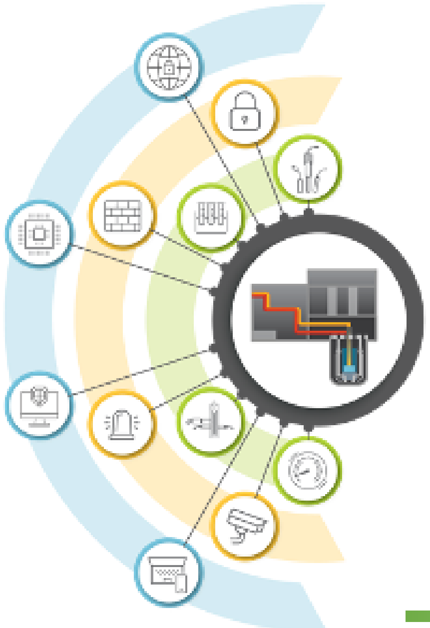

Material Control and Accounting for Liquid-Fueled Molten Salt Reactors: Material Control and Holdup Considerations

Prepared for
US Department of Energy

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Oak Ridge National Laboratory

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Nuclear Nonproliferation Division

MATERIAL CONTROL AND ACCOUNTING FOR LIQUID-FUELED MOLTEN SALT REACTORS: MATERIAL CONTROL AND HOLDUP CONSIDERATIONS

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ABBREVIATIONS

CFR	*US Code of Federal Regulations*
HX	heat exchanger
IAEA	International Atomic Energy Agency
IMSR	integral molten salt reactor
LFTR	lithium fluoride thorium reactor
LWR	light-water reactor
MBA	material balance area
MC&A	material control and accounting
MCFR	molten chloride fast reactor
MSR	molten salt reactor
MSRE	molten salt reactor experiment
NRC	US Nuclear Regulatory Commission
SNM	special nuclear material
TID	tamper-indicating device

EXECUTIVE SUMMARY

The US Nuclear Regulatory Commission (NRC) will likely require license applicants for liquid-fueled molten salt reactors (MSRs) with circulating fuel to submit a nuclear material control and accounting (MC&A) plan or detailed MC&A program description for the facility. In liquid-fueled MSRs with special nuclear material (SNM) in bulk (i.e., not in discrete items) form and rapidly changing quantities due to fuel transmutation and depletion, using traditional nuclear material accounting methods with material balance evaluations is challenging. In reactors with changing inventories, these expected quantities of SNM must be calculated based on operational parameters. Reducing uncertainties on these expected quantities is challenging in the case of MSRs without decades of operational experience to verify and validate predictive computational codes. Moreover, many areas in MSRs are inaccessible because of high-temperature and high-radiation environments, making measurements challenging.

A previous effort addressed these concerns by providing several recommendations to MSR developers. A primary recommendation was reliance on material control around a material balance area (MBA) encompassing the reactor (and material accounting with periodic inventories in other MBAs). This approach is consistent with the MC&A approach in light-water reactors. This study has expanded on these previous recommendations in four key areas for MC&A in MSRs: (1) identifying the locations for deploying nuclear material control elements, such as tamper-safing and surveillance, at the boundaries of the high-temperature and high-radiation areas; (2) identifying the material control elements that can be applied at these locations to monitor SNM movements; (3) identifying potential areas of holdup in the facility; and (4) characterizing these holdup areas with respect to the type of nuclear material (irradiated or unirradiated), measurement frequency, and measurement environment.

For material control, this study recommends a control boundary around the reactor system to enable detection of all material movements entering and exiting the area. This boundary should follow a physical boundary surrounding the reactor system to restrict physical access. The control boundary penetrations, such as piping connections, hatch(es), and sampling line(s), have been categorized as (1) SNM transfer pathways into or out of the control boundary (e.g., the feed line) and (2) non-SNM transfer pathways into or out of the boundary (e.g., the cover gas line). These penetrations must be monitored using control elements to ensure that these pathways are not used to steal SNM. Hence, an assessment of control elements to monitor SNM movements through these identified penetrations was conducted, and the results are presented considering different types of SNM movements.

The SNM entering and leaving the control boundary should be monitored. For bulk SNM transfer (batch or continuous) into and out of the control boundary, nontraditional control elements, such as flow, radiation detection, level, or weighing measurements, should be used at each SNM transfer pathway. These in situ monitoring elements must be capable of measuring the total mass of SNM transferred across the control boundary with sufficient accuracy to meet NRC accountancy requirements. For situations with SNM transfers in item form (e.g., as discrete containers), such items should be measured and characterized prior to introducing to or retrieving from the control boundary. Access to the control boundary should be monitored using an electronic seal and a surveillance system, which provide independent evidence of the access and by whom. Additionally, surveillance measures are required to monitor the movement of measured and characterized fuel containers outside the control boundary.

Elements of a traditional physical protection system (e.g., cameras, access restriction) may be proposed by a license applicant as material control elements within their MC&A plan to meet specific MC&A objectives of detecting any theft of SNM. These physical protection system elements have traditionally not been included in MC&A programs but may be leveraged in a risk-informed, objective-based approach to MC&A in novel facility types, such as MSRs with SNM in bulk form.

Depending upon the MSR design and operational characteristics, some of the penetrations (non-SNM penetrations), where SNM movement is not usually anticipated, may not require any control elements. However, control elements should be considered for penetrations in which the design does not absolutely preclude the introduction or removal of SNM. If a credible scenario exists for SNM to be removed through a penetration point, even if not intended or designed for use with SNM, MC&A elements should be identified to prevent or detect removal of SNM through that location. Traditional control elements should be applicable to penetrations with item transfers but may not be applicable for bulk material transfers.

Another technical challenge for MSRs related to MC&A will be quantifying or estimating residual SNM remained in equipment, piping, and containers after these areas have been prepared for inventory. This residual nuclear material, or holdup, is a challenge in existing bulk facilities, such as fuel fabrication and enrichment plants. MSR license applicants will need to address holdup in their MC&A plan to ensure that SNM theft is not concealed through the uncertainty in the holdup measurement. To identify and characterize potential holdup areas, diverse MSR designs were categorized into three groups in this study based on their fuel salt flow paths and system component. Holdup areas in each of these groups were identified, such as the reactor primary system and chemical control and off-gas systems. Additionally, these areas were characterized by detailing the type and form of the SNM, the measurement frequency, and the measurement environment. Moreover, possible schematics of individual systems or components were assessed for further characterizing the identified holdup areas, including presenting use cases of holdup experience gained in uranium and plutonium processing facilities.

This study recommends the following to prepare MC&A plan by MSR license applicants:

- Consider the extent of the control boundary around the reactor system, including the pros and cons of handling SNM transfers as bulk material or in item form.
- Consider appropriate design choices to limit the need for control elements, such as
    - minimizing control boundary penetrations,
    - using design options that preclude the introduction of fertile material into or withdrawal of SNM through non-SNM penetrations, and
    - planning robust physical boundaries that align with the identified control boundary to the greatest extent possible.
- Identify control elements applicable for monitoring each penetration for which the presence of SNM cannot be precluded.
- Consider appropriate design choices to minimize the holdup of SNM, including
    - choosing long-lifespan components to limit replacement,
    - limiting the number of bends and reducing thermal gradients in connection piping, and
    - selecting component material such that settled or reacted deposits can be easily removed during flushing of the primary system.

Building on this effort, future work will focus on identifying specific material control elements and assessing each element's performance for various SNM theft scenarios. A review will be undertaken to identify nontraditional control elements (e.g., radiation detectors, flow meters, level sensors, weighing scales) and any other suitable elements outside of conventional tamper-safing solutions. Lastly, a performance assessment of these control elements will be conducted to evaluate their effectiveness to detect the removal of SNM from inside a control boundary.

In the area of SNM holdup measurements, future work will assess the current capabilities of measurement systems to operate effectively in harsh high-radiation and high-temperature environments. This future investigation will enable the determination of R&D needs and propose measurement strategies for holdup quantification, which will be crucial to provide assurance that all nuclear material is accounted for during operation, equipment or component replacement, and at the end of the reactor's design life. Overall, these planned efforts will provide further guidance for developing an effective MC&A plan for MSRs.

1. INTRODUCTION

A non–light-water reactor (LWR) applicant to the US Nuclear Regulatory Commission (NRC) must provide information in its application about the material control and accounting (MC&A) program to meet the requirements of 10 *US Code of Federal Regulations* (CFR) Part 74, "Material Control and Accounting of Special Nuclear Material" [1]. The liquid-fueled molten salt reactor (MSR) with circulating fuel[1] is a non-LWR in which such a requirement on MC&A by NRC is applicable.

