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Prioritizing standardisation needs and bridging gaps

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Advancing molten salt reactor technologies: Prioritizing standardisation needs and bridging gaps☆

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ABSTRACT

This article outlines key standardisation needs for specific topics related to molten salt reactors (MSR), namely measurements of thermo-physical properties, safety evaluation, qualification of fuels and fuel cycles, and codes & standards for materials and components. It also explores strategies for bridging gaps in international standardisation, harmonisation and collaboration, and raises the importance of building MSR prototypes and investing in testing facilities. This article is based on a survey and direct inputs from a Putting Science into Standards workshop held on 18 and 19 March 2024 and organised by the European Commissions' Joint Research Centre (JRC) and European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC). The workshop gathered 100 experts from research, industry and policy making to discuss the development and standardisation of MSR technologies. By working together at European and international levels, standardisation will be a key instrument to enable the development and commercialisation of mature MSR technologies to support the European Union's goal of achieving fully functioning small modular reactors by 2030.

1. Introduction

The European Union (EU) has set ambitious targets for reducing greenhouse gas emissions and transitioning to a more sustainable energy system, aiming to achieve net-zero emissions by 2050. To support this goal, the EU has established the Net Zero Industrial Act, which recognizes the potential contribution of Small modular reactors (SMRs) to achieving the energy and climate objectives of the EU Green Deal (European Commission, 2023a, 2023b, 2024; European Union, 2024).

Molten salt reactor (MSR) technologies have gained significant attention in recent years due to their advantages over traditional nuclear reactors, including improved safety, increased efficiency, and reduced waste generation (Ho et al., 2023). MSRs offer a promising solution for the EU's energy transition, and their development and commercialisation might be crucial for achieving the EU's climate goals.

However, the successful development and deployment of MSR technologies require a robust standardisation framework to ensure consistency, reliability, and compatibility across different designs and applications (Benes and Konings, 2013; Gangyang et al., 2021; Clarno et al., 2023; Ho et al., 2023; El-Emam et al., 2024). Standardisation will play a crucial role in accelerating the development, deployment, and commercialisation of MSR technologies, enabling the EU to achieve its goal of fully functioning small modular reactors by 2030.

The production of nuclear energy in a safe and secure way is

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dependent on the establishment of comprehensive regulatory frameworks. In the European Union (EU), a great deal of regulation for nuclear technology falls in the horizon of national legislation of EU Member States. Under the umbrella of the Euratom treaty, the European Council serves as the primary forum for intergovernmental deliberations on nuclear matters. While several Member States have chosen to phase out and abandon the use of nuclear power for energy generation, paradoxically, numerous nuclear design enterprises, allied with leading research organizations, are forging innovative concepts in nuclear technologies, in particular those related to small modular reactors (SMRs) (Hidayatullah, Susyadi and Subki, 2015). Some of these enterprises are based in countries that are concurrently decommissioning their nuclear assets along with their regulatory capabilities (Nian, 2017; Aldave De Las Heras et al., 2024).

In recent years there has been a growing interest in the development of molten salt reactors (MSRs), a technology that was initially proposed in the 1950's and 1960's and that thanks to several advantageous features such as flexibility and improved safety is becoming a promising technology for the future deployment of SMRs (Serp et al., 2014; IAEA, 2023).

The International Atomic Energy Agency considers the development and implementation of SMRs a game changer, as they will play a crucial role in the coming decades in reaching the goals for reducing CO_2 emissions to mitigate the effects of climate change (IAEA, 2015).

Nuclear energy represents today about 9 % of the total world electricity production, provided by approximately 440 large scale reactors (Ruth et al., 2014; Lovering, Yip and Nordhaus, 2016). It is estimated that to meet the goals to combat climate change, the nuclear industry should triple its capacity, delivering by 2050 an extra 1000 GW of electric power, which represents the construction of more than 3000 SMRs until 2050, if we assume an average power capacity of 0.3 GW per reactor (Grubler et al., 2018). Clearly it will be a substantial challenge for the nuclear industry to meet these needs in the coming 25 years, and small modular reactors (SMRs) can allow a faster deployment.

Many countries around the world with no previous experience in the production of nuclear energy are now planning to deploy SMRs (Nøland et al., 2024). Due to their smaller size, SMRs have the potential for off-the shelf production, reducing time and costs for installation and operation, as well as increased reliability. SMRs are also easily adaptable to various environments. In a country like the Philippines, with thousands of islands, SMRs can be an ideal solution, providing diversification of the energy mix and thus energy security. SMRs can also be used for district heating, located near cities or in floating barges, or to serve the high energy needs of steel production, petrochemical plants, or to power large data centres. The use of SMRs also avoids modifications to the grid and their smaller size may result in higher acceptance from the public. The following five positive prospects for a flexible managed energy grid have been identified: high security, long-term sustainability, high efficiency, passive safety features, and reduced nuclear waste (Riley et al., 2019; Chen et al., 2022; Ho et al., 2023). In Europe, countries like Romania, and Slovakia are planning to build SMRs in the next decade (Brown, 2022; U.S. Government, 2024; Van Hee et al., 2024).

While there is a clear market for SMRs, the actual implementation depends on establishing a regulatory framework supported by standardisation and harmonisation that can ensure the safe installation, operation and decommissioning of SMRs. Standardisation and harmonisation are the two most pressing needs for the safe and cost-efficient deployment of SMRs, which along with regulation will result in a new business model for a more efficient licensing of SMRs covering the whole supply chain. This model will enable a new era for the development of nuclear energy: innovation, implementation and cooperation, where cooperation is key in view of the many actors involved to deliver commercially available equipment.

To deploy a single design across multiple markets, it is useful to focus on regulatory alignment and industrial standardisation, while meeting the diverse requirements in different markets and regions across the world through a risk-based framework. An integrated approach to safety, security, and safeguards necessitates the collaboration of designers, vendors, and operators at all stages. This approach addresses vulnerabilities (safety) and protection (security) simultaneously, with a Small modular reactor (SMR) mindset.

Within this global perspective that sets the highest priority on establishing a regulatory and standardisation framework that can enable the deployment of SMRs in the next decade, the Joint Research Centre (JRC), together with the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC), organised on 18 and 19 March 2024 the Putting Science into Standards workshop on molten salt reactors. The workshop brought together over 100 experts from research, industry and policy making in Europe and beyond to explore the development and standardisation of MSR technologies (Jenet et al., 2024).

This article outlines the key standardisation needs that were identified during the workshop and explores strategies for bridging gaps in international standards, collaboration, and capacity for standardisation, enabling the successful development and commercialisation of MSR technologies and supporting the European Union's ambitious goal of achieving fully functioning small modular reactors by 2030.

The workshop highlighted that standardisation is critical for ensuring the consistent and reliable performance of MSR technologies across different designs and applications. Several key areas of standardisation were identified, including measurements of thermo-physical properties, safety evaluation (common approach), qualification of fuels and fuel cycles, and codes & standards for materials and components.

To bridge the gap between research and development activities and design codes & standards, this article emphasizes the importance of investing in testing facilities and prototypes. Collaboration with international partners is also crucial for sharing data and knowledge, promoting joint publications, and participating in future meetings.

1.1. Research and development status in European Union

At the European level, MSR research and development (R&D) began in 2001 with the MOST project (Konings et al., 2005), which aimed to evaluate existing knowledge and data, and identify gaps for future research (OECD/NEA, 2002; European Commission, 2017; IAEA, 2023). To date, seven MSR EU projects have been funded, as shown in Fig. 1. With the recent MSR renaissance, the EU is currently funding two parallel projects: (i) MIMOSA (MultI-recycling strategies of Light Water Reactor spent nuclear fuel focusing on MOlten SAlt technology), the first enterprise-coordinated project, focusing on utilizing molten chloride reactors in the fast spectrum for plutonium multi-recycling as part of the strategy to close the nuclear fuel cycle, and (ii) the newly launched ENDURANCE (EU knowledge hub for enabling molten salt reactor safety development and deployment) project, which aims to establish an EU knowledge hub for MSR safety, development, and deployment.

The JRC has been carrying out MSR research & development since 2003. Over the last two decades, the JRC has been recognised as one of a few reference centres in the world for gaining important insights into MSR fuel systems and their interactions with reactor structural materials. A thermodynamic database describes key fuel and coolant systems for MSR technology and includes data on binary, ternary, and higher-order systems for fuel components (such as uranium, thorium, and plutonium), as well as coolant components and some fission and corrosion product components. Current work covers the following areas of expertise: fuel synthesis and purification methods (Claux et al., 2016; Souček et al., 2017; Tosolin et al., 2018); reference centre for fuel salt property measurements (Beneš et al., 2021; Tosolin et al., 2023; Fache et al., 2024); database development (Beneš and Konings, 2009; Beilmann et al., 2011; Benes and Konings, 2013; Capelli, Beneš and Konings, 2018); reactor safety; post-irradiation examination (Souček et al., 2024); materials testing; and safeguards.

