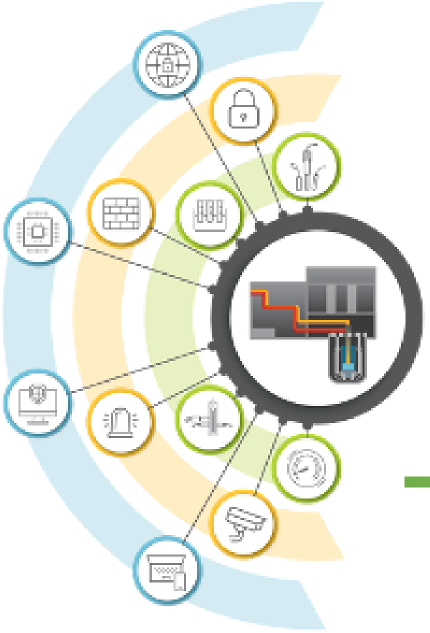


Planning for Material Control and Accounting at Liquid-Fueled Molten Salt Reactors

Prepared for
US Department of Energy

Karen Koop Hogue, PhD
Nicholas Luciano, PhD
Matthew Krupcale, PhD
Rabab Elzohery, PhD
Louise G. Evans, PhD

Oak Ridge National Laboratory

January 2024
ORNL/SPR-2023/3181

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

DOCUMENT AVAILABILITY

Online Access: US Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via https://www.osti.gov.

The public may also search the National Technical Information Service's National Technical Reports Library (NTRL) for reports not available in digital format.

DOE and DOE contractors should contact DOE's Office of Scientific and Technical Information (OSTI) for reports not currently available in digital format:

US Department of Energy
Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831-0062
Telephone: (865) 576-8401
Fax: (865) 576-5728
Email: reports@osti.gov
Website: www.osti.gov

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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

ORNL/SPR-2023/3181

Nuclear Nonproliferation Division

Planning for Material Control and Accounting at Liquid Fueled Molten Salt Reactors

Karen Koop Hogue, PhD
Nicholas Luciano, PhD
Matthew Krupcale, PhD
Rabab Elzohery, PhD
Louise G. Evans, PhD

January 2024

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AI	active inventory
BOL	beginning of life
EFPY	effective full power years
EOL	end of life
FEES	flow-enhanced electrochemical sensors
FNMC	Fundamental Nuclear Material Control
HALEU	high-assay low-enriched uranium
IAEA	International Atomic Energy Agency
ICA	item control area
ID	inventory difference
IMCI	inventory-monitor containment-inventory
LEU	low-enriched uranium
LWR	light water reactor
MBA	material balance area
MC&A	material control and accounting
MCSFR	Molten Chloride Salt Fast Reactor
MFIT	modular flow instrument testbed
MOSART	Molten Salt Actinide Recycler and Transmuter
MSDR	Molten Salt Demonstration Reactor
MSFR	Molten Salt Fast Reactor
MSR	molten salt reactor
MSRE	Molten Salt Reactor Experiment
NDA	nondestructive assay
NMMSS	Nuclear Materials Management and Safeguards System
NRC	Nuclear Regulatory Commission
REBUS	Reactor Burnup System
SEID	standard error of the inventory difference
SNM	special nuclear material
SSNM	strategic special nuclear material
TID	tamper-indicating device

ACKNOWLEDGMENTS

This work was funded under the US Department of Energy Office of Nuclear Energy's Advanced Reactor Safeguards and Security program. The authors would like to acknowledge several individuals for their contribution to this report. Thomas Pham provided recommendations for engaging the US Nuclear Regulatory Commission on the topic of material control and accounting. Donny Hartanto and David Chandler developed the model for the generic fast-spectrum molten chloride reactor and completed the calculations using SCALE 6.3.1. Kevin Robb, Don Kovacic, Steve Skutnik, Mathew Swinney, Greg Westphal, Joanna McFarlane, David Holcomb, Peter Sobel, and Nathan Rowe provided technical reviews or considerations related to the technical assessments.

DISCLAIMER

The recommendations and conclusions in this report have been developed through extensive discussions with the US Nuclear Regulatory Commission Material Control and Accounting Group, but the content of this report is attributable to the authors. No part of this report should be considered to have the explicit or implicit endorsement of the US Nuclear Regulatory Commission.

EXECUTIVE SUMMARY

The purpose of this report is to provide molten salt reactor (MSR) developers and future US Nuclear Regulatory Commission (NRC) license applicants with recommendations for developing an effective and practical material control and accounting (MC&A) plan, focused primarily on MSR designs that use circulating liquid fuel. Because of the breadth of MSR designs, there is no single, generic, detailed MC&A plan that will work for every design. The wide variation of fresh fuel salts, the method and frequency of loading fresh fuel, the reactor system design components (e.g., tanks, filtration systems, chemical processing streams), and waste streams will determine the specific measurement locations and instrumentation that can best meet MC&A objectives throughout an MSR facility. Additionally, MSR designs are rapidly evolving, and new design features and deployment scenarios that will affect MC&A are being explored and pursued. This report defines a generic MC&A approach that was developed for terrestrial (as opposed to maritime) deployments to meet the intent of NRC domestic safeguards and MC&A.

