and Gas-cooled Fast Reactor (GFR) are organized through system arrangement and have ongoing project arrangements, the Lead-cooled Fast Reactor (LFR) and MSR are organized under MoUs. Under the previous framework agreement

there were 7 signatories of the MSR MoU: Australia, Canada, Euratom, France, Russia, Switzerland, UK, and USA. With the recent renewal of the framework agreement, the MoU needs to be updated. Early in 2025 two countries signed the MSR MoU; 5 signatures are expected in the near term, including possible new signatory Korea. Japan and China have participated in GIF MSR activities as observers for several years.

The provisional System Steering Committee (pSSC) for MSR has been meeting bi-annually to exchange information about the research progress in member countries and to coordinate open, collaborative activities. The meetings have been predominantly in person. However, hybrid options have been provided since the pandemic and during the pandemic fully virtual meetings took place.

The past objective of MSR projects in some member countries was to propose, through national research centers and universities, conceptual designs with the best system configuration for a given application. Other member states have always focused on developing and validating MSR technologies and evaluation methods to enable private sector MSR developers to successfully develop and deploy their technologies. More member states have transitioned to supporting roles in research and development in national research centers and universities as a result of private company MSR advancements.

The GIF Experts Group initially recommended six possible MSR areas for potential collaboration:

- materials and components;
- liquid salt chemistry and properties;
- fuel and fuel cycle;
- system design and operation;
- safety and safety system assessment;
- system integration and assessment.

The MSR system arrangement and the related MSR project arrangements were, however, not signed. Later the proposed projects were reduced to 3:

- Fuel salt properties
- Materials and components
- System integration

The major obstacle in signing the system and project arrangements is the desire by several member states to focus collaboration on open, scientific information such as the physical properties of salts and reactor safety characteristics and safety evaluation methods while leaving other development aspects for private sector competition. In addition, the variety of MSR concepts and the dynamically evolving situation with MSR designers complicates selecting specific projects for collaboration. To illustrate the variety of MSR concepts a useful MSR taxonomy (employed by IAEA and GIF) is shown in Fig. 1.

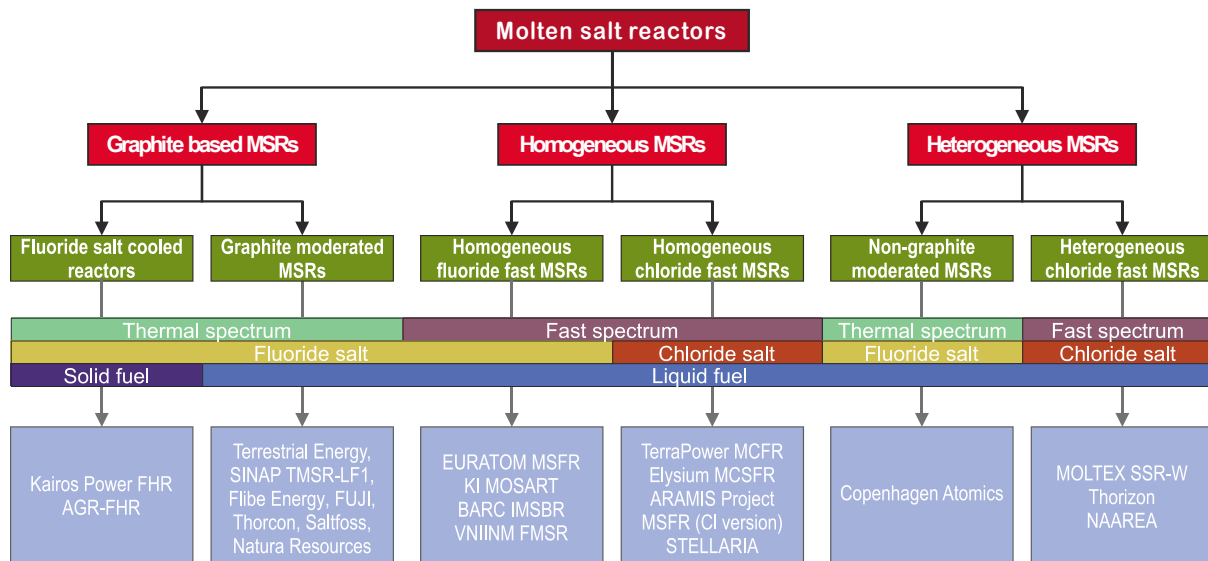


Fig. 1.: Overview of the MSR classes and families together with the MSR concepts ([GIF annual report 2024](#)) [10].

Within GIF, the MSR pSSC interacts with the Proliferation Resistance and Physical Protection Working Group and they jointly published a Molten Salt Reactor - Proliferation Resistance and Physical Protection White Paper in 2024. The MSR pSSC also interacts with the GIF Risk and Safety Working Group. Development of an MSR safety white paper and MSR safety assessment is currently in progress.

