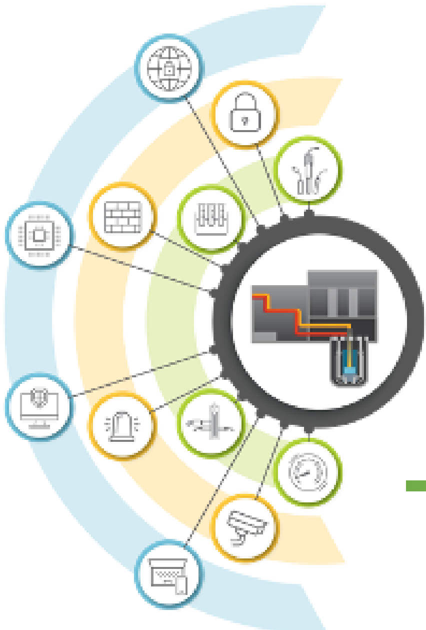

Control Boundary Analysis for Liquid-Fueled Molten Salt Reactors

Prepared for US Department of Energy

Sunil S. Chirayath, Thomas G. DeGuire, Manit D. Shah, Maggie M. Arno, and Karen K. Hogue

Oak Ridge National Laboratory

September 2025
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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

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ABBREVIATIONS

CUI	controlled unclassified information
HX	heat exchanger
ICA	item control area
ID	inventory difference
MBA	material balance area
MC&A	material control and accounting
MSBR	molten salt breeder reactor
MSDR	Molten Salt Demonstration Reactor
MSR	molten salt reactor
NMCFSR	nominal molten chloride fast-spectrum reactors
NMMSS	nuclear materials management and safeguards system
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
SEID	standard error of the inventory difference
SNM	special nuclear material

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 provide a detailed MC&A program description for the facility. In liquid-fueled MSRs with special nuclear material (SNM) in bulk form (i.e., not in discrete items) and with rapidly changing quantities due to fuel transmutation and depletion, a novel MC&A approach is needed because traditional nuclear material accounting methods with material balance evaluations will not be sufficient. This report details the continued efforts carried out at Oak Ridge National Laboratory (ORNL) during FY 2025 to develop a distinct MC&A approach suitable specifically for domestic safeguards of the first-of-a-kind MSRs. These efforts are built on previous ORNL efforts reported in ORNL/SPR-2023/3181 and ORNL/SPR-2024/3555.

The material balance area (MBA) structure with three MBAs recommended for MSRs in ORNL report ORNL/SPR-2023/3181 and the conceptual control boundary proposed around the MSR confinement along with the penetrations were further investigated to answer the following questions:

1. What are the effects of uncertainties in code predictions and measurements on an SNM inventory-based MC&A approach in the MBA-containing reactor primary system?

2. How will a control measures–based versus SNM measurement-based MC&A approach work for the MBA containing reactor primary system?

3. What are the other options for MBA structures? Compared to a three-MBA approach, what are their benefits and challenges?

4. What are the measurement strategies to be adopted for monitoring the evolution of SNM holdup within the control boundary and residual SNM in components transferred out of the control boundary?

A quantitative and technical analysis conducted using the results of fuel burnup simulations of MSRs of various sizes showed that an inventory-based MC&A approach for the MBA containing the reactor primary system may not be a suitable option for the first-of-a-kind MSRs. This is because of the uncertainties of even a few percent in both the SNM accounting measurements and the corresponding multiphysics computer code predicted reference values that lead to SNM mass discrepancies in the range of kilograms between ground truth and reported inventory values based on either measurements or predictions. Therefore, effective material control measures using control elements for the boundary penetrations around the reactor primary system may be the prudent option for MC&A of first-of-a-kind MSRs.

Subsequently, a study was conducted to identify control elements for detecting the unauthorized removal of SNM via the nine penetrations of a conceptual MSR control boundary, which were described in the ORNL/SPR-2024/3555. The analysis considered both traditional and nontraditional techniques and measures for meeting the US domestic nuclear safeguards goal of detecting the theft of SNM from the MBA containing the reactor primary system without the need for depending on SNM measurements. At the control boundary penetrations where SNM is expected to be present during operations, the selected control elements were sufficiently robust to discriminate approved movements of SNM from nonapproved ones. For other penetrations of the control boundary, safety-related or other operational measures are recommended to detect the presence of any unexpected SNM. The list of selected control elements for each penetration and the rationale for the selection of these control elements are described in this report. Additionally, a qualitative (but objective) efficacy analysis of these selected control elements was conducted using a set of hypothetical SNM theft scenarios. The hypothetical theft scenarios considered were for the fresh fuel feed, sampling line, and irradiated fuel removal line penetrations. These penetrations were selected because SNM is expected to move through these penetrations during reactor operations. In all theft scenarios, each control element was considered to discuss the role it would have in detecting the theft of SNM via the selected control boundary penetration.

Further, a detailed analysis conducted on various options of MBA structures along with the option of item-controlled areas helped to understand the benefits and challenges associated with these options compared to the three-MBA structure for an MSR. Analysis considered three different approaches to an MBA structure, including MBA structures with three MBAs, two MBAs, and one MBA. Each option has its own benefits and challenges, which are discussed in detail. When considering the best MBA structure for a particular MSR facility, designers should consider when and how the SNM within the reactor's physical boundary should be quantified and reported. Reporting options and MBA structures go hand in hand because the MBA structure will inform where inventories that need to be reported in the Nuclear Materials Management and Safeguards System are taken, and the reporting options could dictate where MBAs should be drawn (i.e., whether there should be an MBA around the reactor's physical boundary). For example, SNM quantities could be measured during operation and reported in the Nuclear Materials Management and Safeguards System, and computational codes could be used to predict SNM quantities, although the related unknown uncertainties may make this option better in the future once the relevant codes have been validated.

A final component of the FY 2025 MSR control study suggested strategies for monitoring the evolution of SNM holdup and subsequent ground truth measurements within the control boundary during shutdown and estimating the residual SNM in components when they leave the control boundary. A near-real-time holdup monitoring approach is proposed to localize and monitor the evolution of SNM holdup at specific locations within the primary system inside the control boundary. This approach relies on fixed detectors based on gross radiation count instruments deployed at specific locations. The online holdup monitoring should inform in-field holdup measurements, which should use high-resolution gamma spectroscopy and neutron counting techniques. These measurements should enable ground truth verification measurements to determine isotopic compositions and SNM mass at each holdup location. Three approaches are proposed for measuring residual SNM in components removed from the control boundary. These measurements should use medium-to-high resolution radiation detectors followed by the component transfer to an item-controlled area, if necessary.

Details of each of these four investigations carried out and inferences drawn are presented in the report.

1. INTRODUCTION

This report details the activities carried out at Oak Ridge National Laboratory (ORNL) during FY 2025 to develop a material control and accounting (MC&A) approach for domestic nuclear safeguards of liquid-fueled molten salt reactors (MSRs)[1]. These activities were a continuation of the work reported by the ORNL research team in September 2024 [1].

In domestic nuclear safeguards, the main objective of the US Nuclear Regulatory Commission (NRC) is to "enable the safe and secure use and deployment of civilian nuclear energy technologies and radioactive materials through efficient and reliable licensing, oversight, and regulation for the benefit of society and the environment." One way the NRC meets its obligations is by implementing domestic safeguards to ensure that special nuclear material (SNM) is not stolen or otherwise diverted from civilian facilities. All NRC-regulated fuel cycle facilities that process SNM are required to have an MC&A program to detect theft of SNM.

In support of this objective, *material control* refers to the use of control and monitoring measures to prevent or detect loss when it occurs or soon afterward. *Material accounting* is defined as the use of statistical and accounting measures to maintain knowledge of the quantities of SNM present in each area of a facility, which includes the use of physical inventories and material balances to verify the presence of material or to detect the loss of material after it occurs (loss may result from theft by one or more insiders). Hence, both the material control and material accounting measures are combined to meet the domestic safeguards objectives established by the NRC [2].

MSRs are bulk nuclear material facilities for MC&A purposes because they handle SNM in bulk form and not as discrete items that can be easily accounted for. Compared to other bulk nuclear material handling facilities (e.g., uranium enrichment and fuel fabrication facilities), an MC&A approach to MSRs must be different because of the following characteristics:

1. Quantities of SNM in MSRs can rapidly change within the core due to fuel depletion and transmutation.

2. Presence of high-radiation and high-temperature environments within the reactor control boundary.

3. Errors in computational code predictions and measurements of SNM in the reactor could affect the physical inventory accuracy because of the safeguards goal quantities for detecting SNM theft are relatively small.

4. Lack of ample operational experience in verifying and validating computer codes against material accounting measurements.

Considering these characteristics, ORNL recommended a three-material balance area (MBA) structure for an MC&A approach in MSRs (Figure 1) in January 2024 [3]. The MC&A approach recommended relied heavily on material accounting with periodic inventories for MBA 1 and MBA 3 and leveraging primarily material control for MBA 2.