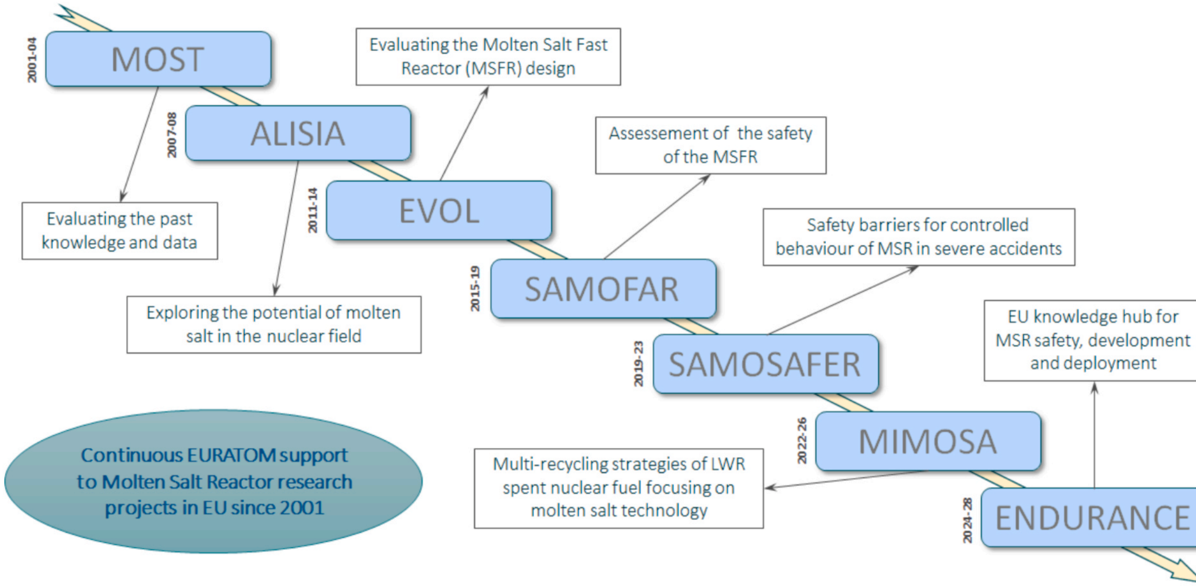

Fig. 1. An overview of the EU granted MSR projects (IAEA, 2023).

France has been actively involved in the development of MSRs through various initiatives and collaborations partnering with institutions like the French National Centre for Scientific Research (CNRS) and Université Paris-Saclay to create a dedicated research laboratory for molten salt chemistry. Launched in 2021, the France 2030 programme was set. This re-industrialisation plan includes 54 billion Euro in funding schemes over five years. A portion of this funding, 1 billion Euro, is dedicated to innovative reactors, including MSRs. The French government has awarded grants to companies like Naarea, Thorizon and Stellaria, to develop fast spectrum MSRs (IAEA, 2023). Orano is in consortium with the last two for chloride fuel salt development (IAEA, 2023) and has set up in July 2024 two sharing groups, among which one on fast spectrum MSRs to pool the three companies' needs relating to the development of their common fuel. Finally, three national programs related to MSR technology (ISAC, MOSARWASTE and PORTHOS) are also currently funded by the French government.

The MSR related R&D in Italy was historically primarily connected to European framework projects (described above). The Italian consortium CIRTEN, an academic collaboration initiative, is a key participant in this project, with the Polytechnic University of Milan coordinating the new EU project ENDURANCE. The CIRTEN consortium is recognized for its expertise on advanced experimental and numerical techniques, including large loop systems.

The Netherlands is actively involved in the development of MSRs through several key initiatives and research projects. Researchers at TU Delft are working on thorium-based MSRs, which are considered a promising technology for sustainable and safe nuclear energy. The Nuclear Research and Consultancy Group (NRG) has been conducting extensive research on MSRs, including irradiation tests and studies on construction materials, molten salt processing, and purification. THORIZON, a spin-off from the NRG, is developing the Thorizon One reactor, a 250 MWt/100 MWe MSR. This reactor aims to provide flexible electricity and industrial heat, with plans to be operational by 2032.

Denmark is making significant fingerprint in the development of MSRs through innovative companies and research initiatives. Saltfoss Energy, a Copenhagen-based company, is at the forefront of MSR development in Denmark. They are working on the compact molten salt reactor (CMSR), which is designed to be safe, efficient, and cost-effective. Saltfoss Energy's CMSR will be deployed on modular floating power barges, capable of producing between 200 and 800 MW of electricity. Copenhagen Atomics is another key player that is developing a thorium-based MSR fitting into a 40-foot container. Their approach focuses on mass manufacturing these reactors on an assembly line, like automotive production, making nuclear energy more accessible and scalable.

The Czech MSR programme includes both theoretical and experimental research. This work is conducted by a consortium of Czech institutions and companies, supported by the Ministry of Industry and Trade. The research covers various aspects of MSR technology, including reactor physics, fuel salt and fuel cycle chemistry, on-line reprocessing technology, molten salt thermo-hydraulics, and structural material development.

1.2. Research and development status in the United States

The United States (US) restarted molten salt reactor development efforts on a limited scale in 2001 with the inclusion of MSRs as one of the six advanced reactor classes in the Generation IV International Forum. The US focus for the first few years of the renewed program was on solid fuelled, liquid salt cooled reactors also known as fluoride salt-cooled high-temperature reactors (FHRs). The renewed MSR program under US Department of Energy's Office of Nuclear Energy (DOE-NE) from the onset featured substantial university involvement. Notably, larger-scale (5–8 M US Dollars per project) integrated university projects contributed substantially both by producing a new generation of skilled staff and through technology advancement. Over time, the US MSR program diversified to include liquid salt-fuelled reactors and eventually fast spectrum liquid salt-fuelled reactors.

The US MSR program began to feature support for industrial developers in the mid-2010s. In 2017, the national laboratory portion of the DOE-NE MSR development program was organized into a national MSR technology development campaign which serves as the hub for efficiently and effectively addressing, in partnership with other stakeholders, the technology challenges for MSRs to enter the commercial market. Six national laboratories are working collaboratively engaging 1) universities through the Nuclear Energy University Program and 2) private sector MSR developers through the Gateway for Acceleration of Innovation in Nuclear (GAIN) program to enable the design, discovery, and production of salt, salt fuels, coolants, advanced materials, off gas management required for the safe operation of various MSR concepts in complex, evolving, and challenging environments. DOE-NE also supports larger-scale private sector MSR demonstration activities through the Advanced Reactor Development Program.

Molten salts have the potential to advance energy technology not only as liquid nuclear fuels but also as heat transfer or energy storage media. A major effort has been undertaken by the DOE-NE MSR campaign to determine experimentally and computationally the thermophysical and thermochemical properties of molten salts for system design, engineering, and operation. Indeed, thermophysical properties are rated as the highest priority needs by MSR developers since the thermal hydraulic design of an MSR relies on properties such as density, specific heat capacity, vapor pressure and volatility. The property values generated from both computation and experimental methods are used to develop models that constitute the Molten Salt Thermal Properties Database (MSTDB) (Birri et al., 2024). While the building blocks of MSTDB are fundamental in nature, its data facilitates constructing engineering models that allow stakeholders to investigate the behaviour of specific compositions of interest and supports broader modelling and simulation of MSRs through coupling to multi-physics, multi-scale mass accountancy tools supported by the DOE-NE Advanced Modeling and Simulation (NEAMS) program (McMurray et al., 2021). As the off-gas contains the vast majority of mobile radionuclides containing and managing the off-gas is essential. Various optical spectroscopy analysers such as Laser Induced Breakdown Spectroscopy (Andrews et al., 2021) or Raman spectroscopy are developed to monitor xenon, krypton, tritium, and iodine in the off-gas system. DOE-NE Material Recovery and Waste Form Development (MRWFD) campaign is partnering with the MSR campaign to develop sorbents and waste-forms to trap and encapsulate gaseous species as well as spent fuel salt (Riley et al., 2019).