For MC&A purposes, MSRs will be categorized as bulk nuclear material facilities because they handle special nuclear material (SNM) in bulk form and not in the form of discrete items that can be easily counted. Traditionally, bulk facilities, such as uranium enrichment and fuel fabrication plants [2, 3], have previously submitted MC&A plans to the NRC in the form of a Fundamental Nuclear Material Control plan and have relied heavily on nuclear material accounting to detect the theft of SNM from their facility. However, material accounting in nuclear reactors, such as MSRs, is inherently more challenging because quantities of SNM can rapidly change due to transmutation and depletion. Moreover, quantifying SNM in MSRs is difficult because of the use of bulk fuel and because many areas in this facility are inaccessible owing to high-radiation and high-temperature environments. Additionally, to detect the theft of nuclear material, measured quantities must be compared with expected quantities of SNM to identify the difference. In reactors with changing inventories, these expected quantities must be calculated based on operational parameters. Reducing uncertainties on these expected quantities is challenging without decades of operational experience to verify and validate predictive computational codes.

Previous work by Hogue et al. [4] addressed these concerns by providing recommendations on an MC&A plan for MSR designers that are planning to submit a license application to the NRC [5, 6]. One of the recommendations was a three–material balance area (MBA) structure for MC&A in MSRs, as shown in Figure 1. Alternatively, each of the MBAs in Figure 1 could be a sub-MBA within a single MBA. To ensure that all SNM is accounted for, the previous study recommended that the MC&A plan rely heavily on material accounting with periodic inventories for MBA 1 and MBA 3 and leveraging primarily material control for MBA 2, which is the high-temperature and high-radiation area housing the reactor system.

[1] All instances of MSRs in this document refer to liquid-fueled MSRs with circulating fuel.

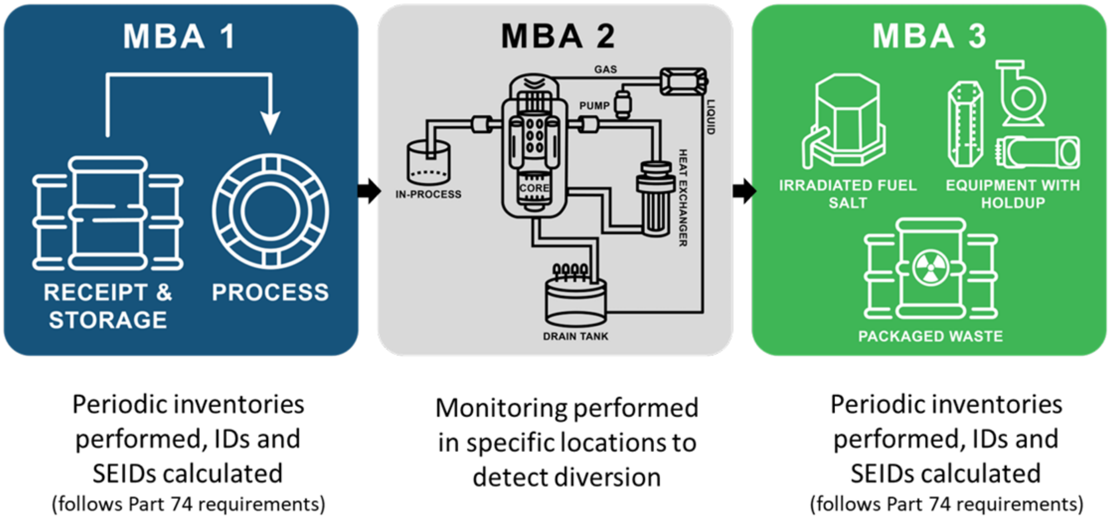


Figure 1. A proposed three-MBA structure for an MSR. Image reproduced from [4] with permission from ORNL.

Because no established NRC guidance exists to help develop an MC&A plan for an MSR, previous work proposed a methodology to develop an MC&A plan and emphasized the need for close coordination with the NRC. This proposed methodology focused on

- developing a process flow diagram to identify and track MC&A relevant parameters, with specific parameters defined (e.g., fuel salt temperature, reactor power);
- identifying MC&A objectives aimed at preventing and detecting theft of SNM; and
- determining practical MC&A measures necessary to achieve the objectives of preventing and detecting theft (e.g., measurement systems, sensors, tamper-safing methods, surveillance methods, extended surveillance or monitoring elements, and administrative controls).

The research presented here builds on the recommendations from previous work and focused on four major tasks [7]: (1) identifying the locations for deploying nuclear material control elements, such as tamper-safing and surveillance, at the boundaries of the high-temperature and high-radiation areas; (2) identifying the material control elements that can be applied at these locations to monitor SNM movements; (3) identifying potential areas of holdup[2] in the facility; and (4) characterizing these holdup areas with respect to the type of nuclear material (irradiated or unirradiated), measurement frequency, and measurement environment.

These four tasks were undertaken with the goal of providing assurance that SNM has not been removed from an MSR while considering the material accounting challenges in MBA 2 described earlier. To this end, MC&A plans for MSRs may need to include control elements to meet the NRC safeguards goal of preventing and detecting the theft of SNM. Material control elements could include tamper-safing (e.g., seals or other tamper-indicating devices [TIDs]) to detect unauthorized access into the control boundary, surveillance (e.g., cameras) to monitor whether planned access is consistent with anticipated operations, and nontraditional surveillance (e.g., flow measurements) to monitor for the theft of SNM from identified pathways.

[2] The NRC defines *holdup* as the inventory component remaining in and about process equipment and handling areas after those collection areas have been prepared for inventory [8, 9].

Material accounting in an MSR will require estimation of SNM quantities within holdup in the reactor and supporting systems, especially when used reactor components are removed from the system at their end of life. Some components may need to be replaced at time periods that are shorter than the life of the facility (e.g., graphite in thermal MSRs). In MSRs, SNM is mixed with fluoride- or chloride-based salt in a salt eutectic referred to as *fuel salt*. This fuel salt is in liquid form and freely circulates within the piping and equipment of the reactor system. During this continuous circulation, fuel salt may react chemically with inner surfaces of the system to settle or deposit, which leads to holdup of SNM. In some MSRs, with the circulating fuel salt containing SNM on the order of 10,000 kg or more, there is a potential for holdup in components. This holdup needs to be quantified for material accounting, especially when these components are removed from the control boundary. The theft of SNM may not be detected if the quantity removed is within the uncertainty of the holdup measurement and is not detected by other security measures. Additionally, unaccounted holdup in a system or equipment raises the risk of criticality, radiation exposure to the plant personnel, and a shorter lifespan of equipment retaining SNM. Overall, SNM holdup must be identified, quantified, and controlled in reactor system components to ensure safe operation and prevent and detect theft.

Section 2 presents the results on identifying both the locations for deploying control elements and suitable elements at these locations for performing nuclear material control. Results on identifying and characterizing potential areas of SNM holdup within high-temperature and high-radiation areas of MSRs are presented in Section 3. Conclusions of the study are presented in Section 4, along with the recommendations for MSR license applicants to develop an MC&A plan. This section also outlines future work.

2. MATERIAL CONTROL

Control elements are expected to be used for monitoring a "control boundary" around the reactor system (i.e., around MBA 2), within which material is primarily inaccessible for traditional material inventory because of the harsh high-radiation and high-temperature environments. In this effort, the *control boundary* is defined as a delineation around the reactor system that is controlled to detect and account for all material movements entering and exiting the area. The control boundary should follow, if possible, a physical boundary (such as the biological shielding) surrounding the reactor system to restrict physical access. In some areas, however, the control boundary may deviate from the physical boundary to better align with an MBA or sub-MBA. The control boundary must be monitored using control elements at all locations where SNM could be physically accessed to detect material movement across it. All SNM must be accounted for when crossing the control boundary and documented for reporting to the NRC (i.e., if it is an MBA) or for internal recordkeeping (i.e., if it is a sub-MBA). License applicants developing an MC&A plan or program will need to determine their proposed control boundary and the control elements necessary to monitor it. This study considered expected NRC requirements but did not address international safeguards considerations, which may affect the control boundary approach and associated control elements.

The use of material control for MSRs is expected to be like other reactor types such as LWRs, in which SNM is not quantified through measurements while in a sealed reactor pressure vessel. Unlike LWRs, however, identifying control elements for MSRs is much more challenging because MSRs are reactors with bulk material, and numerous penetrations through the control boundary exist that offer pathways for SNM to be removed from the reactor system. These unique challenges require nontraditional control elements for MC&A compared with what is typically seen in other NRC-licensed facilities. For example, control elements in an MSR may include additional sensors such as flow meters, radiation detectors, weighing scales, and level sensors in addition to more traditional NRC tamper-safing elements such as TIDs.

