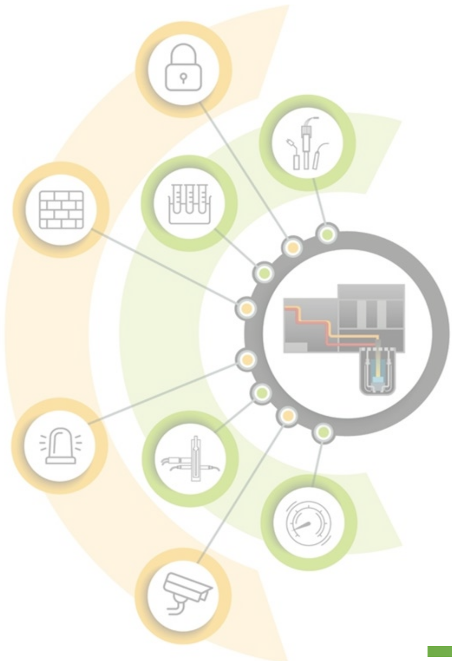

Domestic MC&A Recommendations for Liquid-Fueled MSRs

Prepared for
US Department of Energy

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Physics and Nuclear Nonproliferation Divisions

DOMESTIC MC&A RECOMMENDATIONS FOR LIQUID-FUELED MSRS

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ACRONYMS

ARS	Advanced Reactor Safeguards
CFR	Code of Federal Regulations
DOE	Department of Energy
FNMC	Fundamental Nuclear Material Control
HEU	high-enriched uranium
ICA	item control area
ID	inventory difference
LEU	low enriched uranium
LWR	light water reactor
MC&A	Material Control and Accountability
MBA	material balance area
MSR	molten salt reactor
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
SEID	standard error of the inventory difference
SNM	special nuclear material
TID	tamper indicating device
WGPu	weapons-grade plutonium

EXECUTIVE SUMMARY

Investments by the US Department of Energy (DOE) are providing opportunities for vendors and developers of advanced reactor technologies to move toward experimental reactor systems, leading to commercial scale facilities. One facet of complementary research under the Advanced Reactor Safeguards program in the DOE Office of Nuclear Energy (NE-5) is motivated to assist vendors in licensing under the existing US (domestic) regulatory body's federal regulations. This report provides concepts, approaches, and recommendations for liquid-fueled molten salt reactor (MSR) vendors to meet the material control and accountability (MC&A) and licensing requirements set forth by the US Nuclear Regulatory Commission (NRC) to possess and handle special nuclear material.

Domestic MC&A is instituted to safeguard special nuclear material (SNM). SNM is defined in the Atomic Energy Act of 1954 as Pu, ^{233}U, or enriched uranium in mass 233 (^{233}U) or 235 (^{235}U), and the NRC follows those definitions [1]. MC&A ensures that the SNM within a facility is not stolen or diverted because these materials can be used in a nuclear weapon. Quantities of SNM are characterized by the NRC on a graded scale based on the ease with which it could be used by an adversary: (1) strategic SNM, (2) SNM of moderate strategic significance, and (3) SNM of low strategic significance.[1] The category of the material in use at a facility dictates the performance-based MC&A criteria needed to properly safeguard the material. The licensee submits the proposal to meet MC&A licensing requirements in a Fundamental Nuclear Material Control (FNMC) plan to the NRC.

Commercial power-producing nuclear reactors in the United States are not required (by exceptions) to submit an FNMC plan. However, the NRC's interpretation of what is defined as a *nuclear reactor*, including an exception to an FNMC plan, will not likely extend to liquid-fueled MSRs. This different treatment is primarily due to the significant difference in fuel form and other operational characteristics compared to solid-fueled reactors with large fuel assemblies that can be counted distinctly.

Therefore, the licensee must determine the type of SNM that will be consumed (e.g., fresh fuel) and produced (e.g., SNM in irradiated salt produced via neutron-capture reactions, waste material, and fuel salt) during the operation of a liquid-fueled MSR. The type and quantity of SNM, the chemical form of the SNM, and the onsite processing of SNM to produce fuel salt should all be considered when developing the FNMC plan. The characteristics of the fuel salt are based on quantitative measurements during inventory balance periods, containment and surveillance, and monitoring of operations to detect diversion.

The FNMC plan must address the main design components, which are categorized using the following considerations:

Irradiated Fuel Salt—Irradiated fuel salt is extremely radioactive and lethal doses would be encountered in short time, thereby deterring or preventing direct access to the material. Irradiated fuel salt can be accessed only with specialized handling equipment (i.e., a hot cell). Monitoring and sampling the SNM within an irradiated fuel salt should be performed during times of planned and unplanned maintenance and drainage and during the process of removing SNM from the reactor containment. Irradiated fuel salt samples should be measured and can be coupled with modeling results to provide a strong case for considering SNM in irradiated fuel salt (reactor containment) as strategic SNM 1B or below (e.g., Category II). Details of how irradiated fuel salt will be transferred from reactor containment to storage tanks and containers should be presented.

[1] Safeguard Categories of SNM, NRC.gov, https://www.nrc.gov/security/domestic/mca/snm.html.

Fresh Fuel—Whether fuel salt ready for direct use (e.g., UF_4 in a salt matrix) or raw fuel salt components to be processed onsite are received, the facility should be able to perform analysis of SNM-bearing salt material, including uranium enrichment, to resolve any discrepancies resulting from gross weight inconsistency, seal failure, or excessive inventory difference. Practical aspects of adding initial and makeup salt, including where and how containers will be opened, where the transfer of fresh fuel salt material will be performed, and how the SNM will be accounted for, must be addressed. Online or batch fueling in which containers of SNM are opened outside of reactor containment or that includes physical barriers preventing access will require more significant material accountancy efforts.

Reactor Containment—Loop-style designs will have more access points to the primary fuel loop and fewer physical barriers, whereas integral designs reduce access points and provide greater intrinsic barriers to access of the fuel salt. All side streams, off-gas systems, drain tanks, and other supporting infrastructure that could contain SNM and that could be located within reactor containment should be monitored to ensure a high likelihood of detecting any fuel salt diversion. Planned and unplanned outages and maintenance periods provide opportunities for quantitative measurements. In particular, inventories based on measurements should be performed during shutdowns and maintenance periods for quantification of SNM in areas where fuel salt is deliberately held/stored and, during extended shutdowns, to determine SNM holdup within the system. Monitoring practices and measurements should be included in the FNMC plan.

Wastes—Irradiated fuel salt removed from containment as waste should be sampled and measured to validate the reactor model. Equipment removed from reactor containment should be measured and surveyed to determine whether any fuel salt holdup contains residual SNM. If SNM is present, then the SNM must be quantified through measurements and included in physical inventories. Details of how irradiated fuel salt will be transferred from reactor containment to storage tanks and containers should be presented.

An MC&A approach requires defined identifiable physical areas to quantity or identify nuclear material being moved into or out of the boundary. Material balance areas (MBAs) should be defined to optimally localize nuclear material losses or thefts and minimize the standard error on the inventory difference. A generalized MC&A approach was developed and is presented for a liquid-fueled MSR. This plan defines

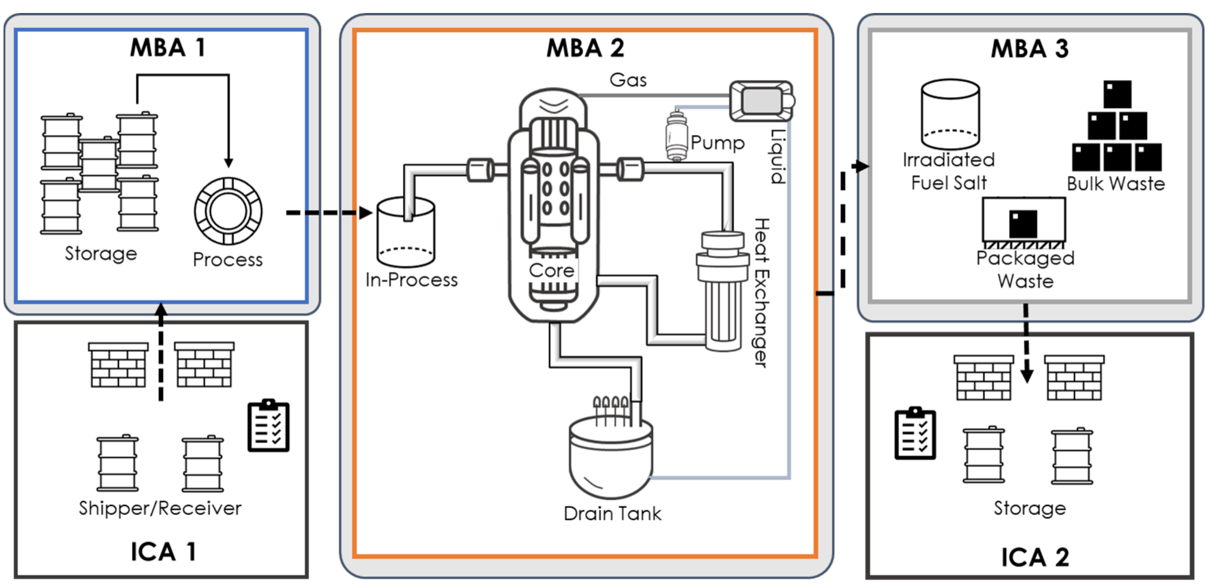

Figure 1. Multiple MBA MC&A approach for a liquid-fueled MSR.

five areas composed of two item control areas (ICAs) and three MBAs as indicated in Figure 1. This divided approach may help to ensure that distinct categories of SNM (e.g., Category III fresh fuel salt vs. Category II irradiated salt) undergo appropriate MC&A to meet requirements. The proposed boundary approach, coupled with suggestions for handling the various types of SNM in the facility, provides the licensee with a framework to apply to their proposed facility.

1. INTRODUCTION

This report provides information, guidance, and technical assistance to vendors, developers, and utilities that can be used in efforts to license a liquid-fueled[2] molten salt reactor (MSR) under the existing US (domestic) regulatory body's federal regulations. This report clarifies the regulations that guide the processing (including utilization) and possession of special nuclear material (SNM) and material control and accountancy (MC&A). The recommendations for US liquid-fueled MSR vendors or designers are based on the licensing process under the US Nuclear Regulatory Commission (NRC), and this document is a compilation from a research and development project funded under the Advanced Reactor Safeguards (ARS) program in US Department of Energy (DOE) Office of Nuclear Energy (NE-5) [2]. The concepts, approaches, and recommendations presented have been formulated by the authors in consultation with members of the NRC and informed by other research efforts supported by the ARS [3, 4, 5, 6].

The licensing process for constructing any domestic nuclear facility involves obtaining construction and operating licenses through engineering design and environmental impact reviews by the NRC. Next, the proposed facility applies for a license through the NRC to possess and utilize SNM. This report focuses on the licensing and regulations for SNM and necessary actions to provide MC&A for SNM.