Understanding material interaction with salt as well as interfacial reactions is supported by the Advanced Materials and Manufacturing Technologies (AMMT) campaign under DOE-NE and this provides insights into mitigating corrosion. Other offices under DOE also support research on molten salts. As an illustration, the Energy Frontier Research Center – Molten Salt in Extreme Environments, sponsored by the Office of Science (2018–2026) combines cutting-edge experimental capabilities for high-temperature research with a unified computational effort performing molten salt simulations to examine the atomic basis of molten salt behaviour and provide a predictive description of molten salt chemistry under the coupled extremes of high temperature and ionizing radiation. Finally, in 2007, the national academies recommended the US congress to establish an Advanced Research Projects Agency – Energy (ARPA-E) within DOE to fund advanced energy R&D (Stine, 2009; Khosla and Beaton, 2017). ARPA-E advances high-potential, high-impact energy technologies that are too early for private-sector investment, e.g. modular off-gas treatment system, metal halide perovskite fluoride salt waste-form, and optical and electrochemical sensors for molten salt measurement. ARPA-E is currently championing seven projects related to MSR.

The various MSR programs under DOE work in a collaborative way to develop the technological foundations to enable MSRs for safe and economical operations while maintaining a high level of proliferation resistance.

The US is planning commercial deployment of its first MSRs by 2030 (Brown, 2022; U.S. Government, 2024).

2. Needs for future standardisation

The European Industrial Alliance on Small modular reactors is an initiative aimed at accelerating the development, demonstration, and deployment of small modular reactors, including MSRs, in Europe by the early 2030s (European Council, 2023; European Parliament, 2023; European Commission, 2024). The Alliance's key objectives include accelerating deployment within the EU, guiding the deployment of the first small modular reactors, creating a robust European supply chain, and reinforcing the nuclear supply chain and promoting EU cooperation.

MSR technologies differ significantly from previous generations of nuclear reactors, and their designs are highly diverse, including fast and thermal systems, differing fuel types, and coolant salts. As a result, previous codes and standards are only partially applicable, and new standardisation efforts are needed to ensure the safety and security of MSR technologies. Prototypes and demonstrations along with pre-normative research, such as definitions of regulatory requirements, codification of new components, libraries of validation data, and identification of benchmarks, are milestones in the process of deployment of MSR technologies.

2.1. Standardisation needs to support R&D

Although there are high prospects and potentials for an adoption of the molten salt reactor technology, the technology cannot directly profit from the experiences and solutions of forerunner generations of reactor designs (Schlegel and Bhowmik, 2024). The fast development of the molten salt reactor technology requires various issues to be overcome, necessitating extensive fundamental studies to find technical solutions. Key areas requiring attention include experimental verification of continuous online fuel salt reprocessing, high-performance graphite sealing and manufacturing, and the development of structural materials with high neutron-irradiation and corrosion resistance withstanding the direct contact with fuel. Furthermore, long-term data on high-temperature creep and creep-fatigue of structural materials, as well as the solubility of lanthanides and actinides, need to be investigated. Addressing these issues is crucial to facilitate the deployment of MSR technology (Wang et al., 2024).

Standardisation supports this type of research and technological development in MSR technologies. This includes the development of testing methods, benchmarking, and validated models, as well as the management of data generated by experimental work. Standardisation can help to ensure that research and development activities are consistent and aligned with industry best practices.

2.2. Standardisation needs in safety assessment

Safety assessment is a critical aspect of MSR technology development. Standardisation is needed to ensure that safety assessments are consistent and reliable across different MSR designs and applications.

Distinguishing between the International Atomic Energy Agency (IAEA) safety standards and more specific ISO/CEN standards is crucial for the development and deployment of reactors. IAEA safety standards provide a general framework for nuclear safety, while ISO/CEN standards offer more specific and detailed guidelines tailored to the unique characteristics of SMRs and MSRs. The latter's innovative design and use of liquid fuels or coolants require specialized standards to ensure safe operation, maintenance, and decommissioning. Via the adoption of distinct standards, developers and regulators can address the specific challenges and risks associated with MSRs, ultimately enhancing their safety, efficiency, and public acceptance. Standards facilitate the harmonisation of regulatory requirements, allowing for more efficient and effective development of MSRs, and mapping the way for the adoption.

During the standardisation process of safety assessments, stakeholders including industry can streamline the licensing process and ensure the consistent and reliable performance of MSR technologies across different designs and applications to facilitate the latter commercialisation of MSR technologies. This includes developing common approaches for safety evaluation and establishing guidelines for the design and operation of near-deployment reactors. In 2023, a comprehensive safety analysis has been carried out among MSR designs (de la Rosa Blul et al., 2023). The analysis encompassed various safety aspects that are considered crucial for achieving the goals set by the Generation IV International Forum. As part of this assessment, the researchers made a basic comparison between the safety features of molten salt reactors, and those of current reactors that are widely used and accepted as the standard.

According to a recent comprehensive review, the licensing of novel reactor concepts is hindered by five significant barriers, which collectively contribute to lengthy timelines, increased costs, and regulatory complexities (Sam et al., 2023). The study argues that the existing legal and regulatory framework requires adaptation to accommodate SMRs such as molten salt reactor types, while the traditional prescriptive regulatory approach needs to be revised to facilitate innovation in this field of diverse reactor designs. According to the study, the novelty of SMR technology also poses challenges, as regulators must develop new assessment methods and standards. Furthermore, regulatory fragmentation forces SMR vendors to modify their designs to comply with varying national requirements, resulting in additional costs and delays. Finally, the absence of an in-factory certification process slows down the deployment of mass-produced components.

To overcome these barriers, a joint effort is needed to harmonise regulations, create an in-factory certification process, and enhance regulatory capabilities. The need of a concerted effort is reflected by Fig. 2 which highlights that participants of the Putting Science Into Standards workshop on Molten salt reactors did not set a clear path that would lead to a faster commercialisation pace. European and International standardisation participants are of the opinion that harmonisation of design code efforts promoted by the American Society of Mechanical Engineering (ASME) and the French Association for Design, Construction, and In-Service Inspection Rules for Nuclear Island Components (AFCEN) could as well deliver timely common agreements.

2.3. Standardisation needs in context of regulatory requirements

Achieving nuclear safety and compliance requires harmonised collaboration of various international and national organizations. At the forefront of this effort are the International Atomic Energy Agency (IAEA), the International Organization for Standardization (ISO), the European Committee for Standardization (CEN), American Society for Testing and Materials (ASTM)); regulatory bodies, the French Institute for Radiological Protection and Nuclear Safety (IRSN), and design code organizations AFCEN or ASME. Each of these entities plays a distinct yet complementary role, ensuring that nuclear activities are conducted in accordance with stringent safety standards and regulatory requirements.

The IAEA and ISO provide high-level, non-binding standards and guidance that serve as a foundation for nuclear safety and quality management. The IAEA develops international safety standards for nuclear safety, radiation protection, and security, while ISO focuses on broad technical and quality management standards relevant to the nuclear sector. These standards offer a framework for national and international use, influencing the development of legally binding regulations by regulatory bodies.

Regulatory bodies, such as the US Nuclear Regulatory Commission (NRC) and the French Nuclear Safety Authority (ASN), establish and enforce national laws and regulations specific to their jurisdictions. They draw upon IAEA and ISO guidance to inform their standards, ensuring that nuclear operators adhere to safety principles and technical requirements. The IRSN, as a technical support organization, provides safety recommendations and analyses to support regulatory processes, while AFCEN or ASME delivers detailed, industry-specific guidelines for nuclear design and construction.

In terms of compliance, the IAEA advises member states on aligning their nuclear frameworks with international safety norms but does not enforce compliance. ISO, CEN and ASTM standards offer frameworks that help meet regulatory requirements, although they remain voluntary unless formally adopted. Regulatory bodies directly enforce compliance with national laws, ensuring that operators meet safety standards. The IRSN supports this effort by conducting technical evaluations to ensure adherence to safety principles. AFCEN and ASME design codes are instrumental in demonstrating compliance with regulatory requirements, providing detailed methodologies for implementation.

The process of licensing is the responsibility of national regulatory bodies, which grant approvals for nuclear reactor construction, operation, and decommissioning. The IAEA provides recommendations and tools to support national licensing frameworks, while for instance in France the IRSN conducts technical assessments during licensing. AFCEN or ASME design codes serve as reference points during evaluations to verify compliance with technical requirements.