European Commission Activities

EU Knowledge Hub for Enabling Molten Salt Reactor

The EU Knowledge Hub for Enabling Molten Salt Reactor ([ENDURANCE](#)) project is an EU-funded initiative under the Euratom Research and Training Programme [11]. It commenced in October 2024 and is scheduled to conclude in September 2028. ENDURANCE aims to bolster the safe operation and the technological development of MSR in Europe, through the knowledge advancement in different fields of the MSR research, connecting the design developers and industry needs with the university and research centre capabilities and the regulator requirements.

The objectives of the project are to create an environment for constructive alignment by connecting the needs of reactor designers and industry with the capabilities of universities and research centres and the requirements of regulators, thereby maintaining and strengthening MSR-related competences in Europe. It also aims to enable the safe development and deployment of MSR technology by increasing both the Scientific Readiness Level (SRL) and the Technological Readiness Level (TRL) of key enabling phenomena, technologies, and methodologies, identified as Critical Technology Elements (CTEs), while addressing existing

R&D gaps. Finally, the project seeks to identify the future research and development needs required for the safe advancement of MSR technology in Europe and to define a corresponding technology roadmap that preserves European leadership in MSR research and industry.

The project has identified CTEs as priority areas where intensified R&D and safety assessment are needed to close existing gaps and demonstrate that MSR technology can be deployed in full compliance with the highest safety standards, while achieving excellence in waste management and proliferation resistance, thereby making a significant contribution to the integrated European energy vision. The five CTES includes the chemistry of fuel salt and structural materials in reactor environment, the experimental evidence on safety related phenomena, the modelling preparedness for safety assessment and licensing, the sustainability and safeguards compliance of MSR fuel cycle, the demonstration of MSR adaptability in future decarbonized energy scenario.

The related R&D activities include thermo-physical property measurements, front-end modelling and simulation, and post-irradiation examinations (PIE) in reactor environments; experimental analyses of solid fission product transport and deposition, neutronic parameters, and natural circulation; the development and application of PIRT, TAR, and computational methods for supporting safety analysis and licensing, including numerical and experimental benchmarking; assessment of MSR fuel cycle sustainability, including reprocessing schemes, off-gas systems, and safeguard ability; and evaluation of operational flexibility of MSRs in poly-generation applications and their associated safety aspects.

Safety Assessment of the Molten Salt Fast Reactor

The Safety Assessment of the Molten Salt Fast Reactor ([SAMOFAR](#)) project, conducted from 2015 to 2019, focused on developing the safety basis for the Molten Salt Fast Reactor (MSFR) [12]. The project aimed to improve understanding of the unique safety features of MSFRs, such as strong negative feedback effects and passive heat removal capabilities.

Although SAMOFAR did not include experimental testing, it developed advanced simulation tools and performed safety analyses for normal and off-normal conditions. Key topics included neutronic and thermal-hydraulic coupling, decay heat removal, and containment strategies. The project also helped identify modelling gaps and laid the groundwork for follow-up efforts like SAMOSAFER, contributing to the long-term development and assessment of MSFR safety.

Severe Accident Modelling and Safety of Fluoride-salt-cooled Energy Reactors

The project of Severe Accident Modelling and Safety of Fluoride-salt-cooled Energy Reactors ([SAMOSAFER](#)) is one of the major Research and Innovation projects in the European HORIZON 2020 project started in 2019 which aimed at developing and demonstrating new safety barriers for more controlled behaviour of Molten Salt Reactors in severe accidents, based

on new simulation models and tools validated with experiments [13]. The SAMOSAFER consortium included universities, research institutes, and industry from Europe and Canada. Its key objectives are developing advanced, validated simulation models for MSRs under severe accident conditions, providing experimental evidence and models to assess and enhance safety systems, proposing new safety design principles for MSRs to prevent or mitigate radioactive releases and contributing to licensing frameworks and public acceptance of future MSR deployment.

To support education and training, SAMOSAFER also organized summer schools, youth MSR conferences and promoted collaborative research exchanges across participating institutions. In 2023, the project concluded with a [final meeting and exploitation workshop](#) where SAMOSAFER work package teams presented the main results of the SAMOSAFER project and invited speakers presented an update on the status and future of MSR [14].

Multi-recycling strategies of LWR SNF focusing on Molten Salt technology

The Multi-recycling strategies of LWR SNF focusing on Molten Salt technology (MIMOSA) project (2022-2026) is a collaborative Horizon Europe project launched in 2022 and expected to run until 2026 [15-17]. MIMOSA aims to develop an accessible, cost/risk optimised multi-recycling strategy of LWR spent fuels in the EU, based primarily on multi-recycling of Pu (and reprocessed U) in LWRs combined with the CI MSR, using available infrastructure in the EU such as the reprocessing plant in La Hague, France. The project focuses on the demonstration of the technical feasibility and performance of CI MSRs on Pu and MA conversion through assessment of chloride salt properties to support studies of reactor performance and safety; simulations of chloride salt composition evolution in the reactor; R&D on MSR key technologies; study of salt recycling and back-end options, particularly in synergy with La Hague plant. MIMOSA also evaluates the production of valuable isotopes for other applications, and the way to extract, separate and purify them from molten salt. Results are considered in scenario studies that analyse the role chloride MSRs may play in the EU's future nuclear energy systems to further the sustainable management of SNF from LWRs.