To possess and utilize SNM, an applicant must develop and demonstrate plans and processes for handling and accounting for that material. The objective of the NRC's safeguards requirements is to ensure that SNM is not stolen or otherwise diverted by, for example, an insider or an individual or group of individuals gaining access to the facility. The facility's proposed methods are developed into a Fundamental Nuclear Material Control (FNMC) plan and submitted to the NRC for approval. The (licensing) approval process involves NRC review of the proposed FNMC plan, iterations with subgroups of the NRC, and private and public hearings.

This report builds on previous research and is organized to facilitate efficient location of a reference, definition, or relevant subject matter expert guidance [7, 8, 9, 10, 11, 12, 13]. The main research findings are provided first and are intended to identify and describe the challenges and differences that a liquid-fueled MSR may face under current licensing regulations.

This report does not address MC&A recommendations to account for International Atomic Energy Agency (IAEA) safeguards obligations. However, if a liquid-fueled MSR will be operated in a country that has a legally binding safeguards agreement with the IAEA, then the IAEA will also apply their own independent safeguards measures to the nuclear material, including both fertile and fissile material, at the facility.

[2] The term salt-fueled may also be found in the literature. They imply the same and can be used interchangeably; essentially that fissile (and/or fertile) material is contained in the molten salt which is also used as the primary coolant for power generation.

2. DOMESTIC MC&A AND LICENSING REGULATIONS

The current code of federal regulations (CFR) in the United States includes multiple pathways to license nuclear power reactors and their supporting fuel cycle facilities (details given in APPENDIX B). First, the construction of a nuclear power plant is licensed and permitted under 10 CFR Part 50–Domestic Licensing of Production and Utilization Facilities [14] or 10 CFR Part 52–Licenses, Certifications, and Approvals for Nuclear Power Plants [15]. Next, the facility requires licensing to possess, handle, or use SNM. This licensing is accomplished under 10 CFR Part 70–Domestic Licensing of Special Nuclear Material [16]. Further, the NRC is currently developing a new regulation: Part 53–Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors for "optional use by applicants for new commercial advanced nuclear reactor licenses by December 31, 2027" [17].

The current domestic fleet of commercial power reactors and fuel enrichment and fabrication facilities all handle SNM. All domestic nuclear power production is accomplished using light-water reactors (LWRs), which include boiling and pressurized water reactors. LWRs use controlled and sustained fission of UO_2 material in pellet form that is enriched in ^{235}U to less than 5 wt %. A fuel rod contains the solid-fuel form (i.e., a cylindrical sintered pellet), and an assembly comprises many fuel rods constrained in a grid. A typical power reactor may contain more than 100 assemblies composed of tens of thousands of fuel rods, which equates to millions of fuel pellets [18].

The NRC requires safeguards programs in place at all licensed facilities in the U.S. to "ensure that [special nuclear material] is not stolen or otherwise diverted from the facility" [19]. The NRC defines SNM as "plutonium, uranium-233, uranium enriched in the isotope U-233 or in the isotope U-235, and any other material which the Commission, pursuant to the provisions of Section 51 of the Atomic Energy Act of 1954, as amended, determines to be special nuclear material, but does not include source material" [19]. SNM MC&A is one component of an NRC safeguards program in addition to physical protection.

Part 74 outlines the requirements for the control and accounting of SNM at fixed sites and for documenting the transfer of SNM. Licensees authorized by the NRC to possess more than 1 ekg (effective kilogram) of SNM (see APPENDIX A) must submit an MC&A plan in the form of an FNMC plan. However, 10 CFR Part 74.31 exempts production and utilization facilities from this requirement. Furthermore, the implications of the NRC's definition of a production and utilization facility (see APPENDIX A for definitions) in 10 CFR Part 50 conveys that a (traditional LWR) nuclear reactor is by default an exception and is not required to develop an FNMC plan for MC&A. When the regulatory framework was developed, the NRC accepted a nuclear reactor to be a facility that uses solid fuel in large assemblies that can be counted (e.g., LWR) [20]. The regulations are not expected to be modified or updated in the near term to accommodate liquid-fueled MSRs.

Furthermore, *the NRC's interpretation of a nuclear reactor and exception from an FNMC plan does not extend to liquid-fueled MSRs due to the significant difference in fuel form and other operational characteristics compared with solid-fueled reactors with fuel in large item forms that can be counted*.[3] There is no existing approved template or NRC document assisting in the development of an FNMC plan for advanced reactors, including liquid-fueled MSRs. MC&A guidance for fuel fabrication and enrichment facilities exists, but liquid-fueled MSRs are expected to be significantly different because the quantities of SNM will dramatically change throughout the reactor's operational cycle.

[3] Discussions with MC&A staff of the NRC.

2.1 NRC DEFINITIONS OF SNM

SNM is categorized by the NRC based on the risk of that material being used directly—or to produce nuclear material for—an explosive device [21]. The NRC distinguishes the risk of the SNM defined by the following safeguards categories.

- Category I: Strategic SNM (SSNM)
  - ≥2 kg Pu
  - ≥5 kg ^{235}U (in U enriched to ≥20 wt % [i.e., highly enriched uranium (HEU)])
  - ≥2 kg ^{233}U
  - ≥5 kg of a *formula quantity* (i.e., [g contained ^{235}U] + 2.5 × [g ^{233}U + g Pu)
  - Divided into IA and IB material [22]. Category IB must meet at least one of the following criteria:
    - unusable without further processing to construct a nuclear explosion device
    - could not be removed from the material access area without detection owing to its size, weight, or chemical hazard
    - excessive quantities would be needed to equate to a formula quantity because SSNM concentrations are too low
- Category II: SNM of moderate strategic significance
  - Less than a formula quantity of strategic SNM but
    - >1 kg of ^{235}U (in U enriched to ≥20 wt %)
    - >0.5 kg of ^{233}U or Pu
    - >1 kg of (g contained ^{235}U) + 2 × (g ^{233}U + g Pu)
    - ≥10 kg ^{235}U (in U enriched to ≥10 wt % but <20 wt %)
- Category III: SNM of low strategic significance
  - Less than an amount of moderate strategic significant but
    - >15 g ^{235}U (in U enriched to ≥20 wt %)
    - >15 g of ^{233}U
    - >15 g of Pu
    - >15 g of (g contained ^{235}U) + (g Pu) + (g ^{233}U)
  - <10 kg but >1 kg of ^{235}U (in U enriched to ≥10 wt % but <20 wt %)
  - ≥10 kg ^{235}U (in U enriched above natural but <10 wt %)

An ekg is sometimes used to define SNM, and its definition is stated in APPENDIX A. As defined, the NRC recognizes that 5 kg of a formula quantity is SSNM. Therefore, the following equivalencies are used:

- For Pu and ^{233}U, a formula quantity is equal to 2 ekg.
- For ^{235}U, a formula quantity varies from 1 ekg (20 wt %) to 5 ekg (100 wt %) because ^{235}U depends on uranium enrichment.

The recommendations in this report are based on the categorical definitions of SNM and the assumption that a liquid-fueled MSR cannot be licensed with a similar 10 CFR Part 50/52 exception that applies to LWRs. Based on publicly available information, most commercial-scale liquid-fueled MSRs will contain Category I (SSNM) or Category II (SNM of moderate strategic significance) material.

2.2 CURRENT REQUIREMENTS FOR MC&A AND FNMC PLANS BASED ON SNM

The category of SNM licensed at a facility directly influences the MC&A requirements. The MC&A requirements included in 10 CFR Part 74 are presented in a graded approach and summarized below for

SSNM, moderate, and low strategic significance material [23]. Applicants are required to submit an FNMC plan that meets the graded performance objectives.

- Category I: SSNM (Subpart E, §74.51) requirements are designed for licensees that possess SSNM, *excluding nuclear reactors licensed under 10 CFR Part 50*, irradiated fuel, reprocessing plant, waste disposal, or a spent fuel storage facility licensed pursuant to 10 CFR Part 72. The objectives for this category are the most demanding.
  - Requires timely detection and rapid determination that the loss of ≥5 kg of a formula quantity has occurred.
  - Requires process monitoring for internal transfers, storage, and processing of SNM.
  - Requires item monitoring, alarm resolution, and quality assurance implementation.
- Category II: Moderate strategic significance (Subpart D, §74.41) requirements are designed for licensees that possess SNM of moderate strategic significance or SNM in a quantity exceeding 1 ekg of SSNM for various facilities (e.g., irradiated fuel reprocessing, waste disposal).
  - Requires internal control, inventory, and records of SNM.
  - Requires an item control program to "assure that SNM items are stored and handled, or subsequently measured, in a manner such that unauthorized removal of 200 grams or more of plutonium or uranium-233 or 300 grams or more of uranium-235, as one or more whole items and/or as SNM removed from containers, will be detected" [23].
- Category III: Low strategic significance (Subpart C, §74.31) requirements are designed for licensees that possess more than 1 ekg of low strategic significance SNM. Special guidelines exist for uranium enrichment facilities.
  - Requires confirming the presence of special nuclear material.
  - Requires resolving indications of missing material.
  - Requires aiding in the investigation and recovery of missing material.

The exclusion of nuclear reactors in 10 CFR Part 50 for SSNM MC&A implies that spent fuel from an LWR contains formula kilograms of SNM. However, these facilities are licensed under the NRC without an approved FNMC plan. All NRC licensees that possess, or who had possessed in the previous reporting period, at least 1 g of SNM must complete and submit Material Balance Reports through the Nuclear Materials Management and Safeguards System [23].

2.2.1 Periodic Inventories

Based on the strategic significance of the SNM at the facility, 10 CFR Part 74 outlines the requirements for the periodicity of physical inventories [23]:

- SNM of low strategic significance: 12 months
- SNM of moderate strategic significance: 9 months
- SSNM: 6 months

Therefore, MSR licensees must perform physical inventories and submit related accountancy reports to the NRC based on the material categorization. Although liquid-fueled MSR operators will likely need to shut down the MSR and perhaps drain the irradiated salt at some periodicity to perform maintenance, the frequency for maintenance is extremely unlikely to be less than or equal to 12 months [7]. A few liquid-fueled MSR designers who have publicly spoken on the subject suggest plans for equipment replacement at a frequency of ≥4 years [10]. Full, static physical inventories (i.e., requiring the reactor to be shut down and the fuel salt drained from the system) likely could not be performed at the frequency required by 10 CFR Part 74. However, the NRC currently allows for dynamic (i.e., non-shutdown) physical inventories of SNM in enrichment plants. Therefore, this research recommends that licensees of liquid-fueled MSRs include plans to perform static inventories whenever reasonable and include dynamic inventories in operational areas (i.e., of irradiated salt within functional containment of the reactor system). For example, the facility's MC&A plan could incorporate static inventories of SNM in fresh fuel salt in containers or irradiated fuel salt in a cooling tank but incorporate dynamic inventories of material within the reactor system.