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

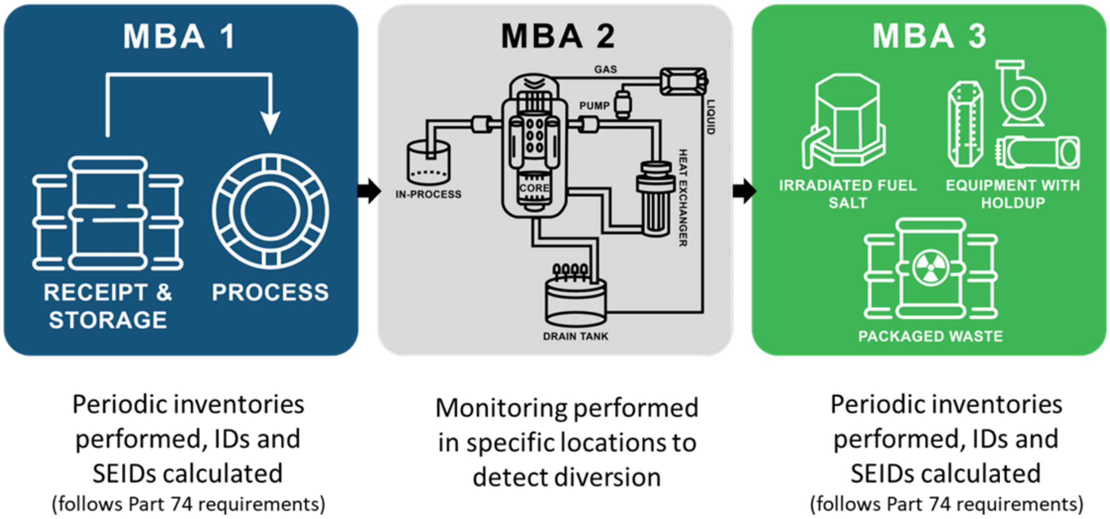

Figure 1. Proposed three-MBA structure for an MSR. Image reproduced from [3] with permission from ORNL. Note, ID is the inventory difference, SEID is the standard error of the inventory difference, and Part 74 refers to CFR Part 74.

MBA 1 consists of fresh fuel salt storage and processing areas. MBA 2 houses the MSR fuel salt loop and the core confinement. A *control boundary* around MBA 2 is defined for MC&A planning purposes. This control boundary is a delineation around the reactor system that is controlled to detect and account for all material movements entering and leaving the area. If possible, the control boundary should follow a physical boundary (such as the biological shielding) surrounding the reactor system to restrict physical access. A conceptual drawing of an MSR control boundary is shown in Figure 2 [1] with the penetrations deploying nuclear material control elements identified. MBA 3 consists of removed irradiated salt storage, waste storage, equipment with holdup, and packaging areas.

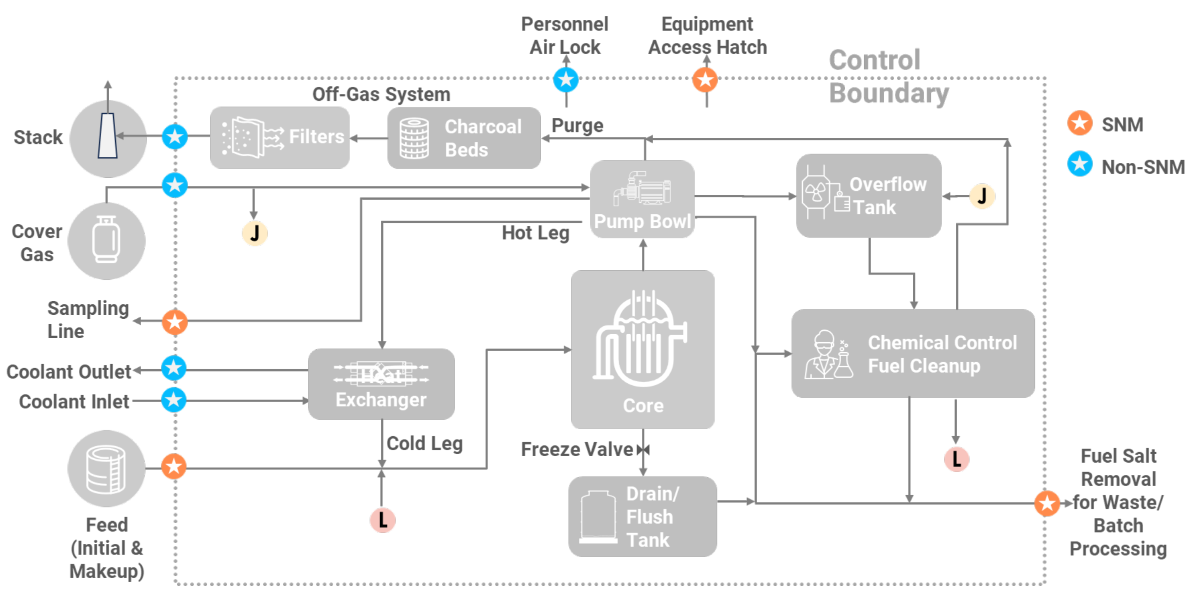

Figure 2. Control boundary penetrations (identified as the locations for deploying nuclear material control elements) in an MSR that must be monitored or secured against theft, including those intended for SNM and non-SNM movements. Image reproduced from [1] with permission from ORNL.

In FY 2025, research efforts focused on the following five aspects to further analyze this three-MBA structure for MC&A of MSRs, specifically MBA 2 and the associated MC&A measures:

1. Impact of uncertainties in code predictions and measurements on physical inventory of SNM in MBA 2

2. Selection of control elements at MSR control boundary penetrations

3. Efficacy analysis of the selected control elements at certain penetrations of the control boundary against theft scenarios

4. Other options for MBA structures with their benefits and challenges

5. Measurement strategies for holdup and residual SNM

Each of these five analyses are described in the following sections (Sections 2–5), and a summary of these studies is provided in Section 6.

2. IMPACT OF UNCERTAINTIES IN CODE PREDICTIONS AND MEASUREMENTS ON PHYSICAL INVENTORY OF SNM IN MBA 2

A study was conducted to investigate the potential impact of both predictive code uncertainties and measurement uncertainties on inventory-based approaches for MC&A in MBA 2 (Figure 1). The motivation for this study was to better understand whether an inventory-based MC&A approach like commonly leveraged currently in NRC-licensed bulk material handling facilities, (e.g., uranium enrichment and fuel fabrication facilities) is applicable to MBA 2 in an MSR.

All NRC-licensed facilities report inventory and inventory differences to the Nuclear Materials Management and Safeguards System (NMMSS) at a frequency of every 9 or 12 months, depending on if the SNM at the facility is considered Category II or Category III material [4,5], respectively. This reported inventory may be based on measurements of the SNM when practical or on code-predicted values for facilities where SNM measurements may be difficult, such as in nuclear reactors. This study explored possible discrepancies between reported values of SNM inventory and true inventory in the reactor core (part of MBA 2) that result from the uncertainties associated with unvalidated measurement techniques and reactor multiphysics codes for first-of-a-kind MSRs. The influence of these uncertainties is particularly relevant to MSRs because the SNM is present in bulk form in portions of the MSR facility. To study the consequences of these assumed uncertainties, four reactor designs were modeled and simulated using three power histories. The reactor designs included both fast-spectrum and thermal-spectrum systems with small (hundreds of megawatts thermal) and large (thousands of megawatts thermal) power outputs. Power histories were selected to capture both baseload-like operating histories and a more variable power intended to be more reflective of nontraditional deployment scenarios. Figure 3, Figure 4, and Figure 5 display the baseload, realistic, and variable [6] power histories, respectively, that were used in this study.

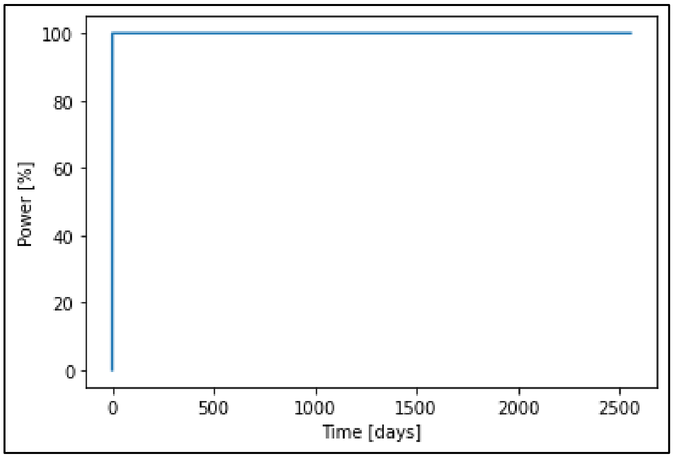

Figure 3. Baseload power history.

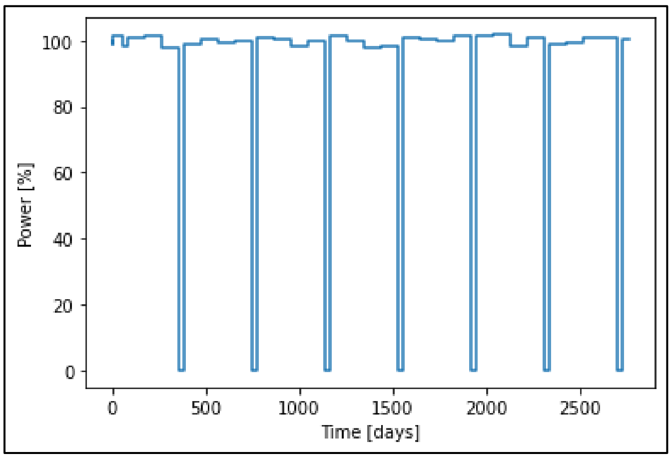

Figure 4. Realistic power history.