To understand the type of material control elements needed, this study identified control boundary penetrations that may be required in MSR designs. These penetrations (identified as the locations for deploying nuclear material control elements), shown in Figure 2, include piping connections, hatch or door openings, and exhaust systems. These penetrations are of two kinds: (1) for SNM transfer and (2) non-SNM transfer. SNM penetrations are for transferring materials containing SNM, which may include a fuel salt feed line for initial and makeup fuel salts, a fuel salt removal line for removing or processing irradiated fuel salt, and a sampling line. Non-SNM penetrations are not expected to transfer materials containing SNM; examples include coolant lines to and from the heat exchanger (HX), a cover gas line, an off-gas exhaust line for purging fission gas products, and a hatch to support maintenance activities.

The control boundary is along the penetration between the feed, irradiated fuel or waste, and sampling stations and the reactor, as shown in Figure 2. These penetrations (see Figure 2) must be considered in the development of an MC&A plan to identify the control elements necessary to ensure that these pathways are not used to steal SNM from within the defined control boundary. The selection of a control boundary and associated facility design will have a significant effect on the control elements necessary for monitoring this boundary. In some cases, the introduction of fertile material into or withdrawal of SNM from the non-SNM penetrations can be precluded through facility design characteristics, and this possibility could be credited in the MC&A plan as justification showing that the penetration is controlled.

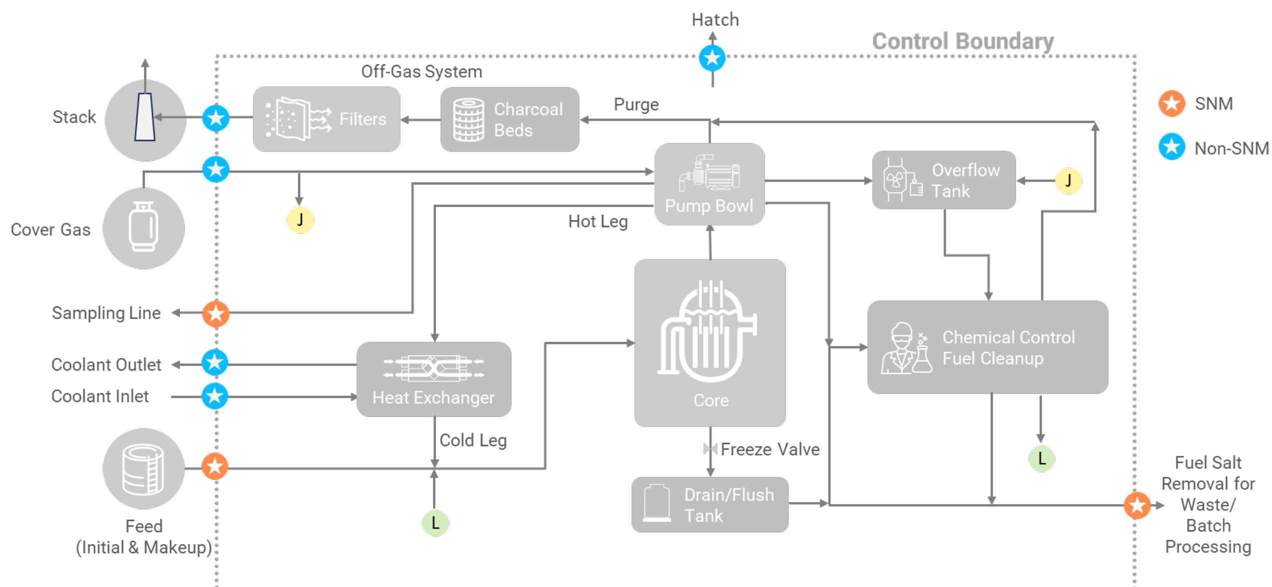


Figure 2. Control boundary penetrations (identified as the locations for deploying nuclear material control elements) in an MSR that must be monitored or secured against theft, including those intended for SNM and non-SNM movements.

2.1 SNM PENETRATIONS

For penetrations intended to transfer bulk SNM (feed, irradiated fuel/waste, sampling), material would need to be accounted for using nontraditional control elements as the material crosses the control boundary. For example, in a feed system, the control boundary would be set at the feed pipe, where the fuel salt would be accounted for as it moves between the feed loading station (MBA 1) and the reactor core (MBA 2). The transfer of SNM can be accounted for using in situ measurements, such as flow, at each SNM transfer pathway. These in situ monitoring elements must be capable of measuring the total mass of SNM transferred across the control boundary with sufficient accuracy to meet NRC accountancy requirements. This approach has the advantage of facilitating easier access to the transfer stations because they are outside the control boundary. MC&A approaches for feed monitoring have been separately investigated [10]. For situations with SNM transfers in item form (e.g., as discrete containers), such items should be measured and characterized prior to introducing to or retrieving from the control boundary.

Because of the extreme challenges of inventorying SNM inside the control boundary, control elements with appropriate redundancy should be implemented instead of material accounting inside the control boundary. This implementation is consistent with the NRC guideline to use redundant, independent, and diverse systems and components to ensure their reliability and availability. For example, during operation, the hatch can be monitored by deploying two different types of TIDs, such as pressure-sensitive and fiber-optic seals, providing redundancy for material control. Alternatively, a surveillance camera and a TID could be deployed for detecting any attempt of theft. Overall, access to the control boundary should be monitored using an electronic seal and a surveillance system, which provide independent evidence of the access and by whom. Lastly, surveillance measures are required to monitor the movement of measured and characterized fuel containers outside the control boundary.

The elements of a traditional physical protection system (e.g., cameras, access restriction) may be advantageously utilized by a license applicant as control elements within their MC&A plan to meet specific MC&A objectives. These physical protection system elements have traditionally not been included in MC&A programs but may be leveraged in a risk-informed, objective-based approach to MC&A in novel facility types, such as MSRs.

2.2 NON-SNM PENETRATIONS

Depending upon the MSR design and operational characteristics, some of the penetrations (non-SNM penetrations), where SNM movement is not usually anticipated, may not require any control elements. However, control elements should be considered for penetrations in which the design does not absolutely preclude the introduction or removal of SNM. For example, the off-gas line going to the stack may be precluded from having SNM because of the filtration on this line inside the control boundary, which would capture any SNM contaminants. In such a scenario, the off-gas penetration may not require any control elements. Theft through each penetration, including the waste stream, should be assessed for credibility. If a transfer pathway is determined to be credible, an MC&A plan should include control elements or measurements to detect theft through that penetration. Additionally, it is necessary to measure wastes (e.g., filters), which may contain SNM, to accurately quantify the material for accounting purposes beyond just implementing control elements. Traditional control elements should be applicable to penetrations with item transfers but may not be applicable for bulk material transfers.