2.3 INVENTORY DIFFERENCE AND ERROR

In practice, statistical methods are implemented for material balance to ensure that the licensee meets MC&A regulatory requirements. These practices determine the inventory difference (ID), active inventory (AI), and the standard error of the inventory difference (SEID) for SNM in the defined internal control areas[4]. The ID is the book inventory minus the inventory determined during physical inventory:

$$\mathrm{ID} = \mathrm{BI} + \mathrm{A} - \mathrm{R} - \mathrm{EI}, \tag{1}$$

where BI is the beginning/book inventory, A are additions (receipts), R are removals (shipments and/or discards), and EI is the ending (physical) inventory. The ID can be positive or negative, and it is statistically expected to be nonzero because of measurement uncertainties (systematic and random), material holdup, and other unmeasured material loss. The ID is calculated per inventory period based on individual measurements of each type of SNM (e.g., ^{233}U, Pu, ^{235}U).

The AI is used to evaluate the ID and other facility parameters. It is defined as:

$$\mathrm{AI} = \mathrm{BI} + \mathrm{A} + \mathrm{R} + \mathrm{EI} - \mathrm{C}, \tag{2}$$

where C are the common terms (material values) that appear in the active inventory calculation multiple times and come from the same measurement.

The SEID is the variance on the ID, where the variance, σ^2, is the square of the standard deviation (σ). Common statistical practices and definitions are available in the literature [24]. According to rules for error propagation, variances add regardless of the sign and their effect on the ID calculation:

$$\sigma^2(\mathrm{ID}) = \sigma^2(\mathrm{BI}) + \sigma^2(\mathrm{A}) + \sigma^2(\mathrm{R}) + \sigma^2(\mathrm{EI}). \tag{3}$$

Modeling was performed to evaluate ID and SEID of irradiated fuel salt in reactor containment for thermal and fast-spectrum MSRs. A diversion analysis (of removing fuel salt from the primary fuel loop) was also performed [3]. The models were based on bulk measurements taken during periodic inventories. Due to the large amounts of material in the primary fuel loop, even considering a very low measurement error (0.01%), the probability of detecting the diversion solely by using process monitoring measurements of SNM in the fuel salt is low. However, as discussed and presented in Section3.3, diversion of fuel salt from the primary fuel loop (amounts needed to equate to SNM loss of interest) is very improbable and can be accommodated by strict physical boundaries, surveillance, and quantification of the ingoing and outgoing fuel salt and side streams.

An MC&A system for a liquid-fueled MSR should incorporate layers of components for which the probabilities of detection build on each other. Even if online measurements of SNM quantities in fuel salt within functional reactor containment while the reactor is operational do not have a high probability of

[4] Other references (e.g., by the IAEA) may include terms such as material unaccounted for (MUF). MUF is equivalent to ID in definition and mathematical formulation.

detecting theft or diversion, multiple other elements can prevent and/or detect theft of the fuel salt in containment.

In practice, the SEID is used to evaluate the ID value during inventory. SEID and ID stringently require investigation and reporting in the following situations:

- Category I: SSNM:
  - SEID ≥ 0.1% of AI
  - ID exceeds both 3× SEID and 200 g of (Pu or ^{233}U), or 300 g of ^{235}U in HEU
  - Net cumulative shipper/receiver differences accumulated over a 6 month period exceed the 1 kg of a formula quantity or 0.1% percent of the total material received for like material types (i.e., measured by the same measurement system)
- Category II: SNM of moderate strategic significance:
  - SEID ≥ 0.125% of AI
  - ID greater than 3× the SEID and 200 g Pu or ^{233}U, or 300 g ^{235}U in HEU, or 9,000 g ^{235}U in low-enriched uranium (LEU)
- Category III: SNM of low strategic significance:
  - Warning-level: ^{235}U ID ≥ 1.7 SEID + 500 g ^{235}U or U ID ≥ 1.7 SEID + 10 kg of U
  - Significant ID: U or ^{235}U inventory difference ≥ 3 SEID
  - Major ID: ^{235}U ID ≥ detection quantity − 1.3 SEID

2.3.1 A Boundary Case Example

To determine the best categorization of facility boundary areas that minimizes measurement error and improves the MC&A approach, a preliminary analysis of a facility should include calculations using realistic measurement error. A simple example of a batch facility with two parallel processing lines is provided in the literature [25]. The simplified example provides calculations for ID (i.e., MUF) and SEID to demonstrate how MBA selection can affect the plan effectiveness. Schematically, the facility is represented as shown in Figure 2.

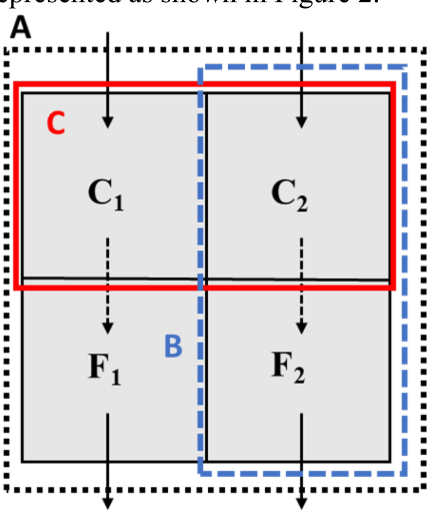

Figure 2. Simplified batch processing plant. Arrows represent material movement, and subscripts represent the processing line. Colored boxes graphically represent the distinction of the MBA selections.

The facility has two parallel identical lines composed of conversion (C) and fabrication (F) processes for material batches. The following calculations assume a fixed measurement uncertainty (±0.25%) and batch inventories (2 kg) and total plant inventory uncertainty of ±0.2% (0.28% for single MBA measurement), but systematic error and measurement covariance were not considered. The inventory period was 2 months with a total of 250 kg. Consider (A) one MBA for the entire facility, (B) two parallel MBAs (C1+F1 and C2+F2), or (C) two series MBAs (C1+C2 and F1+F2). SEID calculations were performed for these hypothetical scenarios. The evaluation is intended to elucidate how the MBA selection affects the SEID and facility material loss rather than to provide an approximation of the ID.

Using Eq. (1) and (3) and the provided material quantities and measurement uncertainties, calculations were performed for each MBA selection, and the results are provided in Table 1. The calculations show that the loss detection capability increased per MBA by separating the facility into multiple MBAs, (501 g and 502 g vs. 708 g). However, the total plant SEID ($SEID_t$) did not change significantly for the two MBA plans. Therefore, the capability to detect loss is afforded for portions of the material but not for the total facility. An ability to detect smaller amounts of material with higher probability is afforded.

Table 1. Calculations of SEID for the three MBAs in Figure 1. RSD is the relative standard deviation.

	BI **[kg]**	***EI*** **[kg]**	$\sigma_{B,E}$ **[g]**	$RSD_{B,E}$ **[%]**	***A*** **[kg]**	***R*** **[kg]**	$\sigma_{A,R}$ **[g]**	**SEID* [g]**	$SEID_t$ **[g]**
A	250	250	500	0.20	60	60	27.4	708	
B	125	125	354	0.28	30	30	19.5	501	709
C	125	125	354	0.28	60	60	27.4	502	710

*This is the facility SEID for A because there is one MBA but for B and C this represents the SEID per MBA.

A mathematical analysis should be performed and considered for liquid-fueled MSRs with circulating fuel defining multiple MBAs (or ICAs) within a facility to improve the capability of detecting loss of SNM in certain process streams or areas. However, resource requirements (e.g., costs, reporting burden, staff time) and practical limitations (e.g., certain process streams are not easily subdivided into separate MBAs) associated with each MBA or ICA must be considered.

2.4 MODIFYING AN FNMC

The approval and implementation of an FNMC plan allows the licensee to change the FNMC plan without NRC approval if any changes do not degrade the plan's effectiveness. The licensee should notify the NRC of any changes. However, if proposed changes to the plan reduce the effectiveness of the MC&A program, then NRC approval is required before implementing the change [20]. In facilities with Category I material (i.e., SSNM), if an MC&A alarm[5] results in loss of SSNM, then the licensee must modify the MC&A system to prevent future similar alarms [26].

Alternatively, the NRC can contact the licensee and request changes to their FNMC plan. The changes may be based on an MC&A alarm or a plan ineffectiveness by the NRC during inspections. The licensee is obligated to consider any such requests and must revise and resubmit their FNMC plan.

2.5 DISCUSSIONS RELATED TO MC&A FOR LIQUID-FUELED MSRS

Recurring meetings between subject matter experts from DOE's Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL), and the NRC's MC&A group have been held to discuss MC&A for liquid-fueled MSRs. One goal of these meetings has been to better understand existing NRC regulations pertaining to MC&A as applied to liquid-fueled MSRs. Another goal has been to identify and discuss details of various elements of an MC&A plan that are most critical to MRSs. Discussions have focused on how and how often periodic physical inventories should be performed, uncertainties of measurements and inventories (i.e., SEID limits), and how potential exemptions from existing regulations might be addressed.

Most FNMC plans that the NRC's MC&A group reviews are for fuel fabrication facilities and enrichment plants; therefore, they are not especially representative of liquid-fueled MSRs. The ORNL and SNL project team and the NRC MC&A group have discussed the potential relevance of the MC&A plan for

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[5]An alarm is "a situation in which there is: (1) an out-of-location item or an item whose integrity has been violated, (2) an indication of a flow of SSNM where there should be none, or (3) a difference between a measured or observed amount or property of material and its corresponding predicted or property value that exceeds a threshold established to provide the detection capability required by § 74.53" [23].

the proposed medical isotope production facility being developed by SHINE Technologies. The design is based on a subcritical assembly that will irradiate SNM in liquid form for production of ^{99}Mo. The facility has been approved and represents a modern bulk processing facility with Category II SNM. Similar components of their FNMC plan likely are appropriate for liquid-fueled MSR facilities.

3. MSR DESIGN AND FACILITY COMPONENTS

A liquid-fueled MSR has various operational components (e.g., off-gas streams, online refueling) that are not present in LWR, enrichment, and fuel fabrication facilities. These facility components may require additional consideration regarding their effect on the ability to account for and control SNM. These considerations depend on how the licensee chooses to implement material boundary and control areas in the FNMC plan. This section includes a description of the operational components and facility- and design-specific elements that are unique to a liquid-fueled MSR.

Multiple process streams exist at an MSR, and each has different types and quantities of SNM. Therefore, process streams and inventories may have different NRC safeguards categories of material at different locations within the facility. The recommendation is that the license applicant propose to leverage the NRC's graded approach for MC&A requirements to incorporate different levels of MC&A rigor into different process streams, based on the category of the material. Other characteristics of the process stream in which SNM is contained, such as the radioactivity levels, concentration of SNM within the material, and the accessibility of the SNM could provide justification for reducing the material categorization [10].

