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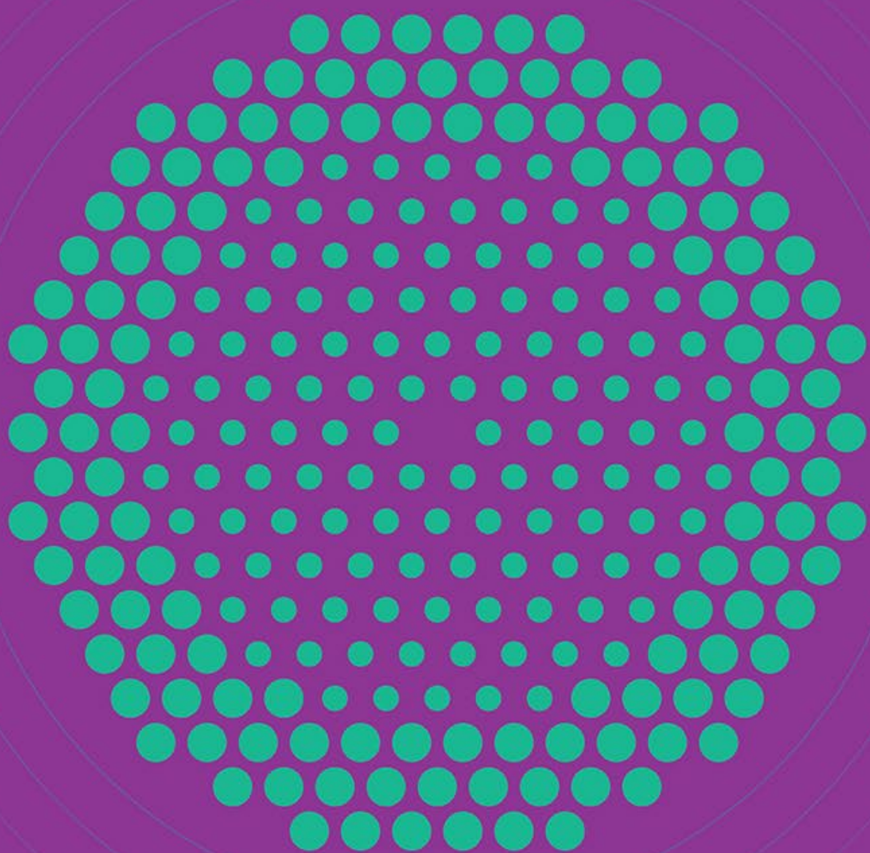
Molten Salt Reactor Technologies

Putting Science Into Standards



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Contents

Abstract

This report presents insights from the Putting Science into Standards (PSIS) workshop on Molten Salt Reactors (MSR), aiming to accelerate the market adoption of MSR technology by leveraging the expertise of the European research and innovation community using standardisation. The imperative for MSR deployment arises from the pressing need to reduce greenhouse gas emissions and enhance energy security in the European Union (EU) while striving to achieve the targets set forth in the Net Zero Industry Act. MSRs offer significant potential to contribute to decarbonizing energy mixes, providing baseload energy production and fortifying energy security alongside intermittent renewable sources like wind and photovoltaic power. The workshop focused on collecting stakeholder needs and promoting scientific community participation in standardisation efforts, identifying gaps in existing standards and prioritising areas for future standardisation. By harnessing the collective expertise and insights of stakeholders and the scientific community, the PSIS workshop laid the groundwork for a standardisation and harmonisation roadmap ensuring the safety, security, and accessibility of MSR technologies in the market.

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Foreword

Over the last ten years, the Putting Science Into Standards (PSIS) workshops have addressed a wide range of emerging policy topics and enabled innovation in multiple standardisation areas. This shows the great value of the PSIS initiative, where scientists and technicians meet industry, policy-makers and standard setters, merging their fields of expertise to pave the way towards new ways of collaborating and working together. The aim of this year's PSIS workshop was to explore how recent developments in science and technology can accelerate in small modular reactors, particularly molten salt reactors, to support the implementation of the Net Zero Industrial Act. While small modular reactors are referenced in the act, European legislators, developers, nuclear industry and science can facilitate the policy and market uptake of these technologies by consenting on aspects related to safety, security and common approaches.

The Joint Research Centre (JRC) is a Directorate General of the European Commission, providing independent scientific advice and support to EU policy making. It operates at the intersection of science and policy, contributing to various stages of the EU policy cycle by focusing on understanding future challenges, bridging scientific and policy domains, and assisting policymakers in assessing policy effectiveness. Originally established under the Euratom Treaty, the JRC offers scientific expertise across a wide range of disciplines, supporting almost all EU policy areas.

The work programme of the JRC includes several portfolios, namely Innovative Policymaking [33], Small Modular Reactors [5], and Safety of Nuclear Technology [4], that have played a key role in driving technical support for this initiative, enhancing the scientific basis for policy formulation, and providing essential input for policy implementation to support the transition towards climate neutrality.

The workshop marked the inaugural event of the 2024 Nuclear Summit in Brussels, drawing 104 participants from 20 countries, including 11 from associated and likeminded nations, demonstrating a strong commitment to cooperation and joint efforts to enhance policies that benefit people.

1 Introduction

The JRC organised on 18 and 19 March 2024, together with the European standardisation organisations CEN and CENELEC, the Putting Science into Standards workshop on Molten Salt Reactors. The workshop discussed the following domains:

- Safety evaluation (common approaches)
- Measurements of thermo-physical properties
- Qualification of Fuels and Fuel Cycle
- Codes & Standards for Materials and Components

Molten Salt Reactors (MSR) are a unique type of advanced nuclear reactor that unlike conventional reactors that use solid fuels cooled by water, use a liquid mixture of salts (chloride or fluoride) with both fuel and coolant in a homogeneous configuration. The use of homogeneous liquid fuel allows for flexibility and efficient heat transfer within the reactor and allow for several advantageous features and higher safety standards (de la Rosa Blul et al., 2023).

Although MSRs were developed in the 1950s and 1960s, MSR technology was not further developed as the light water reactor technology became the industrial standard. However, in recent years, there has been a growing interest in this technology, leading to renewed development activities across all major economies, including EU, US and Asia (IAEA 2023; Humphrey and Khandaker 2018). MSR R&D encompasses various aspects, including materials science for reactor components, reactor physics and modelling, safety analysis, and regulatory considerations. Experimental efforts often involve small-scale prototype reactors and test loops to validate concepts and technologies. The current state of research involves governmental initiatives, university research, private sector involvement, international collaborations and prototype and demonstration plants. Research efforts are focused on addressing technical challenges, such as materials compatibility, fuel cycle optimization, safety, and licensing considerations. Additionally, there is a growing interest in the potential for using MSRs in applications such as district heating, industrial processes, and energy storage.

Researchers are exploring different types of MSRs. These include thermal spectrum reactors (operating at lower temperatures), fast spectrum reactors (operating at higher temperatures), and hybrid reactors (combining features of both). Scientists are also exploring different types of fuels for MSRs. Some of these include thorium, uranium, plutonium, and transuranic elements. MSRs have inherent safety features that make them less prone to accidents. For instance, the liquid fuel can be drained from the reactor in the event of an emergency, which prevents a meltdown. A few experimental MSRs have been built and more prototypes are being called for. While many believe MSRs have the potential to revolutionize nuclear energy, the technology is still in the research and development phase. Commercialization will depend on overcoming technical challenges, demonstrating the safety and reliability of MSRs, and winning public acceptance. Some of the challenges faced by MSR technology include handling corrosive molten salts, managing waste, and ensuring the long-term stability of the fuel.

The JRC is at the forefront of MSR research and development. Its MSR R&D activities date back to more than 20 years ago and today they spread across 3 different sites: Karlsruhe in Germany, Petten in Netherlands and Ispra in Italy. JRC's mission is to support research activities in EU member states, including universities, research organisations, industry and licensing authorities, and to provide direct policy support to European decision makers. The JRC collaborates internationally and acts as an implementing agent for the Generation IV forum on behalf of Euratom. It coordinates research within Europe and has actively participated in several EU-funded projects related to the

MSR reactor technology, including projects such as MOST, EVOL, SAMOFAR, SAMOSAFER, MIMOSA, and the recently granted ENDURANCE. JRC is also convener of CEN WS064 that addresses the development of nuclear design codes for innovative reactors and materials qualification.

The increased interest in Molten Salt Reactors can be attributed to several political drivers. Firstly, MSRs can diversify energy sources, enhancing energy security and mitigating geopolitical risks from single-source dependence. Secondly, their fuel flexibility, including thorium, can aid countries in achieving energy independence by reducing reliance on imported uranium. Thirdly, MSRs can generate electricity with lower greenhouse gas emissions, helping nations meet climate change targets under international agreements. Fourthly, MSR development can create new industries and jobs, fostering economic growth. Fifthly, MSRs can be designed with inherent safety features, contributing to nuclear non-proliferation efforts. Lastly, MSRs have the potential to produce less long-lived nuclear waste, addressing waste management concerns, and positioning countries as leaders in advanced nuclear technologies. The development of molten salt reactors is very challenging primarily due to the potentially corrosive nature of molten salt, high temperature and the complexity of molten salt chemistry.

In the field of nuclear technology, standardisation plays a central role in ensuring safety, security, and efficient utilization. Standardization ensures that nuclear processes are carried out consistently, reducing the likelihood of errors or deviations that could compromise safety. By adhering to standardised practices, nuclear facilities can minimize risks, prevent accidents, and protect both people and the environment from harmful effects of ionizing radiation. Nuclear technology involves complex systems, from reactor designs to instrumentation (de la Rosa Blul et al. 2023). Standardisation ensures that different components and systems can interoperate without problems. Compatibility between equipment, software, and procedures is crucial. Standardised interfaces allow for efficient communication and integration across various nuclear applications. Standardization is also important to provide an efficient market and industrial supply chains.

CEN and CENELEC, both European standardisation bodies, contribute significantly to the development and harmonisation of European standards, including those related to Small Modular Reactors. Their efforts focus on: a) Developing and maintaining European SMR standards covering design, safety, operation, maintenance, and decommissioning; b) Collaborating with international organisations like ISO and IEC to align European SMR standards with global ones; c) Engaging stakeholders to ensure relevance and applicability of standards to the SMR sector; d) Participating in European SMR research projects like SAMOSFEU and SAMOSINFRA to integrate latest findings into standardisation; e) Supporting national standardisation organisations in developing and implementing European SMR standards consistently across the EU.

2 Needs for future standardisation

Policy development and implementation are often depicted as distinct stages within the policy cycle. However, in practice, these are interwoven. During policy development, both political and technical aspects must be addressed. Political considerations involve acquiring support, setting a vision, and managing opposing views. Simultaneously, technical aspects include evidence gathering, best practices, planning and implementation.