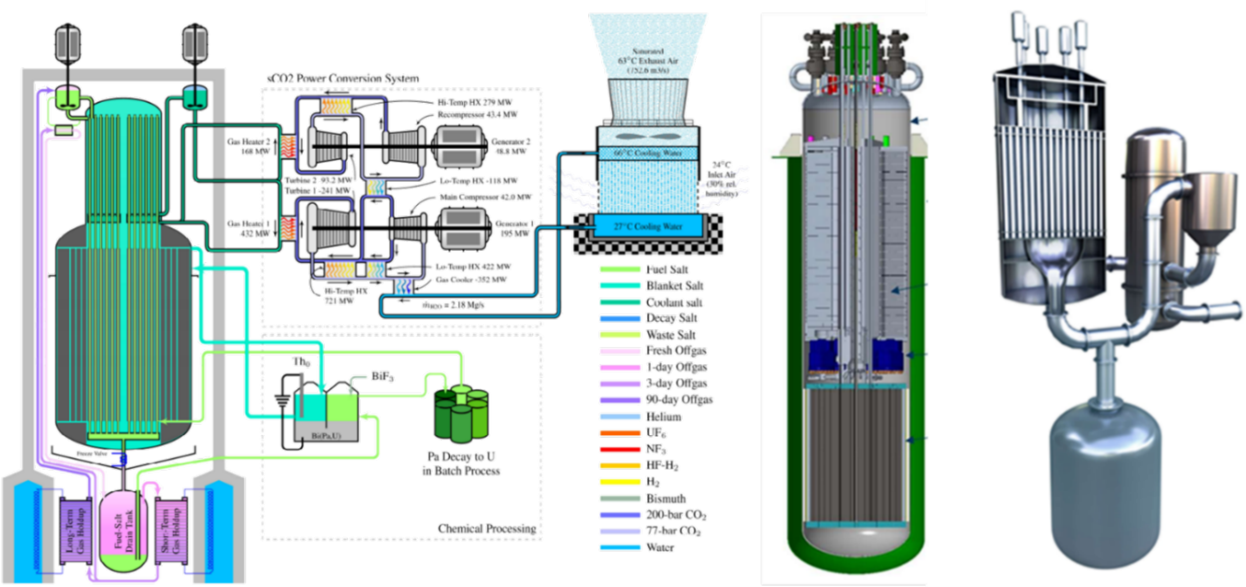
3. HOLDUP

During MSR operation, some nuclear material within the fuel salt may settle or deposit in pipes, valves, pumps or motors, the HX, the off-gas treatment system, storage tanks, and at various locations within the fuel cleanup system. Various phenomena occurring during reactor operations lead to settling or deposition, including the entrapment of nuclear material in fission product gases and the transfer of nuclear material to an off-gas treatment system, which is unique to MSR designs. The deposition of nuclear materials within reactor system components leads to holdup and needs to be quantified through measurements. Holdup in an MSR system raises certain challenges and concerns, which are (1) safety concerns for the plant personnel and public because of potential criticality issues and radiation exposure and (2) security threats because theft of nuclear material may go undetected if the quantity stolen is within the uncertainty of the holdup measurement and is not detected by other security measures.

To identify potential holdup areas, MSR designs were categorized into three groups based on their design characteristics and operational activities:

- Group 1—Designs with makeup fuel salt and online fuel cleanup, such as TerraPower's molten chloride fast reactor (MCFR) [11] and Flibe Energy's lithium fluoride thorium reactor (LFTR) [12].
- Group 2—Designs with makeup fuel salt but without online fuel cleanup, such as Terrestrial Energy's Integrated MSR (IMSR-400) [12].
- Group 3—Designs without makeup fuel salt or online refueling. Presently, based on the available information, no US-based design falls within this group. However, the group includes non-US designs, such as Thorizon's reactor [12] and Seaborg Technologies' compact MSR [12].

Figure 3 shows an MSR design layout from each group [12]. Despite the differences between these groups, every MSR design is anticipated to include systems for chemical control and off-gas treatment as remedial measures against corrosion, redox reactions, gaseous fission product buildup, and contamination. Because the Group 1 MSR designs contain diverse systems and components, its analysis for potential areas of SNM holdup presented in this report (Section 3.1.3) is comprehensive enough to cover the reactor systems in Groups 2 and 3.



Group 1: LFTR **Group 2: IMSR-400** **Group 3: CMSR**

Figure 3. An example of an MSR design from each of the three groups, where the categorization into three groups aims to identify potential SNM holdup areas. [12] Advances in Small Modular Reactor Technology Developments: A Supplement to: IAEA Advanced Reactors Information System (ARIS) © IAEA, 2022 https://aris.iaea.org/publications/SMR_booklet_2022.pdf.

3.1 GROUP 1 MSR DESIGNS

3.1.1 Reactor Operation Overview

A general understanding of MSR designs and operational characteristics is necessary to determine the potential areas of SNM holdup. These characteristics include the movements of SNM within the facility and reactor systems. Although diverse designs are within each group, the MCFR design under Group 1 was employed as a reference MSR in this study to provide a fundamental understanding of SNM movement and operation. An MCFR design available in open literature is a large nuclear power plant with a rated power of 800 MWe. This MCFR is a fast-neutron spectrum reactor and is planned for commercial deployment in the mid-2030s. It uses a uranium–plutonium fuel cycle [13–15].

Notable design information, including an online fuel salt polishing system, of the MCFR is as follows:

- The initial core loading uses high-assay, low-enriched uranium as fresh fuel salt in quantities that qualify as Category II SNM [16].

- The makeup fuel salt, consisting of depleted; natural; or high-assay, low-enriched uranium, is added online to replenish for fissile material depletion. Conversion of ^{238}U to ^{239}Pu also replenishes the fissile material depletion during reactor operation.

- The fuel salt flows from the reactor core through the primary HX, which may be physically located outside the core, and the salt circulates back to the core.

- Mechanical filters apart from the off-gas system are employed to remove impurities of insoluble fission products and noble metals.

MSR designs in Group 1 are expected to have a longer core life than those in the other two groups because of the use of online fuel cleanup and makeup for fissile material depletion. In these designs, the initial core loading, including makeup fuel, may involve melting solid fuel (e.g., in a feed tank) and transferring it into the core via a feed line. The overflow tank will collect excess fuel salt, whereas the drain tank will collect the drained fuel salt. Fuel in these drain and overflow tanks might be relocated to a transportable tank or canister for transportation off-site for recycling or permanent disposal. MSR designs could exist in which the drain tank also serves as the overflow tank. A small fraction of the fuel salt in the reactor core is expected to circulate through the off-gas and online fuel cleanup system, which contains mechanical filters. These filters, which trap insoluble fission products and noble metals, would be located outside the reactor vessel but will remain inaccessible to humans during normal operation. These filters will be replaced routinely during maintenance.

3.1.2 Holdup Identification and Characterization

Potential areas of holdup in the case MSR designs in Group 1 [12, 13] are marked in Figure 4. These areas include

- the reactor system, consisting of the core, HXs (fuel-side), pumps, and associated equipment or pipe connections, and

- the chemical control, off-gas, and fuel cleanup systems and associated equipment or pipe connections.

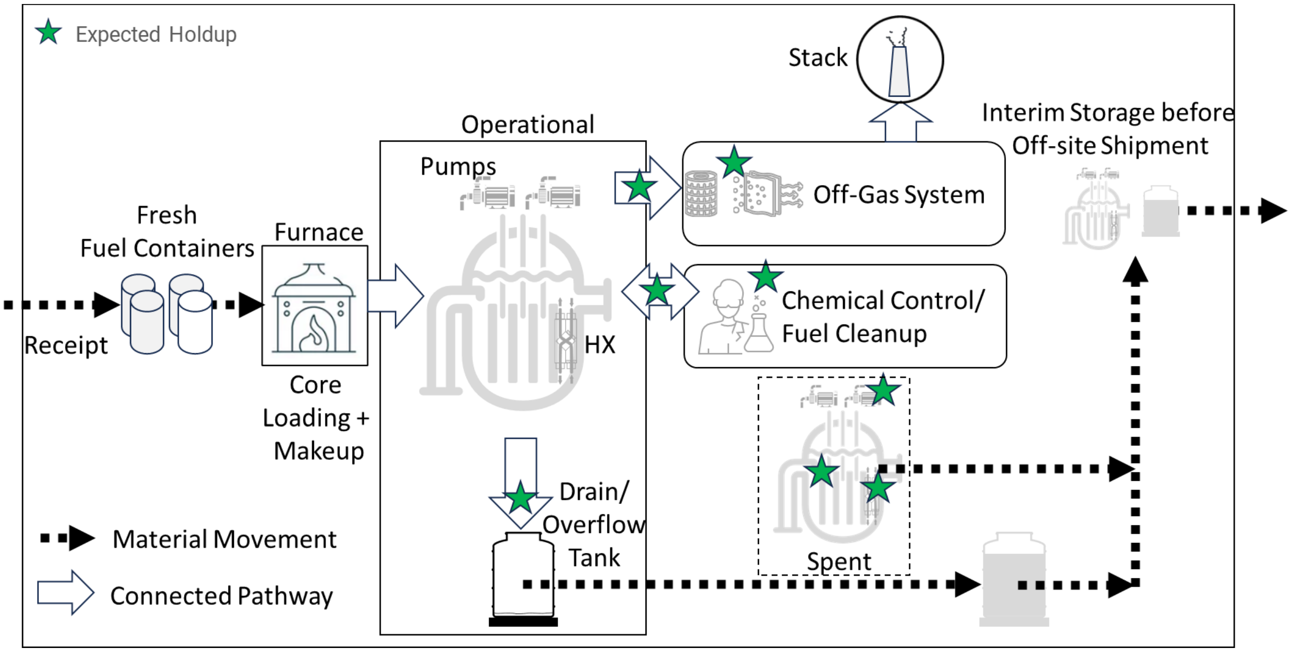


Figure 4. Potential SNM holdup areas in designs under Group 1 MSRs.

Each potential area for SNM holdup should be characterized by detailing the type and form of the material, the measurement frequency, and the measurement environment, such as radiation levels (see Table 1). SNM holdup in the reactor system will generally be quantified at the end of its design life, whereas holdup in other systems (e.g., off-gas) may be quantified during maintenance or component replacement.