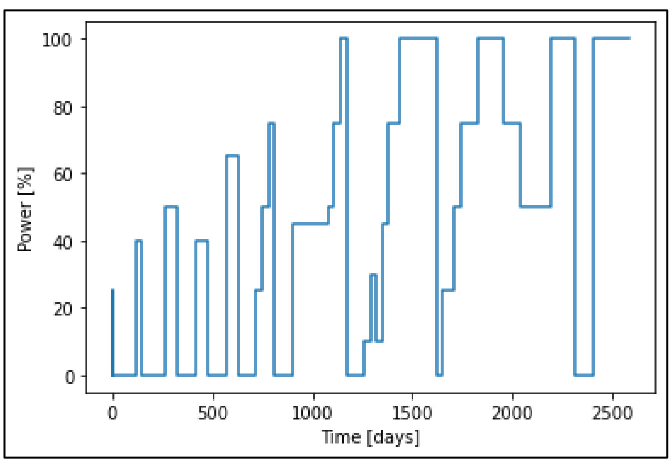

Figure 5. Variable power history.

The four MSR designs studied include a variant of the molten salt breeder reactor (MSBR) [7], a variant of the Molten Salt Demonstration Reactor (MSDR) [8], and two nominal molten chloride fast-spectrum reactors (NMCFSR) with different sizes and power levels [9,10]; Table 1 displays key design parameters of these four MSRs. These MSR designs were selected to leverage previous work performed at ORNL and to incorporate designs that reflect those currently under consideration by private industry. All simulations were conducted using the TRITON reactor physics sequence in the development version of neutronics simulation code, SCALE 7.0 [11].

Table 1. Reactor parameters.

Parameter	MSBR variant	MSDR variant	180 MW_{th} NMCFSR	1,200 MW_{th} NMCFSR
Power (MW_{th})	2,250	750	180	1200
Initial fuel salt (mole %)	LiF–BeF_2–UF_4 (60–30–10)	LiF–BeF_2–UF_4 (67–28–5)	NaCl–UCl_3 (66.7–33.3)	NaCl–UCl_3 (66.7–33.3)
Initial salt ^{235}U enrichment (wt.%)	2.29	2	13.3	11.7
Makeup salt ^{235}U enrichment (wt.%)	5	5	19.75	No makeup salt used
Length of reactor operations simulated (years)	4	7	7	7

The SCALE simulation results were considered ground truth values, representing the mass of SNM in the modeled reactor. The ground truth values were then used to generate hypothetical code-predicted and measured inventory values to represent the values reactor operators might report to the NRC. To create these hypothetical inventories, Gaussian distributions for both code-predicted and measured SNM masses were generated, with the distributions' statistical mean values set equal to the ground truth values and the distributions' statistical standard deviations based on assumed relative uncertainty values derived from a literature review of current measurement techniques for light water reactor irradiated fuel and previous code validation results [9, 12]. For each time step, these Gaussian distributions were randomly sampled to produce code-predicted and measured SNM inventories. The code-predicted and measured inventories were assumed to have the same relative uncertainty as was used to generate the gaussian distribution from which the values were sampled. Finally, the code-predicted and measured values were compared to both the ground truth inventories and each other to study the impact of uncertainty on an inventory-based MC&A approach for MBA 2.

An insight from this study is that uncertainties of even a few percent can lead to SNM mass discrepancies in the range of kilograms between ground truth inventory values and reported inventory values, depending on the size of the reactor. For example, Figure 6 shows differences between ground truth plutonium mass values in the MSR and possible multiphysics code predicted values on the left and differences between code predicted values and hypothetical measured values on the right. For the top portion of Figure 6, the assumed relative uncertainty value is 5% for hypothetical measured values and 8% for code predicted values, while the bottom portion assumed 1% relative uncertainty for both hypothetical measured values and code predicted values.

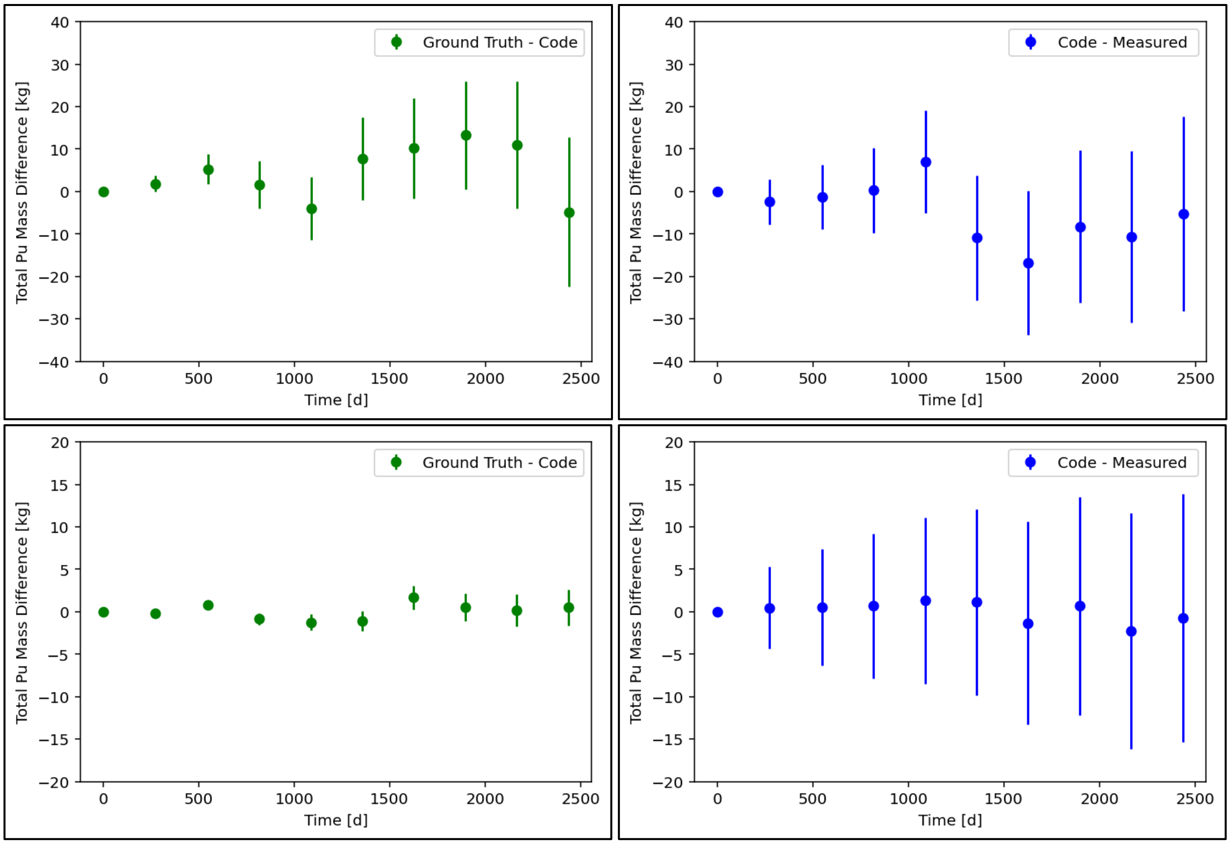

Figure 6. Plutonium inventory difference for 180 MW_{th} NMCFSR with a baseload power history assuming 8% relative uncertainty for code predictions and 5% relative uncertainty for measurements (top) and assuming 1% relative uncertainty for both (bottom).

From Figure 6, it can be noted that the error bars increase over time of reactor operation as plutonium inventories increase over the course of reactor operations. Larger reactors, which have a higher SNM inventory in the core, further exacerbate these differences. Attributing the source of these discrepancies (Total Pu mass differences between ground truth vs code predictions or code predictions vs measurements) may be a difficult task. Moreover, balancing the SNM inventory values reported between consecutive material balance periods may be further complicated because during operation SNM is depleted and transmuted in addition to SNM feed-in and removal from the reactor in bulk material form. Hence, relying on a physical inventory-based approach for MBA 2 to detect SNM theft may not be prudent. This inference is because realistic possibilities exist for the true plutonium value in the reactor core to be different than its predicted or measured value due to the associated uncertainties. As the MSR operational experience improves over several years, the uncertainties in code predictions and measurements of bulk SNM should improve and if they reduce to less than 1%, a physical inventory-based approach for MBA 2 may be considered.

In the bottom portion of Figure 6, it should be noted that the error bars for the (Code-Measured) shrink less than for the (Ground Truth-Code) because the measurement uncertainty is assumed as the square root of the mass. Hence, even very accurate measurements could have sizeable uncertainty.

Analysis of all four reactor models across each of the power histories that were simulated led to a similar conclusion. Given that such low levels of uncertainty are difficult to achieve for currently operating light water reactors, such levels of accuracy may be difficult to achieve for MSRs as well, particularly for first-of-a-kind systems. Therefore, effective material control measures at MBA 2 may be the prudent option for MC&A of first-of-a-kind MSRs.

3. SELECTION OF CONTROL ELEMENTS AT MSR CONTROL BOUNDARY PENETRATIONS

Control elements are suggested to be used for monitoring the control boundary around the reactor system (i.e., around MBA 2) because material balancing to detect potential theft of SNM using physical inventory may not be effective based on the description provided in Section 2. As part of this project, in fiscal year 2024, a conceptual drawing of control boundary for a generic MSR design was created (Figure 2) [1], with the penetrations identified. These penetrations, identified as the locations for deploying nuclear material control elements, include piping connections, hatch or door openings, personnel airlock, 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.