REGULATORY FRAMEWORK RELEVANT TO LIQUID FUELED MSR MC&A

MSR license applicants should consider nuclear safeguards (both domestic and international) and security throughout the design, as early as the preconceptual design phase. MC&A of special nuclear material (SNM) is an aspect of the NRC's domestic safeguards program, alongside physical protection. Because liquid-fueled MSRs are reactors with SNM in nondiscrete form, it is likely that the NRC may require liquid-fueled MSR license applicants to submit a formal MC&A plan as a part of their license application. Currently, the NRC licensing protocol presents a challenge because the NRC MC&A regulations have not been updated to accommodate advanced reactors, including types of MSRs. Because no liquid-fueled MSR has been licensed for operation at the time of this report, no template or precedence for a successfully licensed MSR MC&A plan exists. However, the MSR license applicant can take advantage of the NRC's published commitments to performance-based regulations. The authors recommend that the license applicant, or MSR designers, develop an MC&A plan throughout the design lifecycle and plan to submit a detailed MC&A program description, or MC&A plan, to the NRC as a part of a license application.

DEVELOPING A LIQUID-FUELED MSR MC&A APPROACH

To date, no MC&A plan template or guidance exists that is specific to liquid-fueled MSRs. The authors recommend that license applicants discuss the topic of MC&A during preapplication engagement. Because of the uniqueness of MC&A for liquid fueled MSRs, the authors recommend that liquid-fueled MSR developers engage with the NRC on the topic of MC&A in the early phases of its design development and follow up any time there are significant modifications in design plans that would affect MC&A. For example, topics like modifications in fuel handling processes, changes in uranium enrichment, or additional chemical processing streams added to the design could be discussed with the NRC specifically on the topic of MC&A.

Before identifying the specific program elements (e.g., measurement systems) that will be described in an MC&A plan, the license applicant must develop an overall MC&A approach. NRC does not have guidance on developing such an approach. This report describes a recommended methodology to develop an MC&A approach for liquid-fueled MSRs with circulating fuel. The recommended methodology for developing an MC&A approach for a liquid-fueled MSR is as follows:

- Develop a process flow diagram for the design tracking MC&A-relevant design parameters for each process step or flow. The process flow diagram could be used in preapplication engagement discussions with the NRC to convey relevant information to the NRC MC&A group about the specific design.

- Identify the high-level MC&A objectives across the facility that would be necessary to prevent or detect diversion of material.

- Perform a diversion path analysis to identify potential specific paths of diversion from process streams. This is not explicitly required by the NRC, but the authors recommend this methodology to ensure that the NRC's intent for MC&A performance objectives is met in the absence of guidance specifically for liquid-fueled MSRs. Following a risk-informed, performance-based methodology focused on meeting the objectives of MC&A will help liquid-fueled MSR license applicants justify exemption requests from aspects of the current MC&A requirements in Title 10 of the Code of Federal Regulations Part 74, "Material Control and Accounting of Special Nuclear Material" (10 CFR Part 74), that are tailored to bulk facilities that are not reactors (e.g., fuel fabrication facilities, enrichment facilities).

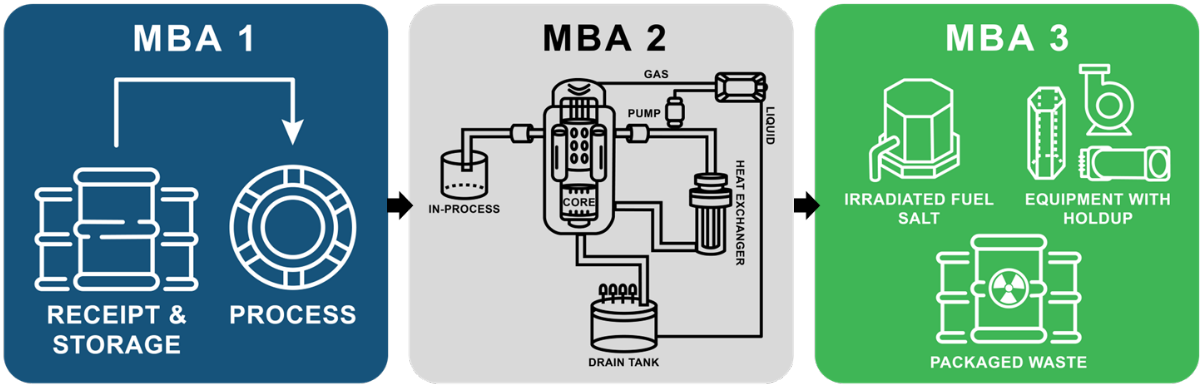
- While considering constraints like the measurement environments and measurement technique limitations, identify specific MC&A elements (i.e., devices like tamper-indicating devices [TIDs], spectrometers, scales) to meet each MC&A objective and prevent or detect every plausible diversion path. There should be at least two independent elements to prevent or detect every diversion path.

These combined MC&A elements across the facility will be incorporated into the MC&A plan. Combined with descriptions of how the licensee will manage its MC&A program, this will form the basis of an MC&A plan that can be submitted to the NRC as a part of a license application.