Effective policy implementation is essential for achieving desired outcomes. Poorly implemented policies can hinder progress, regardless of their initial design. Therefore, considering plausible implementation streams during policy development is critical.

Standards, often referred to as an invisible layer of governance, have quietly supported EU legislation for decades. They offer a means to address the complexities posed by today's environment while delivering evidence-based and consensus-driven solutions. They align seamlessly with policymakers' objectives and add value by providing consistency, safety, and reliability. For Molten Salt Reactors, standards can:

- Enhance safety as they ensure that reactor designs adhere to the highest safety standards, protecting workers, citizens, and the environment.

Streamline deployment, as they address technical aspects and facilitate efficient Small Modular Reactor (SMR) deployment:

- Quantify benefits, as standards allow us to quantify the benefits of SMRs, including cost savings, safety improvements, and environmental impact.

Molten Salt Reactors represent an innovative solution for Europe's energy needs. Their scalability and increased safety features make them promising candidates. Standards can guide design and construction, and ensure that MSR designs meet safety, quality, and performance criteria. In addition, they can facilitate streamlined licensing processes to accelerate MSR deployment. They can also support interoperability and promote compatibility across MSR technologies and components.

2.1 Net Zero Industrial Act and European Industrial Alliance on Small Modular Reactors

As the European Union is committed to achieving net-zero emissions by 2050, the role of clean energy sources becomes increasingly critical. While clean technologies dominate the discourse, nuclear technology emerges as a strategic player, as it offers a promising avenue for reducing greenhouse gas emissions (European Commission 2023a). The EU's transition to a net-zero emissions economy necessitates a radical transformation of its industrial landscape using a multifaceted approach. The Net Zero Industrial Act (NZIA), an integral part of the Green Deal Industrial Plan, aims to boost the manufacturing of clean technologies within the EU. Among the promoted technologies, nuclear energy stands out due to its unique attributes and potential contributions. The NZIA recognizes nuclear technology as a strategic net-zero solution as it provides plannable electricity and transmission grid support. Key aspects include (European Commission 2023b; Ho et al. 2023):

- Fuel Cycle Innovations: Advanced technologies allow for minimal waste from the fuel cycle. Small modular reactors (SMRs) and best-in-class fuels enhance efficiency and safety.
- Decarbonization Impact: Nuclear power contributes significantly to reducing carbon emissions. Its inclusion in the NZIA accelerates progress toward climate and energy targets.

- Industrial Competitiveness: A robust nuclear industry fosters innovation, creates quality jobs, and strengthens the EU's industrial competitiveness.

While large-scale nuclear reactors have dominated the energy landscape for decades, Small Modular Reactors are now emerging as a versatile and efficient alternative (DiLisi et al. 2018)(IAEA 2023). Molten Salt Reactors utilize fuel in a molten state, allowing for safe drainage during emergency scenarios. Unlike conventional water-cooled reactors, MSR cores are cooled using salts. This design feature offers several advantages, as MSRs can operate at high temperatures while maintaining low pressure. MSRs operate at around 700°C, significantly hotter than conventional light-water reactors (LWRs) that operate at 300°C (IAEA 2023). This elevated temperature characteristics enhances electricity-generation efficiency and opens up process-heat opportunities, such as hydrogen production or water desalination. Additionally, molten salt coolants possess high heat capacity, enabling MSRs to safely function under these conditions (DiLisi et al. 2018). Their inherent passive safety characteristics make MSRs resilient to accidents and reduce the risk of core meltdown. More importantly, hydrogen evolution, which was responsible for the explosions during the Fukushima accident, does not occur in MSRs.

Depending on the neutron spectrum MSRs can generate less long-lived radioactive high-level waste compared to traditional reactors and some can be designed as actinide incinerators, contributing to overall waste reduction.

While nuclear technology offers promising solutions, challenges persist. These include waste management, safety protocols, and public perception (Andrews et al. 2021; Riley et al. 2019). Corrosion of hot salts and changing chemical compositions due to neutron flux require careful engineering (Wang et al. 2018). Nevertheless, the NZIA simplifies regulatory frameworks, promoting competitiveness and CO_2 storage capacity. It promotes investment and research, and most importantly supports standardisation as an enabler for building trust, safety and protection.

The European Commission has established for this reason the European Industrial Alliance on Small Modular Reactor (SMR Alliance) as a significant initiative aimed at accelerating the development, demonstration, and deployment of SMRs in Europe by the early 2030s. Its key objectives include:

- Accelerating Deployment: The Alliance aims to guide the deployment of the first SMRs in Europe by the early 2030s, creating a robust European supply chain.
- Strengthening Cooperation: By leveraging manufacturing capacity and innovation, the Alliance reinforces the nuclear supply chain and promotes EU cooperation.

Given the global push for decarbonization and climate neutrality, SMRs play a crucial role. Deploying SMRs efficiently requires addressing challenges related to regulatory frameworks, industrial practices, and safety standards. Here is where standardization and harmonization come into play:

- Common Industrial Standards: To facilitate deployment within the European Union, SMRs need standardized manufacturing processes, codes and licensing requirements. A harmonized approach ensures consistent safety standards regardless of the installation country.
- Regulatory Alignment: Different nuclear regulatory approaches among the EU Member States and of third countries must converge to create a conducive environment for SMR deployment. This alignment enhances safety and streamlines licensing procedures.

The SMR Alliance brings together a diverse range of stakeholders, including vendors, utilities, research organizations, and civil society. The Alliance reinforces the European nuclear supply chain by leveraging the region's manufacturing and innovation capacity. It also ensures that SMRs are developed and deployed efficiently by promoting collaboration.

The deployment of the first SMRs in Europe should take place by the early 2030s, bringing practical benefits, including:

- Decarbonization Pathway: SMRs complement renewables by providing low-carbon energy and heat.
- Safety and Sustainability: Deployment adheres to the highest standards of nuclear safety and environmental sustainability.
- Innovation Boost: The Alliance fosters innovation in new technologies.

The Net-Zero Industry Act complements the efforts of the European Industrial Alliance on SMRs. By recognizing SMRs, including MSRs, as net-zero technologies, the Act simplifies the regulatory framework for their manufacturing. This streamlined approach enhances the competitiveness of the net-zero technology industry in Europe and accelerates the capacity to store CO2 emissions.

Moreover, the Nuclear Harmonization and Standardization Initiative (NHSI), launched by the International Atomic Energy Agency (IAEA), complements the SMR Alliance. It brings together policy makers, regulators, designers, vendors, and operators to develop common approaches to SMRs. The NHSI aims to maximize SMRs' contribution to global climate goals and energy security while ensuring safety and efficiency.

2.2 Needs for future standardisation in safety assessment

The need for future standardisation regarding safety assessment is paramount, especially in the nuclear energy domain. This necessity arises from the complex challenges and opportunities that the industry faces in ensuring the safe operation of advanced nuclear power systems, including MSRs (Was et al. 2019).

The Institute for Radiation Protection and Nuclear Safety (IRSN) is an internationally operating technical organisation in support to the French Nuclear Safety Authority. Through a combination of in-depth analysis, expertise, inspections, and dedicated research and development programs, IRSN enhances safety and protection for existing and advanced nuclear power systems, as well as nuclear and radiation facilities.

When considering MSRs within the global safety infrastructure and environment, it is crucial to assess the status of their design and associated standards. In the pre-conceptual stage, the MSR design has demonstrated feasibility and attained technological maturity. Key challenges include the increasing role of predictive simulations, potential multi-unit configurations near nuclear reactors, and the exploration of unconventional fuel cycle options. Security concerns regarding enrichment and plutonium accessibility play a role. MSRs safety requirements include various elements such as national policy, legal frameworks, funding, radiation protection, safety assessment and radioactive waste management. It underscores the evolving landscape of MSR development within the broader context of safety and environmental stewardship of IRSN.

Based on public information from IAEA and OECD-NEA, IRSN has identified two main approaches to molten salt reactors: i) using solid fuel with high-assay low-enriched uranium (HALEU) and possibly thorium/233U in a thermal setting; ii) using circulating salt with transuranic elements and chloride salt in a fast setting, both aimed at producing electricity and/or high-temperature industrial heat.

This shift in thinking highlights the need for standardised methods and guidelines that can be applied to all types of MSR designs, requiring updates to accident scenarios, hazard rankings and other factors. IRSN work shows that standardising MSR technology is complex and requires a comprehensive approach to address different reactor designs.

IRSN points out the difficulty of standardising the various MSR concepts. To address this, they introduce a process called the "back-end cleaner," which involves circulating fuel, heavy metals (minor actinides), fission products, and fissile materials. The MSR can use different types of fuel: solid, circulating salt and liquid salt, each leading to different outcomes. HALEU combined with fluoride salt works in a thermal spectrum, while transuranic fuel with chloride salt works in a fast spectrum. Both pathways ultimately serve as a heat source for generating electricity and/or high-temperature industrial heat.

IRSN stresses the need for a paradigm shift towards relevant methods and standards that cover all potential MSR concepts. However, certain aspects such as accident scenarios, hazard rankings, phenomenology, and reference cases need to be revised.

Insights have been gained from EU Horizon projects like SAMOFAR and SAMOSAFER, pointing out areas within their expertise that need clarification and improvement. Safety, particularly the Extended Kessler Criteria for solid fuel, requires replacement and the development of comprehensive definitions related to the progression and aggravation levels of barriers. The defence-in-depth strategy needs improvements in terminology and metrics, with clear definitions addressing different phases of barrier progression. Reactor control and risk management stress the importance of high-fidelity modelling and establishing the maturity of predictive capabilities in measurement technologies.

Making sure there are standardised protocols and best practices for knowledge preservation is crucial. The importance of prototypes, observations, and experimental benchmarks calls for clear compliance criteria and standardised protocols. Overall, focusing on these improvements can lead to safer and more efficient nuclear energy solutions.

2.3 Needs for future standardisation to support common approaches for industrial production and operation of near-deployment reactors

Harmonisation plays a crucial role in ensuring regulatory consistency and efficiency in the deployment of SMRs. By aligning regulatory approaches and codes, stakeholders can facilitate the smooth integration of SMRs into the global energy landscape. This harmonisation effort extends to the supply chain, where adherence to standardised codes and standards is essential for ensuring the quality, safety, and reliability of components used in SMR projects.

The established taxonomy of SMRs helps to categorise reactors based on their design characteristics, facilitating a better understanding of the diverse range of modular reactor technologies. This classification system not only simplifies the categorisation of SMRs but also contributes to the standardisation of design and operational practices within the nuclear industry. As the global development of SMRs progresses, the emphasis on simplification becomes increasingly important.