These penetrations must be monitored for SNM movements to detect theft using control elements at all locations where SNM could be physically accessed to detect material movement across it. License applicants developing an MC&A approach 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 light water reactors, in which SNM is not quantified through measurements while in a sealed reactor pressure vessel. Unlike light water reactors, however, identifying control elements for MSRs needs a distinct approach, such as the use of nontraditional control elements because MSRs are reactors with bulk material. 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 tamper-indicating devices.

In this study, control elements were identified for detecting the unauthorized removal of SNM via the nine penetrations shown in Figure 2. These penetrations are the equipment hatches, personnel air lock, off-gas outlet lines, cover gas inlet lines, coolant salt lines in, coolant salt lines out, sampling lines, fresh fuel feed lines, and irradiated fuel removal lines. The analysis considered both traditional and nontraditional techniques and measures for meeting the US domestic nuclear safeguards goal of detecting the theft of SNM. For penetrations where SNM is not expected to be present as part of routine operations, the selection of control elements focused on leveraging safety-related or operational measures that could detect the presence of SNM. In penetrations where SNM is expected to be present during operations, the selected control elements need to be sufficiently robust to discriminate approved movements of SNM from nonapproved ones. The selected control elements for each penetration are described in Annexure A, titled “Selection of Control Elements for MSR Control Boundary.” Annexure A consists of controlled unclassified information (CUI) and will be distributed by ORNL only to approved personnel.

4. EFFICACY ANALYSIS OF THE SELECTED CONTROL ELEMENTS AT CERTAIN PENETRATIONS OF THE CONTROL BOUNDARY AGAINST THEFT SCENARIOS

A set of hypothetical SNM theft scenarios were identified to determine the efficacy of the selected control elements (Annexure A) at certain penetrations of the MSR control boundary. The hypothetical theft scenarios considered were for fresh fuel feed, sampling line, and irradiated fuel removal line penetrations. These penetrations were selected because SNM is expected to move through all these penetrations during reactor operations. In all these theft scenarios, each control element from Annexure A was considered to discuss the role it would have in detecting the theft of SNM via the selected control boundary penetration. This analysis is contained in Annexure B, titled "Analysis of Control Elements for Selected Control Boundary Penetrations." Annexure B consists of controlled unclassified information (CUI) and will be distributed by ORNL only to approved personnel.

5. OTHER OPTIONS FOR MBAS STRUCTURES WITH THEIR BENEFITS AND CHALLENGES

In this section, an analysis of various options for MBA structures, compared to the three-MBA structure of MSR shown in Section 1 is provided. Benefits and challenges associated with these options of MBA structures are also discussed.

Item control areas (ICAs) and MBAs are key components of a MC&A program for nuclear facilities. The American National Standard for Methods of Nuclear Material Control's guidance on "Special Nuclear Material Control and Accounting Systems for Nuclear Power Plants" states that ICAs are "a defined area within the owner controlled area for which the SNM is maintained in such a way that, at any time, an item count and related SNM quantities can be obtained from the records for the SNM located within the areas" [13]. This guidance, recommended by the NRC, does not fully address the complexities of MSRs, which are bulk facilities instead of item facilities.

For MSRs, however, MBAs or sub-MBAs in conjunction with ICAs could be used analogously to ICAs in a traditional light water reactor. In an effort to define the most effective MBA structure for an MSR, which in turn will help facilitate domestic safeguards at such facilities, this study considers three different approaches to an MBA structure, including MBA structures with three MBAs, two MBAs, and one MBA. Specific terms used in this study are defined in Table 2. An overview is provided of each MBA structure, potential iterations, and the accompanying benefits and challenges associated with taking inventories and US domestic safeguards required reporting into the NMMSS [14].

Table 2. Key terms and definitions with respect to control boundary.

Term	Definition
Internal control boundary	A physical or notional boundary surrounding an area inside the reactor facility that is used to control the material it encompasses (e.g., an MBA or ICA)
Physical boundary	A physical boundary that encompasses the reactor
Subinternal control boundary	A physical or notional boundary surrounding part of the area in an already defined internal control boundary (e.g., sub-MBA or sub-ICA)

5.1 MBA STRUCTURE 1: THREE MBAS

In the first MBA structure, three MBAs are planned—one encompassing the fresh fuel feed area and fresh fuel storage, one around the physical boundary of the reactor, and one around irradiated fuel salt and waste storage. If a chemistry laboratory is part of the facility, it could be placed in a fourth MBA. This structure is illustrated in Figure 7 (redrawn Figure 1).

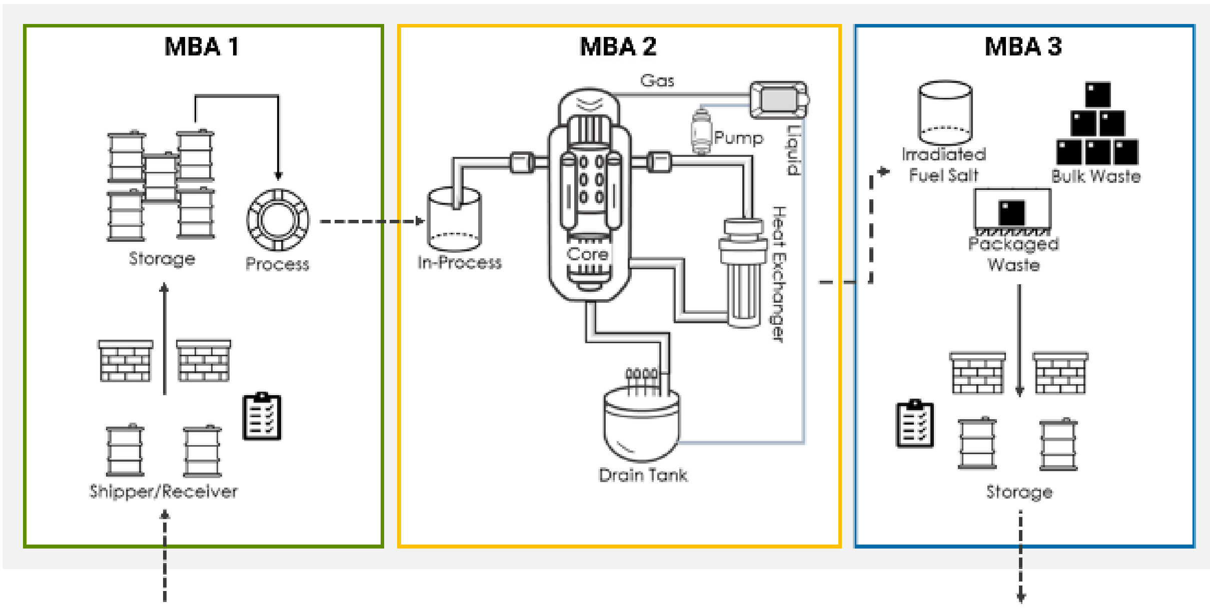

Figure 7. MBA structure with three MBAs—one encompassing the fresh fuel feed and storage area, one encompassing the reactor's physical boundary, and one encompassing irradiated fuel salt storage.

This structure could be further segmented to still have three MBAs and include two ICAs around the shipper/receiver area and spent fuel salt and waste storage (Figure 8).

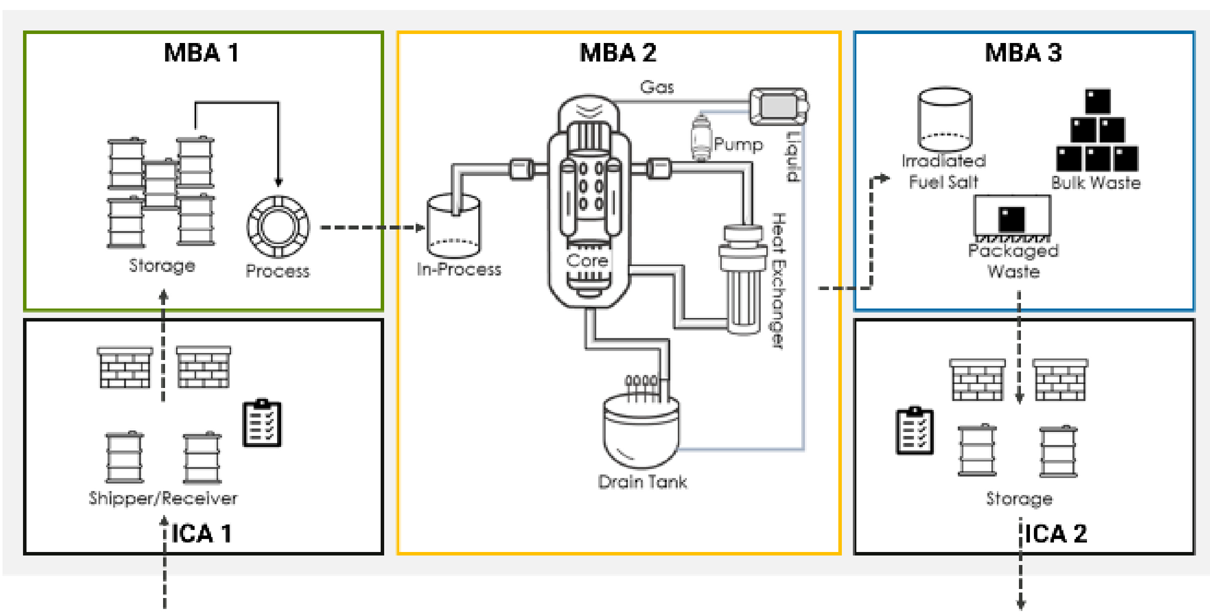

Figure 8. MBA structure with three MBAs and two ICAs—one ICA encompassing the shipper/receiver area, one MBA encompassing the fresh fuel feed and storage area, one MBA encompassing the reactor's physical boundary, one MBA encompassing irradiated fuel salt processing, and one ICA encompassing spent fuel salt and waste storage.