All the identified areas for holdup (see Figure 4) are characterized as very high-radiation areas except for the fresh fuel containers and feed tank system, which may be characterized as radiation areas (>0.05 mSv/h at 30 cm) [17] assuming the fuel uses unirradiated uranium. The reason for defining most areas as very high-radiation is based on experience from the Molten Salt Reactor Experiment (MSRE). For example, in 1985, radiation exposure rates in the reactor vessel of the MSRE, which operated between 8 and 10 MWt, were measured to be approximately 22 Gy/h primarily because of the contributions of ^{60}Co [18]. After decay correction for ^{60}Co, the estimated exposure rates shortly after flushing and 5 years later were 200 Gy/h and 100 Gy/h, respectively. Scaling the MSRE's thermal power by 30 times to represent a commercial power level, the exposure rate would be approximately 10^3 Gy/h. This exposure level is equivalent to a gamma dose rate of 10^3 Sv/h, which is a very high-radiation area (≥5 Sv/h at 1 m for gamma radiation) [17]. This radiation environment influences the time that systems and components must be cooled down after the fuel salt is flushed or emptied. The environment will also govern the design of detector systems, including shielding, collimation, and standoff distance, framing the measurement strategy.

Additionally, emptied fresh fuel containers, drain or overflow tanks, the feed tank, and associated connections will likely have residual material remaining in them, such as the heels found in UF_6 cylinders [17]. Residual SNM material leaving the control boundary will also need to be measured and accounted for.

Table 1. Characterizing potential SNM holdup/residual areas in designs under Group 1 MSRs

Holdup/residual areas	Nuclear material	Measurement frequency	Measurement environment+
Chemical control system	Irradiated nuclear material	During maintenance or component replacement	Very high-radiation area
Drain/overflow tank*	Irradiated nuclear material	During removal of drain/overflow tank (at the end of their design lifespan)	Very high-radiation area
Fuel cleanup system	Irradiated nuclear material	During maintenance or component replacement	Very high-radiation area
Feed tank and associated connections*	Unirradiated nuclear material	During maintenance or component replacement	Radiation area
Fresh fuel containers*	Unirradiated nuclear material	After initial core loading and every inventory period	Radiation area
Off-gas system	Irradiated nuclear material	During maintenance or component replacement	Very high-radiation area
Pipes (e.g., connections between various systems/ components)	Irradiated nuclear material	During maintenance or component replacement	Very high-radiation area
Reactor primary system:			
Core	Irradiated nuclear material	After their design lifespan	Very high-radiation area
Graphite	Irradiated nuclear material	After their design lifespan	Very high-radiation area
HXs (fuel-side)	Irradiated nuclear material	After their design lifespan	Very high-radiation area
Pumps and associated connections	Irradiated nuclear material	After their design lifespan	Very high-radiation area
Reactor core	Irradiated nuclear material	After their design lifespan	Very high-radiation area

+ Considers fuel cycle uses an unirradiated uranium
* Indicates residual material such as heels found in UF_6 cylinders

3.1.3 Reactor Systems

Possible schematics of individual reactor systems or components under Group 1 MSR designs are discussed herein for further characterizing the identified holdup areas. For each system, schematics containing possible components are explored, and associated use cases based on the holdup experience gained in uranium and plutonium processing facilities, if any, from reference [19] are presented. The expected holdup experience from these facilities is in much different operating conditions (such as temperature, composition, and flow rate) than in MSRs. A separate effort is required to estimate holdup in MSR facilities. Note that these diverse systems and components cover the systems expected in Groups 2 and 3 MSR designs.

3.1.3.1 Chemical Control System

The chemical control system is primarily used to monitor and control chemistry of the fuel salt and, in turn, corrosion of pipes and vessels. Main chemistry control is carried out by oxidizing impurities. Such a system is expected to house electrodes for monitoring and facilitating redox reactions. The system will also contain strainers or filters to collect corrosion products. For redox reactions, instead of electrodes, reagents with a positive oxidation state can be added, such as beryllium. Figure 5 shows a simplified schematic of a possible chemical control system and highlights both redox reaction approaches.

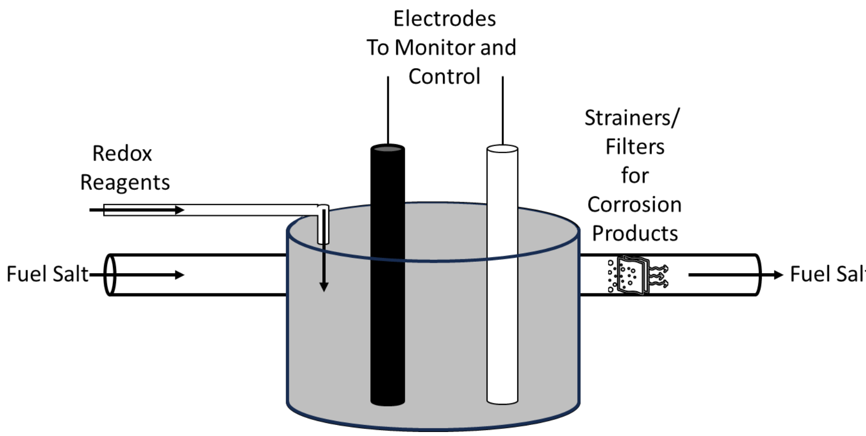


Figure 5. Schematic of a possible chemical control system.

In such a system, the tank, electrodes, filters, and connecting pipes are specific locations where holdup can occur. The tank in this study's case is similar to the use case of an equipment interior (after routine cleaning), which is expected to have holdup of 10–50 g/m^2 of the facility material under process [19]. The use case of a final filter and a pipe (after destructive cleaning) are expected to retain holdup of approximately 10–100 g and 0.3 g/m of the facility material under process [19], respectively.

3.1.3.2 Drain and Overflow Tanks and Fresh Fuel Containers

The drain and overflow tanks as well as fresh fuel containers are essentially cylindrical tanks that will retain residual SNM after being emptied, which needs to be accounted for. These tanks in this study's case are similar to the use case of an equipment interior (after routine cleaning), which is expected to have holdup of 10–50 g/m^2 of the facility material under process [19]. Alternatively, drain and overflow tanks with annular designs are similar to the use case of an annular tank, which is expected to have a holdup of 1–10 g of the facility material under process [19].

3.1.3.3 Fuel Cleanup System

Many MSR designs propose inclusion of a fuel cleanup system to improve chemical properties of fuel as well as to remove some fission products. All MSR designs will likely include off-gas systems to vent volatile fission products, but only some MSR designs include additional components to further remove a select set of fission products through mechanical filtration or chemical treatment. These additional components are referred to here as the *fuel cleanup system*. Figure 6 shows a simplified schematic of such a system, which is expected to consist of

- a chemical treatment system for the extraction of oxides,
- trapping and filters for purification, and
- fuel heating and mixing for improving fuel concentration.

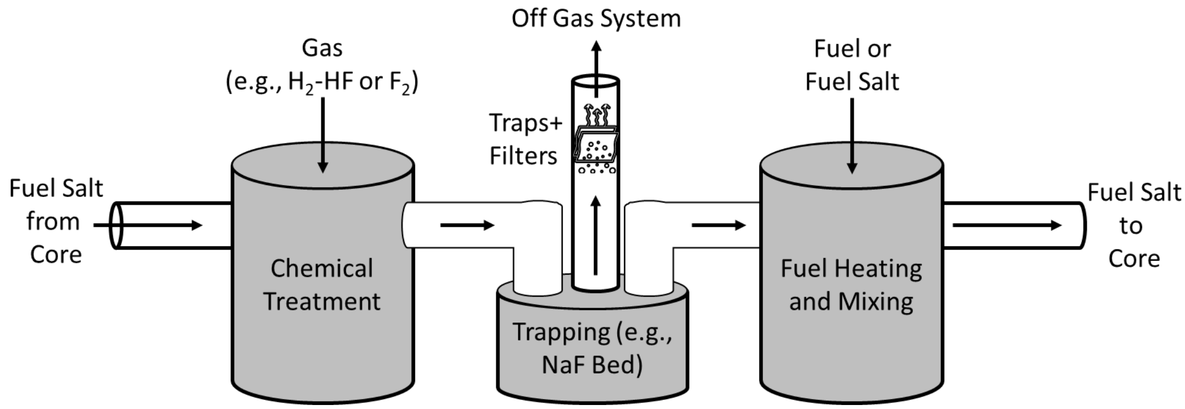


Figure 6. Schematic of a possible fuel cleanup system.