For conformity certifications, the IAEA and ISO offer frameworks

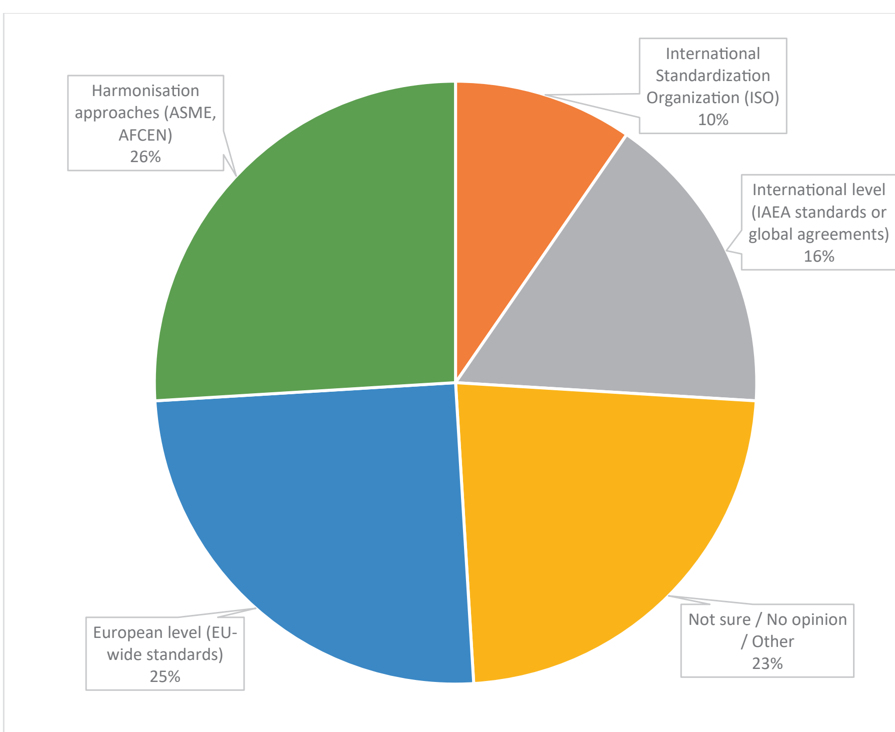

Fig. 2. Areas where standardisation initiatives advance at a faster pace. The percentages reflect opinions of workshop participants about the potential pace of advancements of standards that support molten salt reactor technologies.

that are audited by member states or independent third parties. AFCEN and ASME design codes provide industry-specific benchmarks that facilitate the certification of components and systems, typically conducted by operators or certifying entities. Regulatory bodies incorporate conformity certifications into their licensing and inspection processes.

Finally, monitoring compliance is a shared responsibility among these organizations. The IAEA conducts peer reviews and advisory missions to assess member states' adherence to international standards. ISO relies on independent auditors to verify ongoing compliance with its standards, while AFCEN and ASME depend on external parties to oversee the application of their engineering codes during construction and operation. Regulatory bodies are directly responsible for monitoring licensed nuclear activities through inspections and oversight, with the IRSN complementing this effort by conducting independent safety assessments and providing monitoring support.

3. How to bridge the gap

The development and commercialisation of molten salt reactor (MSR) technologies require a robust standardisation framework to ensure consistency, reliability, and compatibility across different designs and applications. In the following we discuss the standardisation needs and challenges associated with the development of MSR technologies and explore strategies for bridging gaps in international standards and design codes, as well as in collaboration and capacities for standardisation.

3.1. Bridging the gap to international standards

Organizations such as the European Committee for Standardisation (CEN) and the International Standardization Organization (ISO) actively participate in standardisation activities related to nuclear energy technologies, and radiological protection. The European and the International technical committees for nuclear energy, nuclear technologies, and radiological protection (CEN/TC 430 and ISO/TC 85) propose and endorse existing standards, ensuring harmonisation and consistency across international frameworks. European standards are aligned with those of ISO/TC 85 and its subcommittees, promoting the adoption of established practices within the nuclear industry.

The collaboration between CEN/TC 430 and ISO/TC 85 extends to exploring new projects and initiatives aimed at advancing nuclear technologies. Proposals for new standards or modifications are rigorously evaluated to meet the evolving needs of the industry. The emphasis is on leveraging international standards to drive innovation and enhance safety measures within nuclear facilities.

The CEN Workshop (CEN/WS 64) serves as a platform for fostering pre-standardisation activities, codification, and international standardisation in support of the AFCEN Code dedicated to innovative reactors (RCC-MRx). This group acts as a catalyst for the development of new standards and the alignment of European practices with global benchmarks. The efforts of CEN/WS 64 contribute to the continuous improvement and standardisation of nuclear technologies, ensuring compliance with international best practices.

ISO develops voluntary, consensus-based international standards that support innovation and provide solutions to global challenges. In the nuclear field, ISO standards often focus on quality management systems, environmental management, and other areas that support the safe and efficient use of nuclear technology.

Whilst ISO follows a bottom-up approach focusing on satisfying the specific requirements of the immediate mainly industrial customers the codes of the International Atomic Energy Agency (IAEA) follow a top-down approach focused on meeting the overall safety requirements for the plant, personnel and the society in general.

The IAEA is primarily concerned with nuclear safety and security. Its standards are designed to protect people and the environment from the harmful effects of ionizing radiation. The IAEA's safety standards are categorized into three main sets:

- Safety Fundamentals: Establish the fundamental safety objectives and principles.
- Safety Requirements: Outline the necessary requirements to ensure protection.
- Safety Guides: Provide recommendations and guidance on how to comply with the requirements.

These standards are used by regulatory bodies, organizations involved in nuclear activities, and other relevant authorities to ensure a high level of safety worldwide.

The IAEA's Nuclear Harmonization and Standardization Initiative (NHSI), established in 2022, is looking at how to speed up the deployment of advanced reactors, including MSRs, through harmonising regulatory approaches and industrial standardisation. In October 2023, the IAEA and the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (OECD-NEA) jointly organised the International Workshop on the "Chemistry of fuel cycles for molten salt reactor technologies" in Vienna (IAEA & NEA, 2023).

3.2. Bridging the gap from R&D to design codes

Establishing robust guidelines and standards is crucial for the safe and efficient design, construction, and operation of MSRs. RCC-MRx, a design code developed by AFCEN for innovative reactors, serves as tool for nuclear equipment design, construction, and commissioning. AFCEN's diverse membership consists of stakeholders in the nuclear industry, including nuclear power plant operators, engineering companies, manufacturers of nuclear equipment, regulatory authorities, research organizations, and academic institutions. RCC-MRx's working groups, composed of domain experts, draft the code.

Modification requests for RCC-MRx can be submitted by prenormative task groups, often linked to industrial or research projects and CEN Workshop Agreements (i.e. CEN/WS 64), as well as users of the code. RCC-MRx specifically focuses on providing design and construction rules for mechanical components of advanced, research, and fusion reactors, ensuring the safety, efficiency, and reliability of these nuclear systems. The code has evolved over time to adapt to new technologies and concepts in the nuclear industry, making it as a useful guidance for developers, manufacturers, regulators, and other stakeholders.

Throughout its history, RCC-MRx has adapted to the changing landscape of nuclear technology, incorporating new concepts and materials. The code's primary objectives revolve around simplifying processes, reducing costs, and enhancing efficiency through standardisation. By providing a common ground for sub-contractors, manufacturers, and suppliers, the code streamlines interactions and clarifies contractual dialogues. Moreover, it aims to strengthen relationships with regulators and safety authorities, ensuring compliance with stringent nuclear safety standards.

Standardisation plays a key role in advancing nuclear technology in a sustainable manner, particularly for innovative reactors like MSRs. By integrating standardisation early in the design process, developers can facilitate the transition of concepts into industrial components. The need for a public document as a tool for discussions with various stakeholders, including industries, regulators, and notified bodies, underscores the growing importance of standardisation in the nuclear sector. Users' active involvement in shaping rules tailored to their specific needs reflects a collective effort towards advancing nuclear technology.

The historical evolution of RCC-MRx, from its inception to its current projects, highlights its adaptability to diverse reactor designs and technologies. Projects such as ITER, MYRRHA, CALOGENA, and NEWCLEO have contributed to the refinement of the code over the years. The tools embedded within RCC-MRx, including dedicated code sections for research and development, probationary phase rules, and guidelines for new materials and coolants, demonstrate its flexibility in accommodating novel concepts and designs.

ASME plays a significant role in bridging the gap from R&D to design codes for molten salt reactors. ASME's Boiler and Pressure Vessel Code (BPVC) provides a widely accepted framework for the design, construction, and operation of boilers and pressure vessels, including those used in nuclear applications. To address the unique needs of MSRs, ASME has established a dedicated committee to develop standards and guidelines for MSR design, construction, and operation. This committee works closely with industry stakeholders, regulatory bodies, and research organizations to ensure that ASME's standards reflect the latest advancements in MSR technology and address the specific challenges associated with these innovative reactors.

Developing design codes is a critical step in the commercialisation of MSR technologies. To bridge the gap between research and development activities and design codes, it is critical to invest in testing facilities and prototypes. This will help to validate experimental work and support the development of consistent and reliable design codes. By aligning research and development activities with design codes, stakeholders can ensure the reliable performance of MSR technologies and facilitate their deployment in commercial applications.