There are many benefits of using a structure with three MBAs. First, there is a relatively clean delineation between the areas where inventories are being taken, which could facilitate entries into NMMSS. Second, this MBA structure aligns well with the physical boundary of the reactor, which increases the effectiveness and ability of an MC&A system to detect theft. Unfortunately, this MBA structure may increase the reporting burden of the facility because three MBAs would require more NMMSS entries. In contrast, a traditional light water reactor has one MBA.

The effectiveness of such an MBA structure would depend on the specific design of the reactor, specifically in terms of what happens during salt removal and where the salt removed at the end of life goes. For example, if the spent salt is removed from MBA 2 and needs to be processed before being placed in long-term storage, then the MBA structure shown in Figure 8 may be a better option than the structure shown in Figure 7.

5.2 MBA STRUCTURE 2: TWO MBAS

In the second MBA structure option, there are only two MBAs—one around the fresh fuel salt storage, processing, and feed areas as well as the reactor, and one around the irradiated fuel salt and waste storage. In addition to the two MBAs, there would be an ICA around the shipping/receiving area (Figure 9).

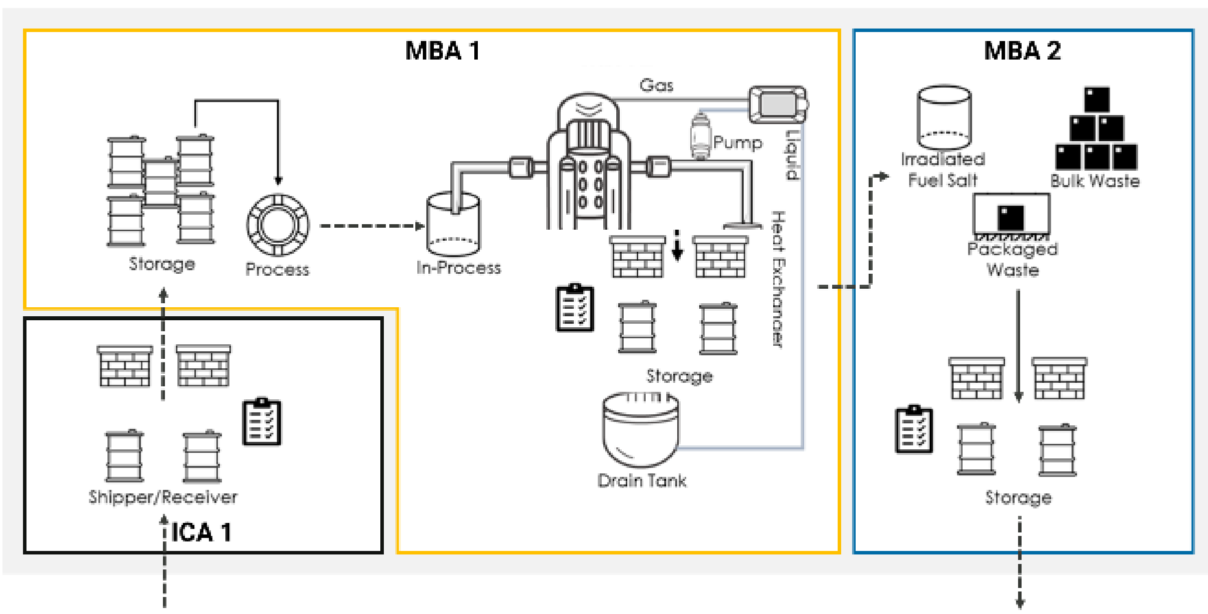

Figure 9. MBA structure with two MBAs and one ICA—one ICA around the shipper/receiver area, one MBA encompassing the fresh fuel feed and storage area as well as the reactor's physical boundary, and one MBA encompassing irradiated fuel salt storage.

One benefit of an MBA structure with two MBAs is that material in the facility that is in item form is in an ICA outside of an MBA. MC&A guidance for item facilities could then be leveraged to the fullest extent when developing an MC&A plan for these parts of an MSR facility. Similarly, all bulk material is inside an MBA. Unfortunately, in this scenario, the MBA boundary does not align with the physical boundary of the reactor. This structure could complicate MC&A because inventories of material being transferred into the reactor are not required, creating more opportunities for material to be diverted from the reactor through the feed line as well as for undeclared material to be added to the reactor. A control boundary that does not align with the physical boundary of the reactor could lead to less effective theft detection. As an alternative, a second ICA could be added around the spent fuel salt and waste storage (Figure 10).

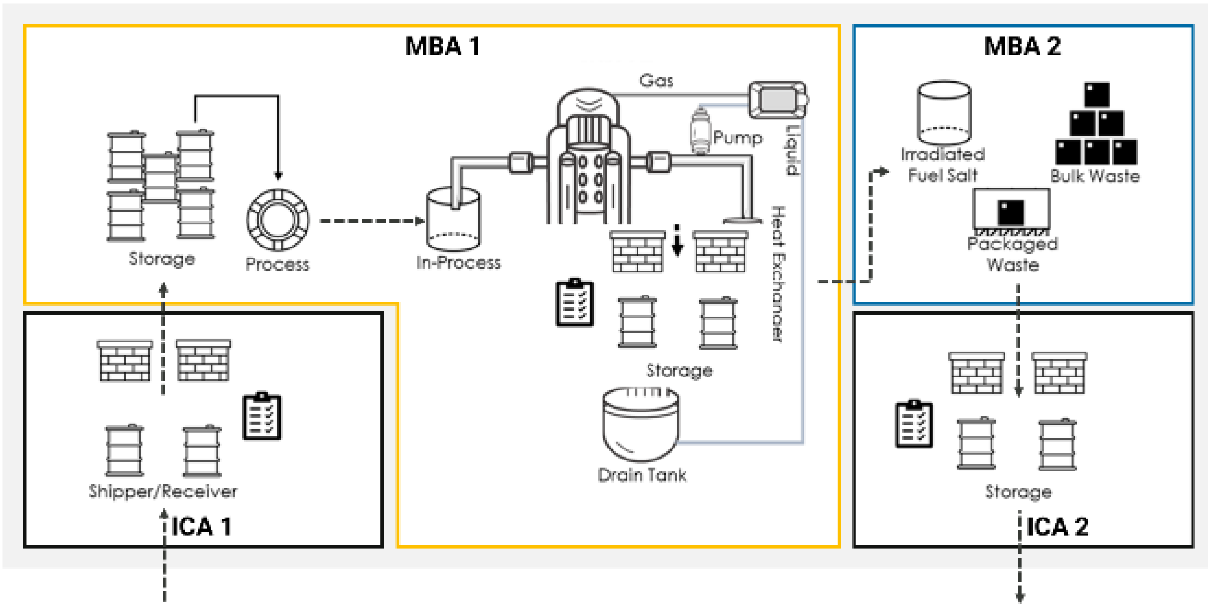

Figure 10. MBA structure with two MBAs and two ICAs—one MBA encompassing the fresh fuel feed and storage area as well as the reactor's physical boundary, one MBA encompassing irradiated fuel salt processing, one ICA around the shipper/receiver area, and one ICA around spent fuel salt and waste storage.

5.3 MBA STRUCTURE 3: ONE MBA

In the third MBA structure, the entire MSR facility is in the same MBA, as shown in Figure 11.

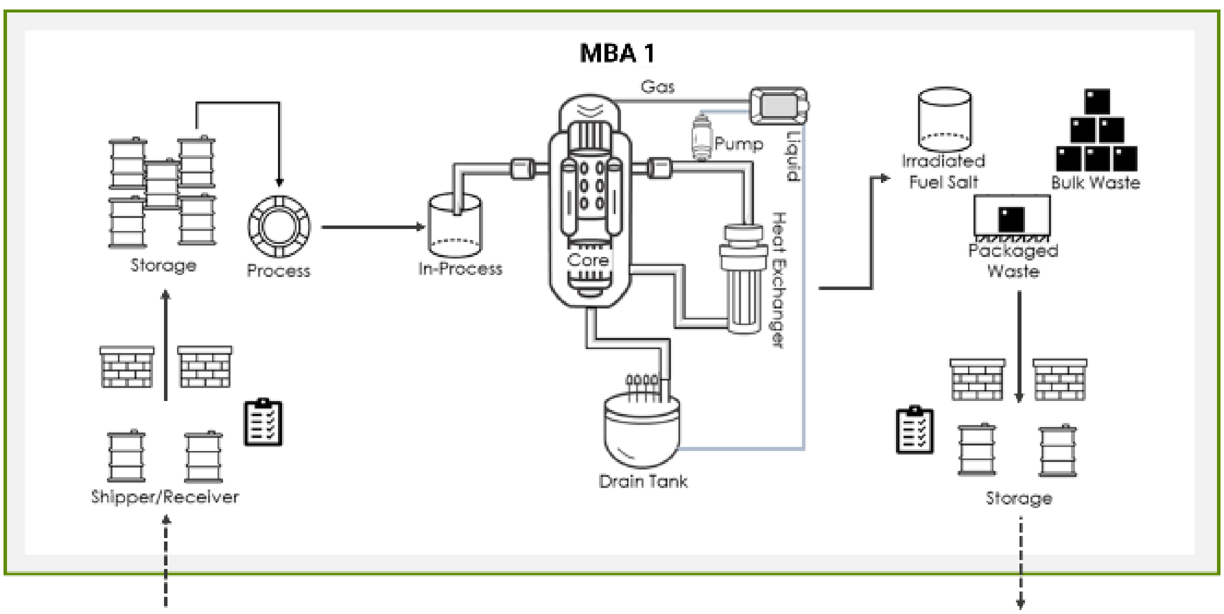

Figure 11. MBA structure with one MBA encompassing the entire MSR facility.