3.1 IRRADIATED FUEL SALT

Irradiated fuel salt from the reactor attains extremely high levels of radioactivity almost instantly. The radioactivity of irradiated salt prevents direct access to the material and must be considered during times of planned and unplanned maintenance and drainage, and for storage of any material removed from the reactor containment. Modeling results provide a strong case for considering SNM in reactor containment as SSNM 1B or below (e.g., Category II).

Modeled inventories from a 550 MW_{th} thermal spectrum 5 wt % ^{235}U LEU loop-style reactor were used to calculate the dose of irradiated fuel salt and the concentrations of SNM in various locations of the process stream in reactor containment [7]. Dose rates of irradiated fuel salt were calculated for the beginning, midpoint, and end of a 5-year reactor cycle. The geometries modeled were the primary fuel loop pipe and the drain tank. Details of the geometry and methods used are described in Dion et al. [7]. The dose rates for the primary fuel loop pipe and drain tank at the beginning of cycle are shown in Figure 3. Not surprisingly, the dose rates are excessive ($\sim 4\times10^5$ rem/h on contact with the primary fuel loop). The irradiated fuel salt for this reactor model and similar designs requires specialized equipment to handle, poses immediate danger and hazard, and is not amenable to direct use without subsequent processing.

In addition to dose and radioactivity concerns, the SNM in the primary fuel loop is in low concentrations during the reactor cycle. Modeled inventories for concentrations of ^{235}U and total Pu (^{233}U for a U/Pu fuel cycle is at trace levels) are shown in Figure 4. In this model, the ^{235}U is kept constant (~3400 μg/g) during the reactor cycle to coarsely model online fueling. The concentration of total Pu in the fuel salt increases during the cycle, reaching a maximum of about 980 μg/g. However, the ^{240}Pu content increases rapidly, and by week 11 in the cycle, the Pu no longer meets the DOE's definition of weapons-grade material [27]. Therefore, it requires substantial processing for direct use if removed from containment.

Suggestions for Irradiated Fuel Salt: Irradiated fuel salt is very radioactive, deterring or preventing direct access to the material. However, monitoring and sampling should be performed during times of planned and unplanned maintenance and drainage and before storage of any material removed from the reactor containment. Samples that can be measured can be coupled with modeling results to provide a strong case for considering SNM in irradiated fuel salt (reactor containment) as strategic SNM 1B or below (e.g., Category II).

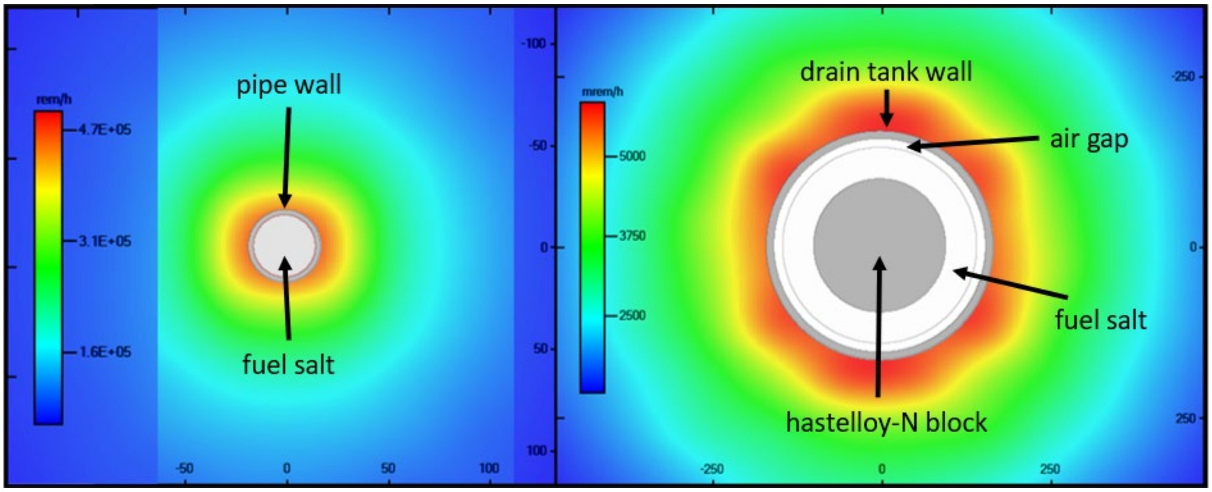

Figure 3. Dose rate contours of the primary fuel loop pipe (left) and the drain tank (right).

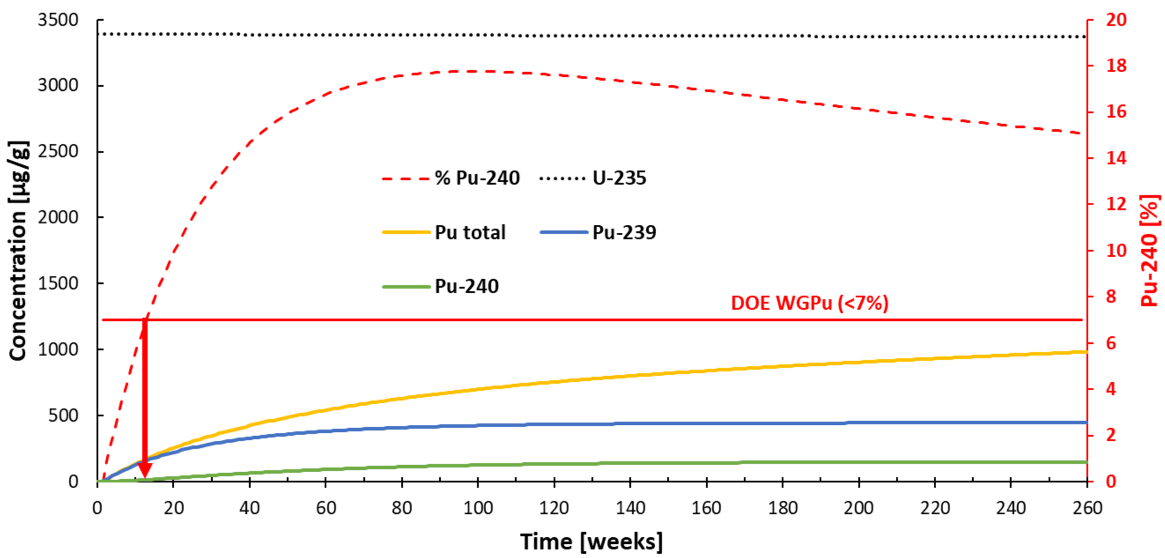

Figure 4. Concentrations of SNM isotopes in the primary fuel loop of the model thermal reactor. The Pu content is not defined as DOE weapons-grade Pu after 11 weeks of operation.

3.2 FRESH FUEL

Fresh fuel, either as initial or makeup fuel, is required in all liquid-fueled MSRs. Breeder designs (e.g., Th/^{233}U) also requires SNM as a driver/starter fuel. To avoid reactor shutdown and maintain output power, many designs perform fueling continuously throughout the reactor cycle. Traditional LWRs receive fuel assemblies from a fuel fabrication facility, whereas MSRs require fresh fuel—potentially in a salt matrix—that is added to the reactor core in batches or continuously. Depending on the enrichment and quantity of ^{235}U in uranium (or Pu or ^{233}U) in the fresh fuel salt, initial and makeup fresh fuel salt may be Category I, Category II (e.g., fuel salt with high-assay low-enriched uranium) or even Category III (e.g., makeup salt with LEU) SNM. Designs that propose to use spent LWR or heavy-water reactor (e.g., CANDU) fuel as initial fuel or designs that plan for reuse of irradiated fuel salt outputs from previous-generation designs may be Category I SNM.

Natural U, depleted U, or Th fuel in makeup salt of breeder designs is not classified as SNM by the NRC and therefore may not be subject to reporting. However, these materials' quantities are intrinsically linked to the quantities of SNM (Pu, ^{233}U) produced within the reactor system. Therefore, the license applicant should maintain detailed accountancy reports for quantities of fertile material to predict the addition (A) term within the ID for the SNM in the MBA associated with the reactor system.

Currently, US fuel fabrication facilities are not equipped to produce fuel for direct use in MSRs. Enriched U is shipped as UF_6 in approved containers in the US (e.g., from enrichment to fuel fabrication facilities). The containers are approved based on enrichment and mass of UF_6 per cylinder [28]. Therefore, the present assumption is that UF_6 would either be delivered to the reactor site for synthesis into a usable form, or a separate processing facility would receive raw material (as input) and transfer useable material (as output) to the reactor site.

Understanding how online or continuous fueling is accomplished is a necessary component of the facility's MC&A plan. One option is to move the fresh fuel containers into a physical boundary (reactor containment) where material would be heated and transferred into the reactor via an automated process. Alternatively, the fresh fuel material could be physically outside of containment, heating and transfer could be accomplished by using piping that breaches into reactor containment and transports the material to the reactor core. These two options present different challenges. The latter method requires more significant MC&A measures because sealed containers are opened outside of the reactor containment physical boundary.

3.2.1 Fresh Fuel Delivery, Receipt, and Storage

Like receipt of UF_6 at a fuel fabrication facility, the MSR facility would receive approved containers of fresh fuel, marked with serial identification, labeled with tare weight of the container, and sealed with a tamper indicating device (TID). The receipt of fresh fuel (SNM) and the SNM inventories would be based on the shipper reported values. Fuel salt ready for use in the reactor would be in the facility's required chemical form, needing only mechanical processing (heating and transfer) for use in the reactor.

3.2.2 Fuel Salt Synthesis/Processing

If the licensee intends to chemically (or by other means) process fresh fuel salt (e.g., UF_6 from a vendor) from raw materials onsite, then that process requires inventories with measurements of all SNM-bearing material with supporting ID and SEID analysis. Two proposed control area methodologies are discussed in Section 4.

Suggestions for Fresh Fuel: All MSRs require fresh fuel, and the proposed method of fuel synthesis and online fueling affect the accountancy requirements. Whether the facility receives fuel salt ready for direct use (e.g., UF_4 in a salt matrix) or raw fuel salt components to be processed onsite (UF_6), the facility should be able to analyze that material (UF_4), including uranium enrichment, to resolve any discrepancies resulting from gross weight inconsistency, seal failure, or excessive ID. The licensee should describe how the reactor will be fueled, where containers will be opened, where the transfer of fresh fuel salt material will be performed, and how the SNM will be accounted for. Online or batch fueling outside of reactor containment or physical barriers preventing access requires more significant material accountancy efforts.

3.3 REACTOR FUNCTIONAL CONTAINMENT

For shielding and security, the reactor core and supporting subsystems are contained in physical barriers. Entry to the containment boundary during reactor operations is not possible without extreme risk and entry through barriers. Any forced entry into containment during operation (and even after shutdown) results in fatal radiation dose, so removal of irradiated fuel salt from containment is very unlikely [7]. The MC&A plan for SNM within containment should include TIDs and surveillance (e.g., cameras) on all entry points—including physical access points to containment and to material entry/exit points (e.g., sampling lines, feed piping to add fresh fuel salt) to detect any entry to or fuel salt removal from containment.