Initial steps towards standardisation have started by tackling the taxonomy of MSRs, as they represent a paradigm shift in reactor design, utilizing liquid fuel rather than traditional solid fuel rods. From the IAEA's perspective, understanding MSR taxonomy is essential for effective research, regulation, and collaboration. The recently published Technical Reports Series No. 489 provides a comprehensive overview of MSR technology. The report examines reactor designs, technological innovations, and experiments related to MSRs. It identifies challenges, areas requiring further research, and the current status of MSR development worldwide. The taxonomy outlined in this report classifies MSRs into families (such as graphite-based, homogeneous, and heterogeneous) and provides insights into specific types and their characteristics.

- Graphite-based MSRs: These reactors utilize graphite as a moderator. They can be further categorized into specific families.
- Heterogeneous MSRs: These MSRs have a heterogeneous core, meaning they contain different materials within the reactor.

MSR Family:

1. LiF Fluoride Salt-Cooled Reactors: These belong to the Graphite-based MSRs category. They operate with a fluoride salt coolant.
2. Thermal Spectrum: This family is characterized by the neutron spectrum (thermal neutrons).
3. Fast Spectrum: These reactors operate with fast neutrons.
4. Chloride Fast Reactor: A specific type within the fast spectrum family.

MSR Class:

- Neutron Spectrum: Refers to the type of neutrons (thermal or fast) used in the reactor.
- Fuel Cycle: Describes the fuel processing and management.
- Coolant: Specifies the type of coolant (e.g., fluoride salt).

The Nuclear Harmonization and Standardization Initiative (NHSI), led by the International Atomic Energy Agency (IAEA), aligns with the SMR Alliance to help with the global deployment of industrial and advanced nuclear reactors. The initiative connects regulatory and industrial tracks, encouraging communication and collaboration among regulators, governments, technology holders, operators, and international organisations. It focuses on promoting information sharing, multinational pre-licensing reviews, and standardised nuclear technology integration.

The NHSI aims to harmonise user requirements, codes and standards, experimental testing, and accelerate SMR infrastructure implementation. They offer various compliance paths, such as the complete fit-for-purpose tailoring approach, which aligns with stringent standards, and the justification approach, seeking exemptions through equivalence arguments. The regional approach adapts to local contexts, while the standard design approach prioritises adherence to established standards. These strategies provide flexibility and conformity in compliance within targeted jurisdictions.

NHSI Industrial Track Topical Group 2 (TG2) focuses on quality management systems, engineering standards, equipment qualification standards, and the specific requirements for advanced manufacturing in SMRs. It also emphasizes the importance of leveraging proven industrial-grade items, compliance with broader legal and regulatory frameworks, and effective oversight mechanisms. The achievements of the NHSI include the development of the Management, Supply Chain and Quality (MSCQ) – NHSI Industry TG2 Platform and the convening of a Technical Meeting on Harmonisation/Use of Industrial Codes/Standards for SMRs.

The IAEA outlines strategies to create a stable environment for investing in nuclear energy. It emphasizes the roles of various stakeholders in this endeavor. Policy makers are encouraged to provide clear signals and support regional supply chain development. Nuclear regulators are urged to collaborate for consistent regulations and early engagement in licensing processes. Owner/operators are tasked with managing supply chain risks and incentivizing suppliers, while technology developers/vendors are advised to demonstrate proven technology and engage early with the supply chain. Suppliers of products/services are encouraged to showcase deployment capabilities and collaborate with stakeholders for once-through design readiness. These concerted efforts aim to boost confidence and readiness for investment in the nuclear energy sector. These concerted efforts aim to bolster confidence and readiness for investment in the nuclear energy sector.

2.4 Needs for future standardisation to support R&I

The Generation IV International Forum (GIF) Molten Salt Reactor (MSR) project represents a collaborative effort among leading nations in nuclear energy research and development to advance the next generation of nuclear reactor technology. The GIF MSR project aims to address key technical challenges and accelerate the commercialization of MSRs by fostering international cooperation, sharing expertise, and coordinating research efforts.

The current safety regulations are based on long time experience with the Light Water Reactors (LWRs). The source term is crucial for understanding the types and quantities of radioactive or hazardous materials that could be released into the environment following an accident. Its assessment is complex and considers factors such as the composition of radioactive materials, their chemical mobility, the presence of driving forces, and the effectiveness of barriers. While LWRs maintain high safety standards, their safety heavily relies on mechanical barriers within the containment system. There are various layers of containment within the LWR system, emphasizing the importance of safety measures and the role of barriers in preventing radioactive releases during accidents.

The MSR safety performance may strongly differ from LWR. Both the source term and the applied barriers may have different character. The LWR safety is based on presence of pressure and temperature, strong barriers and complex engineering system for protection of these barriers. In MSR the driving forces can be minimized by design and the barriers can also rely on chemical stabilization and separation. The control of the fuel state can be equally important as the maintenance of barrier protection.

There exists a temperature window between the salt melting temperature and the maximal temperature at which the integrity of structural materials is still assured. This window is very narrow for some designs. It should be the object of multi-parametric optimisation because the melting temperature also competes with fuel cycle parameters like actinides composition and molar share.

Using liquid fuel simplifies treatment. It eliminates the need for fuel fabrication, allows for higher decay heat levels, and enables the use of pyrochemical methods for treatment. The greatest potential for MSRs lies in simplified salt treatment. This will decrease closed fuel costs compared to solid fuel breeders that rely on aqueous reprocessing.

Some terms related to the fuel cycle and safety are not yet standardised. The salt treatment in-situ or ex-situ and during the operation or after salt discharging are not consolidated. A dedicated session in this workshop discusses the topic. Fuel cycle terms are complex, and nuances like in-line / at-line or processing / reprocessing are not negligible. The following terms could serve as an example:

- Salt cleanup (a process where impurities, activation products or selected fission products are removed from the salt by physical method and actinides and carrier salt is not affected)
- Salt treatment (a process where selected fission products or actinides are removed from the salt, e.g. by salt fluorination, but other actinides and carrier salt are not affected)

- Salt processing (a set of processing steps, where typically the fission products, carrier salt and actinides are separated from each other, and processed salt is created as a combination of two or more previously separated materials).

The Generation IV International Forum (GIF) MSR project gathers global trends and evidence from MSR research and assesses it for further valorisation. The close link to standardisation and harmonisation organisation marks its strategic importance.

3 How to bridge the gap

This section provides a non-exhaustive overview of platforms that can support harmonisation and standardisation activities. These platforms include technical committees of standards organisations at the European and international level, or code and standards developing bodies, such as AFCEN.

3.1 Bridging the gap to international standards

Organizations such as the European Committee for Standardisation (CEN) and the International Standardization Organization (ISO) are actively involved in standardisation activities related to nuclear energy, technologies, and radiological protection via their respective technical committees, CEN/TC 430 and ISO/TC 85. These entities collaborate to propose and endorse existing standards, ensuring harmonisation and consistency across international frameworks. The focus lies on aligning European standards 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 the exploration of new projects and initiatives aimed at advancing nuclear technologies. Proposals for new standards or modifications are carefully 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.

CEN/WS 64 serves as a platform for fostering pre-standardisation activities, codification, and international standardisation work in the nuclear sector. It acts as a catalyst for the development of new standards and the alignment of European practices with global benchmarks. The group's efforts contribute to the continuous improvement and standardisation of nuclear technologies, ensuring compliance with international best practices.

3.2 Bridging the gap from R&D to design codes

To ensure safety usage of MSRs, it is crucial to establish robust guidelines and standards for their efficient design, construction, and operation. RCC-MRx is such a design code developed by AFCEN, a codes and standards developing organisation dedicated to establishing rules for nuclear equipment design, construction and commissioning, whose members include various stakeholders involved in the nuclear industry, such as nuclear power plant operators, engineering companies, manufacturers of nuclear equipment, regulatory authorities, research organizations, and academic institutions. RCC-MRx is drafted by AFCEN working groups, composed of experts in their domain. The modification requests can be performed by pre-normative task groups often linked to industrial or research projects, CEN Workshop Agreements (i.e. CEN WS064) and users of RCC-MRx.

Specifically, RCC-MRx focuses on providing design and construction rules for mechanical components of nuclear installations, particularly advanced, research and fusion reactors. This code sets the standards and guidelines for ensuring the safety, efficiency, and reliability of these nuclear systems. RCC-MRx has evolved over time to adapt to new technologies and concepts in the nuclear industry, making it a crucial tool for developers, manufacturers, regulators, and other stakeholders involved in the nuclear sector.

Over the years, the RCC-MRx design code has evolved to adapt to the changing landscape of nuclear technology, incorporating new concepts and materials. The main objectives of RCC-MRx revolve around simplifying processes, reducing costs, and enhancing efficiency through standardization. By providing a common ground for sub-contractors, manufacturers, and suppliers, the code facilitates smoother interactions and clarifies contractual dialogues. Moreover, it aims to strengthen relationships with regulators and safety authorities, ensuring compliance with stringent nuclear safety standards.

For innovative reactors like MSRs, standardisation plays a paramount role in elevating technology readiness levels and providing a structured framework for research and development. By integrating standardisation early in the design process, developers can streamline the transition of concepts into industrial components. The need for best practices through codes and standards 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 in a sustainable manner and bridging research and development towards design codes.

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, such as 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.

3.3 Bridging the gap in collaboration

In Europe, the JRC plays a pivotal role in the field of MSR technology. Their core focus lies in investigating nuclear fuel properties and their interactions with reactor components. Notably, the JRC has gained global recognition as a reference laboratory for determining essential thermo-physical data and for the development of an extensive thermodynamic database, known as JRCMSD. In the recent years, JRC gradually explored other fields of interest and today it covers the following areas of expertise:

- Fuel Synthesis and Purification Methods (Karlsruhe site): Focuses on developing efficient methods for synthesizing and purifying MSR fuels.
- Reference Centre for Fuel Properties (Karlsruhe site): Provides essential data on fuel behaviour and properties.
- Thermodynamic Database Development (Karlsruhe site): Continuously enhances the JRCMSD to support MSR modelling and analysis.
- Reactor Safety (Petten site): Investigates safety aspects related to MSR operation.
- Post-Irradiation Examination (Karlsruhe site): Analyses fuel samples after irradiation to understand their behaviour.
- Material Testing (Petten site): Evaluates materials for MSR components.
- Safeguards (Ispra & Karlsruhe site): Ensures the secure and peaceful use of nuclear technologies.

Molten Salt Reactors represent a considerable area of research within the US nuclear industry. A collaborative approach ensures that research efforts are aligned with industry needs and regulatory standards, ultimately 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. The program encompasses 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 essential for the effective design and 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 models represents a significant milestone in MSR research. These databases provide substantial information on salt compositions, phase behaviour and other key properties, 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. 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. 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 models offer valuable insights into the behaviour of radioactive isotopes within the reactor system, aiding in the design of robust safety protocols and measures.