For NMMSS reporting, one MBA would mean fewer entries and would reduce the reporting burden on the facility. Unfortunately, it will be more difficult to relate the beginning inventories with the ending inventories without an understanding of inventories that enter and leave the reactor's physical boundary. For internal facility operations or reporting, sub-MBAs and/or sub-ICAs could be defined that align with the structures associated with two or three MBAs and accompanying ICAs, as shown in Figure 12–Figure 15.

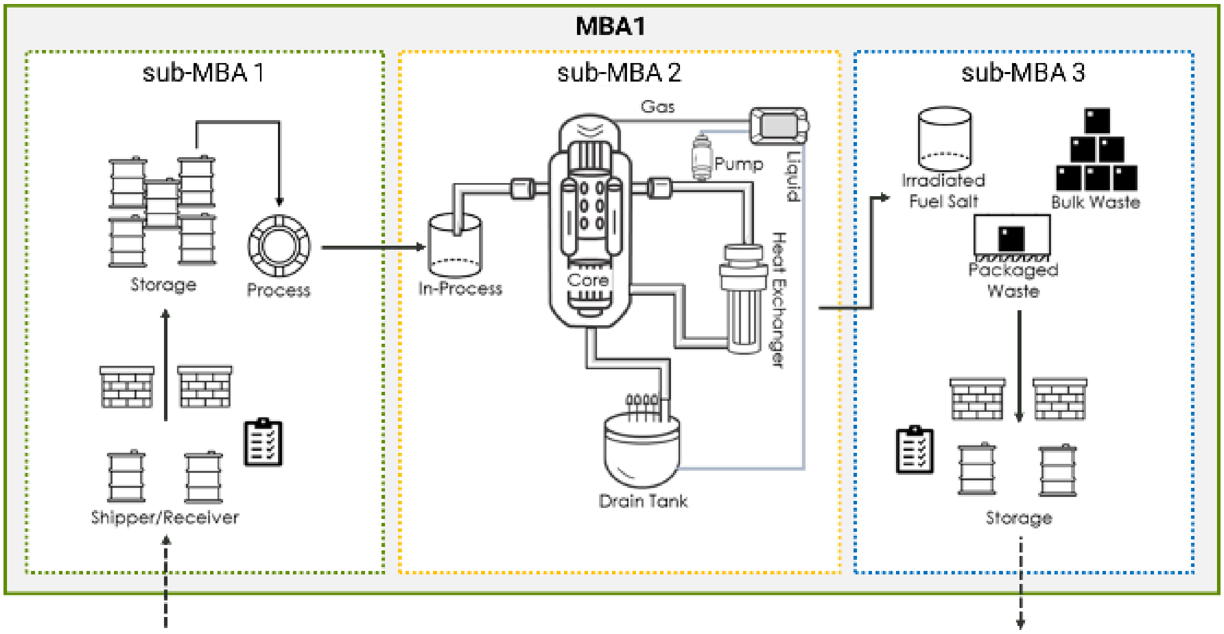

Figure 12. MBA structure with one MBA encompassing the entire MSR facility and three sub-MBAs.

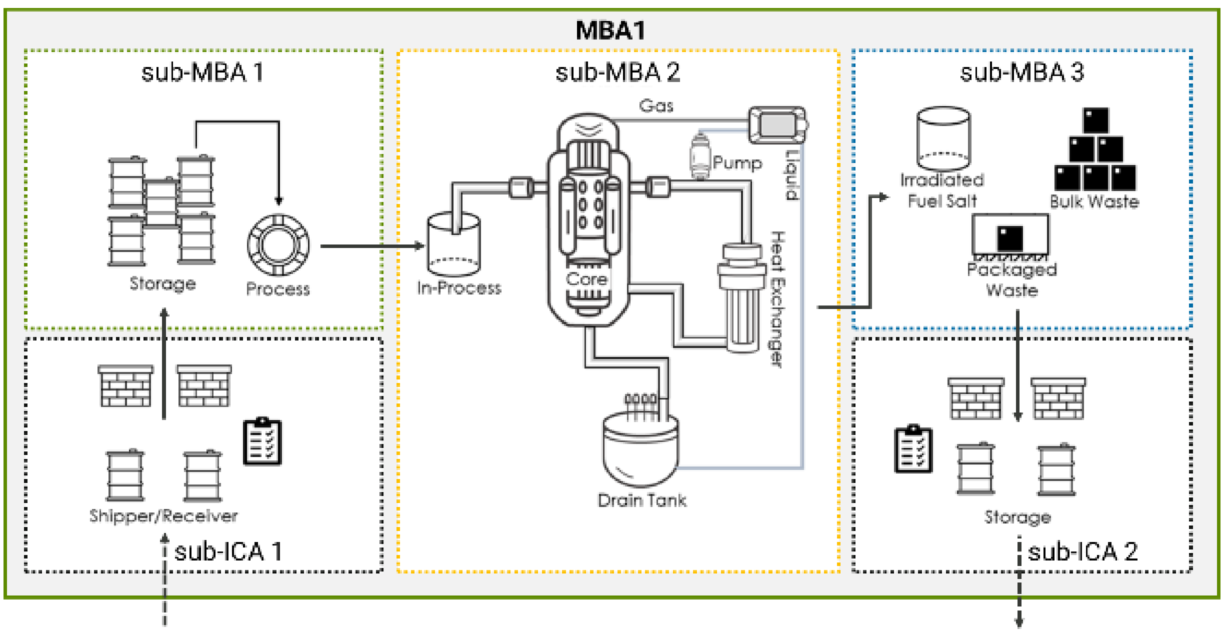

Figure 13. MBA structure with one MBA encompassing the entire MSR facility with three sub-MBAs and two sub-ICAs.

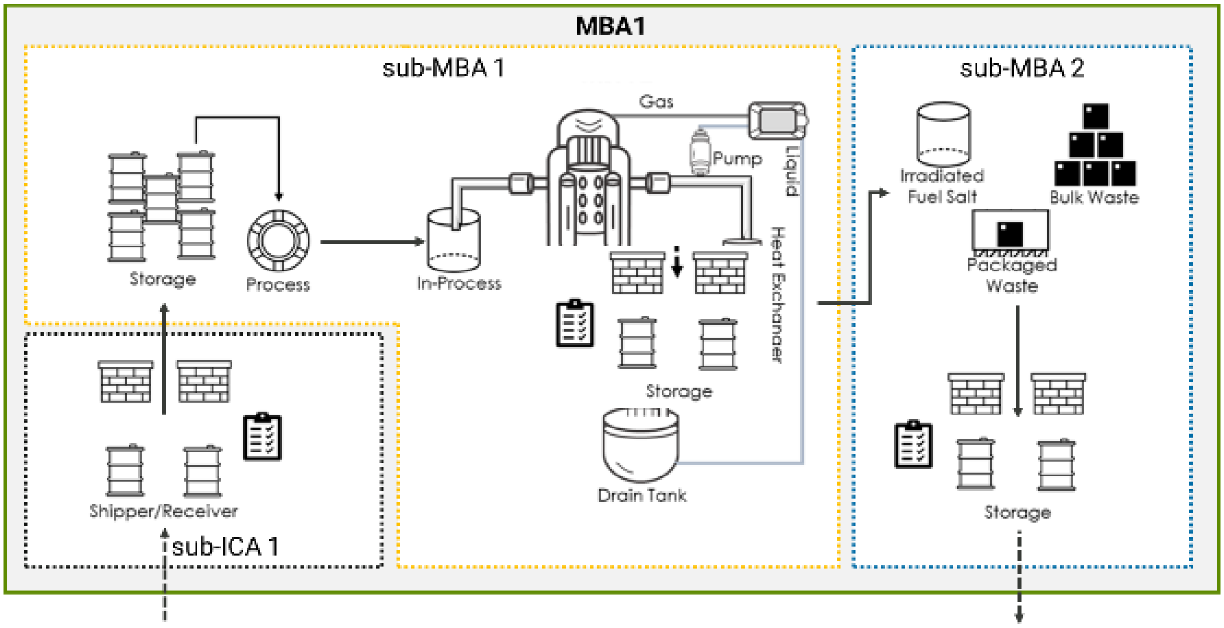

Figure 14. MBA structure with one MBA encompassing the entire MSR facility and two sub-MBAs and one sub-ICA.

