# U.S.–UK Bi-Lateral Collaboration on

# Safeguards Analysis for

# a Nominal Molten Salt Reactor Design

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**Abstract**

This work introduces a nominal molten salt reactor (MSR) design and the basis for developing a broadly applicable safeguards analysis. The simplified methodology is presented as a baseline from which more complex designs can be assessed, and the starting point for what is likely to be a multi-year programme to investigate the component-level safeguards considerations. This will include benchmarking where existing safeguard technology and methods are appropriate and where novel approaches for achieving the IAEA objectives are required.

## INTRODUCTION

Several economic and environmental factors are driving new levels of innovation in the advanced nuclear sector. Advanced reactor technologies represent a significant departure from conventional reactor technology and offer both new opportunities and new challenges. One technology generating significant interest across the global nuclear community is the Molten Salt Reactor (MSR). MSRs, like all generation IV reactors, promise the potential for improved safety, efficiency, and deployment flexibility for a variety of industrial and power generation applications. However, MSRs are distinct among this generation of reactor in using a liquid fuel[[1]](#footnote-2). Alongside their transformative potential, the proliferation risks associated with MSR technology necessitate rigorous International Atomic Energy Agency (IAEA) safeguards to ensure nuclear non-proliferation objectives are upheld.

The IAEA plays a pivotal role in establishing and implementing safeguards measures to prevent the diversion of nuclear materials for non-peaceful purposes while facilitating the peaceful uses of nuclear energy. To this point, IAEA safeguards approaches for reactors have been applied predominantly to the operational fleet comprised of light water reactors (LWRs) and pressurized heavy water reactors. MSRs are notably distinct from these designs that utilize fuel in large, distinct items, and they pose unique challenges that present an opportunity to reevaluate conventional safeguards approaches. The IAEA recently published some of the known challenges for safeguarding liquid fuelled reactors and how member states should support in overcoming these challenges [1].

In this endeavour, partners from across the UK and the U.S., as part of a newly established technical collaboration, have combined efforts to define a joint approach to MSR safeguards. The paper describes the unique challenges of MSRs, and explores how a paradigm shift in safeguards philosophy, grounded in a systems perspective, could result in a more efficient verification regime. The approach remains steadfast in achieving the fundamental objectives and outcomes of safeguards – “*To detect any diversion of declared nuclear material or production of undeclared nuclear material*” [2] – while challenging some of the conventional methods employed by the IAEA.

In re-evaluating safeguards for MSRs, this paper endeavours to contribute to the ongoing discourse surrounding nuclear non-proliferation and the safe and secure deployment of advanced nuclear technologies. By bridging the gap between technological advancements and safeguards implementation, this research aims to foster confidence in the peaceful uses of MSRs while safeguarding against the diversion of nuclear material or misuse of future MSR facilities. Ultimately, the development of an effective safeguards regime for MSRs is imperative for unlocking the full potential of this innovative technology to address global energy challenges. Open minds, collaboration and innovation will be needed to ensure the safe, secure, and sustainable deployment of MSRs on a global scale.

## Conventional Safeguards approaches

For existing commercial reactors, nuclear material safeguards have been largely standardized, primarily because of the low variation in reactor and fuel designs. Most reactors are either pressurized, light-water reactors (PWRs) or boiling, light-water reactors (BWRs) that use a static, metal clad, low enriched fuel of less than 5% 235U. The fuel is a series of uranium-dioxide pellets stacked inside metal cladding then fabricated with supporting components into a single “fuel rod”, These fuel rods are then combined in specific geometric patterns called “fuel assemblies”, assemblies may also include space to accommodate moderators and control rods. Due to this configuration, conventional reactor safeguards utilize *item accountancy*, where each fuel assembly has a unique, identification (UID) number that must be documented by the reactor operator and confirmed by the IAEA.

The IAEA has decades of experience implementing safeguards for conventional reactors, and the safeguards approaches for traditional reactor and fuel designs are well developed and documented. Fuel identification practices must be combined with some nondestructive assay (NDA) measurement for verification and integrating elements of containment and surveillance ensures continuity of knowledge through the fuel’s lifecycle. Refueling requires a reactor shut-down period that occurs in known intervals, and spent fuel discharged from a reactor is monitored constantly. Similar combinations of visual confirmation and surveillance are combined with NDA measurements to provide assurance that spent fuel is handled as declared.