3.3.1 System Design

The design of the MSR reactor type—an integral or loop style—may introduce design features that require extra attention and discussion in the MC&A plan. Integral liquid-fueled MSR designs contain the SNM and fuel salt within a core unit or vessel. Primary heat exchange occurs in the reactor core unit. A loop-style design has an external (outside of the core) primary heat exchanger that uses piping to transport the fuel salt outside the core to the heat exchanger. Designs that include a heat exchanger, off-gas systems, and other chemical processing systems (e.g., Pa/^{233}U separation in some Th/^{233}U designs) outside of the core unit may require additional nuclear material accountancy components. A loop-style MSR has substantially more piping, valves, and infrastructure external to the core. These components present access points to the SNM (liquid fuel). TIDs and surveillance should be used on all valves and any additional access points to protect and monitor the SNM-bearing pipes.

3.3.2 Secondary Reactor Systems

Auxiliary and/or secondary systems within reactor containment that may or do contain SNM should be minimized, especially if online measurements are not part of the MC&A plan. These side streams could present opportunities for holdup of molten salt, which may contain SNM and should therefore be minimized. During shutdown and/or inventory, side-stream pipes could be measured to evaluate levels of holdup. Therefore, access to these streams (for measurements) or in situ monitoring should be considered in the reactor design.

3.3.3 Off-Gas System

MSR designs that propose to have off-gas sparge systems for removal of noble gases and metals from the molten salt primary fuel loop should monitor the system, including major processing components, for consistent operations and to ensure that fuel salt or SNM is not diverted out of containment. SNM becomes entrained in the system and requires liquid/gas separation to subsequently recirculate the liquid salt back into the primary loop. This system poses a potential for SNM holdup and requires measurements and monitoring during outages and maintenance periods. If the licensee monitors the off-gas stream for operational purposes, then this data should also be used for MC&A and included in the FNMC plan.

3.3.4 Sampling Ports

Sampling ports on the primary fuel loop present direct access to the molten fuel salt–containing SNM. The sampling ports could be used to analyze the fuel salt during operation. These measurements provide a means to verify computational burnup codes and/or understand isotopic production and inventories in the primary fuel loop. The sampling ports require TIDs, surveillance, and physical security measures to prevent unauthorized access and potential removal of SNM.

3.3.5 Heat Sinks and Other Storage Volumes

Drain tanks, heat sinks, and other storage volumes that contain or store fuel salt or any other material that contains SNM require MC&A measures. Static physical inventories on these volumes that may contain SNM should be performed during planned and unplanned outages and maintenance periods to quantify SNM in the fuel salt or as holdup.

> *Suggestions for Reactor Containment:* Loop-style designs have more access points to the primary fuel loop and fewer physical barriers to the SNM in reactor containment. Integral designs reduce access points and provide greater intrinsic barriers to fuel salt access and could be advantageous because the SNM is contained in a high-radiation area. Side streams, off-gas systems, drain tanks, and other supporting infrastructure within reactor containment should be monitored for consistent operation and to ensure a high likelihood of detecting fuel salt diversion. The SNM in these systems must be quantified during planned and unplanned outages and maintenance periods. Monitoring practices and measurements should be included in the FNMC plan. Inventories based on measurements should be performed during outages, shutdowns, and other maintenance periods to determine SNM holdup and to quantify SNM in areas where fuel salt is deliberately held/stored.

3.4 WASTE FUEL SALT, EQUIPMENT, AND STORAGE

Irradiated fuel salt and expired or out-of-service equipment that is removed from reactor containment must be stored, and any SNM within the equipment must be accounted for. All material or equipment with residual SNM must be stored in tamper-evident containers. Once in storage, physical inventories and weights of the items are required at regular intervals based on the category of SNM (e.g., 6, 9, or 12 months). Any weight discrepancy from a previous material balance period requires quantitative measurements. Irradiated fuel salt is highly radioactive and may require specialized equipment for handling.

3.4.1 Irradiated Salt Handling

Irradiated fuel salt is highly radioactive and requires remote handling or automated processes to move the salt out of reactor containment. The FNMC plan should contain details of the transfer of irradiated fuel salt from reactor/functional containment to storage, transfer off-site, or potentially to a salt processing area (e.g., for conditioning into a stable waste form). Like the online fueling case, the licensee should consider how the irradiated fuel salt will be removed from the physical reactor containment boundary and transferred to approved storage containers. The licensee should also consider whether the transfer will take place within containment with a sealed container being transferred out of containment or whether a pipe breach containment will be required to transfer irradiated fuel salt into an approved container outside of reactor containment.

The licensee could take the opportunity to measure the SNM mass and isotope abundances of the irradiated fuel salt to validate or parameterize the reactor model. These measurements could be used to reduce the uncertainties in computational models, which can be used to predict SNM values contained in irradiated fuel salt.

3.4.2 Waste Streams

Other waste streams from reactor containment (e.g., off-gas waste) are radioactive and may contain SNM. If the facility performs fresh fuel processing or synthesis, then waste from those processes may contain SNM. Any waste removed from physical containment should be measured to determine whether SNM is present. If the waste contains SNM, then it must be inventoried for MC&A purposes. If the waste is stored onsite, then periodic weights must be performed and recorded while the material is in storage, as determined by the SNM category.

3.4.3 Out-of-Service Equipment

Out-of-service, damaged, or replaced equipment or other consumables from the facility may contain SNM. Storage containers and TIDs for used equipment and waste material may be different than what is required for irradiated fuel salt storage. Measurements should be performed to determine whether SNM is present and documented. If SNM is present, then periodic inventories and weights must be performed and recorded while the material is in storage, according to the FNMC plan.

Suggestions for Wastes: The FNMC plan should include details for measurements on all waste streams to determine whether SNM is present. Irradiated fuel salt should be sampled and measured to validate the reactor model. Equipment removed from reactor containment should be measured and surveyed to determine whether any SNM-containing fuel salt holdup is present. If SNM is present, then the SNM must be quantified and included in physical inventories. The details of how irradiated fuel salt is transferred from reactor containment to storage tanks and containers may affect the MC&A plan. Therefore, the licensee should incorporate the details of their proposed system in the FNMC plan.

3.5 OPERATIONAL MEASUREMENTS AND REPORTING REQUIREMENTS

The MSR facility requires operational measurements to baseline and monitor operations (e.g., power, temperatures, flow rates) for non-safeguards purposes. These data could become dual use and valuable to the MC&A program and should be included in the FNMC plan.

Demonstration-type reactors should incorporate more measurement points for operational needs and validation of reactor physics models. More-accurate reactor models allow for lower uncertainties in predicted SNM values within irradiated salt. The licensee must include monitoring of operational parameters (e.g., power, temperature, flow rates) within their MC&A plan because these parameters directly influence the quantities of SNM that are produced and removed. If reactor physics models prove to be accurate (potentially after years of validation from operational reactors), then a licensee's FNMC plan for inventories could include measurements of samples of irradiated salt from within the operational reactor system and could compare SNM quantities against predicted values obtained via a computational model informed by operational parameters.

3.6 MODELING AND SIMULATION

MSR operators and vendors require methods to model the dynamic thermal-hydraulic system so that characteristics such as fuel utilization, fresh fuel needs, decay heat, and isotopic inventories of spent fuel can be understood. Modeling and simulation tools must developed and used well before the licensing phase to optimize the reactor design [29]. These tools must be updated as experimental test reactors are constructed and used for preliminary validation. The developers require modeling tools, and the NRC "staff must have adequate computer models and other analytical resources to conduct its review of non-LWR designs in an independent manner" [30]. The evaluations of a new design performed by the NRC include accident scenarios, safety margins, and other hypothetical events. For MSRs, some examples of events requiring investigation are [30]

- Loss of forced flow or coolant
- Unprotected loss of flow
- Inadvertent reactivity insertion transients
- Over-cooling events and partial fuel solidification
- Station blackout
- Loss of heat sink

Therefore, the ability to accurately model and simulate a liquid-fueled MSR allows the vendor to optimize the design and efficiency and to provide the NRC a method of evaluating the safe practice of the design. The use of the developed modeling and simulation efforts are neither expected nor recommended to stop after the licensing phase. Instead, these tools will become an important component of the FNMC plan.

The modeling and simulation tools developed for the reactor provide isotopic inventories at various locations of the facility during operation. Accurate initial fuel loading, consideration for online fueling, and accounting for any SNM in side streams in reactor containment are required. Therefore, the modeling methodology provides a declared initial predicated value of SNM in the reactor core and boundary area (i.e., reactor containment). During operation, the model predictions are used and compared with operational measurements (e.g., thermal power, in-core/out-core neutron flux) and can be used to produce dynamic SNM inventories. The modeled isotope inventories are compared with measurements (either destructive or non-destructive) of irradiated spent fuel removed from reactor containment. Any statistically significant discrepancies between the model and measurements can be used to validate and verify the modeling tool. This capability is not available for LWRs because of the fuel characteristics (large fuel assemblies, high radioactivity) that provide some of the licensing exceptions.

4. PROPOSED MATERIAL BOUNDARY AREA DESIGNATIONS

Domestic licensing of a liquid-fueled MSR under NRC regulations requires an FNMC plan. Furthermore, to meet NRC MC&A requirements, the licensee must divide the facility into designated internal control areas. The internal control areas can be assigned as an MBA or ICA [31]. This is required if the licensee will possess greater than 1 ekg of SNM. Section 70.58 of 10 CFR requires the following [25]:

- Each MBA is an identifiable physical area, and the quantity of nuclear material being moved into or out can be represented by measurement.
- The number of MBAs should localize nuclear material losses or thefts.
- All nuclear material within an MBA or ICA is the responsibility of an individual.
- For previously determined SNM quantities, ICAs established to control material into and out of such areas and be item identity and count. TIDs are applied to containers unless the items are sealed sources.

Boundary areas should be developed and defined to minimize loss and provide a means to locate the material loss by measurements if loss occurs. Another consideration is the development of the appropriate number of boundary areas to establish the ID and the SEID. These measurement control program parameters and their required values change based on the type and category of the facility (or of the SNM being utilized or processed). For SNM of moderate strategic significance (Category II facility), the occurrence of SEID > 0.125% of the active inventory or an ID greater than 3× the SEID and 200 g of Pu or ^{233}U or 300 g of ^{235}U in HEU, or 9000 g of ^{235}U in LEU requires the licensee to officially notify the NRC.

Generally, a good starting point for determining a facility's boundary and/or control areas is to understand the type of material being held or processed and the flow of that material in the facility. Evaluating the material type includes parameters such as physical or chemical form, whether the material has been irradiated or not (e.g., fresh fuel), packaging, and considerations for how measurements would be performed.