Additionally, the authors define MC&A-relevant design parameters to enable the use of modeling and simulation tools to develop a process flow diagram with information that is pertinent to planning for MC&A. For example, modeling tools can be used to predict SNM inventories throughout a reactor facility for a specific design and based on specific operational assumptions. These MC&A-relevant design parameters include type, chemical and physical form, quantities, and accessibility of SNM, which is affected by the radioactivity of the material containing SNM and concentration of SNM.

INTERNAL CONTROL AREA APPROACHES

Until computational multiphysics codes are validated so that they can reliably and accurately predict quantities of SNM throughout liquid-fueled MSR process streams, the authors recommend that an MC&A plan should be developed that does not rely on material balances on SNM within a difficult-to-access area or physical boundary surrounding the reactor system. Instead, periodic inventories consistent with existing NRC requirements in 10 CFR Part 74 should be performed on all SNM located outside of a physical boundary analogous to reactor confinement (i.e., a biological and physical barrier, where one side is access-restricted and the dose rates are high during irradiation). Within this physical boundary, the authors also recommend that MC&A should not rely on material accounting measures but instead on material control, using a diversion path analysis to identify all plausible pathways for SNM theft. Figure 1 depicts a proposed approach, where internal control areas are identified as material balance areas (MBAs).



Periodic inventories performed, IDs and SEIDs calculated
(follows Part 74 requirements)

Monitoring performed in specific locations to detect diversion

Periodic inventories performed, IDs and SEIDs calculated
(follows Part 74 requirements)

Figure 1. A proposed MBA structure for a terrestrial-based liquid-fueled MSR

With further development, a diversion path analysis, described in this report, could serve as a tool toward risk-informed, performance-based development of effective MC&A elements to prevent or detect all plausible paths for theft of SNM within confinement. Also, for regulations that cannot be met by liquid-fueled MSRs (because material balances and periodic inventories are inherently challenging in a reactor with rapidly changing quantities of SNM), diversion path analysis could be used as the technical justification for proposed compensatory measures or exemption requests of certain MC&A regulations. Further work is needed to define measurable outcomes for a diversion path analysis, so all reasonable diversion paths for theft are included in the analysis and accurately assessed. The diversion path analysis could include metrics like quantities of SNM that could be removed using the diversion path and the difficulty in completing the path. A few of the many examples of diversion paths include gross diversion of a storage container of fresh fuel, protracted diversion from a container with concealment methods, diversion of SNM through a salt sampling process stream, diversion of SNM from filters, material substitution, or diversion of SNM as residual material (holdup) within equipment being replaced.

Finally, the report contains several technical analyses that demonstrate the use of modeling and simulation tools for MC&A consideration in design decisions. A technical analysis of the MC&A-relevant design parameters of five different nonproprietary liquid-fueled MSR designs demonstrates that parameters, like quantities of SNM and concentrations of SNM within material streams, varies across multiple orders of magnitude across designs. Therefore, detailed solutions for MC&A that apply to every liquid-fueled MSR design do not exist. Additionally, three examples demonstrate how both quantitative and qualitative technical analyses can be performed to assess how design decisions effect MC&A and can enable developers to consider safeguards and security throughout their design lifecycle.

1. INTRODUCTION

1.1 Purpose

The purpose of this report is to provide recommendations to molten salt reactor (MSR) developers and future US Nuclear Regulatory Commission (NRC) license applicants for developing an effective and practical material control and accounting (MC&A) plan. Three distinct types of MSR designs currently exist: (1) solid fueled (salt cooled) MSRs that use solid fuel elements[A] cooled by a flowing coolant salt containing no fissile material; (2) circulating liquid-fueled MSRs that circulate fuel salt containing dissolved, liquid fissile material; and (3) static liquid-fueled MSRs that use nonflowing fuel salt sealed in individual fuel elements. The recommendations in this report are targeted at circulating liquid-fueled MSRs, but some concepts may also apply to static liquid-fueled MSRs. MC&A challenges for solid-fueled MSR designs will be like other non-MSR reactor types. For example, MC&A for reactor facilities using solid pebble fuel with a molten salt coolant would be based on approaches for other (e.g., gas-cooled) pebble bed reactors.

Because of the breadth of MSR designs, there is no single, detailed MC&A plan that will work for every design. The variation of fresh fuel salts, method and frequency of loading fresh fuel, reactor system design components (e.g., tanks, filtration systems, chemical processing streams), and waste streams will determine the specific measurement locations and instrumentation that can best meet MC&A objectives throughout an MSR facility. Additionally, MSR designs are rapidly evolving, and new design features and deployment scenarios that will affect MC&A are being explored and pursued. Most of the recommendations in this report are specific to terrestrial-based deployment scenarios as opposed to maritime applications of liquid-fueled MSR technologies. MC&A for maritime application will require additional considerations, and controlling and limiting access to nuclear material will likely be a higher priority than accounting for material while the reactor is operational. Those factors will impact recommendations related to overall MC&A approach and internal control area structure.