The chemical treatment and trapping and filters in combination can serve a similar function as the chemical control system, which may be kept distinct to extend the lifespan of both systems. The chemical treatment and fuel heating and mixing in this study's case are similar to an equipment interior (after routine cleaning), which is expected to have holdup of 10–50 g/m^2 of the facility material under process [19]. The trapping and filters in this study's case signify the use cases of glovebox prefilters and final filters, which are expected to have a holdup of 2–100 g and 10–100 g, respectively, of the facility material under process [19]. The connecting pipes in this case are similar to the use case of pipes (after destructive cleaning), which is expected to have a holdup of approximately 0.3 g/m of the facility material under process [19].

3.1.3.4 Feed Tank and Associated Connections

The feed tank is expected to retain residual SNM after feeding the reactor core with the initial fuel salt and, subsequently, makeup fuel salt. The feed tank in this study's case is similar to the use case of an equipment interior (after routine cleaning), which is expected to have holdup of 10–50 g/m^2 of the facility material under process [19]. The associated connections in this case are similar to the use case of pipes (after destructive cleaning), which is expected to have a holdup of approximately 0.3 g/m of the facility material under process [19].

3.1.3.5 Off-Gas System

The off-gas system's primary role is to remove volatile and gaseous fission products. However, SNM and other fission products could be transported out to the off-gas system as aerosols entrapped in fission product and other noble gases. These materials should be collected in entrapments, such as scrubbers and filters, which are of interest for holdup measurement. Figure 7 shows a simplified schematic of a possible off-gas system, which is expected to consist of a scrubber to collect aerosols, traps for specific elements, an activated charcoal bed for decay, filters to collect volatile fission products, a stack to vent, and pipes for connecting systems.

Each of these systems—except pipes in this study's case—can be closely represented, for lack of other operational experience, by the use cases of prefilters and final filters used in gloveboxes in a uranium and plutonium processing facility. These prefilters and filters are expected to have holdup of 2–100 g and 10–100 g, respectively [19]. The connecting pipes in this case are similar to the use case of pipes (after destructive cleaning), which is expected to have holdup of approximately 0.3 g/m of the facility material under process [19].

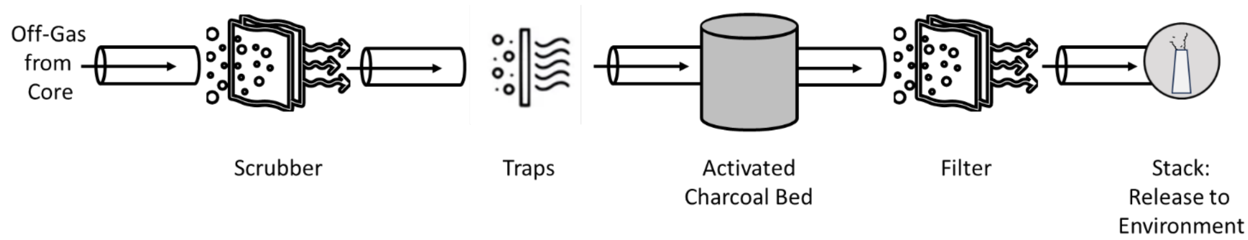


Figure 7. Schematic of a possible off-gas system.

3.1.3.6 Reactor Primary System

The reactor core and the components through which the fuel salt circulates form the reactor's primary system. Figure 8 shows a simplified schematic of a possible reactor primary system, which is expected to consist of

- a reactor core;
- graphite as the moderator in a thermal neutron spectrum reactor;
- motors and pumps to circulate fuel salt, where forced circulation is used compared with natural circulation;
- a steam generator to transfer heat to coolant salt (not containing SNM), which may be inside the reactor vessel; and
- pipes to connect different components.

The reactor core, pumps, motors, and HXs in this case are similar to the use case of an equipment interior (after routine cleaning), which is expected to have holdup of 10–50 g/m^2 of the facility material under process [19]. The connecting pipes in this case are like the use case of pipes (after destructive cleaning), which is expected to have holdup of approximately 0.3 g/m of the facility material under process [19]. For graphite, however, no relevant use case exists for a reference.

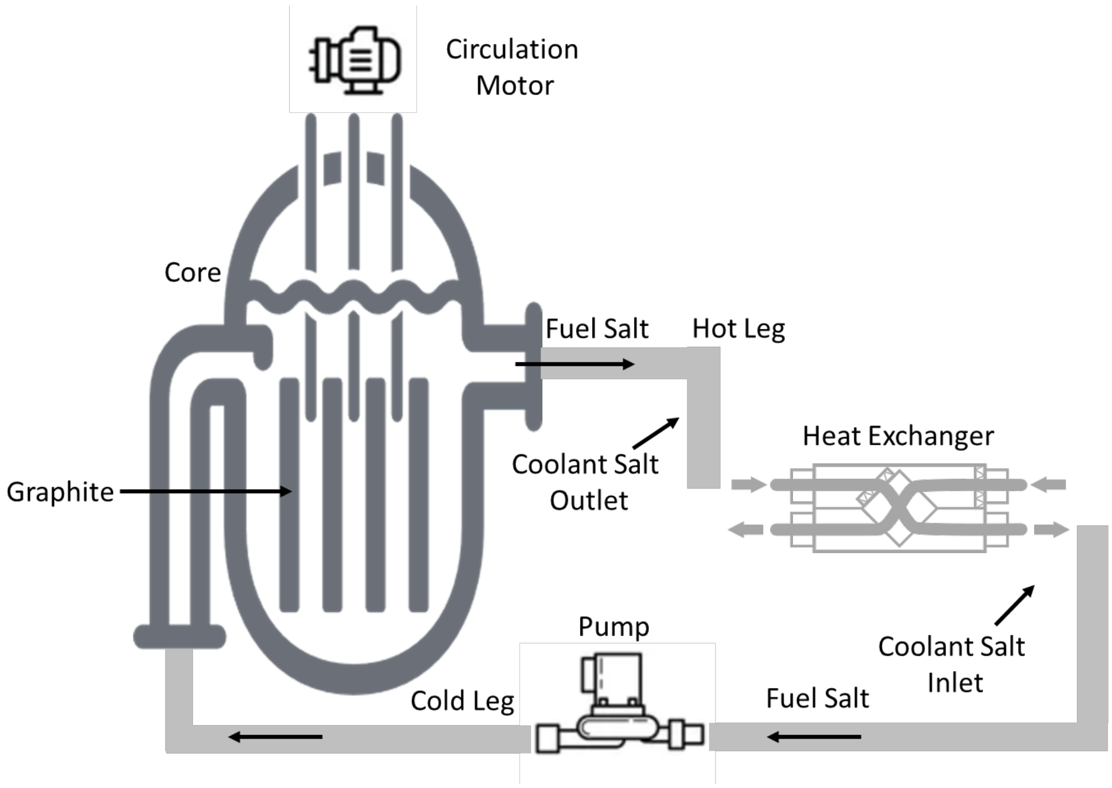


Figure 8. Schematic of a possible reactor primary system.

3.1.3.7 Pipes

Various components and systems in the primary system are connected using pipes, which are subject to holdup. The connecting pipes in this study's case are similar to the use case of pipes (after destructive cleaning), which is expected to have a holdup of approximately 0.3 g/m of the facility material under process [19].

3.2 GROUP 2 MSR DESIGNS

3.2.1 Reactor Operation Overview

Group 2 MSR designs include the provision for makeup fuel salt but do not include any online fuel cleanup. The initial core loading, including makeup, may involve melting the solid fuel in a feed tank—an external tank using a heat source such as a furnace—and fuel salt would be introduced to the reactor system via a feed line. These designs may house HXs within the core unit as integral reactor designs (i.e., designs in which primary components are inside the reactor vessel [12, 20]) [21].

In some Group 2 designs (e.g., IMSR-400), the free volume in the reactor core accommodates the makeup fuel salt. However, other designs may discharge surplus irradiated fuel to an overflow tank over the core life. Plans for surplus or drained irradiated fuel salt include on-site conditioning to stabilize for an interim storage on-site before being shipped off-site. Fuel in these drain and overflow tanks might be relocated to a transportable tank or canister for transportation off-site.

3.2.2 Holdup Identification and Characterization

Figure 9 shows potential holdup areas for MSR designs under Group 2, which include

- the primary system, consisting of the core, HXs (fuel-side), graphite, pumps, and associated connections, and
- the chemical control and off-gas systems (not shown in Figure 9).