4.1 RECOMMENDED APPROACH: MIXED CONTROL AND BOUNDARY AREAS

The NRC does not advise the licensee or require a certain number or type of internal control areas that must be included in an FNMC plan. No NRC license applications have been submitted for a liquid-fueled MSR, and the NUREGs outlining recommendations for FNMC plans do not directly address liquid-fueled MSRs. Therefore, each vendor/licensee must evaluate the current domestic regulations and determine the combination of MBAs and ICAs that provides the highest level or material control by reducing SEID and that enables locating any loss of SNM.

4.1.1 Single MBA

Previous research presented a simplified material balance for a liquid-fueled MSR based on the Molten Salt Demonstration Reactor (MSDR) [7]. That plan was applied to the MSDR to develop an MC&A approach. The MSDR is a loop-style thermal-spectrum LEU-fueled model. The analysis considered only the features that are contained in the MSDR and did not consider components that were not modeled (e.g., fresh fuel receipt, online refueling). The approach considered the entire plant as an MBA with three internal control areas. The three areas, along with a description of the components contained in each, are shown in Figure 5. The movement of material through the facility is indicated by the arrows at the bottom of the figure.

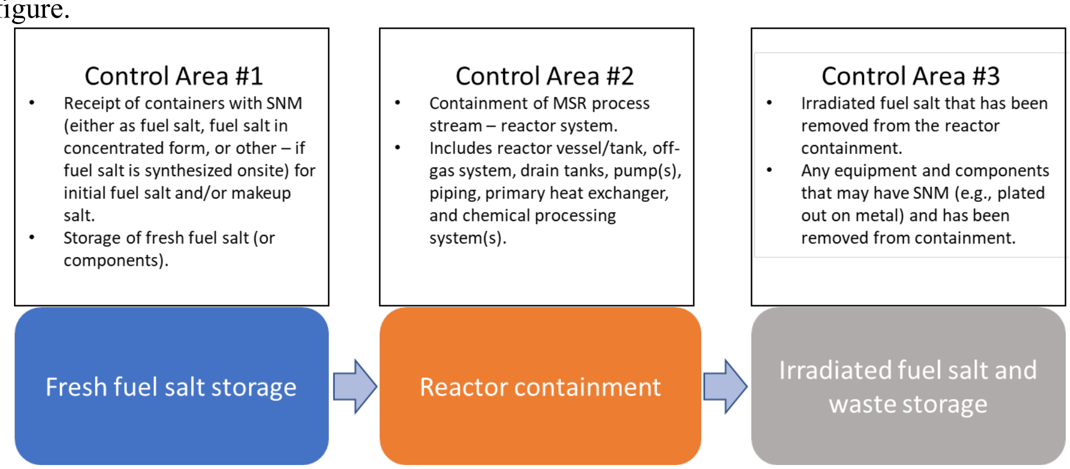

Figure 5. An approach for material mass balance and control areas within one MBA for a liquid-fueled MSR.

A facility requires barriers between control areas—they can simply be a marking on the floor—but physical barriers are encouraged to localize material in the event of material loss or investigation. Graphically, the single MBA approach is shown in Figure 6. Each control area handles SNM. The categorization of SNM in the control areas varies by design (especially in control area #1).

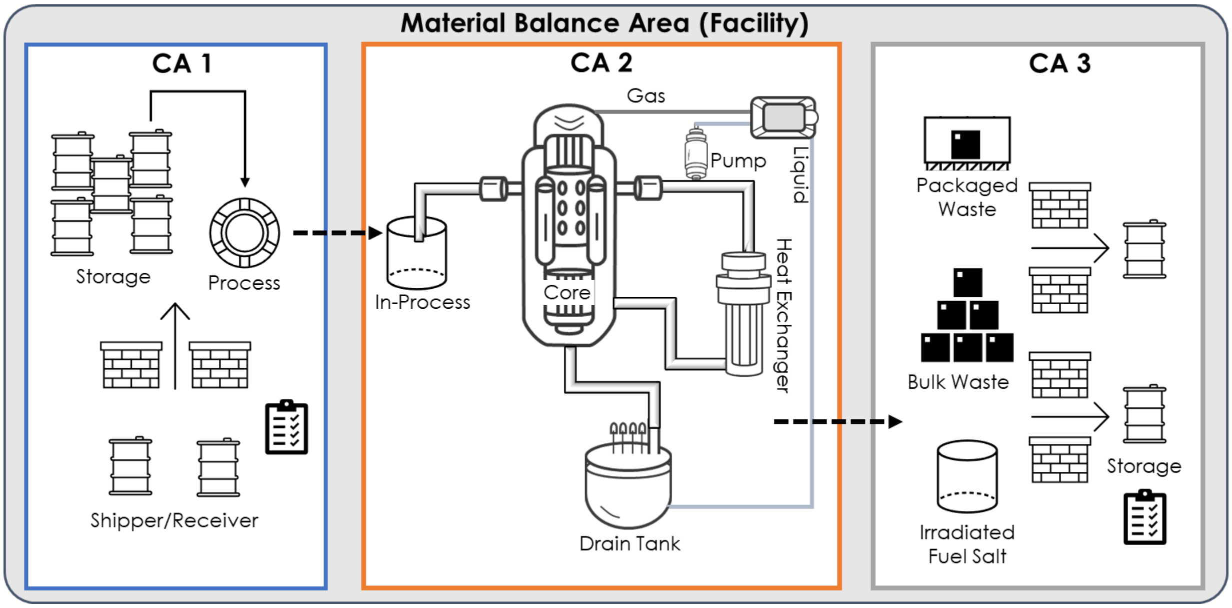

Figure 6. Components of the initial MC&A approach applied to the MSDR. Three control areas (CAs) divide the facility-wide MBA. Dotted arrows indicate material movement across the CA boundary which would require a measuring the SNM.

4.1.2 Multiple MBAs

For some designs, the single-MBA approach may be sufficient. However, the FNMC plan containing the MC&A approach should consider the best method of dividing a facility into areas that minimize the SEID and provide the best means to localize material inventories. For a licensee that intends to process and synthesize fuel salt after receipt of a raw product (e.g., UF_6), the separation of CA 1 into two separate areas may provide a better means to localize material inventory (or loss), store the raw material as an item after receipt, and support distinct physical boundaries based on material type/processing. Moreover, a further divided approach may better facilitate distinct SNM categories (e.g., Category III fresh fuel salt vs. Category II irradiated salt) such that more rigorous MC&A could be applied to material that had more strategic significance. A modified approach with further categorization is shown in Figure 7.

4.1.2.1 Internal Control Area 1: Fresh Fuel Receipt and Storage

All SNM is received in serialized containers with TIDs. Upon receipt of SNM, those items are measured, weights are recorded and compared with shipper declarations, and the TIDs are verified. If items are moved and transferred to other ICAs or MBAs, then those items should be measured (weighed) on the same instruments. Any weight discrepancy of statistical significance requires investigation. Security features—such as administrative controls, including restricted personnel access, two-person entry requirements, and monitored entry—should be incorporated to limit access to the SNM. Security cameras could be added as a surveillance feature to monitor access to the ICA and improve material protection. Periodic inventories would be required to verify TIDs and to weigh items.

4.1.2.2 Material Balance Area 1: Fresh Fuel Processing

Items from ICA 1 are moved to MBA 1 for processing. The material from ICA 1 is processed for fresh fuel (or makeup fuel) feed into MBA 2. The SNM quantities to the MBA could be based on shipper values (see above) and balanced against the feed rate to the primary loop via measurements (e.g.,

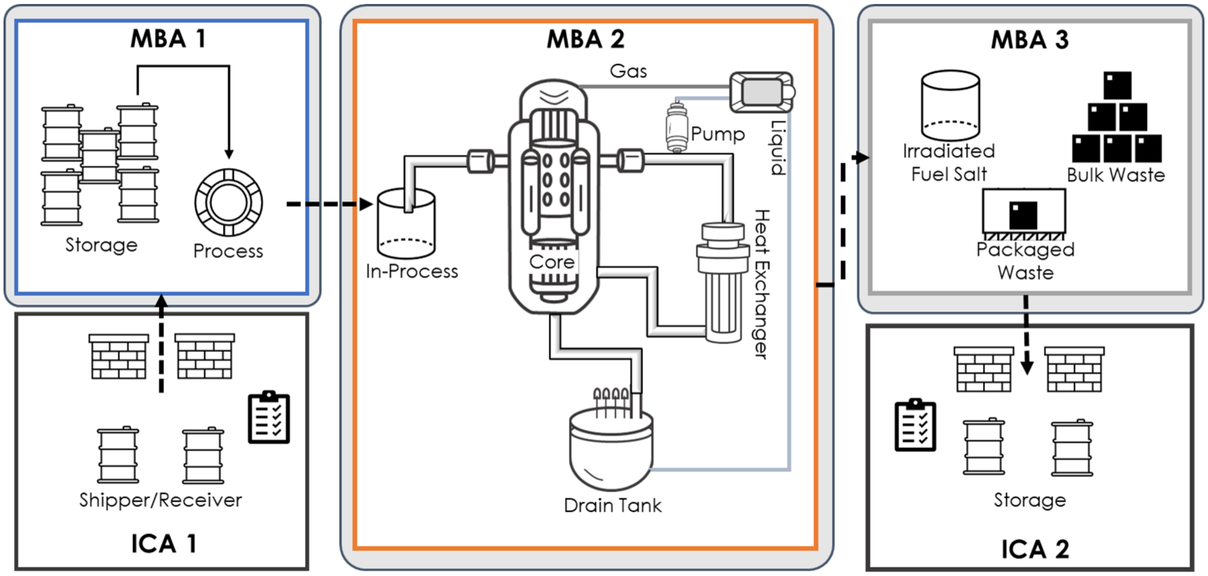

Figure 7. Multiple MBA MC&A approach for a liquid-fueled MSR.

destructive analysis of fresh fuel samples and weight of fuel salt added to the system). MBA 1 requires ID and SEID calculations for each type of SNM during periodic inventories.

4.1.2.3 Material Balance Area 2: Reactor Loop/Core Containment

Irradiated fuel salt is very radioactive, and it is generally inaccessible within reactor containment. It is disadvantageous (or maybe impossible) to shut down and/or drain a liquid-fueled MSR on specified periodic time frames to support static periodical physical inventories to meet NRC MC&A requirements. SNM in MBA 2 is controlled via (i) containment and surveillance, (ii) measurements of all SNM entering or leaving the MBA boundaries, and (iii) surveillance monitoring to detect any diversion of material outside of the MBA.

(i) All physical access points to the MBA must be strictly controlled by using physical and administrative protections. All material entry/exit points (e.g., piping from MBA 1) include TIDs on all valves, administrative controls related to operating the valves, and surveillance cameras to detect operation of any valve.