1.2 Material Flows at Liquid Fueled MSR Facilities

Understanding how nuclear material moves through a facility is essential for developing an MC&A approach. Multiple process streams exist at a liquid-fueled MSR, and each has different types and quantities of nuclear material present. A liquid-fueled MSR has various design features (e.g., off-gas streams, online refueling, liquid fuel under irradiation) that are not present in conventional light water reactors (LWRs), enrichment, and fuel fabrication facilities. These system components require additional considerations to account for and control nuclear material.

MC&A at the liquid-fueled MSR facility should begin when the nuclear material is received on-site. Liquid-fueled MSR facilities should expect to receive containers of nuclear material in a chemical and physical form that has been approved for shipping such as: (1) fuel salt eutectic already containing nuclear material (e.g., $LiF–BeF_2–UF_4–ZrF_4$, $NaCl–UCl_3$), (2) nuclear material in a salt form that is ready to add to the carrier salt (e.g., UF_4, UCl_3), or (3) nuclear material in a form that will undergo conversion in a fuel salt synthesis process (e.g., UF_6). These containers should be marked with serial identification, labeled with the tare weight of the container, and sealed with a tamper-indicating device . The receipt and inventories of fresh fuel would typically be based on the shipper's

---

[A] The solid fuel may remain in a fixed location or circulate through a loop.

reported values but can be confirmed by measurement(s). Fuel salt ready for use would be in the reactor's required chemical form, requiring only mechanical processing (heating and transfer) for use in the core. Unlike conventional LWRs, where the fuel arrives at the facility as large assemblies that maintain their physical form, liquid-fueled MSR fuel may arrive in concentrated form to reduce the volume of fresh fuel. Some liquid-fueled MSR concepts may plan for the combination of carrier salts with nuclear materials, such that nuclear material would arrive in the form of, for example, UCl_3 or UF_4. Other facilities might receive nuclear material in other forms (e.g., UF_6) and have chemical fuel salt synthesis processes on-site to convert shippable forms of nuclear material into fuel salt or fuel salt components. In all cases, nuclear materials should arrive at the site in labeled and weighed containers that can be counted and inventoried.

In many liquid-fueled MSR designs, fresh fuel would be added to the reactor core in batches or continuously, both before and during power operations. Liquid-fueled MSRs may employ fuel salts with different concentrations of nuclear material during different stages of the operating cycle. *Initial fuel salt* is fresh (unirradiated) fuel that is present in the core as the reactor is brought to critical. Initial fuel salt could contain different types or concentrations of nuclear material from fuel salt added during power operations, known as *makeup fuel salt* because it makes up for fuel depletion caused by irradiation.

Fuel salts can contain various quantities and types of nuclear material. Some liquid-fueled MSR concepts use fresh fuel that is either low-enriched U (LEU) with less than 5 wt % ^{235}U (like LWR fuel) or high-assay LEU (HALEU) between 10 wt % and 20 wt % ^{235}U. Some concepts expect to operate using thorium (typically ThF_4) as a component in the initial fuel salt along with fissile isotopes like ^{235}U, ^{233}U, and ^{239}Pu. The LEU, HALEU, and thorium fresh fuels generally will have relatively low dose rates, which makes these fresh fuel salts relatively accessible compared with other fuel salts. Some liquid-fueled MSR concepts propose the use of nuclear material from LWR or pressurized heavy water reactor spent fuel that has been chemically processed to remove fission products. Because of the presence of minor actinides and trace concentrations of fission products, these fuels have elevated dose rates compared with other fresh fuels, though not as high as irradiated fuel containing fission products.

The accessibility of the fuel salt would be diminished because of high temperatures when the fuel is loaded into the reactor and diminished further during irradiation because of high dose rates. Liquid-fueled MSRs do not have traditional containment like LWRs because of significantly lower operating pressures (i.e., slightly greater than atmospheric pressure because of a cover gas) [1]. For radiological shielding and physical security, the reactor core and supporting subsystems will likely be contained in one or more physical structures; *reactor confinement* will be used in reference to these structures. Entry into reactor confinement during reactor operations is unlikely without extreme risk. Any forced entry into these difficult-to-access areas behind biological shielding during operation (and likely even after shutdown) would result in a fatal radiation dose, so removal of irradiated fuel salt is technically difficult for an insider or non-state actor [2].

Quantifying nuclear material in irradiated fuel salt during power operations will be especially challenging because the inventories of nuclear material types (e.g.,^{235}U, Pu_{total}) will be changing significantly over time because of transmutation and depletion. All fuel salt will contain fertile nuclear material (i.e.,^{238}U, ^{232}Th, or both). When irradiated in the reactor, these isotopes will breed fissile material that will be mixed within the fuel salt with fission products, actinides produced through neutron capture, fluoride or chloride carrier salt, activation products, and radioactive progeny.