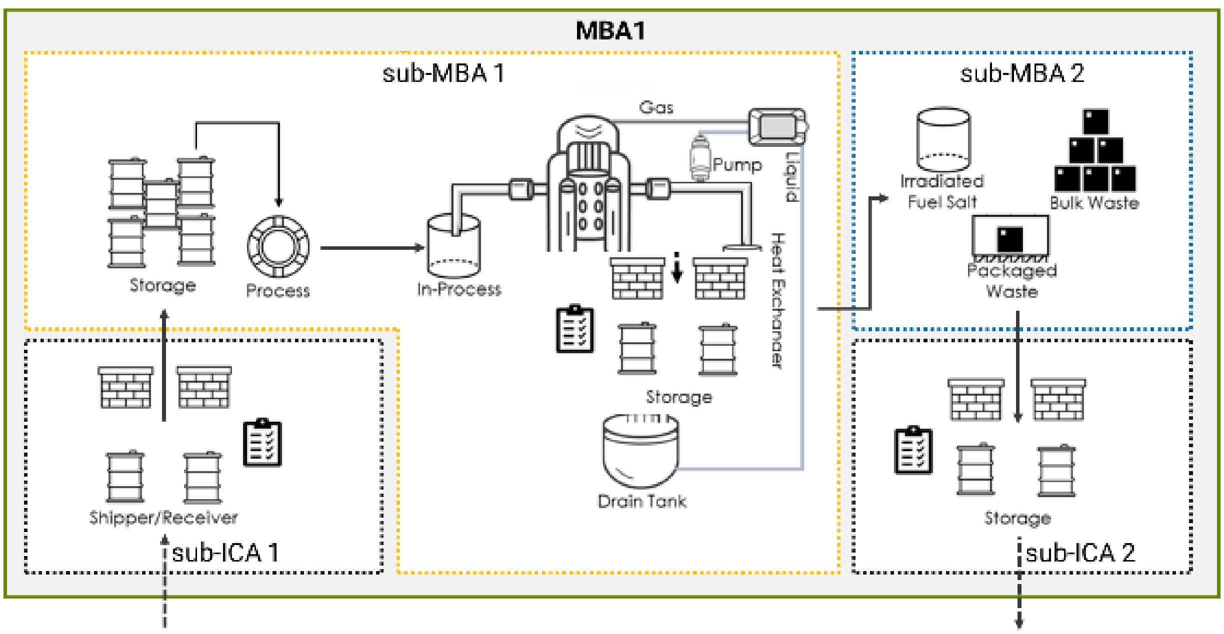

Figure 15. MBA structure with one MBA encompassing the entire MSR facility and two sub-MBAs and two sub-ICAs.

Having sub-MBAs and/or sub-ICAs would allow the facility to have a better understanding of the material throughout the facility without having to report as much to NMMSS. However, it is worth considering whether there is any value in the yearly NMMSS reports when the uranium quantities cannot be determined when the inventories are due.

When considering the best MBA structure for MSRs, designers should consider when and how the SNM within the reactor's physical boundary should be quantified and reported. Reporting options and MBA structures go hand in hand because the MBA structure will inform where inventories that need to be reported into NMMSS are taken, and the reporting options could dictate where MBAs should be drawn (i.e., whether there should be an MBA around the reactor's physical boundary). For example, SNM quantities could be measured during operation and reported in NMMSS, and computational codes could be used to predict SNM quantities, although unknown uncertainties may make this option better in the future once the relevant codes have been validated by benchmarking with material accounting measurements of SNM.

6. MEASUREMENT STRATEGIES FOR HOLDUP AND RESIDUAL SNM

During MSR operation, nuclear material and fuel salt being in the loose bulk form 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 this end, the evolution of SNM holdup in the reactor primary system should ideally be monitored during reactor operation to identify potential locations of holdup for subsequent ground truth verification measurements during shutdown, after the primary system has been thoroughly flushed or cleaned.

Circulating fuel salt containing SNM is expected to be deposited within the reactor system components. These components may be transferred outside the control boundary for replacement, potentially after the primary system has been thoroughly flushed or cleaned. Even after this flushing, residual SNM can be expected in reactor system components. For example, a replaced pump bowl transferred out of the control boundary could contain residual SNM. Such reactor system components transferred out of the control boundary should be subjected to measurements as soon as possible to quantify the residual SNM and then be transferred to an ICA following the MBA structure options shown in Figure 8, Figure 10, Figure 13, and Figure 15. If the components being transferred out of the control boundary cannot be measured immediately, they should be kept under containment and surveillance until accounting measurement is performed for subsequent transfer to an ICA.

Using a combined evaluation of the SNM introduced into the control boundary, SNM discharged from the control boundary (by considering the fuel depletion and residual SNM in transferred components), periodic holdup measurements within the reactor system, and the signals from the control elements around the control boundary, it should be possible to detect SNM theft from the control boundary. This section discusses the strategies for monitoring the evolution of SNM holdup, performing ground truth verification measurements to estimate SNM holdup, and quantifying the residual SNM in replaced components or equipment.

6.1 SNM HOLDUP MONITORING AND MEASUREMENT

A previous ORNL study provided a detailed description of potential holdup areas in MSRs [1] by categorizing MSR designs into three groups based on their design characteristics and operational activities. Although each group contains diverse designs, the Group 1 design included makeup fuel salt and online fuel cleanup and was employed as a reference MSR because it included all types of components and equipment expected in an MSR. Potential SNM holdup areas in the Group 1 MSR designs were identified and are reproduced here in Figure 16. In addition to identifying potential areas of holdup in the Group 1 designs, this study also characterized potential areas of holdup by detailing the type and form of the material, the measurement frequency, and the measurement environment, such as radiation levels [1].

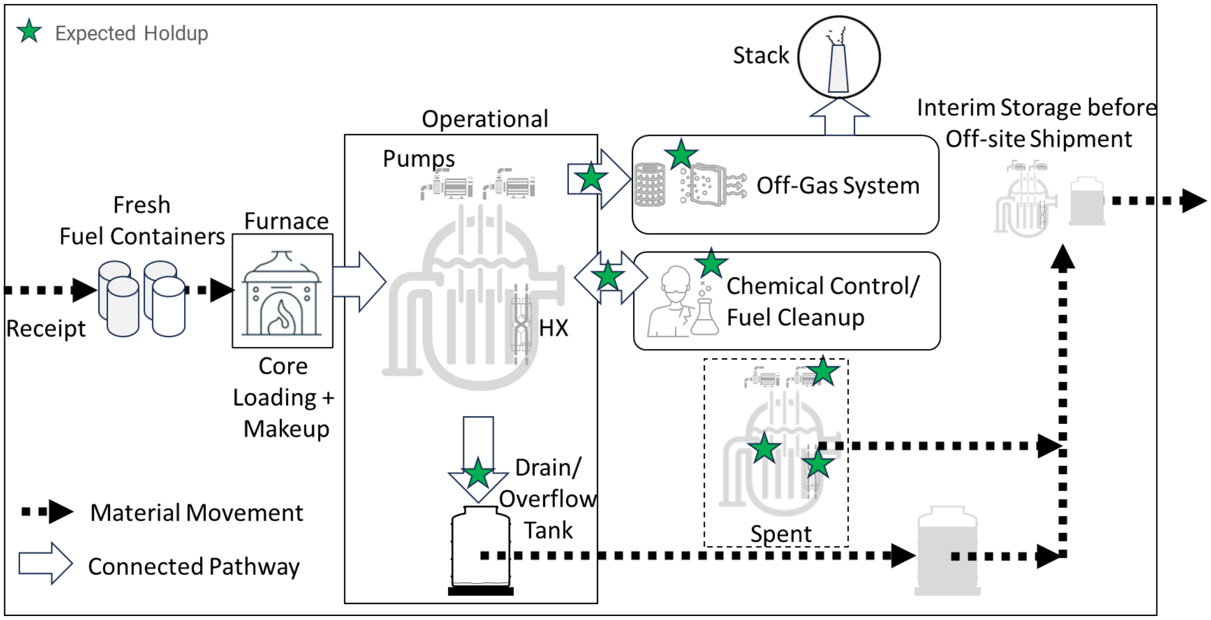

Figure 16. Potential SNM holdup areas in designs under Group 1 MSRs. Image reproduced from [1] with permission from ORNL.

The evolution of SNM holdup within the MSR primary system is desirable to be monitored (not a precise quantification) in real time during reactor operation for several reasons, including equipment integrity assessment, for criticality safety, etc. These measurements, which could support the localization of holdup and monitor its evolution, can be accomplished by deploying radiation detectors at strategic locations, such as filters, pump bowl, inlet and outlet of each heat exchanger, shell side of heat exchangers that contain fuel salt, and inlet and outlet of the fuel cleanup and chemical control system. These fixed detectors fitted with collimators placed within the control boundary can be based on gross count instruments (such as plastic scintillator detector). These detectors deployed can monitor changes in radiation counts—changes that would be driven by holdup. In this setup of fixed detectors, each detector serves as both a background and a source gross counter (i.e., average counts from other detectors will be subtracted from the detector in question to obtain source activity at the measurement location). For components with complex geometry, multiple detectors could be positioned out of each other's line-of-sight to measure different surfaces of the component. Any SNM holdup in these components should alter the measurement of counts downstream in the primary system. By collectively assessing these measurements, it may be possible to identify potential locations of holdup, which requires a separate effort to assess the feasibility of such a holdup monitoring approach.

Locations identified for potential SNM holdup inside the control boundary are desirable to undergo ground truth verification measurements to quantify SNM holdup. These measurements inside the control boundary can be performed either during reactor shutdown or at the end of its design life after the primary system has been flushed. Depending on the radiation levels, holdup measurements can be performed using either remotely operated detectors or portable detectors handled directly by authorized MC&A personnel. These detectors could be based on gamma spectroscopy and neutron counting for characterizing and measuring holdup. For instance, a high-purity germanium detector using the In Situ

Object Counting System and Multi-Group Analysis/Multi-Group Analysis for Uranium software could measure plutonium and uranium deposition [15]. Additionally, there are other systems or detectors under development (e.g., silicon photomultiplier and semiconductor-based detectors such as Perovskite) that can be considered when technology matures. The primary challenge during SNM holdup measurement is anticipated to be the interference caused by radiation from activated structural materials, which must be carefully investigated.