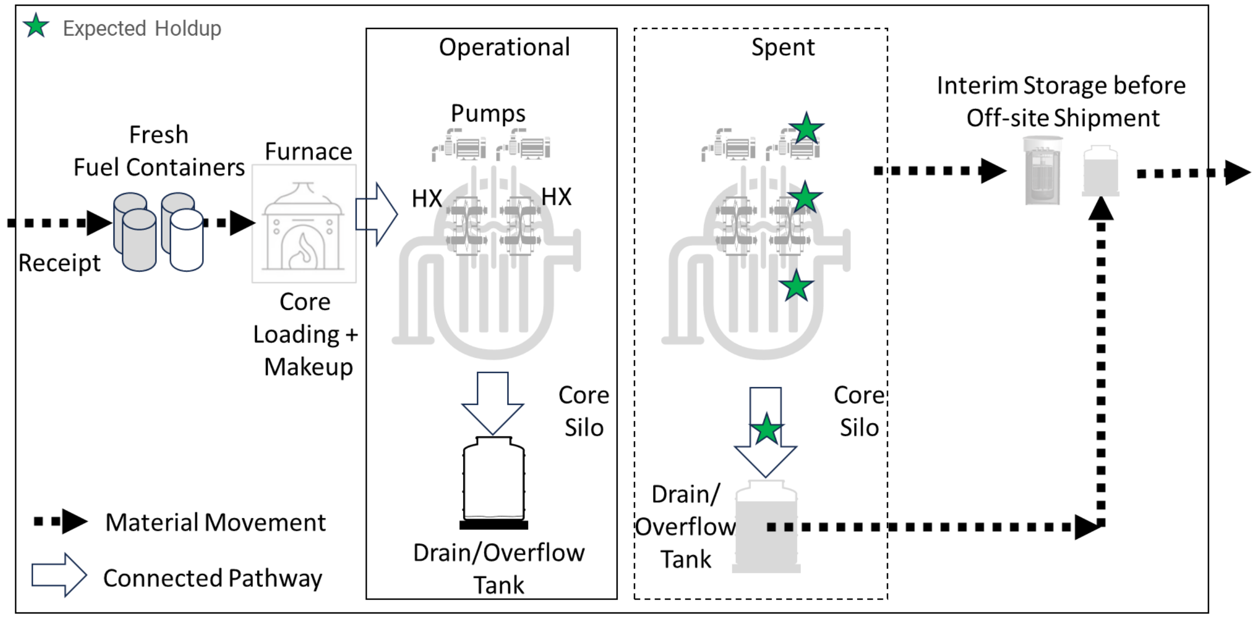


Figure 9. Potential SNM holdup areas in designs under Group 2 MSRs. The chemical control and off-gas systems are not shown.

Table 2 characterizes the identified potential holdup and residual areas, including the nuclear material category, measurement environment, and measurement frequency. All systems will be subjected to irradiated nuclear material except for fresh fuel containers, assuming the fuel uses unirradiated uranium, and the feed tank, which is assumed to handle only unirradiated nuclear material.

The spent core unit will reside in place through an extended cooldown period before being moved to a spent core unit silo. This period has not been determined yet, but considering that the spent core unit will be replaced every 5 to 10 years with a fresh core unit, the holdup measurement will also need to be performed every 5 to 10 years upon replacement.

Additionally, residual SNM quantification will be required for nuclear material remaining in emptied fresh fuel containers, drain or overflow tanks, and feed tanks and associated connections during maintenance, component replacement, or movement of equipment (e.g., drain tank).

Similar to Group 1, most of the holdup areas in Group 2 are characterized as very high-radiation areas except for the fresh fuel containers, feed tank, and associated connections, which may be characterized as radiation areas [17].

Table 2. Characterizing potential SNM holdup/residual areas in designs under Group 2 MSRs

Holdup/residual areas	Nuclear material	Measurement frequency	Measurement environment+
Chemical control system	Irradiated nuclear material	5 to 10 years	Very high-radiation area
Core module			
Graphite	Irradiated nuclear material	5 to 10 years	Very high-radiation area
HXs (fuel-side)	Irradiated nuclear material	5 to 10 years	Very high-radiation area
Pumps and associated connections	Irradiated nuclear material	5 to 10 years	Very high-radiation area
Reactor core	Irradiated nuclear material	5 to 10 years	Very high-radiation area
Drain/overflow tank*	Irradiated nuclear material	During removal of drain/overflow tank (at the end of their design lifespan)	Very high-radiation area
Feed tank and associated connections*	Unirradiated nuclear material	During maintenance or component replacement	Radiation area
Fresh fuel containers*	Unirradiated nuclear material	After initial core loading and every inventory period	Radiation area
Off-gas system	Irradiated nuclear material	Every 5 to 10 years	Very high-radiation area
Pipes (e.g., connections between various systems/components)	Irradiated nuclear material	During replacement of pipes (at the end of their design lifespan)	Very high-radiation area

+ Considers fuel cycle uses an unirradiated uranium
* Indicates residual material such as heels found in UF_6 cylinders

3.3 GROUP 3 MSR DESIGNS

3.3.1 Reactor Operation Overview

Group 3 MSR designs do not include the provision for makeup fuel salt or online refueling. Such designs rely on initial core loading containing excess positive reactivity to offer extended operation. At the end of the core life, fuel salt is emptied into a drain tank for interim storage on-site. The irradiated salt may undergo further conditioning for stabilization before transferring it off-site.

At present, it is uncertain whether the designs under Group 3 will involve melting fuel in an external container before initial loading in the core or if fuel melting will occur within the core itself. In the former approach, the container and associated connections would represent areas where residual nuclear material may remain. For various reasons, including safety and economics, designs under this group are considered to perform the fuel melting process within the core itself.

3.3.2 Holdup Identification and Characterization

Figure 10 shows potential holdup areas for designs in Group 3, which includes the primary system and chemical and off-gas systems. The primary system consists of the core, HXs (fuel-side), pumps, and associated connections. Some designs may incorporate HXs within the core module (e.g., Thorizon), and others may house HXs outside the reactor vessel (e.g., compact MSR). Additionally, the design may maintain separation between the fuel salt and graphite, which is likely achieved by leveraging graphite channels to house graphite. The fuel-side graphite channels in the core are also vulnerable to potential holdup. Similar to other groups, the chemical control and off-gas systems are subject to potential holdup.

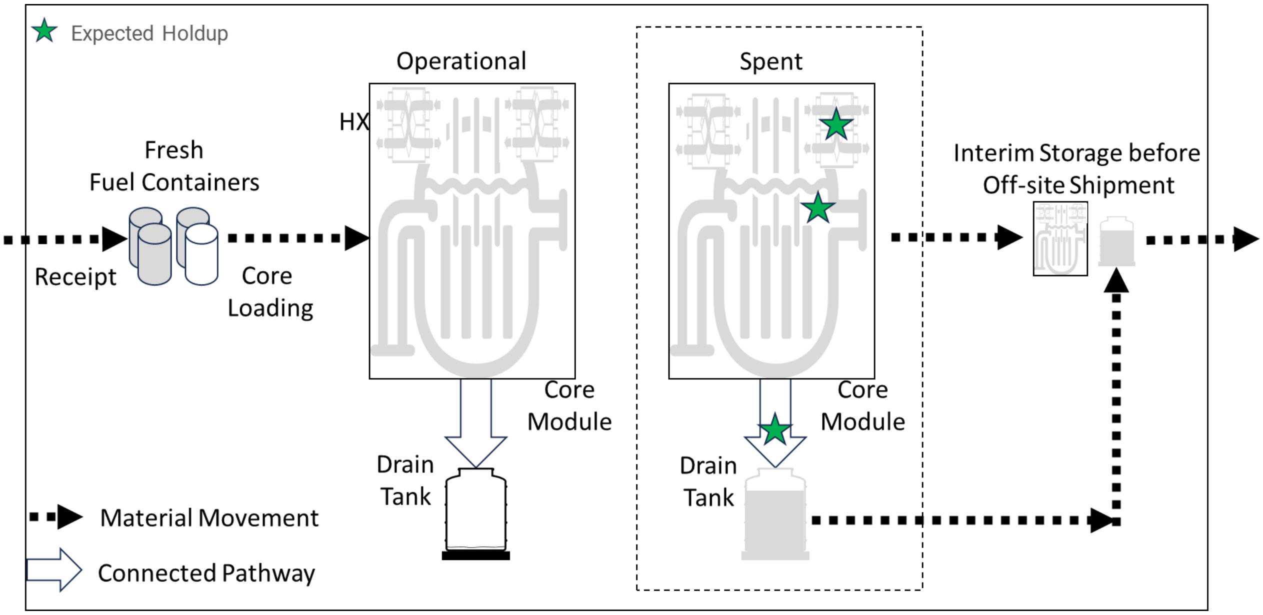


Figure 10. Potential SNM holdup areas in designs under Group 3 MSRs. The chemical control and off-gas systems and HX pumps are not shown.