(ii) If fresh and/or makeup fuel is physically transferred from the sealed container in MBA 1 to MBA 2 through piping, any fuel salt would be measured (weights and isotopic assays) to obtain the quantities of SNM entering MBA 2. Any SNM in process or side streams leaving MBA 2 should also be quantified.

(iii) A diversion path analysis could identify any potential paths to divert SNM from within reactor containment (e.g., through a sampling port). MC&A elements should be placed on these pathways to ensure that multiple independent methods exist for detecting diversion of SNM through each potential path. These methods might incorporate measurements, containment, or surveillance elements and should be described in the FNMC plan.

A dynamic inventory could be reported to the NRC by combining additions and removals from the MBA with quantities of SNM that are produced and depleted via fuel utilization, as estimated by the computational model of the reactor. Thus, the material balance for MBA 2 for each material balance period during operation would be zero, resulting in ID and SEID of zero within the operational time. Coupling a dynamic inventory with computational models and quantification of SNM input from MBA 1 and output to MBA 3 alleviates concerns of excessive SEID, as studied with ideal measurement conditions.

Full inventory measurements must be performed in the event of planned and unplanned reactor shutdown and drain. License applicants should incorporate methods to quantify each type of SNM in the fuel salt in the event of a reactor drain. For example, drain tank levels could be measured and used for total volume calculations and combined with destructive analysis of fuel salt samples, or specialized equipment could perform in situ measurements to quantify SNM within the fuel salt [4, 5, 32]. If the fuel salt containing SNM remains in this tank for extended periods of time, then static physical inventories could be performed for each material balance period, as determined based on the SNM category (i.e., every 9 months if Category II SNM).

If excessive ID is found consistently, then the models must be modified and adjusted to account for the fuel salt properties that cause the large measurement error.

4.1.2.4 Material Balance Area 3: Waste Output and Packaging

Irradiated fuel salt and other waste removed from MBA 2 must be weighed. Samples of irradiated fuel must be measured as an accountability measurement from MBA 2 and as an output (removal) from MBA 2 and input (addition) to MBA 3. Serialized containers with TIDs contain irradiated fuel salt after any sampling. No (re)measurements are conducted unless the container is opened or a discrepancy or another issue is identified. In the event of a problem or a discrepancy, a verification measurement must be performed. If the verification measurements are consistent and the container weight fails verification, then an approved accounting record change must be recorded. If the verification measurement passes, then the original measurement would be retained. All the reportable SNM types are recorded on their own legers as measurements are performed. At the end of the year, a miscellaneous receipt must be created to reflect the creation/transmutation/degradation from MBA 2. This change yields a material balance of zero for each material balance period. This methodology benefits from carefully measuring the SNM masses and isotopic relative abundances used to validate or parameterize the reactor model.

4.1.2.5 Internal Control Area 2: Waste Receipt and Storage

All material is received from MBA 3 in serialized containers with TIDs. All items are measured, gross weights are recorded, and the TIDs are checked for integrity. If items are moved and transferred, then those items are measured (weighed) on the same instruments. Any weight discrepancy requires investigation. Physical protection and boundaries—such as administrative controls, including restricted personnel access, two-person entry requirements, and monitored entry—should be incorporated to limit access to the SNM. Security cameras could be added as a surveillance feature to monitor access to material.

5. FNMC PLAN RECOMMENDATIONS AND CONCLUSIONS

US domestic licensing requirements for production and utilization facilities and nuclear reactors are contained in the CFRs mainly under Part 50 or 52. For MC&A of SNM, the requirements are mainly under Parts 70 and 74. Liquid-fueled MSRs require an FNMC plan that provides necessary information to properly control and account for the SNM (i.e., prevent theft or diversion) and meet the MC&A requirements per NRC regulations. Currently, this licensing protocol presents a challenge because the NRC MC&A regulations have not been updated to accommodate advanced reactors (including MSRs). Because no liquid-fueled MSRs have been previously licensed, no template or precedence exists for such an FNMC plan. However, the licensee can take advantage of the NRC's published commitment to performance-based regulations and the NRC's intention to complete 10 CFR Part 53, Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors. Furthermore, considering MC&A practices early in the design phase should reduce implementation costs.

A discussion of several of the distinguishing characteristics of liquid-fueled MSRs focused on how these design components should be integrated into the FNMC plan. Physical boundaries (e.g., within reactor containment) coupled with radiological hazards and expected low concentrations of SNM (and Pu isotopics over time) in the irradiated fuel salt should be considered as features that inherently prevent theft, diversion, or usefulness of the material. It is critical to ensure that all accessible material that does or may contain SNM is quantified directly or by sampling the fuel salt for measurements. This fuel salt includes, but is not limited to, fresh and makeup fuel salt entering the reactor core, side streams in reactor containment that may contain SNM, and irradiated fuel salt or components leaving reactor containment.

The licensee/applicant should consider the best method of dividing their facility into internal control areas (i.e., MBAs and ICAs) that minimize the SEID and provide the best means to localize material inventories. A generic methodology was presented that divided a facility into five distinct areas: two ICAs (Fresh Fuel Receipt and Storage and Waste Receipt and Storage) and three MBAs (Fresh Fuel Processing, Reactor Loop/Core Containment, and Waste Output and Packaging). This approach integrates measurements to quantify all SNM entering and leaving the reactor core coupled with intensive modeling techniques to avoid periodic static inventory balances of the SNM in-process. It provides the licensee a unique opportunity to validate and verify their reactor depletion model by using quantitative measurements of irradiated fuel salt. Current methods to receive SNM as fresh fuel and to package and store waste material were used in the two ICAs. The FNMC plan and development is unique for each facility, but the presented approach provides a starting point. The licensee should provide predicted SNM produced and consumed within rector containment, supplemented with periodic static physical inventories (with ID and SEID calculations) for each MBA outside of reactor containment.

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APPENDIX A. KEY TERMS

APPENDIX A. KEY TERMS

This appendix is a glossary of terms relevant to MC&A and NRC licensing requirements. It is intended to be a collection of terms whose definitions are dispersed across various NRC publications. The definitions below are also adapted from NRC publications in order to offer practical interpretations and provide an understanding of the significance of the term or concept.

Active inventory (AI): Inventory that has changed within the material balance period. Used to evaluate the significance of IDs and to indicate processing throughput, measurement activity, or both. AI is the sum of beginning inventory (BI), additions to inventory (A), removals from inventory (R), and ending inventory (EI), after all common terms (C) have been excluded. AI is defined by the following equation:

$$AI = BI + A + R + EI - C$$

Common terms are material values or items that appear more than once in the ID equation and in components with opposite signs (i.e., in both BI and EI, or both BI and R, or both A and R, or both A and EI) and come from the same measurement. Common terms are removed from the calculation because they do not contribute to the uncertainty associated with the current period ID. For example, if an item appears in both BI and EI at the same value, it cannot have contributed to the ID or SEID because these quantities cancel each other [31].

Categories of special nuclear material (SNM): These categories apply both to 10 CFR Part 73 (Physical Protection of Plants and Materials) and Part 74 (Material Control and Accounting of Special Nuclear Materials) [31].

- Category I: Strategic SNM (SSNM)
  - ≥2 kg Pu
  - ≥5 kg 235U (in U enriched to ≥20 wt %)
  - ≥2 kg 233U
  - ≥5 kg (i.e., a formula quantity) = (g contained 235U) + 2.5 × (g 233U + g Pu)
  - NUREG-1280 describes how this category is further divided into IA and IB material. IB material must meet at least one of the following criteria:
    - unusable for constructing a nuclear explosive device without further processing
    - not susceptible to undetected removal from the MBA by an insider because of size, weight, or chemical hazard
    - of such low concentrations of SSNM that excessively large bulk quantities would be needed to obtain a formula quantity of SSNM
- Category II: SNM of moderate strategic significance
  - Less than a formula quantity of strategic SNM but
    - >1 kg of ^{235}U (in U enriched to ≥20 wt %)
    - >0.5 kg of ^{233}U or Pu
    - >1 kg = (g contained ^{235}U) + 2 × (g ^{233}U + g Pu)
    - ≥10 kg ^{235}U (in U enriched to ≥10 wt % but <20 wt %)
- Category III: SNM of low strategic significance
  - Less than an amount of moderate strategic significant but
    - >15 g ^{235}U (in U enriched to ≥20 wt %)
    - >15 g of ^{233}U
    - >15 g of Pu
    - >15 g = (g contained ^{235}U) + (g Pu) + (g ^{233}U)
  - <10 kg but >1 kg of ^{235}U (in U enriched to ≥10 wt % but <20 wt %)

- ≥10 kg ^{235}U (in U enriched above natural but <10 wt %)

Dynamic inventory: An inventory often implemented in facilities like enrichment plants where an inventory is conducted during operations. In practice, this is the opposite of a static inventory [31].

Effective kilogram (ekg) of SNM:

- For plutonium and ^{233}U, their weight in kilograms;
- For uranium with an enrichment in the isotope ^{235}U of 1 wt % and above, its element weight in kilograms multiplied by the square of its enrichment expressed as a decimal weight fraction; and
- For uranium with an enrichment in the isotope ^{235}U below 1 wt %, its element weight in kilograms multiplied by 0.0001 [26].

Fundamental Nuclear Material Control plan:

- A Fundamental Nuclear Material Control (FNMC) plan describes what the licensee will do to control and account for the special nuclear material and how the licensee will do it.
- An FNMC plan is required for all licensees authorized to possess more than 1 ekg of SNM. Historically, the NRC has made exceptions for production or utilization facilities (including nuclear reactors) or for operations involved in waste disposal. However, because of the nonfixed fuel and processing potential involved in liquid-fueled MSRs, the NRC will likely require a liquid-fueled MSR licensee to submit a plan describing their facility's proposed MC&A plan with their license application.
- NRC's acceptance criteria for FNMC plans and related information is found in the following documents, none of which are directly relevant to liquid-fueled MSRs:
  - NUREG-2159, Acceptable Standard Format and Content for the Fundamental Nuclear Material Control Plan Required for Special Nuclear Material of Moderate Strategic Significance
  - NUREG-1065, Acceptable Standard Format and Content for Fundamental Nuclear Material Control (FNMC) Plan Required for Low-Enriched Uranium Facilities
  - NUREG-1280, Standard Format and Content/Acceptance Criteria for the Material Control and Accounting Reform Amendment
  - NUREG/CR-5734, Recommendations to the NRC on Acceptable Standard Format and Content for the Fundamental Nuclear Material Control Plan Required for Low-Enriched Uranium Enrichment Facilities

Internal control area: Term used in 10 CFR Part 74, NUREG-2159, and elsewhere in NRC documents that refers to either an item control area (ICA) or a material balance area (MBA). The license applicant designates MBAs and ICAs within their FNMC plan and can interpret internal control area in the generic NRC publications

Inventory difference (ID): The difference between the measured inventory and the book inventory for the material balance period in question. 10 CFR Part 74 includes thresholds for ID that, if exceeded, require reporting to the NRC. Book inventory quantity is equivalent to the beginning inventory (BI) plus additions to inventory (A) minus removals from inventory (R), whereas the physical inventory quantity is the ending inventory (EI) for the material balance period in question (as physically determined). Thus mathematically,

$$ID = (BI + A - R) - EI \text{ or}$$

$$ID = BI + A - R - EI \text{ [26].}$$

The ID will almost never be zero because of the following issues [31]:

- Measurement uncertainties from measurement systems
- Incorrect measurements and improper measurement techniques
- Recording errors or analyst errors
- Unmeasured residual process holdup
- Unmeasured losses

Item control area (ICA): An identifiable physical area for the storage and control of SNM items. Control of items moving into or out of an ICA is by item identity and SNM quantity as determined from previous measurement [31].