3.4 Bridging the capacity gap for standardisation

In EU-funded projects, standardisation practices play a crucial role in ensuring the successful commercialisation of research outcomes (European Commission 2023c). Standardisation serves as a bridge between research and global markets, facilitating the exchange of knowledge and technology to meet industry and consumer needs. By aligning with established standards, projects can build trust, confidence, and credibility in their innovations, ultimately boosting their competitiveness and market acceptance.

HSbooster.eu, a platform dedicated to supporting projects across various sectors, offers services that enhance standardization strategies and practices. Through a training academy, researchers gain access to resources, courses, and training materials designed by experts. This training equips project teams with the necessary skills and knowledge to navigate the complex standardisation landscape.

Key components of HSbooster.eu's support services include the involvement of standardisation experts. These experts provide guidance on navigating the standardisation landscape, identifying relevant standards, and contributing to the development of new standards. By engaging with technical committees and industry stakeholders, projects can gain valuable insights, expand their networks, and optimize their standardization workflows. The initiative facilitates collaboration and knowledge sharing through workshops, training events, and mentoring sessions. These activities aim to foster a culture of excellence in standardisation practices, enabling projects to streamline their processes and enhance their market readiness.

The integration of standardisation practices is vital for EU-funded projects seeking to enhance research valorisation and market uptake. By utilizing platforms like HSbooster.eu, projects can strengthen their standardisation strategies, align with industry standards, and position themselves for success in the competitive market landscape. Through a commitment to excellence in standardisation practices and a collaborative approach to knowledge sharing, projects can maximize their potential, drive innovation, and make a lasting impact on the European research ecosystem.

4 Prioritising standards and pre-normative research needs

4.1 Measurements of thermo-physical properties

A technical session on measurements of thermo-physical properties was set to identify key items in which standardization could lead to more reliable data and minimise uncertainties. The following sub-topics were discussed during the meeting:

- Sample quality (what methods are required to determine purity state of the sample; existence of reference data to benchmark the obtained data; purity requirements and their relation to each measurement conducted)
- Handling of salts (Before measurement, i.e. sample preparation and general handling case; During measurement, if encapsulation of samples is needed, and if so, qualification of developed crucibles for encapsulation; Post measurement characterization where relevant)
- Calibrations (Temperature calibration; Influence of weight of the sample, Standard reference material providers, identification of a reference material of similar properties to salts)
- Measuring techniques (How important is knowledge of the property and the precision to which they are needed; Uncertainty analysis, Procedure standardization; Variety of appropriate measuring techniques for the same property determination)
- Sample sizing (how does size of the sample influence the uncertainty, downsizing of nuclear fuel samples due to radiation protection of personnel or availability)
- Certification/accreditation of labs (quality assurance of the data, certification of the lab by i.e., ISO9001 standards or need of accreditation by ISO17025 standard or the so-called NQA-1 requirements)
- Database developments (One database or multiple databases?; Repository of original data; Management of databases and quality-assurance stamp)
- Collaborations and laboratory benchmarking (e.g. Round Robin; joint publications, joint future meetings)

At the beginning of the technical session, two keynote lectures were held; one presented by Melissa Rose from ANL and the second by Anna Smith from TU Delft. The keynotes provided an excellent opportunity to find that methodologies of setting standards are well aligned, between EU and US (and likely beyond – Japan, Korea, others). Based on the presented lectures and from the following discussion, the following main features of standardization needs were identified:

- High-quality molten salt property values are needed to design, license and operate MSRs
- Measured data must meet quality requirements for licensing (calibration, controlled conditions)
- Development of standard procedures and in-depth data analysis lead to minimization of uncertainty
- Need for reliable databases (thermochemical and thermophysical) and need for their validations

Furthermore, it was stated that differences in measured values can occur via:

- Different environments during measurements (and sample handling)

- Inconsistent calibration practices
- Differences in data processing and analysis
- Variation in sample preparation method (and purity analysis)
- Unexpected (uncontrolled) aspects during measurement
- Differences in measuring methods

From the above, standardization eliminates variations in factors that affect measured property values. As for the uncertainty of the obtained data, it is evident that larger uncertainty leads to large MSR design margins, which leads to increased costs of the reactor. It is therefore fruitful to minimize the uncertainty by applying appropriate measurement controls and to quantify uncertainty by standard methods.

In the context of ensuring that measured data meet quality requirements for licensing, it is essential to conduct measurements under controlled conditions using calibrated devices (Beneš and Konings 2013). One topic of discussion pertained to lab accreditation (certification) and its alignment with criteria for authorities to accept data. ISO 17025 standards were mentioned as a benchmark for fulfilling these requirements. Interestingly, during active discussions among participants from the EU and the US, it became evident that vendors and subsequent authorities often request even higher standards, such as the NQA-1 assurance. As a result, there was a proposal to establish a working group or further discussion forum to assess whether these elevated requirements are truly necessary. Additionally, the importance of property knowledge and the level of precision required should also be clarified.

In addition, it was emphasized that standardization should not favour one method over another when determining a specific property. Instead, a thorough review of any novel method should be conducted to assess its appropriateness, implementation and reliability. Furthermore, each new technique must undergo standardization to ensure its inclusion in the future fleet of methods for property determination.

Towards the end of the session, the topic of database development was addressed. We are aware that several databases containing thermochemical or thermophysical data already exist. Examples include the JRCMSD thermodynamic database describing key MSR fuel and coolant systems, as well as MSTDB-TC and MSTDB-TP. During discussions, a suggestion emerged from the plenum: Instead of fusing various databases, it would be more effective to establish a well-managed repository of original information. This repository would logically reference the data stored in the databases. Such an approach would enhance traceability and ensure that the data remains properly linked.

In light of the feedback received both during and after the session, it is evident that organizing a follow-up meeting with the same or similar consortia is crucial. Within the same context, several potential next steps were discussed:

- Setting Up a Working Group: One proposed solution involves establishing a working group to define standards in collaboration with organizations such as NEA/OECD or IAEA.
- Focus Group via CEN and CENELEC: Alternatively, or perhaps as a primary approach, there was a suggestion to create a focus group through CEN and CENELEC. This group would develop a roadmap outlining the most critical steps necessary to advance toward ISO standardization.

During the discussions, a topic that gained widespread support was carrying out Round Robin tests in the field of thermal properties determination for molten salts. Given the existence of multiple laboratories worldwide dedicated to this area, inter-laboratory testing becomes crucial to the development of standard methods. Although organizing such tests is not a straightforward task, their outcomes are highly valuable. Consequently, there was enthusiastic agreement to coordinate these efforts in the near future. As a specific instance, a Round Robin test is already planned as part of the recently approved EU project ENDURANCE, and potential participants will receive notifications regarding their involvement. Some of the topics were placed by the participants on the graph of Importance and Feasibility of the MSR technology standardisation, as shown in the Figure 1.

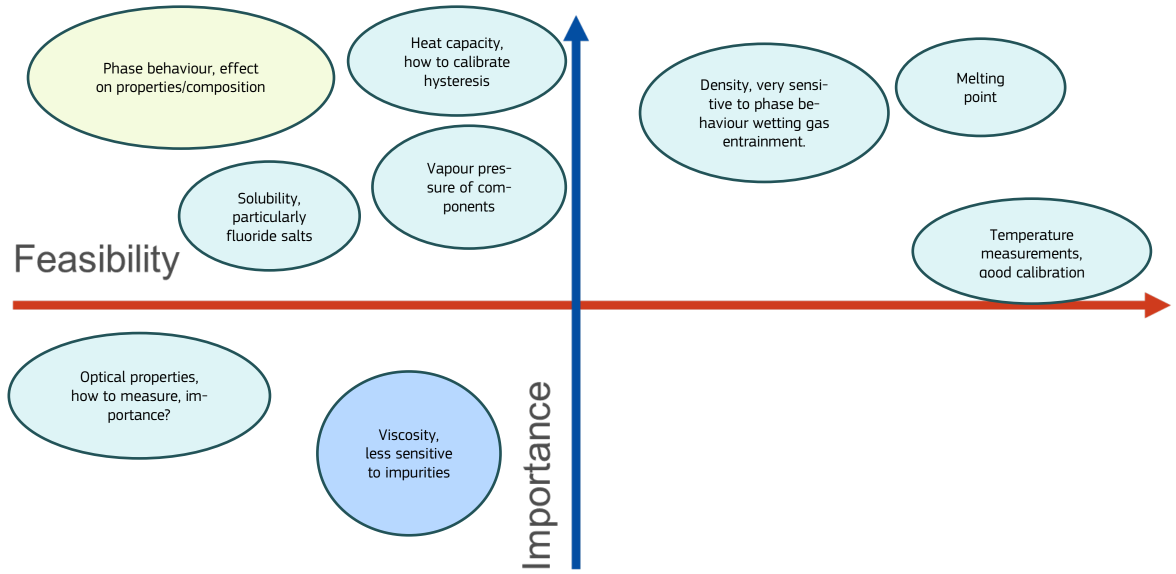

Figure 1 Prioritisation of addressing specific standards and harmonisation gaps considering urgency and current feasibility in the domain of measurements of thermo-physical properties

4.2 Safety evaluation (common approach)

The PSIS workshop brought together experts in the field of nuclear reactor safety, and in particular MSRs, from different realities (i.e. research centres, industry, designers, supranational institutions, etc.) and different geographical areas (Europe, USA, and Asia). The session on Safety Evaluation (common approaches) focused on: i) identifying the most challenging issues related to MSR safety that both industry and research institutions should address in the short term and ii) development of top safety requirements (design-generic / design-specific). 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, which, unlike the United States, sees several regulatory and licensing bodies in the nuclear field for each Member State, each with different maturity, procedures and requirements. This peculiarity poses a further problem for MSRs developers, namely meeting the requirements of the various licensing bodies in order to be able to demonstrate the safety of their proposed designs, thus increasing costs exponentially and making the European market less attractive and competitive for the deployment of fourth-generation reactors such as those based on molten-salt technology.

Safety Adequacy Assessment is central to nuclear power plant licencing. Successful commercial deployment of MSRs is heavily dependent on establish their safety characteristics in a well-coordinated licensing program, because licensing costs, time, and overall uncertainty have become a substantial burden to advanced reactors like MSRs. In essence, MSRs have the same basic safety functions as all nuclear power plants: containing radionuclides, providing adequate cooling, controlling reactivity. These safety functions must be guaranteed for the entire life cycle of the plant, taking into account the possibility of mitigating the consequences of events beyond the design basis. Molten salt fuel and coolant provide desirable safety characteristics (i.e. low-pressure, low-chemical potential energy, partial radionuclide retention, negative reactivity feedback, effective natural circulation heat transfer, etc.) but they have substantial technical differences from other reactor classes that necessitate distinctive systems, structures, and components (SSCs) performance information and customized tools and analysis methods. The development of pathways to efficiently and effectively demonstrate adequate safety remains a central challenge. 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 could focus on two aspects identified as levels in the Defence in Depth approach: accident prevention and mitigation. Both accident mitigation and accident prevention could lead to adequate safety: by preventing all accidents, one would have adequate safety or by completely mitigating all accidents, one would have adequate safety. These concepts are summarized and depicted in Figure 2.