Online refueling designs also exist with known safeguards approaches. Canada Deuterium Uranium (CANDU) reactors can replace fuel bundles during operations, leading to improvements in the efficiency of the reactor operations. These reactors rely on constant process monitoring and surveillance techniques, and they required the development of unique NDA measurement systems to track discharged fuel from the reactor.

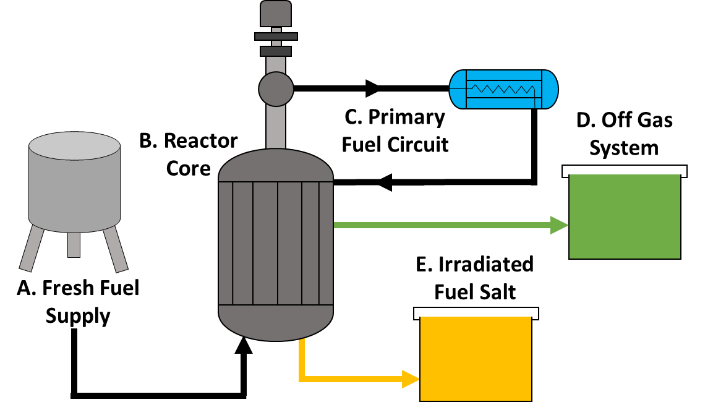
The use of fissile material dissolved into the primary coolant and continuously circulated through the entire reactor system means that some traditional safeguards and material accountancy methods will not suffice. There remains a distinct difference between discrete offline refueling cycles or online refueling of bundles during operation and introducing a set volume of molten salt with known fuel concentrations into a dynamic system. While there is IAEA experience with continuously circulating aqueous reprocessing facilities worldwide, the safeguards methods and approaches for a MSR may require a paradigm shift that merges elements of traditional LWR, CANDU, and reprocessing facility techniques. This may include a greater reliance on containment and surveillance, absence verification, novel and/or indirect monitoring techniques, and the need for more of an objective-focused systems-based approach.

## Defining a nominal msr system

To define a system-level safeguards approach, there needs to be some agreement on a nominal MSR system design. The developmental space for MSR technologies is extremely diverse, so it is important to develop a model that comprises systems and technologies that are common across most designs. While the aspiration is that the methods developed can be applied to complex designs, such as the fast fission spectrum, chloride salt-fueled design that may include online chemical processing, this introduces too much complexity at this early stage.

The following nominal MSR design represents a wide array of domestic design interests from both partner countries (Fig. 1). The basic design is a fuel-salt matrix with a single, loop design. From a point of simplicity, this design would encompass many of the design characteristics of the Molten Salt Reactor Experiment (MSRE) [3] at Oak Ridge National Laboratory. This design does not address all the known safeguards challenges associated with MSRs, but it does provide a model to start developing a systems approach. The nominal MSR design has the following characteristics:

* Liquid-fueled with low-enriched uranium;
* Fluoride-compounded salt;
* Thermal neutron spectrum with graphite moderator;
* Single, primary loop circuit (single loop to balance of plant);
* No online chemical processing; and
* Simplified once through off-gas and waste removal process.



*FIG 1. Nominal MSR flowsheet for safeguards analysis.*

The fresh fuel supply (A) is simplified as a single stage. It contains all necessary equipment to prepare and load the salt into the reactor core; this stage accounts for the entire feed source of fuel salt into the reactor system. In a more realistic representation, there will likely be material balance areas and controls associated with these process steps. However, for this simplified approach, this stage serves primarily to provide the fuel input to the MSR system, both initially at the beginning of the reactor life and over reactor lifetime as makeup fuel salt. It is assumed that all salt that is prepared in this stage enters the reactor, and there is no fuel stockpile.

The reactor core (B) is represented by a series of inlets and outlets to other necessary sub-systems. The material balance across the reactor vessel boundary will represent the primary concern from a safeguards approach, and to simplify this, the fuel salt has two points of entry, from the fresh fuel stage (A → B) and one for recirculated fuel from the primary fuel loop (C, C → B). Similarly, there are three points of outlet from the reactor core, one for discharge to the primary fuel loop (B → C), one for discharge to the off-gas system (D, B → D), and one for discharge to holding tanks (E, B → E). This mass balance will provide the basis for most of the discussion on the safeguards approach, and it is meant to simplify the entire system to allow for such a discussion.