Piping and systems outside of a core vessel introduce locations for residual nuclear material to plate out or accumulate (i.e., holdup) and further complicate MC&A. Liquid-fueled MSR designs that propose off-gas sparge systems for removal of noble gases and metals from the primary salt loop present pathways for material loss through waste streams or filter systems. Nuclear material may become entrained in a subsystem and could require liquid or gas separation to recirculate the liquid salt back into the primary loop. Sampling ports on the fuel salt loop present direct access to the molten fuel salt and thus present a potential additional pathway for material theft. Sampling ports are potentially beneficial and could be used to analyze the fuel salt during operation and provide a means to understand isotopic inventories in the fuel salt loop. However, any sampling ports may require TIDs on valves, surveillance with cameras or radiation detection systems, and administrative measures (e.g., two-person requirements or biometric authentication to withdraw material through a sampling port) to prevent unauthorized removal of nuclear material. Drain tanks, heat sinks, and other storage volumes that contain or store fuel salt will likely also require MC&A measures to ensure any attempt of theft will be detected.

Irradiated fuel salt and equipment that is removed from reactor confinement must be stored until it is shipped out of the facility, and any nuclear material in or on the equipment must be accounted for. Irradiated fuel salt and radioactive waste streams in most designs will be highly radioactive and require remote handling or automated processes to move these materials out of reactor confinement. Out-of-service, damaged, or replaced equipment or other consumables from the facility may contain nuclear material. Storage containers and TIDs for used equipment and waste material may be different from what is required for irradiated fuel salt storage. Measurements should be performed to determine whether nuclear material is present and documented. If nuclear material is present, then periodic inventories and weights must be performed and recorded while the material is in storage.

Many designs propose periodic maintenance periods to replace equipment damaged during irradiation. During these maintenance periods, new access points to material will be introduced. For example, material may be removed from process streams (e.g., as waste) and used equipment may have residual nuclear material holdup and be moved to a different location within the facility. Further, the physical and, potentially, chemical state of the fuel salt may change. For example, material may solidify in tanks or pipes if temperatures drop below melting temperatures. Therefore, during these maintenance periods, additional MC&A program elements will need to be included in an MC&A plan to ensure all pathways for theft of material are prevented or detected.

2. REGULATORY FRAMEWORK RELEVANT TO LIQUID FUELED MSR MC&A

Each NRC licensee authorized to possess and use special nuclear material (SNM) must ensure the control and accounting of licensed materials. SNM is defined in 10 CFR 74.4 as Pu, ^{233}U, or U enriched in the isotope ^{233}U or in the isotope ^{235}U.[B] MC&A of SNM is an aspect of the NRC's domestic safeguards program alongside physical protection. One goal of domestic safeguards is

---

[B] The full definition of SNM is "plutonium, uranium-233, 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 any material artificially enriched by any of the foregoing, but does not include source material [6]."

ensuring that SNM within the US is not stolen or otherwise diverted from civilian facilities. Licensees authorized by the NRC to possess SNM of low strategic, moderate strategic, or strategic significance (defined below) shall establish, implement, and maintain an NRC-approved MC&A system.

Enriched U is reportable to the NRC in the Nuclear Materials Management and Safeguards System (NMMSS) as (1) U_{total} reported to the nearest whole gram and (2) an isotope weight of ^{235}U. Plutonium is reportable to the NRC in NMMSS as (1) Pu_{total} reported to the nearest whole gram, (2) an isotope weight of ^{239}Pu + ^{241}Pu, and (3) an isotope weight of ^{240}Pu.[C] In international safeguards, the International Atomic Energy Agency (IAEA) verifies quantities of Pu_{total}, irrespective of the mass percent of the Pu isotopes, except those materials with isotopic concentration of ^{238}Pu exceeding 80% [3].

Facilities that possess SNM are categorized based on the mass quantity and type of SNM at the facility (Table 1). MC&A requirements are defined in 10 CFR Part 74 in a graded approach, with the most stringent requirements reserved for the most sensitive material: strategic SNM (SSNM, Category I) is more strict than SNM of low strategic significance (Category III). Typically, Pu or ^{233}U will be present in irradiated fuel salt in quantities that meet the definition of Category I SNM. However, Appendix M of 10 CFR Part 110 notes that irradiated fuel that by virtue of its original fissile material content is included as category I or II before irradiation should only be reduced one category level, while the radiation level from the fuel exceeds 100 rd/h at 1 m unshielded. Therefore, license applicants for liquid-fueled MSRs using fresh fuel salt with less than 20% ^{235}U enrichment and no Pu content may consider proposing an MC&A approach consistent with a Category II (^{235}U enrichment >10% but <20%) or a Category III facility (^{235}U is greater than natural enrichment but less than 10%), despite the irradiated salt containing greater than 2 kg of Pu, which would have met the definition for Category I SNM.

Table 1. NRC SNM Categories

Isotope	**Enrichment**	**Category III**	**Category II**	**Category I**
		SNM of low strategic significance	SNM of moderate strategic significance	SSNM
^{235}U	≥20%	>15 g	≥1 kg	≥5 kg
	≥10% but <20%	>1 kg	≥10 kg	—
	≥ natural but < 10%	≥10 kg	—	—
Pu	NA	>15 g	≥0.5 kg	≥2 kg
^{233}U	NA	>15 g	≥0.5 kg	≥2 kg
Formula	NA	>15 g	≥1 kg	≥5 kg
		(g ^{235}U) + (g ^{233}U) + (g Pu)	(g ^{235}U) + 2(g ^{233}U + g Pu)	(g ^{235}U) + 2.5 (g ^{233}U + g Pu)

The category of the facility and the characteristics of the material present will influence the MC&A approach for a facility. The MC&A elements are not explicitly prescribed by the NRC, so the

---

[C] If the ^{242}Pu isotopic weight is 20% or greater, Pu_{total} is reported as ^{242}Pu, and isotopic weights of ^{239}Pu and ^{241}Pu are not reported.

applicant must develop an approach that satisfies the intent of the federal regulations. The license applicant describes the MC&A approach and elements (e.g., instrumentation, TIDs) in the format of a detailed MC&A program description or a Fundamental Nuclear Material Control (FNMC) plan [4].