3.3. Bridging the gap in collaboration

Collaboration is fundamental for the successful development and standardisation of MSR technologies. This includes working with international partners, sharing data and knowledge, and participating in joint publications and future meetings. By fostering collaboration and knowledge sharing, stakeholders can accelerate the development of MSR technologies and ensure their readiness for commercialisation.

Collaborative approaches, such as the US MSR programme (described earlier), ensure that research efforts align with industry needs and regulatory standards, contributing to the development of safe and reliable MSR technologies. Standardised measurement methods are being developed to ensure the quality and reliability of data used in modelling MSR systems. These methods are crucial for characterising the complex compositions and interactions inherent in molten salts, which can significantly influence reactor behaviour and performance. Research programmes encompass salt chemistry, advanced materials, MSR radioisotopes, modelling and simulation tools, and technology development (i.e., radionuclide release monitoring).

MSR innovation is largely dependent on the increased understanding of the thermophysical properties of molten salts, which are crucial for the effective design and safe operation of these reactors. Advanced computational methods, such as machine learning algorithms, are leveraged to accurately predict these properties, enabling researchers to optimise reactor performance and efficiency.

The development of databases for thermodynamic (e.g. melting/solidification temperatures, vapour pressures, heat capacity, etc.) and thermo-physical properties represents a significant milestone in MSR research. These databases provide substantial information on salt compositions, phase behaviour, and other key properties (e.g. density, viscosity or thermal conductivity), empowering researchers to make informed decisions during reactor design and operation. However, challenges persist in obtaining high-quality property data, particularly due to the unique characteristics of molten salts for nuclear applications (corrosive, air-sensitive, radioactive). Ongoing efforts are focused on addressing these challenges and enhancing the accuracy and reliability of data used in MSR development. Materials research is another critical aspect of MSR advancement, with a specific focus on understanding the interactions between structural materials and molten salts at high temperatures. Studies on graphite-salt interactions and the development of surrogate materials are essential for ensuring the structural integrity and safety of MSR components. Additionally, modelling efforts related to radionuclide transport and bulk salt behaviour are vital for evaluating source terms and ensuring the safe operation of MSRs. These modelling tools valuable insights into the behaviour of radioactive isotopes within the reactor system, aiding in the design of robust safety protocols and measures (See Table 1).

Regarding fuel cycle development, the EU and the US have made significant progress in fuel cycle development, while global efforts are still in the early stages. Whereas in materials testing the US and global research institutions have made notable advancements in materials testing, while the EU is still in the development phase. Safety analysis is a critical area that requires further research and development globally.

3.4. Bridging the capacity gap

To support the harmonisation and standardisation of MSR technologies, capacity building within the European Union is needed. This includes investing in research and development activities, providing training and resources for standardisation experts, and facilitating collaboration and knowledge sharing through workshops, training events, and mentoring sessions.

The integration of standardisation practices is crucial for EU-funded projects seeking to enhance research valorisation and market uptake. By building capacity for standardisation, stakeholders can ensure that the European Union is well-positioned to support the development and commercialisation of MSR technologies. Via leveraging services and expertise provided by platforms funded by the EU,[1] projects can strengthen their standardisation strategies, align with industry standards, and position themselves for success in the competitive market landscape.

Table 1
Prototypes and pilots of molten salt reactor designs including R&D status (Dolan and Kutsch, 2024).

Region	Facility/ Prototype	R&D Status	Gap analysis
EU	6 reactor designs (Stellaria, Naarea, Orano, Thorizon, Saltfoss (formerly Seaborg), Copenhagen Atomics)	Advanced research focused on industrial deployment	Standardization, licensing frameworks, and supply chain development
US	2 commercial-scale MSRs (Flibe Energy, ThorCon) beside designs from Terrestrial Energy USA (IMSR), Southern Company (MCFR), Natura Resources/Abilene Christian University (Natura MSR-1), Kairos Power (Hermes) and Elysium Industries.	Advanced research focused on demonstration and commercialization	Regulatory framework, public perception, and funding
China	2 MSRs under construction (TMSR-LF1, TMSR-SF1)	Rapid progress, with focus on demonstration and commercialization	International collaboration, intellectual property protection, and standardization
Global	Several research reactors and small-scale prototypes (e.g., Japan, Korea, Canada)	Ongoing research, with varying levels of funding and support	Standardization, international cooperation, and public awareness

[1] HSbooster.eu.

4. Prioritizing standards and pre-normative research needs

The workshop, that convened over 100 experts from Europe and around the world, highlighted the importance of standardisation in enabling the successful development and commercialisation of MSR technologies. Key harmonisation and standardisation needs identified during the workshop include measurements of thermo-physical properties, safety evaluation (common approach), qualification of fuels and fuel cycles, and codes & standards for materials and components.

Participants ranked standardisation gaps in different proposed fields of molten salt reactor technologies, such as numerical simulation tools, quality assurance of fuels, components and materials, measurements of thermo-physical properties, nuclear design codes and licensing of MSRs.

According to the survey, terminology is the primary requirement for nuclear design codes, numerical simulation tools, and fuel quality assurance, as indicated by 44 %, 38 %, and 45 % of respondents, respectively. For thermo-physical property measurements, 78 % of respondents identified metrology as the principal need. In the areas of components and materials, 32 % of respondents emphasized the need for performance characterisation, while for licensing 44 % highlighted compatibility as the most crucial standardisation category.

When participants were asked to rank the current efforts in order to close the standardisation gaps, the most pronounced effort was in the field of licensing. In parallel, the overall mean for efforts to close the gap was also highest for components and materials and for licensing.

The participants also prioritized the importance of standards in licensing, components & materials, and methods for measurements of thermo-physical properties over those for numeric simulation tools and nuclear design codes. The latter fields were regarded as at the moment less feasible (See Fig. 3).

4.1. Measurements of thermo-physical properties

Standardisation is needed to ensure reliable data and minimize uncertainties in the measurements of thermo-physical properties. This includes establishing guidelines for sample quality, handling of salts, calibrations, measuring techniques, sample sizing, and certification/accreditation of laboratories.

During the technical session on measurements of thermo-physical properties, the key items that require standardisation to obtain more reliable data and minimize uncertainties were discussed. The following sub-topics were considered:

- Sample quality: The methods needed to determine the purity level of the samples were evaluated, as well as the existence of reference data to benchmark the obtained data. The purity requirements and their relation to each measurement conducted were also discussed.
- Handling of salts: The discussion focused on sample preparation and general handling before measurement, encapsulation of samples, if necessary (including the qualification of the developed crucibles for encapsulation), and post-measurement characterization where relevant, to check that the quality of the salt did not diminish prior or during data collection.
- Calibrations: Calibration procedures (e.g. temperature calibration) and the influence of the weight of the sample were discussed, along with the standard reference material providers.
- Measuring techniques: The importance of property knowledge and the level of precision required were assessed. Uncertainty analysis, procedure standardisation, and the variety of different measuring techniques for the same property determination were also considered.
- Sample sizing: The influence of sample size on the uncertainty was discussed, as well as the downsizing of nuclear fuel samples due to radiation protection concerns for personnel. This influence is highly dependent on the technique and the property measured.
- Certification/accreditation of labs: The quality assurance of the data, certification of the laboratories by standards such as ISO 9001, and the need for accreditation by ISO 17025 standard or the so-called NQA-1 requirements were debated.
- Database developments: The discussion revolved around the need for one database or multiple databases, the benefit of benchmarking databases, the development of a repository of original data, and the management of databases and quality-assurance stamps.
- Collaborations and laboratory benchmarking: The benefits of Round Robin tests and joint publications and meetings were emphasized to improve data reliability and standardisation efforts.

The alignment of methodologies for setting standards between the EU and US was found to be well-established, indicating that this cooperative approach could be extended beyond these regions. Addressing these standardisation needs will lead to more reliable data and minimize uncertainties in the measurements of thermo-physical properties, which

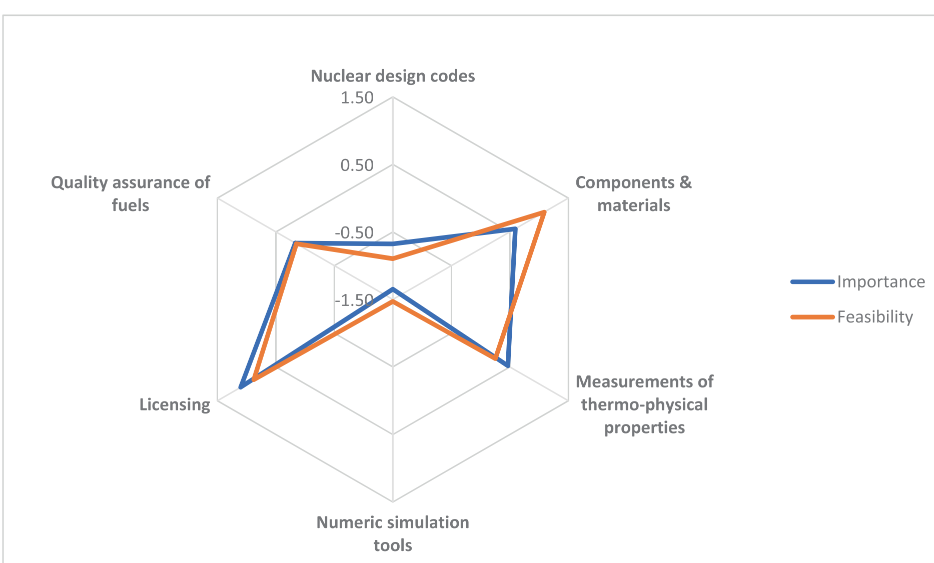

Fig. 3. Participants (n = 100) rated importance (blue) feasibility (orange) in closing standardisation gaps in different fields of molten salt reactor technologies, expressed in standardized ratios of weighted means.

is crucial for the effective design and operation of MSRs.