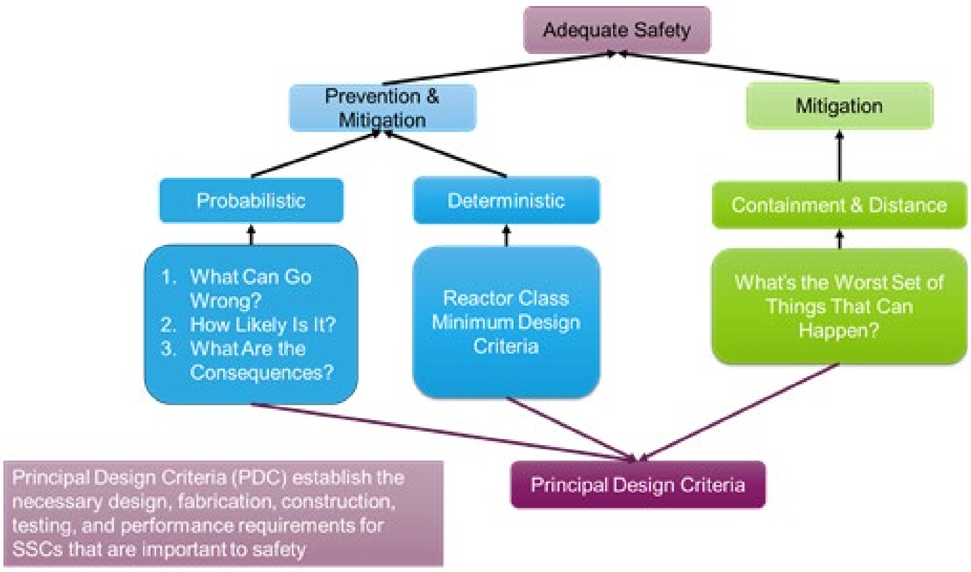

Figure 2 Possible safety assessment methods/pathways (Courtesy of Dr. David Holcomb)

On the basis of the general concepts introduced above, the Nuclear Regulatory Commission (NRC), the Department of Energy (DoE), the American Nuclear Society (ANS) and other institutional bodies in the United States 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 Utilisation 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 (ARDC), criteria developed to translate the safety elements of the General Design Criteria (GDC) to the characteristics of advanced reactors (limited to sodium-fast reactors and modular high-temperature gas reactors). Subsequently, guidance on how to use probabilistic risk modelling to assess the safety of advanced reactors was introduced in NUREG 1.233. More recently, the ANS released its first MSRs safety standard applicable to a broad spectrum of designs.

The discussion continued emphasising that MSR is not a specific NPP design but rather a family of designs only sharing the use of molten salt as one of the system fluids. 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 Figure 3), which makes any approach for harmonization difficult. Nevertheless, it was agreed among the participants that one of the most challenging MSR safety issues that both industry and research institutes should address in the short term, is the lack of experimental data for safety demonstration that can justify a fully probabilistic or even deterministic approach. There is a pressing need to build a demonstration reactor or a FOAK in order to generate the necessary data. Regardless of the method used to demonstrate adequate safety, the understanding and modelling of accident phenomena are fundamental to developing confidence, and this can be done primarily through experimental activities and demonstration reactors. However, in order to obtain a licence for these reactors, there is a need to demonstrate their safety, so it is essential to have a safety approach with the limited amount of information we have that is fully acceptable and agreed. Designers and other interested parties should agree on this and convince regulators and licensing bodies to reassure potential investors who still consider a MSR project too risky. This risk is due to the impossibility of estimating the costs involved with an acceptable level of confidence, which in turn is due to the lack of a clear licensing path for non-light water reactors.

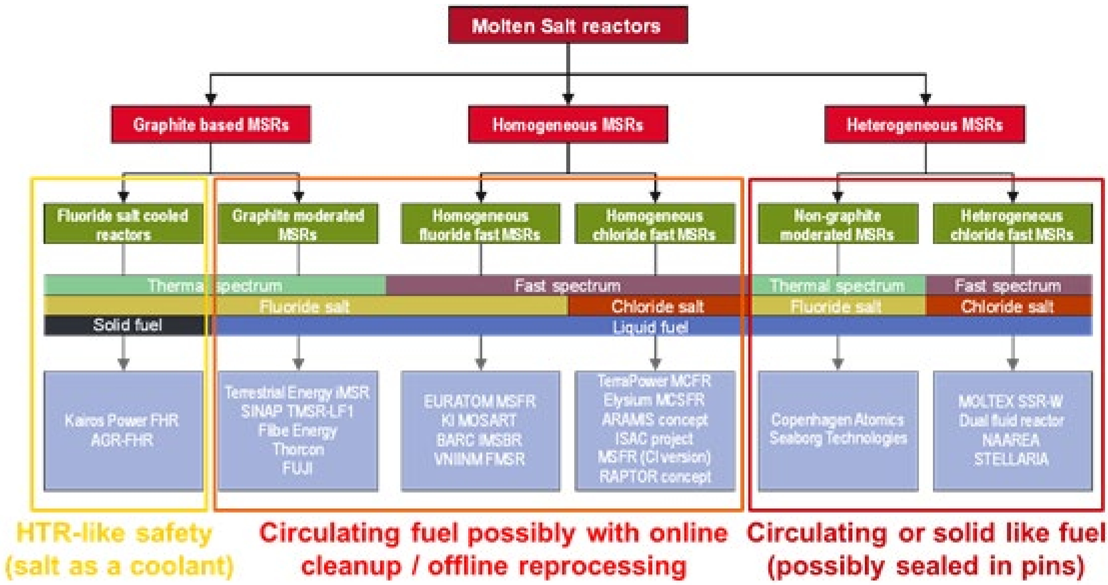

Figure 3 MSR taxonomy: Courtesy of Dr. Jiri Krepel; Adapted from: GIF Annual Report 2022, 2022. Note that Seaborg now uses graphite for the moderator.

One possible approach proposed is to establish a particular maximum credible accident (MCA) that considers the complete release of the chemical and physical energy stored in the reactor. This approach is considered by some to be feasible in the specific case of small reactors such as experimental ones by designing an appropriate containment system. However, certain precautions must be taken, such as maintaining a low pressure and therefore avoiding the use of significant quantities of phase change materials (e.g. water) and combustible materials in order to avoid generating high pressures or significant damage to the safety-related SSCs.

Designers and industrial entities finally emphasized the need not only to produce data but also to share them among all stakeholders through dedicated databases because these data will be indispensable in the future to qualify and certify the models and processes used to demonstrate the safety of the reactors developed.

In concluding the session, the participants agreed that there is no urgency or current need to introduce safety standardisation, given the low level of maturity and the multitude of designs currently proposed, which makes it difficult to define a safety standard for all MSRs. However, it was emphasised that it is necessary to start a harmonisation process that will lead to a shared safety approach for FOAK demonstration reactors. European MSR industries, research organisations and other participants in the session were interested in establishing a working group with the aim of defining a shared safety approach for demonstration reactors, identifying potential showstoppers in the current safety assessment procedures (focused on LWRs) that prevent the development and deployment of MSRs. The results produced by the working group in the form of a white paper could be considered to trigger an initial discussion with regulators and licensing bodies in the various EU Member States. The umbrella within which to establish such a working group could be the Generation IV International forum. Some of the topics were placed by the participants on the graph of Importance and Feasibility of the MSR technology standardisation, as shown in Figure 4.

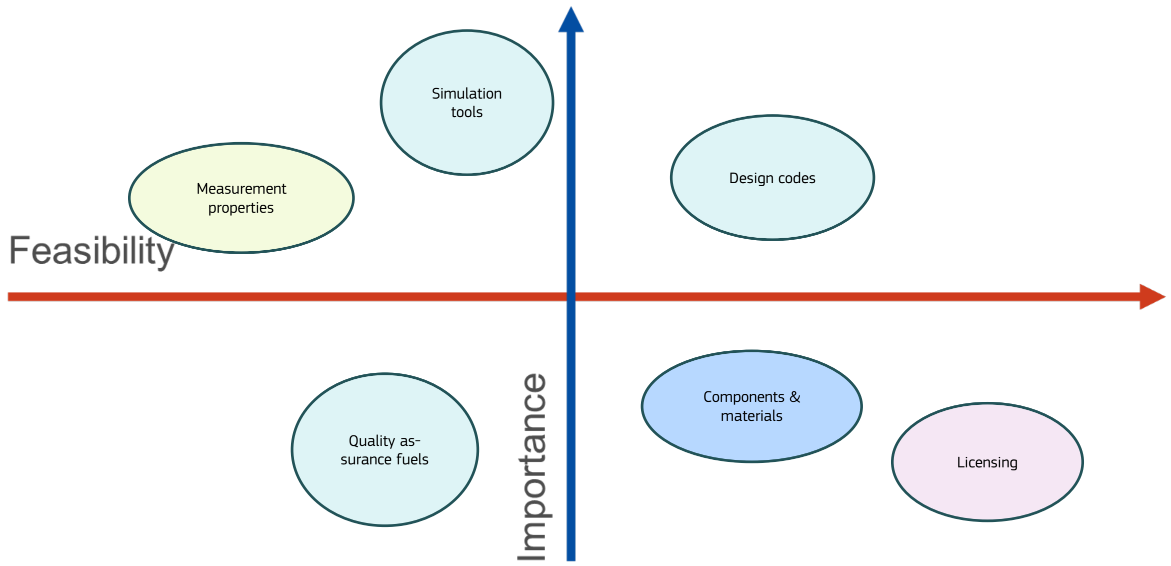

Figure 4 Prioritisation of addressing specific standards and harmonisation gaps considering urgency and current feasibility in the domain of safety evaluation (common approach)

4.3 Qualification of fuels and fuel cycle

The session on Qualification of Fuels and Fuel Cycle focused on two main areas: i) How to bring standards to the characterisation of the MSR fuel and ii) Standards within the MSR fuel cycle. The topics linked to the first area can be generally summarised as standards for the fresh fuel material specifications including the quality control & compatibility assurance and nuclear fuel safety criteria, to which the fuel must conform, comprising safety, operational and design criteria. Particularly, it was discussed how to develop standards practices on sampling and measurements, including associated techniques, keeping an adherence to regulatory requirements and safeguards, and how to define the chemical, nuclear and physical requirements of the fuel.