2.1 License Application MC&A Requirements and Exclusions

Title 10 of the Code of Federal Regulations Part 74—*Material Control and Accounting of Special Nuclear Material* (10 CFR Part 74) defines MC&A requirements according to the category of the SNM [5]. Domestic licensing of SNM is described in 10 CFR Part 70—*Domestic Licensing of Special Nuclear Material* [6]. For liquid-fueled MSR MC&A, it is important to understand both the regulatory requirements and how some exclusions that are applied to other reactor types may not apply to liquid-fueled MSRs.

The regulations in 10 CFR 70.22(b) require that each application for a license to possess and use SNM at any one time and location in a quantity exceeding 1 effective kilogram[D] contains a full description of the program for control and accounting of the SNM. Also required in the application is a full description of how compliance with the applicable requirements in 10 CFR 74.31 (MC&A for SNM of low strategic significance), 10 CFR 74.33 (MC&A for U enrichment facilities), 10 CFR 74.41(MC&A for SNM of moderate strategic significance), and 10 CFR 74.51 (MC&A for SSNM) will be accomplished. Title 10 CFR 74.31, 74.33, 74.41, and 74.51 require each applicant for a license to submit a Fundamental Nuclear Material Control (FNMC) plan. In addition, the provisions of 10 CFR 70.32(c) require the licensee to maintain and follow a program for controlling and accounting for SNM, a measurement control program, and other material control procedures that include corresponding record management requirements.

The requirements in 10 CFR 70.22(b) and 10 CFR 70.32(c) contain exclusions for licensees governed by 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities.” The same exclusions are contained in the MC&A requirements in 10 CFR 74.31, 74.33, 74.41, and 74.51. A *production facility* and a *utilization facility* are defined in 10 CFR 50.2. With a few specific exceptions, a production facility is defined as a reactor specifically designed or used to produce Pu or ^{233}U, a facility to separate isotopes of Pu, or a facility to process irradiated material containing SNM. The definition of a utilization facility includes any nuclear reactor other than one designed or used primarily for the formation of Pu or ^{233}U. Under this definition, a conventional light-water reactor (LWR) power plant is a utilization facility and is not required to submit an FNMC plan to the NRC.

The proposed rule of 10 CFR Part 53, “Risk-Informed, Technology-Inclusive Regulatory Framework for Commercial Nuclear Plants,” is a potential avenue for licensing future commercial nuclear plants, including both non-LWR and LWR advanced reactors. As of the publication of this report, this rule is not final.

Regardless of whether an application is submitted under 10 CFR Part 50, 10 CFR Part 52, or a future 10 CFR Part 53, liquid-fueled MSRs with circulating fuel are highly likely to require an MC&A plan as a part of an application for NRC review. Conventional LWRs are excluded from this requirement because they are categorized as utilization facilities. When the regulatory framework was

---

[D] According to 10 CFR 74.4, *effective kilograms* of SNM has the following meanings: (1) for plutonium and ^{233}U, their weight in kilograms; (2) for U with an enrichment in the isotope ^{235}U of 0.01 (1%) and above, its element weight in kilograms multiplied by the square of its enrichment expressed as a decimal weight fraction; and (3) for U with an enrichment in the isotope ^{235}U less than 0.01 (1%), its element weight in kilograms multiplied by 0.0001.

developed, the NRC understood a *nuclear reactor* to be a facility that used solid fuel in large, countable item fuel forms. Spent LWR fuel assemblies are not only large and heavy but also highly radioactive, which significantly decreases the credibility of theft diversion scenarios. The liquid fuel form and other operational characteristics of liquid-fueled MSRs are significantly different from conventional LWRs. Theft of SNM in bulk form (as opposed to discrete items) is more credible than theft of large, heavy, item LWR fuel assemblies. Other bulk facilities licensed by the NRC, including fuel fabrication facilities and enrichment plants, require FNMC plans. Therefore, liquid-fueled MSRs will likely be required to submit an MC&A program description or an FNMC plan. Rulemaking is not expected in the near-term that would alter any existing MC&A requirements for MSRs but the MC&A group could clarify expectations for license applications depending on design aspects. For example, a MSR facility with on-site fuel salt synthesis may require more MC&A program elements than a facility that receives fuel salt in a form they directly add to the reactor without any further processing. However, any external facilities NRC facilities with fuel salt synthesis would also need to develop an MC&A plan for licensing, as well.

The FNMC plan format and MC&A reporting and recordkeeping requirements are described in detail in APPENDIX A.