The development of standardised measurement methods is key for characterizing the complex compositions and interactions inherent to molten salt systems, which can significantly influence reactor behaviour and performance. Ongoing efforts are focused on addressing these challenges and enhancing the accuracy and reliability of data used in MSR development.

Materials research is critical aspect of MSR advancement, with a specific focus on understanding the interactions between structural materials and molten salts. Studies on the effects of impurities in the MSR fuel salt and their impact on reactor operation and safety are also fundamental. Irradiation experiments using standard procedures are important for the safety assessment and assuring corrosion resistance of the structural materials during the MSR operation.

4.2. Safety evaluation

Standardisation can help ensuring consistent and reliable safety evaluations across different MSR designs and applications. This includes developing common approaches for safety evaluation, establishing guidelines for the design and operation of near-deployment reactors, and reviewing novel methods for determining specific properties.

The session on safety evaluation at the Putting Science into Standards (PSIS) workshop brought together experts in the field of nuclear reactor safety, focusing on MSRs. The main objectives of the session were to identify the most challenging issues related to MSR safety and develop top safety requirements (design-generic/design-specific) to address these challenges.

The safety aspect and its issues are closely connected to the licensing process, and from this perspective, the proposed topics were discussed with particular attention to the European system. Unlike the US, regulatory and licensing bodies in the nuclear field exist for each EU member state, each with different maturity, procedures, and requirements. This peculiarity poses a challenge for MSR developers, as reactor classes (see Fig. 4) necessitate distinct systems, structures, and components (SSCs) performance information and customized tools and analysis methods.

Multiple methods can be employed to demonstrate adequate safety efficiently, depending on reactor characteristics:

- Probabilistic methods that are especially effective at teasing out unanticipated risks from complex systems;
- Deterministic methods that allow relying on pre-established consensus for reactor class.

Moreover, safety considerations can be addressed through two key aspects of the Defence in Depth approach: accident prevention and mitigation. Notably, adequate safety can be achieved through preventing accidents altogether and by effectively mitigating their consequences, thus ensuring that the overall safety is maintained.

Based on the general concepts introduced above, the NRC, the DOE, the American Nuclear Society, and other institutional bodies in the US have started a process to introduce new criteria, rules, and guidelines for assessing the safety of new-generation reactors. Existing NRC rules such as 10 CFR Part 50 (domestic licensing of production and utilization facilities) or 10 CFR Part 52 (licenses, certifications, and approvals for nuclear power plants) are focused on the safety characteristics of existing plants (all large LWRs). A first step in this process was the adoption of NUREG 1.232, which introduced the advanced reactor design criteria, developed to translate the safety elements of the general design criteria to the characteristics of advance reactors.

The current market features a large number of MSR designs with very significant differences among them, such as on the neutron spectrum, fuel configuration and location, size, moderator type, fuel cycle, fuel source, etc. (see Fig. 4), which makes any approach for harmonisation difficult.

Nevertheless, the defence-in-depth strategy necessitates enhancements in the taxonomy and metrics, with clear definitions addressing barriers' progression phases. Reactor control and risk management emphasize the use of high-fidelity modelling and the establishment of predictive capability maturity in measurement technologies. Moreover, standardisation of knowledge preservation protocols and best practices is crucial. The role of prototypes, observations, and experimental benchmarks calls for clarified compliance criteria and standardised protocols. Overall, addressing these enhancements promises safer and more efficient nuclear energy solutions.

The session on safety evaluation at the PSIS workshop highlighted the importance of developing top safety requirements for MSRs and the challenges associated with the licensing process in the European context. Addressing these challenges and fostering collaboration among stakeholders, researchers and industry professionals can accelerate the development and commercialisation of MSR technologies, supporting the European Union's goal of achieving fully functioning small modular reactors by 2030.

4.3. Qualification of fuels and fuel cycle

Concerning the qualification of fuels and fuel cycles workshop participants identified two priorities: i) the establishment of standardised methods to characterise MSR fuels and ii) the need for setting standards for the MSR fuel cycle. The topics linked to the first area can be generally summarised as the development of standards for fresh fuel material specifications, including quality control processes & compatibility assurance with fuel cycle and definition of nuclear fuel safety criteria, to which the fuel must conform. Of particular importance are the development of good practices on sampling and measurements, including associated techniques, keeping an adherence to regulatory requirements and safeguards, and reaching the consensus on the chemical, nuclear and physical requirements of the fuel.

Other specific properties related to the safety of the MSR fuel were also mentioned, e.g. how to assess the capability of the fuel to retain the radionuclides during normal, transient, and accidental conditions, reactivity control during the reactor operation, heat transfer performance and knowledge of related physico-chemical properties including density, viscosity, thermal conductivity and heat capacity.

Concerning the second main area, time constraints limited the discussion to the general aspects of the back-end of the MSR fuel cycle and the needs for standardisation of the fuel cycle related terminology. Other planned topics, such as methods and techniques for tracking the radionuclide inventory at each step of the fuel processing, and identifying the main differences compared to conventional fuel requiring new standards, are recommended to be discussed at a potential follow-up meeting.

The session supported the development of industrial manufacturing methods for chloride-based MSR fuel, including quality control processes to ensure the fuel meets performance specifications and is compatible with the wider nuclear fuel cycle.

On top, standards should guarantee that nuclear fuels meet specific safety criteria, adherence to regulatory requirements and international agreements. While standardisation is considered a high priority for the front-end of the fuel cycle, it is deemed less urgent for the back-end.

It was regarded as highly important to set standards that define the fresh fuel purity. It is very likely that each reactor concept, employing different fuels, would require a specific standard. Standardisation is crucial for both fuel producers and reactor designers. The standards must be practical and achievable, avoiding setting the purity level unnecessarily too high. A list of problematic impurities defining the maximum acceptable level should be included in standards, covering especially oxygen-based and metallic impurities (Cong et al., 2019; Sulejmanovic et al., 2021). It is needed to have purity standards checked both at the production and at the reactor sites, considering the possible contamination during transport.