As the system-level analyses develop and progress, this simplification will be modified; however, a fully efficient flow system drawn around the reactor core boundary allows for a basis of an integrated safeguards approach. Simplifications are also made for all the key system components in a primary fuel loop (C). For this design, the primary loop is a single loop that includes the piping, pumps, two-phase mixers, and other process components. This design includes a heat exchanger (HX), where it is assumed that the thermal energy is discharged to balance of plant and the fuel salt is circulated back to the reactor core. Finally, the two discharge streams for the off-gas system (D) and irradiated salt holding tanks (E) are simplified as generic holding tanks for materials discharged from the system. This system does not include any chemical processing or waste scrubbing. As the component-level analyses develop, these systems will be developed further to allow for a more realistic safeguards assessment.

## MSR Component-Based Safeguards Challenges

MSRs operate differently to conventional reactors; operations are more analogous to a chemical processing plant than a conventional reactor. Fully understanding the material flow paths within the design is essential to ensure that no material is being diverted and the reactor is not being misused to produce undeclared material. Understanding the material flow sheets and confirming the specification and operation of installed components will be critical to effective implementation of safeguards in MSRs. New reactor facilities that differ significantly in design and operations, like MSRs, may require new or modified inspector skill sets.

This section provides an overview of the safeguards considerations for key components of the nominal MSR design. Each of these components will be analysed in depth in follow-on efforts. As a multi-year programme, the component-specific approaches on how to meet IAEA safeguarding objectives for MSRs will develop over time, but the broad, system-level approach defined in this work should serve as the basis for analysis.

### Initial and online fuel additions

The nominal design will have a location to add fresh fuel and/or other non-nuclear materials (e.g., to control chemistry). The frequency and method of addition of fresh or compensatory fuel-salt compounds may vary for specific designs, and each design could rely on either a batch or continuous process of a solid (cool) or liquid (hot, molten) salt additions. The composition of added fuel salt will be predominantly based on modelled and anticipated reactor operations. Monitoring addition of the fuel salt to the reactor system is challenging. Because of increased frequency of additions to control the chemistry, it is anticipated that IAEA inspectors may not always be on site to verify the materials being added to the core. Monitoring quantities and composition of fresh fuel feed added to the reactor is critical to anticipating and detecting potential diversion and misuse scenarios. A full analysis of the fuelling system is required to understand potential diversion pathways; however, because of the air-sensitive nature of the fuel salt (related to its corrosivity [4]), it is likely that the fuel will be managed in air-tight, sealed containers. This may simplify accountancy if containment can be assured after manufacture and prior to addition to the reactor.

### Safeguarding approach to the inside of the core

The core represents a challenging situation from a traditional safeguards approach. The fuel undergoes irradiation and transmutation, and monitoring these changes will be difficult. In addition, the core physics and fuel-salt chemistry will constantly affect each other, causing a series of feedback mechanisms that drives an equilibrium balance. Material monitoring and accounting methods will have to combine elements both item and bulk handling facilities - taking learning from; aqueous chemical processes, liquid metal-cooled reactors, and traditional LWR containment and surveillance methods. Specific challenges for discussion are presented, but this is not meant to be an exhaustive list. The following subsections represent the areas most pertinent to this safeguards analysis.

#### Reactor misuse through fertile material irradiation

Introducing fertile material, such as 238U, into the nominal core can act as a target to produce plutonium (Pu). To safeguard against this in LWRs, the IAEA can inspect components entering the core and inside the core during planned outages, such as maintenance or refuelling to ensure no targets exist. The fluid nature of the fuel in the MSRs does not guarantee homogeneity of the system and assurance that the core does not contain breeding blankets, targets, or pathways for the introduction of fertile material. Moreover, the requirement to keep the core under an inert atmosphere, combined with a high radiation environment, further hampers visual inspections and surveillance, necessitating new or novel sampling strategies.

As with any design, periods of maintenance, where key core components might be replaced, are likely and should be considered. However, the design lives of many MSRs are significantly shorter than LWR, and several designs propose to replace the entire system on a 4-to-7 year cycle. Similarly to LWR safeguards, any maintenance periods would be scheduled, and IAEA inspectors’ presence during the reactor outage would be encouraged. For the nominal MSR, the team will aim to understand what is involved during maintenance periods, but there are misuse scenarios where replaced core elements, such as graphite and metallic components, could contain targets.