Other specific properties related to the safety of the 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 other physic-chemical properties including density, viscosity, thermal conductivity and heat capacity. Concerning the second main area, restriction in time didn't allow much discussion beyond the general aspects of the back end of the MSR fuel cycle and needs for standardisation of the fuel cycle related terminology. The other planned topics concerning methods and techniques on how to follow the radionuclide inventory during each step of the fuel processing, and what are the main differences compared to conventional fuel requiring new standards, are recommended to be discussed during a possible follow-up meeting.

The session supported the development of industrial methods to manufacture chloride based MSR fuel. Standardisation should provide a framework for quality control processes, ensuring that nuclear fuel consistently meets certain performance and material specifications, as well as to ensure compatibility and interoperability among different components within the nuclear fuel cycle. On top, standards should guarantee that nuclear fuels meet specific safety criteria, adherence to regulatory requirements and international agreements. High priority for standardization is for the front-end of the fuel cycle, less urgent for the backend.

It is very 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, not 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 (Sulejmanovic et al. 2021; Cong et al. 2019). It is needed to have purity standards both at the production and at the reactor sides, considering the possible contamination during transport. In addition, standards for commerce will be needed to define a way to determine what is inside each shipped and received container with fresh fuel, to verify if the content is uniform or stratified and to control that the fuel salt meets acceptance criteria.

At the same time, it would be difficult to have a parallel fuel measurement to support safeguards in addition to operations. A standard about enabling IAEA access to fuel salt content measurement would be useful to provide adequate confidence that the measurement is correct and that at the same time does not reveal non-safeguards related information.

Fuel function specific standards are also required, coming likely from reactor designers to fuel producers. They should assure that the fuel keeps its function within the whole range of the reactor operation, including transient and accidental conditions. For example, the density, viscosity and capability to retain important radionuclides must stay within a range acceptable for the reactor operation and safety.

Concerning standardisation within the back end of the MSR fuel cycle, needs strongly depend on the selected option. The backend is likely the least developed part of the MSR technology, and thus it would be premature to develop standards in this field. Generally, there is no clearly defined solution for the molten salt waste streams, and it seems that most of the small and medium enterprises developing MSR technology have not yet specified strategies for the used fuel processing. However, having a disposal route is required in the US to obtain a license and many reactor developers in US are planning to remove fission products online. In Europe, vendors typically do not consider self-processing of the fuel and rely on external services. If hydrometallurgical extraction processes were selected for the fuel processing, there will be less need for new standards, except ensuring the compatibility with existing reprocessing plants. For the advanced pyrometallurgical processes, new standards would have to be developed for each technique.

At present, it is 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.

Some of the topics were placed by the participants on the graph of Importance and Feasibility of the MSR technology standardisation, as shown in Figure 5.

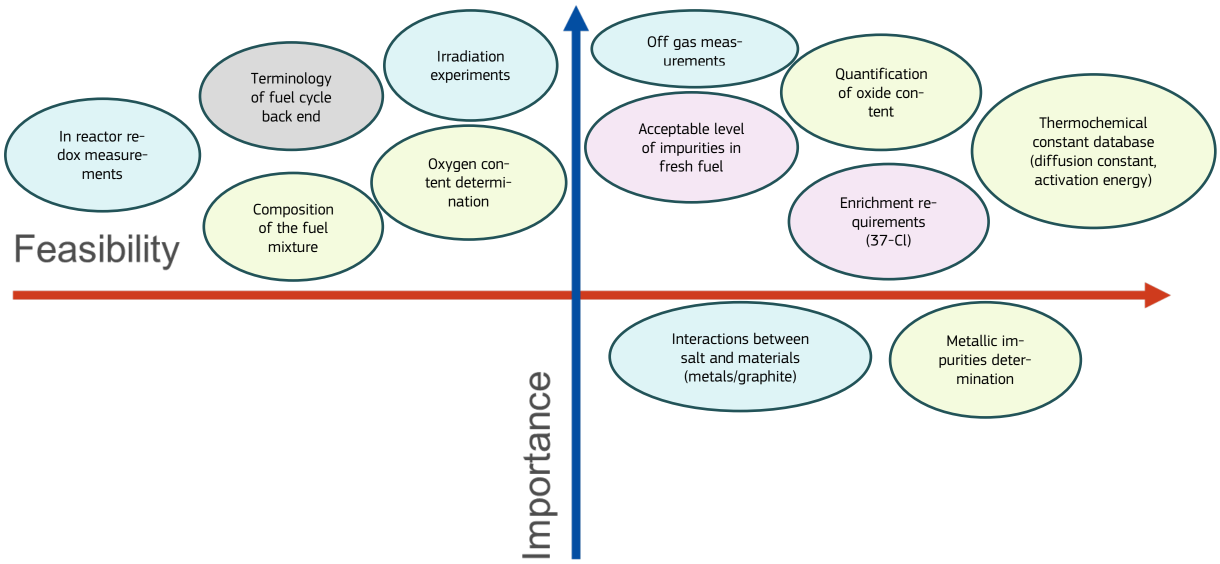

Figure 5 Prioritisation of addressing specific standards and harmonisation gaps considering urgency and current feasibility in the domain of qualification of fuels and fuel cycle

4.4 Codes & standards for materials and components

The objective of this session was to identify the needs for design codes and standards for structural materials and components and their implementation to allow deployment of MSRs in the coming decades. The session provided a discussion split into three parts: i) needs for harmonization and codes & standards; ii) path towards harmonization and standardisation; iii) path for collaboration.

It should be noted that nuclear regular systems differ both between EU Member States and between the EU and the USA, where EU Member States tend to have a more prescriptive approach while the USA favours a more performance-based and risk-informed approach. Harmonized licensing approach also requires some harmonized regulation. Another important MSR-specific feature is that proposed MSR concepts may have different design features such as fast versus thermal neutron spectra; fluoride versus chloride salts; solid fuel or fuel in the molten salt. However, all MSR reactor designs need to address the combined effect of high temperatures (typically 700°C), the corrosive environment from the molten salt and neutron irradiation.

The license of a MSR must account for detrimental environmental effects, however, rules or data for molten salt are included in the Design Codes. Thus, salt exposure data is needed to demonstrate that a specific material is fit for purpose. The first MSR designs have austenitic steels or low Cr nickel-based alloys as reference materials, while in parallel refractory materials and composites are also explored. Irrespective of the material, there is a need for standardized test procedures for corrosion and mechanical tests in molten salt. It has been observed that there is hardly any corrosion of reference materials in pure molten salt, but impurities may drastically affect corrosion rates. Thus, there is an urgent need for test procedures and standards with controlled and measured impurity levels to quantify the effect of impurities. 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.

Some of the topics were placed by the participants on the graph of Importance and Feasibility of the MSR technology standardisation, as shown in Figure 5.

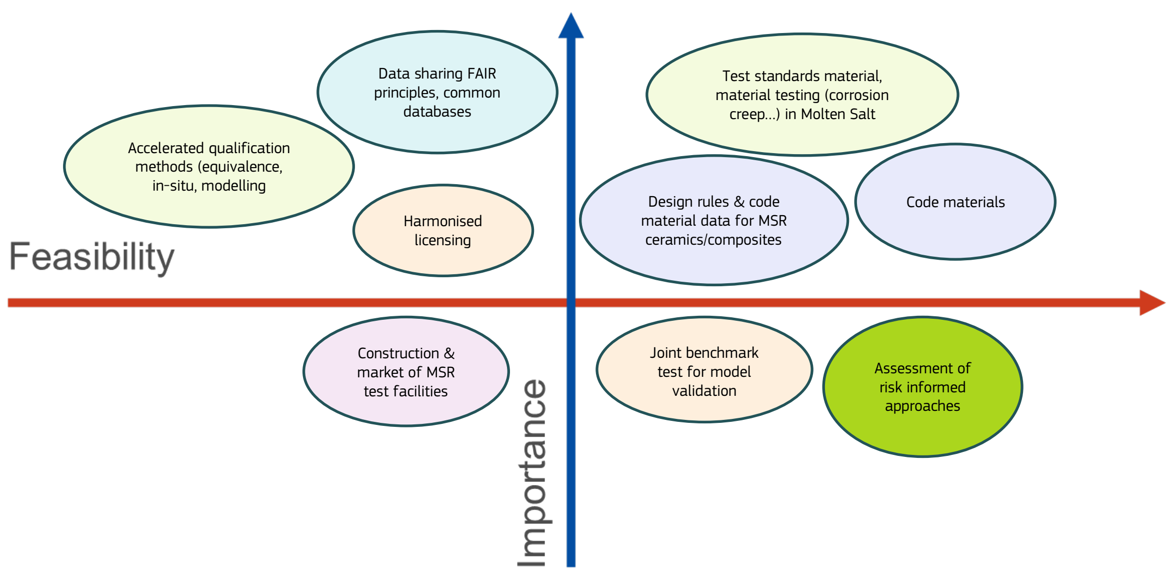

Figure 6 Prioritisation of addressing specific standards and harmonisation gaps considering urgency and current feasibility in the domain of codes & standards for materials and components

Sharing data is not so straightforward and IPR rights need to be recognized. Sharing and exploiting the results of experimental testing also requires data management and data libraries in accordance with the FAIR principles (Findable, Accessible, Interoperable and Reusable). Data generation will also require various test facilities such as dedicated loops, and hence there should be a market for such tests.

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 SiC-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.

There are European and international binding agreements for the energy transition that should take place in a few decades. The traditional statistical-based traditional material qualification for nuclear design with uncertainty is mitigated by massive testing, which in the past often took decades and has questionable results for large and/or small volumes. Thus, accelerated qualification and life-assessment procedures are needed for MSR materials and components. They all rely on reduced testing and includes equivalence-based qualification by analogy with a material; in-situ based qualification that rely on in-sit measurements, usually in connection with data-driven modelling; model-based qualification that rely largely on data driven and physics-based models and validation tests.

The number and total duration of tests should be reduced compared to the traditional approach, but significantly more data need be generated for each test, which could benefit from standardization. Modelling becomes also more relevant; the question to what extent the assessment models can, or should, be standardized is an open question, but requires thorough validation using benchmark tests. Such tests are expensive to conduct, and it would be beneficial if they could be undertaken through European or international collaboration.

5 Molten Salt Reactors Designers

A decade ago, the MSR was considered the least mature technology of the six Generation IV concepts, but this has changed drastically and today MSR is 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 as illustrated in Figure 3. Presently there are five MSR “start-up” design projects in the EU: NAAREA, Stellaria, Thorizon, Seaborg and Copenhagen Atomics, which were all represented at the Workshop. ORANO is a major player for the back and front-end of the fuel cycle and has partnerships with several of the EU MSR designers. There is also a UK-Canadian project, MoltexFlex, and several projects in the USA as well as in Canada and China.