In addition, standards for commerce will be required to establish

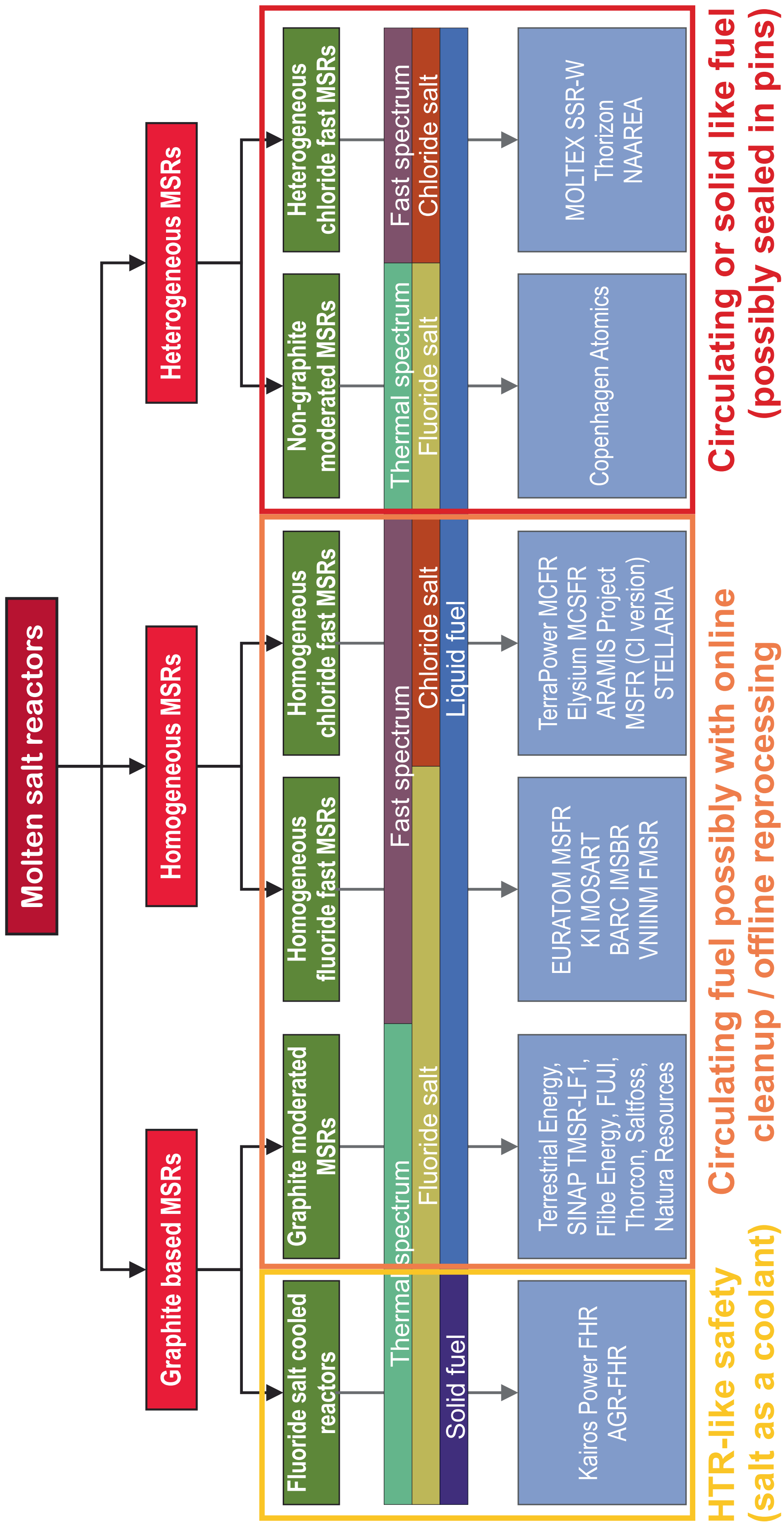

Fig. 4. MSR taxonomy showing classes (red) and reactor designs (green) including prototype references. Courtesy of Dr. Jiri Krepel; Note that Saltfoss (formerly Seaborg) thermal spectrum design based on fluoride salt, now uses graphite for the moderator.
Adapted from: Generation IV International Forum (2025)

methods for determining the contents of each shipped and received container of fresh fuel. These methods should allow to verify if the content is uniform or stratified and confirm that the fuel salt meets acceptance criteria.

At the same time, it may be challenging to implement a parallel fuel measurement system to support safeguards in addition to operations. A standard that enables IAEA access to fuel salt content measurements would be useful. It should provide adequate confidence in the accuracy of the method while ensuring that no safeguards related information is disclosed.

Some fuel function specific standards are also required, likely to be specified by reactor designers and provided to fuel producers. These criteria should assure that the fuel maintains its intended functions throughout the whole range of the reactor operation, including during transient and accidental conditions. For example, properties such as density, viscosity and fuel retention capacity for the key radionuclides must remain within acceptable limits to ensure safe and efficient reactor operation.

Concerning standardisation within the back-end of the MSR fuel cycle, the needs strongly depend on the selected treatment option. The back-end is likely the least developed part of the MSR technology making it premature to develop standards in this field at present. There is no clearly defined single solution for the molten salt waste streams, and it appears that most of the small and medium enterprises developing MSR technology are still in the process of defining or refining strategies for the used fuel treatment. However, having an identified disposal route is required in the US to obtain a license and many reactor developers in US are planning to incorporate online fission products removal in their designs. In Europe, vendors typically do not consider developing in-house capabilities for salt treatment of spent fuel and would rely on external service providers. If hydrometallurgical extraction processes were selected for the fuel treatment, there will be less need for new standards, aside from ensuring compatibility with existing reprocessing plants. For the advanced pyrometallurgical processes, however, new standards would need to be developed for each specific technique.

Standardising the terminology related to the entire MSR fuel cycle is crucial, particularly for terms such as fuel processing, reprocessing, recycling, and polishing, in particular the harmonisation of these terms and clarifying the location of fuel processing activities (on-line, at-line, in-line, and off-line operations). The fuel function-specific standards should guarantee that the fuel performs its intended function throughout the entire range of reactor operations, encompassing key properties such as viscosity, density, and the ability to retain isotopes (i.e. solubility).

At present, it is regarded very important to standardise the terminology connected to the whole MSR fuel cycle. Standards should define fuel-processing, -reprocessing, -recycling and -polishing, and clarify the meaning of the fuel processing location: on-line, at-line, in-line and off-line and similar terms.

Three levels of fuel salt treatment can be distinguished:

- Level 1: fuel salt cleanup through removal of fission products which are not dissolved in the salt (gases or metallic particles), without changing the chemical state and concentration of actinides.
- Level 2: fuel salt treatment, for instance redox potential change, which allows separation of selected fission products and actinides.
- Level 3: fuel salt processing, which typically consist of several methods to separate fission products, actinides and carrier salt from each other.

The standardised method to characterise MSR should also include the definition of the fuel burnup. It is a common parameter used for solid fuels as a criterion for nuclear fuel safety and it also characterizes the fission products amount in discharged fuel and mass of fissioned actinides. The definition of the burnup for liquid fuel is more complex and might not have the same meaning as for solid fuels.

4.4. *Nuclear safety design criteria and functional performance requirements for materials and components*

To deploy MSRs within the next few decades, the integration of regulatory requirements, design codes, and standards for structural materials and components are prerequisite. Three key areas were identified by participants: needs for harmonisation and standardisation, path towards harmonisation and standardisation, and collaboration. As mentioned above the Design and Construction Codes play a crucial role to ensure that reactors are designed and constructed in accordance with the best engineering principles and as possible proven technologies and operating experience. Since MSR is an innovative technology the ASME BVPC and RCC-MRx do not include specific MSR Design Rules and Design Data. This will need to be developed and implemented as data and experience are gained through pre-normative research and feedback from the vendors. This will initially be more as Guidelines.

Nuclear regulatory frameworks differ significantly between EU Member States and the USA, with EU Member States adopting a more prescriptive approach and the USA favouring a performance-based and risk-informed approach. A harmonised licensing approach requires some degree of harmonised regulation. MSRs pose unique design challenges, including high temperatures (700 °C), corrosive environment, and neutron irradiation. Proposed MSR concepts may have different design features, such as fast versus thermal neutron spectra, fluoride versus chloride salts, and solid fuel or fuel in the molten salt.

The license of an MSR must account for detrimental environmental effects, and rules or data for molten salt are included in the design codes. Salt exposure data are needed to demonstrate that a specific material is fit for purpose. The first MSR designs use austenitic steels or low Cr nickel-based alloys as reference materials, while refractory materials and composites are also explored. Standardized test procedures are necessary for corrosion and mechanical tests in molten salt. Impurities can drastically affect corrosion rates, making test procedures with controlled and measured impurity levels essential. A first step could be to develop a code-of-practice using the format of a CEN Workshop, to be subsequently upgraded into CEN or ISO standards involving key stakeholders (reactor designers, code developers, research community). Given the various properties (corrosion, creep, irradiation, fatigue) and associated tests, different materials and molten salt variations, a very extensive test programme is required, which will consequently create an incentive to share data.

Sharing data is crucial, but intellectual property rights need to be recognised. Experimental testing requires data management and data libraries following the FAIR[2]principles. Various test facilities, such as dedicated loops, are necessary, and a market for such tests should be created. Data sharing will create an incentive to share results, but it's not straightforward, and recognised intellectual property rights are vital.

Verified and processed data are the basis for MSR material qualification, design rules and engineering design code data. The general procedure applies to any MSR candidate material and would first be applied to materials already in the codes. Given the harsh conditions in terms of molten salt compatibility, high temperatures and irradiation, non-metals such as silicon carbide (SiC) composites are considered. The non-ductility and potential for tailored properties and design infer that the traditional approach to determine materials qualification based on large number of tests, lower limits and deterministic design may need to be replaced by a risk-informed approach and associated test programme.

European and international binding agreements for the energy transition require accelerated qualification and life-assessment procedures for MSR materials and components. Reduced long-term tests and equivalence-based qualification by analogy with a material, in-situ based qualification, and model-based qualification are recommended. However, more data need to be generated for each test, which could

[2] FAIR = findability, accessibility, interoperability, and reusability of data.

benefit from standardisation. Modelling becomes more relevant, and validation using benchmark tests is necessary, but expensive. European or international collaboration could benefit these efforts. It should be stressed that long-term corrosion and creep tests will remain very important.