Material balance area (MBA): An identifiable physical area for the physical and administrative control of nuclear material such that the quantity of nuclear material being moved into or out of the MBA is represented by a measured value (for both element and isotope) [31].

Material balance period: Period between two physical inventories. The NRC's required periodicity of physical inventories is defined in 10 CFR Part 74 and based on the strategic significance category of the SNM.

Nuclear power plant: A facility used for generating electricity with a nuclear reactor as the heat source. The heat source generates steam to drive a turbine generator.

Nuclear reactor: The energy producing center of a nuclear power plant that uses nuclear fission in a controlled self-sustaining reaction. Nuclear reactors require the use of fissionable material as fuel, and may require moderators, reflectors, and coolant for heat removal.

Physical inventory: The quantity of special nuclear material on hand at a given time, determined on a measured basis. The methods of physical inventory and associated measurements vary, depending on the material to be inventoried and the process involved [26].

Production facility [14]**:**

(1) Any nuclear reactor designed or used primarily for the formation of plutonium or ^{233}U; or
(2) Any facility designed or used for the separation of the isotopes of plutonium, except laboratory-scale facilities designed or used for experimental or analytical purposes only; or
(3) Any facility designed or used for the processing of irradiated materials containing SNM, except (i) laboratory-scale facilities designed or used for experimental or analytical purposes, (ii) facilities in which the only special nuclear materials contained in the irradiated material to be processed are uranium enriched in the isotope ^{235}U and plutonium produced by the irradiation, if the material processed contains not more than 10^{-6} g plutonium per gram of ^{235}U and has fission product activity not in excess of 0.25 mCi of fission products per gram of ^{235}U, and (iii) facilities in which processing is conducted pursuant to a license issued under parts 30 and 70 of 10 CFR, or equivalent regulations of an Agreement State, for the receipt, possession, use, and transfer of irradiated special nuclear material, which authorizes the processing of the irradiated material on a batch basis for the separation of selected fission products and limits the process batch to not more than 100 g of uranium enriched in ^{235}U and not more than 15 g of any other special nuclear material.

Shipper-receiver difference: The difference between the quantity of SNM a sending facility (i.e., shipper) claims was contained in a shipment and the quantity of SNM the receiving facility claims was received, where both the shipper's and receiver's values are based on measurement [31]. The 10 CFR Part

74 outlines requirements for recording these values, addressing discrepancies, and notifying the NRC when values exceed certain thresholds based on the category of SNM.

Special nuclear material (SNM):

(1) Plutonium, ^{233}U, uranium enriched in the isotope ^{233}U or in the isotope ^{235}U, and any other material which the Commission, pursuant to the provisions of Section 51 of the Atomic Energy Act of 1954, as amended, determines to be special nuclear material, but does not include source material; or
(2) Any material artificially enriched by any of the foregoing but that does not include source material [26].

Standard error of the inventory difference (SEID): The standard deviation of an inventory difference that takes into account all measurement error contributions to the ID.

Utilization facility:

(1) Any nuclear reactor other than one designed or used primarily for the formation of plutonium or ^{233}U or

An accelerator-driven subcritical operating assembly used for the irradiation of materials containing SNM. One application is described in a recent application assigned docket number 50–608 [33].

APPENDIX B. REGULATORY BODY

APPENDIX B. US REGULATORY BODY

The US Nuclear Regulatory Commission (NRC) documents contain practices, definitions, and guidelines for the current licensing process for nuclear reactors and for production and utilization facilities. Provided in this section are the regulatory documents used for this report and those that provide valuable information and references for a licensee/vendor of a liquid-fueled molten salt reactor (MSR). The code of federal regulations (CFR) documents presents the official and complete text of federal agency regulations, and NUREG documents are "regulatory decisions, results of research, results of incident investigations, and other technical and administrative information."[6] NUREG documents can be prepared by people outside of the NRC staff.

10 CFR Part 50, Domestic Licensing of Production and Utilization Facilities

This part of the CFR provides information and documentation for construction permits and operation site licenses for a production and utilization facility. Once the requirements of Part 50 are completed, the facility can be built. This license does not provide the licensee the ability to handle special nuclear material (SNM).

10 CFR Part 52, Licenses, Certifications, and Approvals for Nuclear Power Plants

Part 52 of the CFR is a combined license approach and governs "early site permits, standard design certifications, combined licenses, standard design approvals, and manufacturing licenses for nuclear power facilities." Part 52 may provide a more streamlined method of licensing/permitting compared with Part 50, but they contain the same information. The nuclear power plant can be constructed once approved, but this license does not provide the licensee the ability to handle SNM.

10 CFR Part 70, Domestic Licensing Special Nuclear Material

Part 70 allows a Part 50 license holder to "…own, acquire, deliver, receive, possess, use, and transfer special nuclear material." Typically, oversight of this license is granted by the NRC and managed by state regulatory bodies through Agreement State agreements (10 CFR Part 150). The documentation provides coverage for plutonium processing facilities, fuel fabrication plants, or enrichment plants. Exemptions are provided for some facilities, including "except for applications… for those uses involved in the operation of a nuclear reactor licensed pursuant to part 50…"

10 CFR Part 74, Material Control and Accounting of Special Nuclear Material

Part 70 provides regulations describing the requirements for "control and accounting of special nuclear material at fixed sites and for documenting the transfer of special nuclear material." The grades of SNM and their respective requirements are defined accordingly. Exemptions are given in Subpart D and E "…other than a nuclear reactor licensed pursuant to part 50 of this chapter." Alternatively in Subpart C, a license is required "other than a production or utilization facility licensed pursuant to part 50 or 70 of this chapter."

NUREG-1065 Rev. 3, Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Special Nuclear Material of Low Strategic Significance, 2019.
[Previous Rev. 2, Acceptable Standard Format and Content for Fundamental Nuclear Material Control (FNMC) Plan Required for Low-Enriched Uranium Facilities, D. R. Joy, 1995.]

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[6] NUREG-Series Publications, NRC.gov, https://www.nrc.gov/reading-rm/doc-collections/nuregs/index.html.

Revision 3 provides a new structure from Revision 2 and Revision 1 (dated 1985). The document implements the requirements of 10 CFR 74.3 and 74.31 specifically for facilities (other than production or utilization facilities) that are licensed for unencapsulated SNM of low strategic significance. It contains the material control and accountability (MC&A) plans for "(1) the performance objectives that must be met, (2) the MC&A program capabilities that must be achieved to meet those objectives, (3) the incorporation of checks and balances to detect falsification of data and reports that could conceal the theft, diversion, or misuse of SNM, and (4) basic commitments that should be made."

NUREG-1280 Rev. 2 Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Strategic Special Nuclear Material, Final Draft Guidance. [Previous Revision 1, Standard Format and Content/Acceptance Criteria for the Material Control and Accounting Reform Amendment]

The revised document provides guidance for applicants or licensee information for material that should be provided in the MC&A plan (FNMC plan) following revisions for Low and Moderate Strategic Material (Subparts C and D, respectively of 10 CFR Part 74). It specifically includes guidance for "for implementing the new requirements in 10 CFR 74.59 pertaining to tamper-safing, and the designation of material balance areas and item control areas. This NUREG applies to NRC licensees authorized to possess and use at least 5 kg of a formula quantity of strategic special nuclear material (often referred to as a "Category I" quantity of material)."

NUREG-2159 Revision 1, Acceptable Standard Format and Content for the Fundamental Nuclear Material Control Plan Required for Special Nuclear Material of Moderate Strategic Significance, T. Pham, G. Tuttle, S. Ani, 2022.

This document presents performance-based MC&A requirements for Category II SNM, replacing the prescriptive approach as defined in previous 10 CFR Part 70. It provides those performance objectives, system capabilities, checks and balances to detect falsification of data, and other basic commitments.

NUREG/CR-5734, Recommendations to the NRC on Acceptable Standard Format and Content for the Fundamental Nuclear Material Control (FNMC) Plan Required for Low-Enriched Uranium Enrichment Facilities, B. W. Moran, W. L. Belew, G. A. Hammond, L. M. Brenner, 1991.

This NUREG document provides specific information following the addition of 10 CFR 74.33 for licensed uranium enrichment facilities. Because these facilities could enrich the material further and produce moderate or strategic SNM, certain performance objectives and system capabilities are required in the plan. The document contains the recommended information that should be included in the FNMC plan to the NRC.

Reg. Guide 1.232: Guidance for Developing Principal Design Criteria for Non-Light-Water Cooled Reactors, J. Mazza, 2018.

The document provides information for applicants of non–light-water reactor systems that may license under Part 50 or 52. The document focuses on the principal design criteria as required by the NRC for power reactors. Two example reactor systems are considered: sodium-cooled fast reactors and modular high-temperature gas-cooled reactors. These examples could provide useful information to other advanced reactors, including liquid-fueled MSRs.

Regulatory Guide 5.51: Independent Assessment of Nuclear Material Control and Accounting Systems, G. Tuttle, 2016.

This regulatory guide provides information for Category I, II, and III fuel cycle facilities following 10 CFR 74.31, 74.33, and 74.43, respectively. The document provides valuable information for the components of an MC&A system, and an assortment of appendixes guide the applicant.

Regulatory Guide 5.88: Physical Inventories and Material Balances at Fuel Cycle Facilities, G. Tuttle, 2017.

The document describes the methods and acceptable practices for developing an MC&A system per 10 CFR Part 74 at fuel cycle facilities. The document contains valuable information and is a good reference for an applicant to review. However, it is not guidance for "licensees of power reactors, research and test reactors, or independent spent fuel storage installations."

Proposed Framework

10 CFR Part 53, Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors

This document includes proposed guidance for applicants of new commercial advanced nuclear reactor licenses. As of October 2021, NRC staff requested a 9-month extension to the Part 53 timeline. The regulations "…developed in this rulemaking would use methods of evaluation, including risk-informed and performance-based methods, that are flexible and practicable for application to a variety of advanced reactor technologies." A proposed rule is due for review in February 2023, and the Final Rule is scheduled to be provided by July 2025.