2.2 Exemptions from MC&A Requirements

Title 10 CFR 74.7 states that "the Commission may, upon application of any interested person or upon its own initiative, grant such exemptions from the requirements of the regulations in this part as it determines are authorized by law and will not endanger life or property or the common defense and security, and are otherwise in the public interest." The NRC reviews exemption requests and may grant those it determines do not decrease the reasonable assurance of safety, the common defense, and other factors in the public interest. The NRC may consider an MC&A system in place in liquid-fueled MSRs that meets the objectives of preventing and detecting diversion or theft of SNM but does not necessarily meet all existing regulations in Part 74. This might offer some flexibility for license applicants submitting an MC&A approach that justifies how theft of SNM will be prevented and detected while requesting exemptions from specific requirements within 10 CFR Part 74 (e.g., threshold limits that would trigger reporting to the director of the NRC's Office of Nuclear Material Safety and Safeguards).

2.2.1 Justification of MC&A Exemptions Using Diversion Path Analysis

The NRC may accept the idea of a license applicant performing a diversion path analysis to determine how SNM might be stolen from the facility, then developing MC&A systems that include elements to prevent, detect, or prevent and detect SNM from being removed in each pathway. Although this process is not required, it may be beneficial for a license applicant to provide justification that, although they are asking for exemptions, the proposed MC&A approach along with compensatory measures adequately prevents or detects every pathway that could be used to divert SNM from the facility, ultimately meeting the NRC MC&A performance objectives. Use of a diversion path analysis could be consistent with the NRC's commitment to risk-informed, performance-based approaches. The NRC has published and stated multiple times that it intends to use a risk-informed, performance-based regulatory approach [7, 8]. The NRC defines performance-based regulation as "a regulatory approach that focuses on desired, measurable outcomes, rather than prescriptive processes, techniques, or procedures [9]." Furthermore, "performance-based regulation leads to defined results without specific direction regarding how those results are to be obtained [9].” Currently, performance-based approaches are already used by the NRC in safety (probabilistic risk assessment) and physical security (design-basis threat), but not for MC&A. Further work is needed to define measurable outcomes for a diversion path analysis so all credible diversion paths for theft are included in the analysis and accurately ranked and assessed. The diversion path analysis could include metrics like quantities of SNM that could be removed using the diversion path and the difficulty in completing the path. A few of the many examples of diversion paths include gross diversion of a storage container of fresh fuel, protracted diversion from a container with concealment methods, diversion of SNM through a salt sampling process stream, diversion of SNM from filters, or diversion of SNM as residual material (holdup) within equipment being replaced. Additional paths could be identified and defined in more detail.

2.2.2 Exemptions for Reducing Facility or Material Category

Although irradiated fuel salt does not have physical form that is large and heavy like an LWR assembly, the irradiated salt would be highly radioactive like LWR fuel. Applicants may submit appeals to exempt the SNM quantities from some strict MC&A requirements reserved for SSNM because diversion scenarios would be deemed noncredible based on high radioactivity and physical-access constraints to that material. Based on the very high expected dose rates and relatively low concentrations of SNM within fuel salt, licensees could request that the NRC allow irradiated fuel salt in a liquid-fueled MSR facility to be categorized as SNM of moderate strategic significance instead. A change in categorization would need to consider the entirety of the salt processing present in the facility. Some liquid-fueled MSR designs include fuel salt cleanup systems and chemical separation of fissile material for recycle back into the reactor. Additionally, liquid-fueled MSR designs use off-gas and cover-gas management systems to extract the radioactive fission gases from the fuel salt. Thus, liquid-fueled MSRs have several process streams to consider, and some of them may have SNM present without accompanying high dose rates.

2.3 Developer or License Applicant Engagement with the NRC on MC&A

The NRC’s Office of Nuclear Material Safety and Safeguards has responsibility for reviewing the MC&A plans in license applications. Specifically, the MC&A group is in the Material Control and Accounting Branch of the Division of Fuel Management[E]. Because of the uniqueness of MC&A for liquid fueled MSRs, the authors recommend that liquid fueled MSR developers engage with the NRC on the topic of MC&A in the early phases of its design development and follow up any time there are significant modifications in design plans that would affect MC&A. Preapplication engagement with the NRC on MC&A are important to determine: specific MC&A requirements and/or guidance documents applicable to liquid-fueled MSRs, requirements to have an MC&A program description or a submittal of an FNMC plan, or a need to apply for a Part 70 material license beside the Part 50/52/53 reactor application. Any design changes like modifications in fuel handling processes, changes in uranium enrichment, or additional chemical processing streams added to the design would also be relevant to discuss with the NRC within the topic of MC&A.

[E] At the time of this publication, this group is also available to meet with potential license applicants for pre-application engagement. Discussions with the NRC could primarily be held in a virtual format. In-person office meetings where the meeting is docketed by the NRC may be charged licensing fees, which can be expensive, especially when other NRC offices are involved.