5. Molten salt reactor vendors' view

A decade ago, the MSR was considered the least mature technology of the six Generation IV concepts, but this has changed drastically, and MSR is now the technology with the most attention and vibrant development. One consequence of the innovative character and fast development is that there is still a large variety of MSR concepts. Presently, there are five MSR "start-up" design projects in the European Union: NAAREA, Stellaria, Thorizon, Saltfoss Energy, and Copenhagen Atomics.

There are some important commonalities and differences. NAAREA, Stellaria, and Thorizon rely on the fast spectrum and chloride salts, whereas Salftoss Energy and Copenhagen Atomics rely on thermal spectrum and fluoride salts. Another important difference is that NAAREA, Stellaria, and Thorizon are co-funded by the France 2030 investment plan and coordinate their development with the French regulator ASN and plan to use the AFCEN Design Code RCC-MRx. Saltfoss Energy is targeting primarily the Asian market and uses the ASME code.

The US programme comprises many start-ups some of them co-funded by the Department of Energy. All adopt the ASME BPVC design code, and they all need to adhere to NRC regulation.

Given the recent increased interest for MSR and the need for deployment in the coming decades means that the innovation and deployment phases will merge. The design and operation of test facilities and prototypes is an fundamental prerequisite for commercial deployment.

The EU global goals need to be matched with EU-wide research and an industrial deployment plan. The question is then how can the EU support development and deployment of the MSR technology as an important technology to meet the Green Deal and Net Zero Industrial act? To this end, the five MSR vendors were invited to present their perspective along three questions:

1. What can the EU do 'better' to make deployment of innovative reactor technologies attractive for industries?
2. Would it be helpful if EU would have harmonised license for new reactor types?
3. Is the EU market attractive for future nuclear fleet deployment?

The successful transition to a low-carbon energy system is of existential importance for Europe, and there is overwhelming consensus that the EU has a very important role to promote and support an industrial sector willing to invest and build-up a nuclear capacity. In very broad terms, the key expectations from the EU are:

- Ensure stable and predictable conditions including financial frameworks for nuclear energy, reduce regulatory barriers and provide clear paths for nuclear deployment.
- Provide financial support for European pre-normative research and facilities that require large investments.

Nuclear energy involves high upfront investments, extended timelines, strict regulatory requirements, and often political debate. While innovative reactor deployment still faces technical challenges, the current EU landscape—marked by reduced political controversy and strong technical, financial, and policy support—offers a rare and promising opportunity for the nuclear industry and its competitive supply chain to grow in the coming years.

The importance of reliable quality data for the MSR development was stressed in every session of this workshop. Proper data management and sharing is a win–win situation and should be promoted by the EU, but it does not necessarily infer common databases. As a start, all EU-funded activities should enforce data management according to FAIR principles.

The focus of this workshop was to enable scientific support to MSR technology standardisation. Standards are enablers for innovation, reliability & quality, safety, and best practices. The EU should support European and international standards for the MSR technology. Climate change is a global problem, solutions are therefore also global. The EU has a strong foundation in MSR technology and should aim to maintain its position as a key player in this field, while also actively seeking international collaboration and knowledge-sharing to advance the development of MSR technology globally.

There was consensus among the reactor vendors that harmonised licensing would be helpful at the deployment stage as it could drastically reduce the cost and time linked to the licensing procedure. It would clearly also promote a European market and supply chain through larger series, predictability, and more companies willing to invest.

The EU market is a relatively small part of the global nuclear market, and it is therefore crucial to consider other geographical regions as potential markets as well. A global outlook will also help in making informed decisions and maximizing the benefits of nuclear energy deployment across the globe. Partnership with other regions based on European strengths would be of mutual benefit.

6. Conclusions

The MSR technology has gathered significant interest, as evident from the five reactor designs currently being developed in the EU (Stellaria, Naarea, Thorizon, Saltfoss Energy, and Copenhagen Atomics) and more reactor designs in other regions (USA, Canada, and China). Deployment of MSR is expected to take place in the coming decades. To comply with the EU Green Deal and the Net-Zero Industrial Act, MSR deployment is expected to occur within a timeframe of two decades, which is an ambitious goal considering the development and deployment process for nuclear materials.

To accelerate MSR deployment and overcome the associated challenges, stepping up efforts is necessary. A data-driven approach, incorporating a closer integration of experiments and physics-based and data-driven modelling, is crucial for achieving industrial deployment. Harmonisation and standardisation are long-term and continuous processes, but concrete standardisation activities must begin as soon as possible, focusing on key priorities.

Initially, a harmonisation process is useful, rather than standardisation, to address the current level of maturity of the technology and the wide variety of designs being developed. This process should aim to obtain a shared safety approach for First-of-a-Kind (FOAK) demonstration reactors, which are vital for generating the data required to validate safety assessment models. The harmonisation process must commence as soon as possible, with the primary objective of obtaining a shared safety approach for FOAK demonstration reactors.

Accurate measurement of data is critical for satisfying quality requirements for licensing. Standardising measuring methods not only meets these requirements but also reduces data uncertainty, which minimises MSR design margins and lowering associated reactor costs. Addressing the significant data gaps in our knowledge of the thermo-physical properties of MSR fuel and coolant systems is also crucial. This can be achieved through collaborative efforts and a commitment to sharing data.

Ensuring that the fuel maintains its function throughout the reactor's operational range requires standards for the definition of fresh MSR fuel purity, monitoring fuel composition and interaction with reactor materials during irradiation and measuring fuel function-specific properties. Standardisation within the back-end of the MSR fuel cycle depends on the ultimately selected treatment option, and this part of the technology appears to be least developed. Nevertheless, standardising terminology related to the whole MSR fuel cycle and developing standards for each pyro-metallurgical process, if considered for the backend, is beneficial.

Currently, there are no code-qualified materials or design rules for molten salt reactors in RCC-MRx or ASME BVPC. Impurities in the molten salt have a significant impact on environmental degradation. Establishing test procedures (e.g., corrosion, creep) in molten salt with controlled impurity content is a prerequisite. Qualifying MSR structural materials should begin with code-qualified high-temperature materials, but exploring and qualifying materials like silicon-carbide composites for commercial deployment is also necessary.

Rather than developing new specific MSR standards, it is more efficient to review existing nuclear and non-nuclear standards and determine to what extent they can accommodate MSR needs.

Progress requires the construction and operation of MSR prototypes and reactors to gain operational experience and validate solutions for the inclusion of MSR design code rules and data in codes.

A common understanding among MSR stakeholders is that collaboration is necessary for accelerating deployment and reducing costs, particularly with respect to standard and design code development, data sharing, benchmarking, and sharing experimental facilities. European and international harmonised licensing for MSR can facilitate deployment through faster licensing, lower costs, an efficient supply chain, and a competitive market. However, licensing harmonisation also implies harmonised regulation, which is not a straightforward process and may induce delays and reduce benefits.

At the pre-commercial development stage, flexibility is crucial, which is easier when dealing with a national regulator. A first concrete action at the European level could be to start a standardisation roadmap and code-of-practice via the Annual Union Work Programme (AUWP) for standardisation also involving the Industrial Alliance for Small modular reactors addressing key priorities. In 2025 for the first time, the European Commission within the AUWP (European Commission, 2025) identified direct standardisation action on the qualification of small modular reactor materials as a policy priority. This priority aims to strengthen the EU nuclear power sector by developing standards for materials and coolants for small modular reactors, improving safety, promoting innovation and supporting the EU's net zero emissions targets. Codes of practice, guidelines and ultimately standards are the first essential step in creating the right environment and framework to facilitate the development of advanced reactors such as molten salt reactors. In the following, we categorised the standardisation actions and recommendations into short-term and long-term goals.

Short-term goals (2–5 years):

- Develop a standardisation roadmap and code-of-practice
- Standardise terminology and review existing standards
- Harmonise safety approaches for FOAK demonstration reactors
- Establish data sharing and test procedures (e.g., corrosion, creep)
- Qualify high-temperature materials and begin developing design code rules

Long-term goals (5–20 years):

- Develop and implement design code rules for MSR
- Develop standards for the back-end of the MSR fuel cycle, deploy MSR prototypes and reactors
- Qualify structural materials (including new materials like silicon-carbide composites)
- Achieve harmonised licensing and establish a competitive supply chain
- Standardise measuring methods and reduce data uncertainty

The Putting Science Into Standards workshop 2024 marked the beginning of the EU goal of deploying molten salt reactors to support the EU Green Deal and its Net-Zero Industrial Act via the Annual Union Work Programme for standardisation.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nucengdes.2025.114495.

Data availability

Data will be made available on request.

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