Joint Research Centre Molten Salt Database

The Joint Research Centre Molten Salt Database ([JRCMSD](#)) is an extensive thermodynamic database describing the key fuel and coolant systems for Molten Salt Reactor technology [18]. It has been developed since 2002 at the European Commission's Joint Research Centre (JRC) and the development work is open for any interested organization. The database contains assessed data for binary, ternary and higher order phase diagrams for fuel components (U, Th, Pu), fuel solvent and coolant components, and some fission and corrosion product components.

The database is being continuously validated and expanded by novel experimental data and thermodynamic assessments. It provides strong and reliable tool to estimate thermodynamic properties of fresh fuel and/or coolant salts. JRCMSD also provides insight into properties

change influenced by accumulation of fission products during operational lifetime of the molten salt reactor. The same is true for prediction of corrosion effects of the salt towards the structural materials. Universities, research organizations, reactor designers, regulators or e.g. licensing authorities can benefit from the database.

Nuclear Energy Agency Activities

The NEA has been supporting the activities of the Generation IV International Forum since 2005. It provides technical secretariat services, archiving records and documents, as well as maintaining the Forum's internal and external websites.

In addition to this role, the NEA has been initiated a series of activities supporting MSR development. Those are being documented by the NEA and will be added into this document.

Conclusion

The development of MSRs is advancing globally, supported by renewed international interest and coordinated efforts through organizations such as the IAEA, GIF, EC RTD, EC-JRC, and NEA. These organizations have facilitated knowledge sharing, code validation, experimental collaboration, and safety assessments, contributing significantly to the technological maturation of MSR concepts. However, several critical gaps and challenges remain that must be addressed to accelerate the transition from research to commercial deployment.

Key Gaps and Challenges

- Experimental Infrastructure and Data Availability

Dedicated experimental facilities capable of replicating MSR-specific operating conditions is lacking, particularly for long-term material corrosion, salt chemistry under irradiation, and integrated safety tests. Although initiatives like the IAEA's NEXSHARE aim to map and share resources, many facilities are not yet accessible for international validation campaigns.

- Code Development and Multi-Physics Validation

While some progress has been made in developing simulation tools for neutronics, thermal-hydraulics, and salt chemistry, the coupling of these multi-physics domains remains immature. There is a notable absence of internationally validated and licensed codes capable of simulating MSR-specific phenomena.

- Safety Frameworks

Existing IAEA safety standards are not fully applicable to non-water-cooled reactors like MSRs. Gaps remain in areas such as safety demonstration methodologies, licensing approaches for innovative designs, and integration of safeguards into fuel cycle management. The development of MSR-specific safety guides (e.g., under IAEA DS537) is still ongoing.

- International Coordination and Knowledge Gaps

Despite efforts under international organizations, collaboration remains fragmented due to the diversity of MSR concepts and proprietary interests. Many countries and private developers pursue independent paths, leading to slow consensus on shared research priorities.

Priorities for Future Work

- Enhanced Experimental Collaboration

Expand international access to key experimental facilities and promote standardized testing protocols for salt properties, materials behaviour, and safety-relevant phenomena.

- Integrated Code Validation

Accelerate the development and validation of multi-physics simulation tools by leveraging international benchmarks and shared experimental data. Additionally, a comprehensive assessment of the current modelling landscape and existing computational tools for MSRs technologies would provide valuable insights and guide future advancements.

- Knowledge Consolidation

Continue to support international platforms like NEXSHARE to harmonize research efforts.

Addressing these priorities require a coordinated and integrated approach among international organizations. In this context, the IAEA's NEXSHARE initiative, working in collaboration with the NEA, GIF and the EC RDT, has developed a workplan for its MSRs activities. This plan builds on past, ongoing and planned efforts described in this document, aiming to provide a more comprehensive view of available experimental facilities, data and tools that supports code validation of SMRs.

The workplan aligns with existing code validation initiatives to ensure consistent and efficient validation campaigns for SMR design and licensing, while avoiding duplication of efforts among the different Agencies. These efforts are summarized in the NHSI working paper entitled: "*NEXSHARE Efforts Supporting Experiments and Code Validation for Monten Salt Reactors*".

By fostering a shared understanding of validation needs and priorities, this collaborative framework can help accelerate the development of robust, reliable, and licensable SMR technologies.

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