#### Material accountancy

In LWR systems, there is often extensive modelling and simulation efforts to determine the Pu content of each fuel assembly based on its irradiation history. This is confirmed by methods such as gamma spectroscopy or post irradiation examination which can be performed by the IAEA to confirm the burnup, which can be directly linked to the Pu content produced. As LWRs have operated for decades under safeguards, previous operations can be used as a benchmark and the large number of deployed LWRs provides a wealth of experience and data to underpin confidence and validate techniques. A tabled summary of the challenges for in-core material accountancy is provided in Appendix A.

Fission products in MSRs may be dissolved in the carrier salt, deposit in the primary circuit or bubble out as off-gasses – they are not retained in fuel pellets or assemblies like in LWRs [5]. The gaseous fission products may be assisted in leaving the core by helium (or similar gas) bubbling to the off-gas system. The rates at which these processes occur will depend on the MSR design, including the composition of the salt, operating temperature, fuel burn-up etc. Uncertainties and dynamic effects in the chemistry of the system, such as temperature dependence of fission product solubility, make modelling and simulation challenging. Modern computational codes and improved understanding of specific systems may alleviate this challenge, but there are no universal models applicable to all MSRs.

The proportion of the fuel salt in the reactor core versus the primary circuit, and the mass flow rate between them, will also be design specific. Quantification of these properties is challenging since fundamental properties of the fuel salt such as density will change with temperature and, as more fission products, are introduced and the system deviates from an initial composition.

Conventional methods of measurement of reactor fuel may not be appropriate to MSRs. Alternative approaches, design specific codes / models and novel measurement techniques are likely to be needed. These will be explored throughout the programme. It is possible that MSRs will necessitate a shift away from accountancy while the material is in the core utilizing a black-box approach much like a bulk handling facility, and place a greater focus on containment and surveillance, etc.

#### Diversion of material

The diversion of nuclear material in irradiated fuel salt from the core would be simplest through designed inlets and outlets which must be constantly monitored. The ability to divert material from outlets introduced during operation would be difficult due to the potential to introduce air and moisture into the system, not to mention the high temperatures and radioactive environment involved. Several academic studies have assessed the potential measurement techniques and modelled associated uncertainties with novel fuel forms [6] [7].

During normal operation fuel salt flow should be understood and the process flow characteristics would be expected to be shared and understood by the IAEA. All flow paths in the facility, whether they plan to contain nuclear material, should be declared to the IAEA through the Design Information Questionnaire, with the expected materials declared for each path during operation, especially paths that could lead to materials being removed from the core. Methods for monitoring of flow and methods of assisting the IAEA in reviewing the flow diagrams could be beneficial.

If the introduction of non-declared pathways out of the reactor system were possible, methods to detect and identify these undeclared pathways would be critical. Unattended monitoring detection systems on site should be considered to monitor for this scenario with data remotely transmitted to the IAEA. If special equipment was developed by the State to avoid this detection, this would require heavily shielded and sealable systems on site to handle and remove the fuel salt.

One of the most challenging scenarios for diversion is mitigating the risk that small volumes, over a long period of time, are diverted from the core. This is referred to as a bias defect in IAEA Bulk Handling Facility safeguards vernacular. The ability to do this in a liquid fuelled reactor is far greater than those with solid fuel. Appropriate safeguards measures need to be identified or developed to detect this.

#### Operational misuse

For LWRs, the IAEA has verification technologies to monitor power and ensure that the facilities are not misused for undeclared production of Pu. From a safety perspective, LWRs have maximum temperature limits based on the fuel cladding melting point. In MSR systems the core environment may be too hot or too corrosive to effectively deploy traditional detector systems. In addition, the use of a fuel-salt as the primary circuit fluid creates an operational misuse pathway surrounding each engineering component in the system.

Neutron flux detectors outside of the core can provide an indication of the power levels within the facility, but the accuracy of these detectors will be dependent on the physical arrangement of the facility and will need to be validated. Misuse of the reactor to produce Pu may hinder reactor operations and performance over a prolonged period, and the Pu produced would still be in the core and require extraction. It may be possible to build in safeguard controls into MSR instrument and control systems, that could reduce the risk of misuse. A final concern is the use of the reactor flux to irradiate target channels preplaced in the structure of containment regions of the core..