Table 3 characterizes the identified potential holdup or residual areas, including the nuclear material category, measurement environment, and measurement frequency. All systems will be subjected to irradiated nuclear material except for fresh fuel containers, which handle unirradiated nuclear material assuming the fuel uses unirradiated uranium. Similar to Groups 1 and 2, most of the holdup areas in Group 3 are characterized as very high-radiation areas except for the fresh fuel containers, which may be characterized as radiation areas [17].

Similar to Group 2 MSRs, measurements should be performed at the time of core module switchover in Group 3 MSRs (i.e., every 5 to 10 years). Moreover, residual quantification will be required for the SNM remaining in emptied fresh fuel containers and the drain tank during their movement, component replacement, or the end of their design life.

Table 3. Characterizing potential SNM holdup/residual areas in designs under Group 3 MSRs

Holdup/residual areas	Nuclear material	Measurement frequency	Measurement environment+
Chemical control system	Irradiated nuclear material	5 to 10 years, during core module switchover	High-radiation area
Core module			
Graphite channels (fuel-side)	Irradiated nuclear material	5 to 10 years, during core module switchover	High-radiation area
HXs (fuel-side)	Irradiated nuclear material	5 to 10 years, during core module switchover	High-radiation area
Pumps and associated connections	Irradiated nuclear material	5 to 10 years, during core module switchover	High-radiation area
Reactor core	Irradiated nuclear material	5 to 10 years, during core module switchover	High-radiation area
Drain tank*	Irradiated nuclear material	During removal of drain tank (at the end of their design lifespan)	High-radiation area
Fresh fuel containers*	Unirradiated nuclear material	After initial core loading and every inventory period	Radiation area
Off-gas system	Irradiated nuclear material	5 to 10 years, during core module switchover	High-radiation area
Pipes (e.g., connection between core and drain tank)	Irradiated nuclear material	During replacement of pipes (at the end of their design lifespan)	High-radiation area

+ Considers that fuel cycle uses an unirradiated uranium
* Indicates residual material such as heels found in UF_6 cylinders

4. CONCLUSIONS

The US NRC will likely require license applicants for liquid-fueled MSRs with circulating fuel to submit an MC&A plan or detailed MC&A program description as a part of their application. SNM within circulating fuel in MSRs is in bulk form, whereas it is in item form within discrete fuel assemblies in LWRs. MC&A plans for existing NRC-licensed bulk nuclear material handling facilities, such as fuel fabrication plants, have relied heavily on quantitative measurements for nuclear material accounting. However, nuclear material accounting with material balance evaluations is more challenging for reactors with rapidly changing inventory from fuel transmutation and depletion—and specifically so for MSRs with circulating fuel. Moreover, many areas in MSRs are inaccessible because of high-temperature and high-radiation environments, making measurements challenging. Additionally, to detect the theft of nuclear material, measured quantities must be compared with expected quantities of SNM to identify the difference. In reactors with changing inventories, these expected quantities must be calculated based on operational parameters. Reducing uncertainties on these expected quantities is challenging without decades of operational experience to verify and validate predictive computational codes.

A previous effort addressed these concerns by providing several recommendations to MSR developers. A primary recommendation was a reliance on material control around the MBA encompassing the reactor (and material accounting with periodic inventories in other MBAs), which is consistent with the MC&A approach in LWRs. This study has expanded on the previous recommendations in four key areas for MC&A in MSRs: (1) identifying the locations for deploying nuclear material control elements, such as tamper-safing and surveillance, at the boundaries of the high-temperature and high-radiation areas; (2) identifying the material control elements that can be applied at these locations to monitor SNM movements; (3) identifying potential areas of holdup in the facility; and (4) characterizing these holdup areas with respect to the type of nuclear material (irradiated or unirradiated), measurement frequency, and measurement environment.

4.1 SUMMARY OF MATERIAL CONTROL ASSESSMENT

For material control, this study recommends a control boundary around the reactor system to enable detection of all material movements entering and exiting the area. This boundary should follow a physical boundary surrounding the reactor system to restrict physical access. The control boundary penetrations, such as piping connections, hatch(es), and sampling line(s), have been categorized as (1) SNM transfer pathways into or out of the control boundary (e.g., the feed line) and (2) non-SNM transfer pathways into or out of the boundary (e.g., the cover gas line). These penetrations must be monitored using control elements to ensure that these pathways are not used to steal SNM. Hence, an assessment of control elements to monitor SNM movements through these identified penetrations was conducted considering different types of SNM movements.

The SNM entering and leaving the control boundary should be monitored. For bulk SNM transfer (batch or continuous) into and out of the control boundary, nontraditional control elements, such as flow, radiation detection, level, or weighing measurements, should be used at each SNM transfer pathway. These in situ monitoring elements must be capable of measuring the total mass of SNM transferred across the control boundary with sufficient accuracy to meet NRC accountancy requirements. For situations with SNM transfers in item form (e.g., as discrete containers), such items should be measured and characterized prior to introducing to or retrieving from the control boundary. Access to the control boundary should be monitored using an electronic seal and a surveillance system, which provide independent evidence of the access and by whom. Additionally, surveillance measures are required to monitor the movement of measured and characterized fuel containers outside the control boundary.

Depending upon the MSR design and operational characteristics, some of the penetrations (non-SNM penetrations), where SNM movement is not usually anticipated, may not require any control elements. However, control elements should be considered for penetrations in which the design does not absolutely preclude the introduction or removal of SNM. If a credible scenario exists for SNM to be removed through a penetration point, even if not intended or designed for use with SNM, MC&A elements should be identified to prevent or detect removal of SNM through that location. Traditional control elements should be applicable to penetrations with item transfers but may not be applicable for bulk material transfers.

Elements of a traditional physical protection system (e.g., cameras, access restriction) may be proposed by a license applicant as control elements within their MC&A plan to meet specific MC&A objectives.

4.2 SUMMARY OF HOLDUP CHARACTERIZATION

With material control around the control boundary to monitor access, quantifying holdup within the reactor system can assure all SNM is measured and accounted for in MSRs. For identifying and characterizing holdup areas, diverse MSR designs were categorized into three groups based on their fuel salt flow paths and system component. Holdup areas in each of these groups were identified, such as reactor primary system and chemical control and off-gas systems. Additionally, these areas were characterized by detailing the type and form of the SNM, the measurement frequency, and the measurement environment. Moreover, possible schematics of individual systems or components were assessed for further characterizing the identified holdup areas, including presenting use cases of holdup experience gained in uranium and plutonium processing facilities.

4.3 RECOMMENDATIONS

For the MSR license applicants planning an MC&A approach, recommendations from this study include the following:

- Consider the extent of the control boundary around the reactor system, including the pros and cons of handling SNM transfers as bulk material or in item form.
- Consider appropriate design choices to limit the need for control elements, such as
  - minimizing control boundary penetrations,
  - using design options that preclude the introduction of fertile material into or withdrawal of SNM through non-SNM penetrations, and
  - planning robust physical boundaries that align with the identified control boundary to the greatest extent possible.
- Identify control elements applicable for monitoring each penetration for which the presence of SNM cannot be precluded.
- Consider appropriate design choices to minimize the holdup of SNM, including
  - choosing long-lifespan components to limit replacement,
  - limiting the number of bends and reducing thermal gradients in connection piping, and
  - selecting component material such that settled or reacted deposits can be easily removed during flushing of the primary system.

4.4 FUTURE WORK

Building on this effort, future work will focus on identifying specific material control elements and assessing each element’s performance for various SNM theft scenarios. A review will be undertaken to identify nontraditional control elements (e.g., radiation detectors, flow meters, weighing scales) and any other suitable elements outside of conventional tamper-safing solutions. Lastly, a performance assessment of these control elements will be conducted to evaluate their effectiveness to detect the removal of SNM from inside a control boundary.

In the area of SNM holdup measurements, future work will assess the current capabilities of measurement systems to operate effectively in harsh high-radiation and high-temperature environments. This future investigation will enable the determination of R&D needs and propose measurement strategies for holdup quantification, which will be crucial to provide assurance that all nuclear material is accounted for during operation, equipment or component replacement, and at the end of the reactor’s design life. Overall, these planned efforts will provide further guidance for developing an effective MC&A plan for MSRs.

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