Table 1 summarises specifics for NAAREA, Stellaria, Thorizon and Seaborg. There are some important commonalities and differences. NAAREA, Stellaria and Thorizon rely on the fast spectrum and chloride salts whereas Seaborg 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. Seaborg is targeting primarily the Asian market and uses the ASME code. All MSR designers need accurate data thermo-physical molten salt properties, monitoring fuel composition and material resistance to corrosion and creep deformation in representative molten salt environments.

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 essential prerequisite for commercial deployment. The different start-ups promote innovation and explore different ideas, but some consolidation is expected before the deployment stage.

The US programme comprises a large number of start-ups co-funded by the Department of Energy. All adopt the ASME BPVC design code and they all need to adhere to NRC regulation. The US market is larger than that of any individual EU Member State but comparable to the EU as a whole. Clearly 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 view on 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?

Table 1 Survey among the MSR reactor designers

	Naarea	**Thorizon**	**Stellaria**	**Seaborg**
What is the Regulatory system you need to consider	French ASN for the first reactor, then European. Deterministic framework with limited probabilistic approach.	ASN (FR), ANWS (NL), preferably with a harmonized approach between both bodies	French ASN for the first reactor, then European. Deterministic framework with limited probabilistic approach.	Various, but with initial focus on South Korea (NSSC).
MSR technology	Fast spectrum with plutonium chloride, salt fuelled and cooled, max temp 650 °C, timeframe is 2030 for the first reactor.	Fast Spectrum, chloride - fuelled	Fast spectrum with a mix Plutonium-Uranium-Thorium chloride for the fuel salt. Temp 500-700° K critical experiment for 2027 and 2031 for the “vessel-prototype” reactor in the FOAK.	Thermal spectrum (graphite moderated) and fluoride fuel/coolant salt (FUNaK). General temperature range of interest from 540 to 725°C.
Are you familiar with & do you use or intend to use Design Codes, and if so which ones?	We use RCC-MRx for the mechanical part of the design. There is no code for SiC, which we use for our structural material but adaptation are made based on ASTM Guidelines.	Familiar with both, will use RCC-MRX	We ‘ll use RCC-MRx code and we want to use ASME for ALVIN and the “vessel-prototype” with agreement of French ASN.	Yes, ASME Section III Division 5.
What Near-term reference structural materials do you consider	SiC for the parts in direct contact with the salt, Inconel 625 for the load-bearing parts, 316 L(N) for secondary containment.	Metallic materials: high Ni steels	Priority on Inconel 625 for fuel and primary salts, and 316L(N) for secondary containment.	Type 316 stainless steel. Graphite is also an important material for us.
Which Long-term structural materials do you consider	The same materials as for near term.	Composite ceramics such as SiC	Ceramic and CMC materials. Strong interest for a use in 2035-2040.	Hast-N, Alloy 709
Life assessment factors (High temperature/MS compatibility/irradiation)	Irradiation for nickel-based alloys, part design and mechanical constraints for SiC, corrosion for 316 L(N)	Behaviour under irradiation of code qualified materials (see next box), corrosion kinetics (slowly being remedied by projects such as MIMOSA), and testing under environment (GEMMA project for lead environments needs to be developed for MS environments).	Corrosion of Ni alloy and 316.	High temperature mechanical properties, corrosion, degradation due to thermal aging, MS interaction and irradiation, infiltration of salt in graphite (extent and impact)
What gaps and needs do you see for MSR Material/component qualification/codification?	Qualification of nickel-based alloys should follow AFCEN rules, but they lack a general corrosion framework.	There needs to be a large investment in test facilities, notably irradiation rigs and mechanical testing under environment.	We need to build. ALVIN and “vessel-prototype” are made to give results used for codifications. ASME à RCCMRx transposition of the Inconel 625 and AFCEN codification are needed for 2035, not for ALVIN and “vessel-prototype”	Design methodology to evaluate the independent and combined effects of corrosion, thermal aging, and irradiation on mechanical behaviour and structural integrity. Specific standards/code sections are also needed for development of MSR surveillance programs.
What are your expectations, needs priorities for harmonization/standardization in support of MSR at EU or international level	French ASN for the first reactor, then European. Deterministic framework with limited probabilistic approach.	A shared licensing procedure throughout the EU would greatly facilitate things for the sector.	French ASN for the first reactor, then European. Deterministic framework with limited probabilistic approach.	Materials data bases/libraries, benchmark experiments for combined effects (especially, those involving irradiation), Testing standardization (starting from static and dynamic corrosion), Standard for MSR surveillance program development.

What can EU do 'better' to make deployment of innovative reactor technologies attractive for industries?

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 as an important part of the energy transition.
- Reduce regulatory barriers and provide clear paths for nuclear deployment.
- Provide financial support for European pre-normative research.
- Provide financial support for facilities that require large investments to contribute with knowledge and data of general interest such as dedicated test loops and reactor prototypes.
- Provide support for activities related to generating, sharing and management of data in accordance with FAIR (Findable, Accessible, Interoperable, Reusable) principles.
- Support harmonisation and standardisation at EU and international level.
- Encourage international cooperation through a strong European nuclear sector.

Nuclear energy is characterized by large front-up investments, very long timeframes, rigorous regulations, and on top of that also political controversies. The deployment of innovative reactors requires solving technical challenges. The build-up of an industrial sector will require significant investments. If the technical, financial and political long-term perspectives at EU level are convincing then the nuclear industrial sector and competitive supply-chain will develop. The development and deployment of innovative reactors for which there is limited, or no operational experience requires pre-normative research and supporting test facilities and prototypes for testing concepts and material solutions. They would also create a direct link between industry and research. Such facilities are of uttermost importance for the entire nuclear sector, but the costs could be prohibitively high for a single Member State. EU financial support to establish such infrastructures operated by Member State organizations or JRC and supporting the nuclear development and deployment would be central for the development of innovative nuclear reactors.

The importance of reliable quality data for the MSR development has been stressed in every session of this workshop. Due to the high financial investments for generating data, leading to a lack of data, only limited efforts have been invested in managing data according to the FAIR principles. 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 (research projects, facilities) should enforce data management according to FAIR principles. Data is expensive and propriety rights should be respected, but the EU should promote a mechanism for data exchange.

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. Standards are also central in nuclear regulations and design codes. The EU should support European and international standards for the MSR technology. Several examples of standard needs have been discussed during this workshop, for instance standards and guidelines for qualifying fuels, including understanding properties under normal and accident conditions; test procedures for corrosion and creep tests with controlled impurity levels in molten salt. Standards on supporting technologies such as fuel and waste transport and fission product storage are also important. The standards should be science based, and for innovative fields such as the MSR technology, requires pre-normative research, for which EU support through EURATOM projects have been very important in the past. Before embarking on new standardisation, the community should review if MSR standardisation needs can be accommodated by existing standards. Reactor specific standards should be exceptional.

Climate change is a global problem, solutions are therefore also global. The EU should preserve the European leadership in the MSR technology but also actively look for international collaboration through for instance the GIF initiative and other organizations such as IAEA and OECD/NEA.

Would an EU harmonised license for new reactor types be helpful?

There was consensus among the reactor vendors that harmonized licensing would be helpful at the deployment stage as it could drastically reduce the cost and time linked to the licensing procedure, in particular EU Member States with limited experience in nuclear energy. It would clearly also promote a European market and supply chain through larger series, predictability and more companies willing to invest. The increased feedback experience would in turn reduce cost and improve safety. It would also help Member states with limited or no experience in operating nuclear reactors to make informed decisions for their specific needs. It would also be in line with the Green Deal, the Net-zero Industrial Act and the SMR Industrial Alliance to strengthen the European nuclear industry and its competitiveness on the global market. It should be kept in mind though that harmonized licensing also infers harmonized regulations, which may be a difficult and lengthy process exacerbated by political obstacles.

The advantages with harmonised licensing are less obvious in the innovation phase. Nevertheless, Member States with nuclear experience may benefit from harmonisation to license unproven designs through national regulators. Given the very short timeframe from innovation to deployment, and the complex process of harmonized regulation the process of harmonized licensing should start as soon as possible. At any rate, it would be a stepwise process driven by needs and the objective should be to harmonize as much as "practically possible."

Cross-border collaboration would be facilitated as well, providing a shared framework for understanding and regulating new reactor types. This would enable members to collaborate more effectively on the development and deployment of innovative reactor technologies. This applies in particular for standardisation, design code development and in general collaboration on topics of common interest, such as data sharing.

Is the EU market attractive for future nuclear fleet deployment?

The Green Deal, the NZIA and the SMR Industrial Alliance provide a basis for EU nuclear deployment. A strong and competitive European market is a necessity for a strong and innovative European nuclear industry that is supported by standards and design codes. The European Union 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. As seen in Table 1, Seaborg is primarily focussing on the Asian market. A global outlook will help in making informed decisions and maximizing the benefits of nuclear energy deployment across the globe. For instance, some countries or regions may have a more favourable regulatory environment, abundant resources, or a higher demand for clean energy. Partnership with other regions based on European strengths would be of mutual benefit.

6 Conclusions

There is strong interest for the MSR technology as demonstrated by the five concrete reactor designs that are presently being developed in the EU (Stellaria, Naarea, Thorizon, Seaborg and Copenhagen Atomics) and elsewhere (USA, Canada, China) and deployment is expected in the coming decades.

In order to comply with the EU Green Deal and the Net-Zero Industrial Act, MSR deployment needs to be done within two decades, which is a very short time for nuclear materials development and deployment. MSR is an innovative technology and standards are central to bring MSR to industrial deployment: a paradigm shift is needed to accelerate this process, which needs to be more data-driven, including a closer integration of experiments and physics-based and data driven modelling.