### Safeguarding approach to the primary loop to the heat exchanger

In LWRs, there is no nuclear material in the coolant loop. In MSRs, the fuel exists within the primary salt loop (i.e. the flow of coolant, in this case fuel salt) out of, and back into, the core. In all reactors, the primary loop uses a HX to transfer heat away from the core for use in other areas of the plant. As there are delayed neutrons within the MSR HX, this could also be a location for potential breeding targets which should be checked during the commissioning of the facility.

Additionally, almost all MSR designs will include a secondary fluid loop that carries heat away from the primary HX and contains a fluid with suitable heat transfer characteristics, such as another salt, steam, gas, or other material. Controls may need to be introduced to ensure that material cannot be diverted into the secondary circuit. However, for this initial effort the assumption is made that all material remains in the primary circuit and only heat is discharged to the balance of plant.

### Safeguarding approach to the off-gas

The off-gas system in MSR’s provides challenges for material accountancy as the volume of material which reaches the system will depend on operational characteristics e.g. power, temperature, cover gas flow rate, and, if present, bubbling flow rate. Moreover, highly neutron absorbing off-gasses, such as 135Xe will be produced, and this could be removed to increase the efficiency of the system.

The off-gas system could act as a diversion path of material if the core was operated in such a way that unmonitored material could leave the core. The experience of MSRE [8] provided no evidence that uranium or Pu were found within the off-gas system. However, the off-gas system and other two-phase separations components should include an effective safeguards approach should include monitoring for regulatory and operations purposes. For this and subsequent studies, the amounts, and quantities of materials in the off-gas streams for nuclear material. and other dependent components are integral to the system-level mass balance.

Most off-gas systems use an autonomous system due to the high levels of radioactivity. Monitoring the off-gas may provide an opportunity determine some operational parameters [9]. Approaches to characterisation of the off-gas composition for the purpose of safeguarding need to be fully defined.

### Safeguarding approach to the irradiated fuel, drain tank and spill tray

Irradiated fuel removal, including the use of drain tanks and a spill tray, present potential exit points from the MSR system; the methods for monitoring these need to be determined. Some of the implications on safeguards will depend on how the system is being implemented and operated. For example, the spill tray and drain tank might be a single system, or they may be a series of tanks with separate flow pathways.

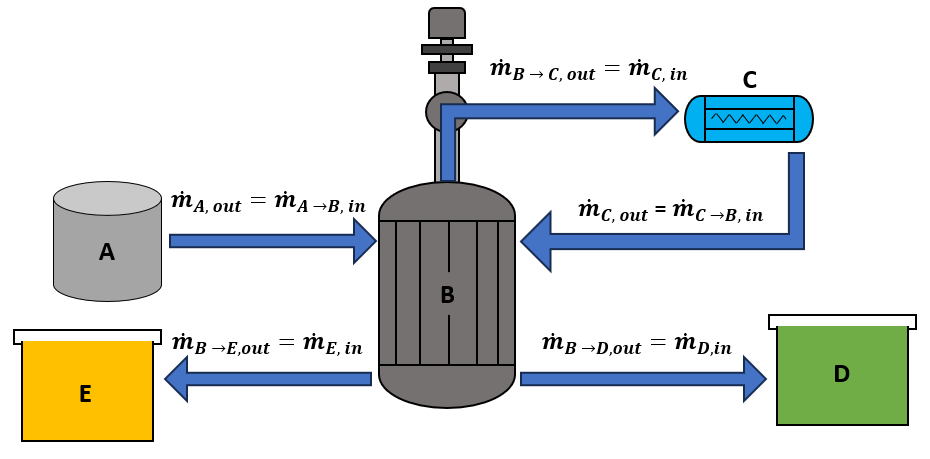
Material accountancy for each of these processes might be possible, by weighing the removed salt for example, but the degree of assurance may be insufficient for current uncertainty standards. As the fuel-salt exits the system, heat may be applied until it reaches the drain tank to maintain a liquid state. However, until the fuel-salt deposits in the waste or drain tank vessels, the use of more conventional safeguards methods during material transit from the primary loop may not be sufficient. It should be noted that the radiation safety concerns associated with these fuels may present challenges, but they will not be covered in this effort.