6.2 MEASUREMENT STRATEGIES FOR ESTIMATING RESIDUAL SNM IN COMPONENTS

When reactor components are removed from the control boundary, measuring each component to account for any residual SNM will be good MC&A practice. However, there is limited experience in measuring residual SNM of highly radioactive components such as in MSRs. To address this challenge, three strategies–aligning with MBA structure options shown in Figure 8, Figure 10, Figure 13, and Figure 15–are suggested for handling replaced components or equipment to perform residual SNM measurements (Figure 17): (1) the replaced component is temporarily stored within the control boundary until its radioactivity level reduces below an established threshold, after which residual SNM measurements are performed outside the boundary and then transferred to an ICA for storage until it is ready for removal from the facility, (2) the replaced component is placed in a temporary shielded storage cask with appropriate control elements employed for secure transfer outside the boundary, where the component is removed from cask for measurements once its radioactivity level is safe and then transferred to an ICA, or (3) the replaced component is transferred immediately to a shielded room outside the control boundary for performing measurements, which is then placed in a shielded storage cask with suitable control elements applied for transfer to an ICA.

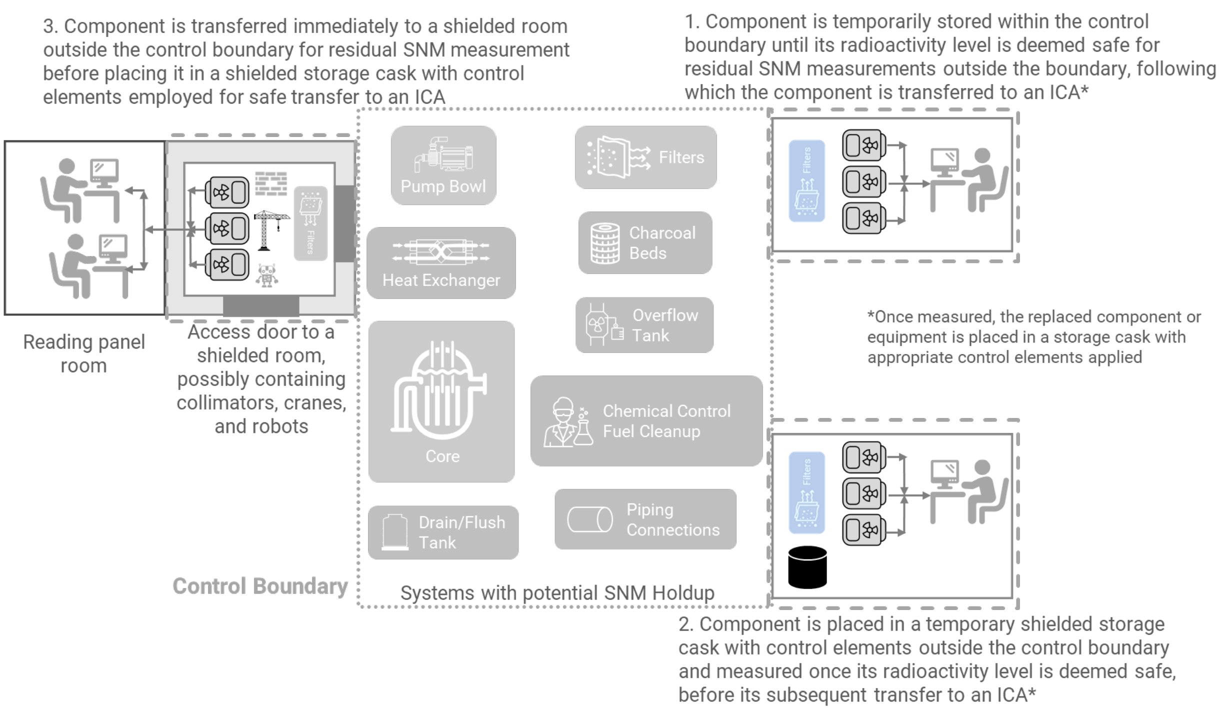

Figure 17. Three strategies for performing residual SNM measurement of a specific component.

In the first and second approaches, after the measurements are completed, the replaced component or equipment will be placed in a storage cask with appropriate control elements applied for transfer to an

ICA until it is removed from the facility. The third approach may require the shielded room to house remotely operated cranes and robots to move components or equipment and retrieve used components that may contain residual SNM. The shielded room could also be equipped with collimators, shielding, and detectors that can remotely perform residual SNM measurements to the best possible accuracy. The measurement system is expected to use cadmium–zinc–telluride detectors with medium gamma energy resolution, high-purity germanium with high gamma energy resolution, and gamma–gamma coincidence or gamma-ray imaging methods. To quantify residual SNM, these systems may require several measurements depending on the geometry of the component and other design and operational factors. Access to the ICA should be controlled and restricted to authorized personnel for specific tasks, such as transferring items containing measured SNM. Additionally, this ICA could also be used for storing measured irradiated fuel canisters, measurement samples, and waste drums.

MSR licensees should carefully evaluate these approaches for SNM holdup evolution and quantification as well as residual SNM measurements for potential implementation in their operations. Further research is required to investigate the performance and lifespan of existing detectors in MSRs and the feasibility of these approaches. This additional effort should guide the development of suitable holdup measurement systems.

7. CONCLUSIONS

Studies on the development of MSR MC&A approach continued at ORNL in FY 2025. Detailed analyses on various MC&A aspects of MSRs for domestic safeguards were conducted by considering the three-MBA structure recommended by ORNL in January 2024 [3] and the conceptual control boundary defined by ORNL in September 2024 [1] around MBA 2, including the penetrations into MBA 2 for a generic MSR design.

A quantitative and technical analysis conducted using the results of fuel burnup simulations for MSRs of various sizes showed that an inventory-based MC&A approach for MBA 2 may not be a suitable option for the first-of-a-kind MSRs. This approach is not suitable because of the uncertainties of even a few percent in both the SNM accounting measurements and the corresponding multiphysics computer code predicted reference values, leading to SNM mass discrepancies in the range of kilograms between ground truth and reported inventory values. Therefore, effective material control measures using control elements for the boundary penetrations around MBA 2 may be the prudent option for MC&A of first-of-a-kind MSRs (Section 2).

Subsequently, a study was conducted to identify control elements for detecting the unauthorized removal of SNM via the nine penetrations of a conceptual control boundary [1] drawn for a generic MSR design. The analysis considered both traditional and non-traditional techniques and measures for meeting the US domestic nuclear safeguards goal of detecting the theft of SNM from MBA 2 without the need for depending on SNM measurements. At the control boundary penetrations where SNM is expected to be present during operations, the selected control elements were sufficiently robust to discriminate approved movements of SNM from nonapproved ones. For other penetrations of the control boundary, safety-related or other operational measures are suggested to detect the presence of any unexpected SNM. The list of selected control elements for each penetration and the rationale for their selection are provided in Annexure A (controlled unclassified information-CUI) in a special version of this report, and brief information about this analysis is provided in Section 3.

The efficacy of these selected control elements (Annexure A) at certain penetrations of the MSR control boundary was carried out qualitatively but objectively using a set of hypothetical SNM theft scenarios. The hypothetical theft scenarios considered were for fresh fuel feed, sampling line, and irradiated fuel removal line penetrations. These penetrations were selected because SNM is expected to move through all of them during reactor operations. In all of these theft scenarios, each control element from Annexure A was considered to discuss the role it would have in detecting the theft of SNM via the selected control boundary penetration. This control boundary efficacy analysis is presented in detail in Annexure B (CUI), and this analysis is briefly discussed in Section 4.

Further, a detailed analysis of various options for MBA structures along with the option of ICAs, compared to the three-MBA structure of MSR (Figure 1) was conducted to determine the benefits and challenges associated with these options. Analysis considered three different approaches to an MBA structure, including MBA structures with three MBAs, two MBAs, and one MBA. Each option has its own benefits and challenges, which are discussed in detail in Section 5. When considering the best MBA structure for a particular MSR facility, designers should consider when and how the SNM within the reactor's physical boundary should be quantified and reported. Reporting options and MBA structures go hand in hand because the MBA structure will inform where inventories that need to be reported into NMMSS are taken, and the reporting options could dictate where MBAs should be drawn (i.e., whether there should be an MBA around the reactor's physical boundary). For example, SNM quantities could be measured during operation and reported in NMMSS, and computational codes could be used to predict SNM quantities, although the related unknown uncertainties may make this option better in the future once the relevant codes have been validated.

A final component of the FY 2025 MSR control study was to suggest strategies for monitoring the evolution of SNM holdup and subsequent ground truth measurements within the control boundary and further estimating the residual SNM in components when they leave the control boundary. A near-real-time holdup monitoring approach is proposed to localize and monitor the evolution of SNM holdup at specific locations within the primary system inside the control boundary. This approach relies on fixed detectors based on gross radiation count instruments deployed at specific locations. The online holdup monitoring should inform in-field holdup measurements, which should use high-resolution gamma spectroscopy and neutron counting techniques. These measurements should enable ground truth verification measurements to determine isotopic compositions and SNM mass at each location containing holdup. Three approaches are proposed for measuring residual SNM in components removed from the control boundary. These measurements should use medium-to-high resolution radiation detectors followed by the component transfer to an ICA, if necessary (Section 6).

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