Harmonization and standardization are long-term and continuous processes, but concrete standardization activities need to start as soon as possible focussing on key priorities:

- As regards safety assessment and the current level of maturity of the technology with the wide variety of designs being developed, there is a need and interest in starting a process of harmonisation, rather than standardisation, which would also speed up the licensing process.
- The harmonisation process must begin as soon as possible, with the primary objective of obtaining a shared safety approach for FOAK demonstration reactors, which are indispensable tools for generating the data that are still insufficient for validating the models used in safety assessment.
- Accurate measurement of data must satisfy quality requirements for licensing. Standardizing measuring methods not only helps meet these requirements but also reduces data uncertainty. This reduction in uncertainty is crucial for minimizing MSR design margins and lowering associated reactor costs.
- Significant data gaps persist in our knowledge of the thermo-physical properties MSR fuel and coolant systems. Addressing these gaps is most efficient through collaborative efforts and a commitment of sharing data.
- Ensuring that the fuel keeps its function within the whole range of the reactor operation requires standards for the definition of the fresh MSR fuel purity, for monitoring fuel composition and interaction with reactor materials during irradiation of related sensors, methods and sampling, as well as for the measurements of fuel function specific properties.
- Standardization within the backend of the MSR fuel cycle depends on the selected option; the backend is the least developed part of the MSR technology and is too premature to develop standards in this field. Nevertheless, it is very important to standardize the terminology connected to the whole MSR fuel cycle and to develop standards for each pyro-metallurgical process if considered for the back end of the fuel cycle.
- There are no code-qualified materials for molten salt reactors in RCC-MRx or ASME BVPC. Impurities in the molten salt have a large impact on environmental degradation. The setting up of test procedures (e.g. corrosion, creep) in molten salt with controlled impurity content is a prerequisite.
- The qualification of MSR structural materials should be first undertaken for code-qualified high-temperature materials, but to exploit the full potential of the commercial deployment of MSR materials such as silicon-carbide composites, corrosion and high-temperature resistance need to be explored and qualified.

- Rather than developing new specific MSR standards, one should should first review existing nuclear and non-nuclear standards and to what extent they could accommodate the MSR needs.

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

There is a common understanding among MSR stakeholders that to accelerate deployment and reduce costs, collaboration is necessary with respect to standard and design code development, data sharing, benchmarking, sharing experimental facilities.

European and international harmonized licensing for MSR can facilitate deployment through faster licensing, lower costs, efficient supply chain, and competitive market. It should be noted that licensing harmonization also implies harmonized regulation, which is not a straightforward process and potentially could 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 standardization roadmap and code-of-practice via the Annual Union Work Programme for standardisation (AUWP, European Commission, 2024) addressing key priorities.

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 (European Commission, 2024). This technical report, together with the support of CEN and CENELEC, including the efforts of the established community, will consolidate our recommendations into the development of a roadmap towards the creation of working groups in CEN TC430 / ISO TC85 and other platforms, to start drafting the first specific standards and codes in support of the deployment of Molten Salt Reactors.

Table 2 Standardisation needs in categories of terminology, metrology, performance characterisation, compatibility and regulatory assessments in selected technical domains

	Terminology	**Metrology**	**Performance Characterisation**	**Compatibility**	**Regulatory requirements**
Measurements of thermo-physical properties	• Important to use proper terminology for type of property and its method that is applied for determination. • Terminology defines what is reference, calibration, standards, certification, accreditation	• Techniques to measure properties must be standardized. • Standardization eliminates variations in factors that affect measured property values • Measurements must be done under calibrated and controlled conditions	• Salt properties depend on the mixture composition, impurity levels (contaminants) and temperature. • Purity of examined material must be defined and must be high enough to ensure proper measurement. • Chemical nature of impurities should be listed and purity levels should be identified (with respect to each property determination)	• Samples must be handled in dry atmosphere, for specific experiments they need to be encapsulated. • It is uppermost important to handle the samples (and mainly at high temperature) in chemically compatible capsules (holders)	• Quality-Assurance meeting defined requirements. i.e. requirements for licensing. • ISO17025 accreditation • NQA-1 requirements
Safety evaluation (common approach)	• Reviewed and extended to meet MSR specific issues. i.e. specific degradation types, definition of salts	• Purification, monitor composition of molten salt, leakage	• Safety assessment (codes) in normal and accident conditions	• Compatibility between different safety solutions (salt concepts x with high boiling, solidification of material when cooling)	• Set framework for basic safety features and methodology (e.g., risk inform approach, passive safety)
Qualification of Fuels and Fuel Cycle	• Terminology of the whole MSR fuel cycle, especially important for the back end, is very important to be harmonized or standardized	• Very important is to standardize techniques for the following measurements: • in reactor red-ox potential of the fuel salt • oxygen content in the fuel salt • composition of the fuel before and during the irradiation • off-gas quantification	• The acceptable level of impurities in the MSR fuel salt should be standardized, and a list of important impurities and their effect on the reactor operation and safety evaluated. • Fuel function specific standards assuring that the fuel keeps its function within the whole range of the reactor operation (e.g. viscosity, density, isotopes retention etc.)	• Irradiation experiments using standard procedures are important for the safety assessment and assuring corrosion resistance of the construction materials during the MSR operation. • Enrichment requirements (37-Cl and 7-Li)	• Monitoring of the fuel composition during the irradiation: standards for the measurements of the composition and safety related fuel properties (e.g. red-ox potential, density, etc.), as well as standards for sensors, measurement techniques and sampling
Codes & Standards for Materials and Components	• Needs to be precise but is not a major issue.	• Accurate measurements of key parameters such as impurities in molten salt are essential and procedures need to be standardized. In general monitoring and measurements degradation, strain etc in molten salt remains an issue.	• Materials testing remains very important but need to be complemented with in-situ measurements physics-based and data-driven modelling to accelerate the material qualification and reactor licensing.	• The compatibility between the molten salt and the material component is the key challenge and must be demonstrated.	• Sets the framework for the material & component qualification, and licensing, e.g. performance-based vs prescriptive, and risk-informed/probabilistic vs. deterministic

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List of abbreviations and definitions

AFCEN - Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires

ANL - Argonne National Laboratory of the United States Department of Energy is administered by the University of Chicago.

CEN and CENELEC - European Committee for Standardization and the European Committee for Electrotechnical Standardization

CEN/TC - European Committee for Standardization technical committee

CEN/WS - European Committee for Standardization workshop

CFR - United States Code of Federal Regulations

EU - European Union

FOAK - First-of-a-Kind

GIF-MSR - Generation IV International Forum (GIF) Molten Salt Reactor

IPR – Intellectual Property Rights

IRSN - Institute for Radiation Protection and Nuclear Safety

JRC - Joint Research Centre

LWR - Light Water reactor

MSR - Molten Salt Reactor

NHSI - Nuclear Harmonization and Standardization Initiative

NPP - Nuclear power plant

NZIA - Net Zero Industrial Act

OECD-NEA - Nuclear Energy Agency of the Organisation for Economic Co-operation and Development

PSIS - Putting Science into Standards

R&D - Research and development

RCC-MRx – AFCEN design code for high temperature, research and fusion reactors, derived from abbreviation “regles de Conception et de Construction des Materiels des Chaudieres Electro-nucleaires

SMR - Small Modular Reactor

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Annexes

Annex 1. Agenda

Time line	18. March 2024 Topic and presenter	
13:00 - 13:30 GMT+1	***Location:*** *University Foundation 11, Rue d'Egmont, Brussels, Belgium* **Opening** (Moderation Fabio Taucer) **Ulla Engelmann**, Director, Joint Research Centre **Andreea Gulacsi,** Director for Policy & External Affairs, CEN & CENELEC	
13:30-14:15	**Needs for future standardisation** (Karl-Fredrik Nilsson) • Nikos Pantalos, DG-Grow, NZIA and Alliance • Pekka Tapani Pyy, IAEA, Common approaches for industrial production and operation of near-deployment reactors (incl. SMRs) • Jiri Krepel, GIF-MSR, GIF-MSR project and variety of the systems	
14:15-15:15	**How to bridge the gap** (Ondrej Benes) • Olivier Marchand CEN TC430 / ISO TC85 • Antoine Martin, Framatome, RCC-MRx: AFCEN Design Code for Innovative reactors • Patricia Paviet, US-DOE, Overview of the US MSR program • Nicholas Ferguson, HS Booster	
15:15-15:45	**Coffee break**	
15:45-17:45	**Parallel sessions**	
	Measurements of thermo-physical properties (Keynote **M Rose** (ANL), **A Smith** (TU Delft), Chair/Rapporteur **O Benes/P Soucek**) • Sample quality check • Calibrations • Uncertainty analysis • Certification/accreditation of labs • Database developments • Collaborations and laboratory benchmarking (Round Robin) ***Location:*** *Joint Research Centre, CDMA -1, Rue du Champ de Mars 21, Brussels, Belgium*	**Safety evaluation (common approach) (**Keynote **D Holcomb (**INL), Chair/Rapporteur **A Caverzan/K-F Nilsson**) Key safety issues • Comparison of enveloping accidents between conventional NPPs vs MSRs • DID implementation and approach in MSRs • Source Term characterization of MSRs Specific topics of MSRs • Cliff-edge effects in MSRs • Tritium control in MSRs • Development of top safety requirements, both MSR design-generic and MSR design-specific ***Location:*** *University Foundation 11, Rue d'Egmont, Brussels, Belgium*
18:00	**Social Dinner (University Foundation Souterrain)**	

<table>
<tr><td>08:30-
09:00</td><td colspan="2">19. March 2024, Coffee and registration
Location: Joint Research Centre, CDMA -1, Rue du Champ de Mars 21, Brussels, Belgium</td></tr>
<tr><td>09:00-
11:00
GMT+1</td><td>Qualification of Fuels and Fuel Cycle (Keynote E. Capelli (Orano), Chair/Rapporteur P. Soucek/O Benes)
How to bring standards to the characterisation of the fuel
• Fresh Fuel Material
• Nuclear Fuel Safety Criteria
Standards within the MSR Fuel Cycle
• Terminology (processing / reprocessing / recycling,...)
• Monitoring and control of the composition & radionuclide inventory during each step of the fuel processing
• MSR fuel vs. conventional fuel</td><td>Codes & Standards for Materials and Components (Chair/rapporteur K-F Nilsson/A Caverzan)
MSR designers' views on harmonization and standardization needs (30 min)
Discussion (1h)
• Common needs
• Path for harmonization
• Paths for collaboration
Conclusions/synthesis (15 min)</td></tr>
<tr><td>11:00-
11:15</td><td colspan="2">Coffee break</td></tr>
<tr><td>11:15-
11:35</td><td colspan="2">Speed briefs by rapporteurs (5 min each)</td></tr>
<tr><td>11:35-
12:30</td><td colspan="2">Panel and plenary discussion: the way ahead
Molten Salt Reactors Designers: Orano, Copenhagen Atomics, Naarea, Stellaria, Thorizon, Seaborg</td></tr>
<tr><td>12:30-
13:00</td><td colspan="2">Closing remarks
Fabio Taucer, JRC and Cinzia Missiroli, Director Standardisation, CEN and CENELEC</td></tr>
</table>

Annex 2. Participants

Prenom	Name	Country	Institution
Eriona	Kilja	Albania	QKTB
Amparo	Gonzalez Espartero	Austria	IAEA
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Amanda	Sejersen	Belgium	European Commission - JRC
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Ted	Besmann	United States of America	Oak Ridge National Laboratory
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