Diversion is a risk in all pathways that exit the reactor system unless continually monitored, which will be challenging. Opportunities to control material removal needs consideration, e.g. containment of removed material until periodic inspection and permission for release or automated procedures with near real time data remotely transmitted to the IAEA.

## Systems-LEvel Safeguards Approach

This work aims to use a nominal MSR design to illustrate how a systems approach can aid in the construction of an effective and efficient verification regime that meets IAEA safeguards objectives. Defining the MSR system with a series of key material flow assumptions allows for the development of a repeatable methodology that provides the framework to assess the sufficiency of existing safeguards methods to MSR designs. Where gaps or limitations in existing safeguards approaches are identified, recommendations can be made for novel methods, technologies or underpinning research required to meet IAEA safeguards objectives.

The proposed methodology relies on process repeatability at both the full system, sub-system, and component levels of the nominal MSR design. Each assessment begins with the definition of key assumptions that create an ideal material flow state. there is no material loss as the fuel-salt matrix flows between two sub-systems of the MSR. From this initial assumption, each sub-system will be analysed with a series of hypothetical scenarios or alterations that could challenge this assumption. The system-level construction for this ideal system is shown in Fig. 2.



*FIG 2. Material flow boundary conditions for safeguards approach of nominal MSR.*

This exercise allows a team of experts to test and benchmark the MSR system against IAEA safeguards objectives from the perspective of a state proliferator. Some of the analytical “challenges” can include assessing how including necessary sub-system components (such as pumps, piping, and vessels) alters the ideal state assumption and introduces diversion pathways. Additionally, assessing any mechanical, nuclear, or chemical changes to the material from operational conditions provide a comprehensive analysis for reactor misuse scenarios. For each identified diversion pathway or misuse scenario, either a solution can be proposed to re-establish an ideal flow state, or a gap in the safeguards approach can be defined for future assessment. As the sub-system assessment develops, series of these analyses should be integrated, first as coupled sub-system analyses, then into a system-level safeguards approach.

The next stage of the programme will be to define the nominal and related systems in detail (starting from MSRE), followed by the initiation of sub-system safeguards analyses, each will be interrogated by a community of technical experts. As the methodology is adapted and refined, it should provide useful recommendations to MSR developers on how to consider safeguards during the design phases of their reactors, and to the IAEA on the implementation of safeguards approaches and where work is required to address gaps.

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ACKNOWLEDGEMENTS

This work is supported by national sponsors at the United States National Nuclear Administration’s Office of International Nuclear Safeguards and the United Kingdom’s Department for Energy Security and Net Zero. Additional acknowledgements are given to the team of U.S. subject matter experts that contributed to discussions and reviewed this work. This group included Karen Hogue and Hunter Andrews from Oak Ridge National Laboratory, Ammon Williams from Idaho National Laboratory, and Patricia Paviet and Rob Marek from Pacific Northwest National Laboratory.

Appendix A: Summary of In Core Nuclear Material Accountancy Challenges

TABLE 1. Summary of in core material accountancy challenges

|  |  |
| --- | --- |
| **Challenge** | **Description** |
| Change due to fission | The material composition is continuously changing due to fission. |
| Material added to the core | Fresh fuel and other elements to control redox chemistry may be added. These will impact thermophysical and thermochemical properties of the salt, and the quantities of nuclear material within the system. All penetrations into the system needed to be monitored to identify introduction of undeclared fertile material or any undeclared removal of nuclear material. |
| Plating out in the core | Some insoluble fission products may plate out inside the primary circuit. |
| Movement of material | The composition at any point of the fuel salt during its flow through the primary circuit is challenging to assess. |
| Movement of off-gas | Gases will be produced and may carry salt or fission products into the off-gas treatment |
| Flow rate | The mass flow rate of the fuel can increase the power and therefore make it challenging to accurately determine the power profile and therefore Pu content. |
| Material leaving the core | Nuclear material in unintentional material leaks, sampling and irradiated fuel removal would need to be quantified. Measurement of hot, corrosive molten salt is challenging. |

1. For the purposes of this paper, MSRs are considered to have fuel dissolved in a carrier salt, or a “liquid-fueled MSR”. The authors acknowledge this is not the case for all molten salt reactors. [↑](#footnote-ref-2)