3. DEVELOPING A LIQUID-FUELED MSR MC&A APPROACH

3.1 MC&A Relevant Design Parameters

Liquid-fueled MSR design features or parameters that are relevant from an MC&A perspective are not necessarily the same features that are relevant from a performance or operations perspective. MC&A objectives depend on the types, quantities, and locations of the SNM (Figure 2). Other design features will affect the ability to apply various MC&A measures (e.g., destructive, or nondestructive measurements to quantify isotopes). This section identifies several design features that will affect the MC&A approaches to meet domestic MC&A objectives. Because such diverse designs exist within the class of liquid-fueled MSRs in different stages of development, representative design feature examples are referenced. The following design features will be relevant from an NRC MC&A perspective[F] (adapted from [10]).

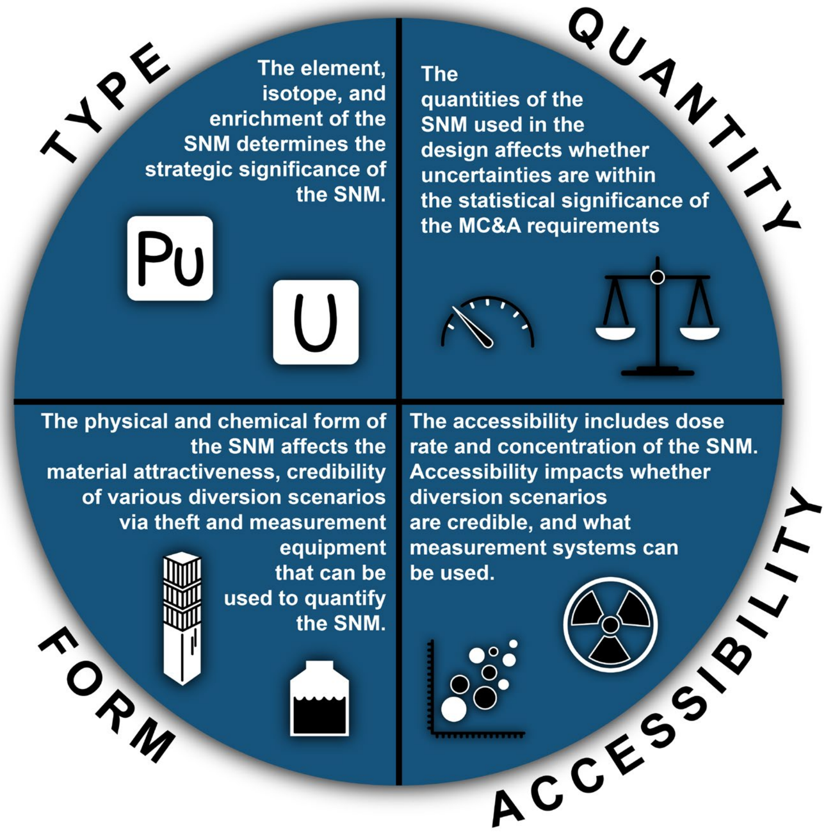


Figure 2. MC&A-relevant design parameters

Type of SNM: The element, isotope, and enrichment of the SNM affect the strategic significance category of the SNM. The MC&A requirements are defined by 10 CFR Part 74 for each category of

---

[F] This list is not exhaustive, but it identifies many categories of design features that may have a significant influence on how the design meets the NRC's MC&A requirements, as defined in 10 CFR Part 74.

SNM, although the NRC can exempt the SNM from some MC&A requirements if diversion by theft is deemed noncredible for certain materials or locations.

Physical and chemical form of SNM: The physical and chemical form of the SNM will affect the material attractiveness, which will affect the difficulty of various diversion scenarios of SNM via theft. Physical form identifies whether the SNM is in item form (e.g., in containers, fuel tubes) that can be individually counted or bulk form. The physical and chemical form of the SNM will also influence the measurement techniques and equipment that can be used to quantify the SNM.

Quantities of SNM: The quantities and types of the SNM determine the strategic significance category of the SNM.

Accessibility of SNM: The physical accessibility of the SNM will impact whether theft scenarios are credible. This could affect whether various MC&A requirements are deemed necessary by the NRC. Accessibility will also influence what measurement techniques are feasible for MC&A.

- **Radioactivity of material in which the SNM is located**: The radioactivity of the material in which the SNM is located affects whether the theft scenarios are credible. This could affect whether material is viewed as self-protecting. Radioactivity will also affect what measurement techniques can be used to produce MC&A-relevant data—both chosen measurement modality and detection efficiency.

- **Concentration of SNM within the material**: The volumetric concentration of the SNM within the material (e.g., the SNM concentration in fresh fuel, the SNM concentration in fuel salt) will impact the total quantity of the material required to be diverted to obtain a quantity of strategic significance. This could affect whether various MC&A requirements are deemed necessary by the NRC.

Such wide variation across different liquid-fueled MSR design concepts makes it impossible to generalize a MC&A approach to meet specified objectives. Table 2 (adapted from [11]) is a list of some of the design features of liquid-fueled MSRs that have been identified as MC&A-relevant. Features are organized into four main categories: fuel selection, operational practices, physics of the reactor design, and other systems included in the design. Table 2 also includes a brief description of the features and how each feature might be relevant to domestic MC&A requirements.

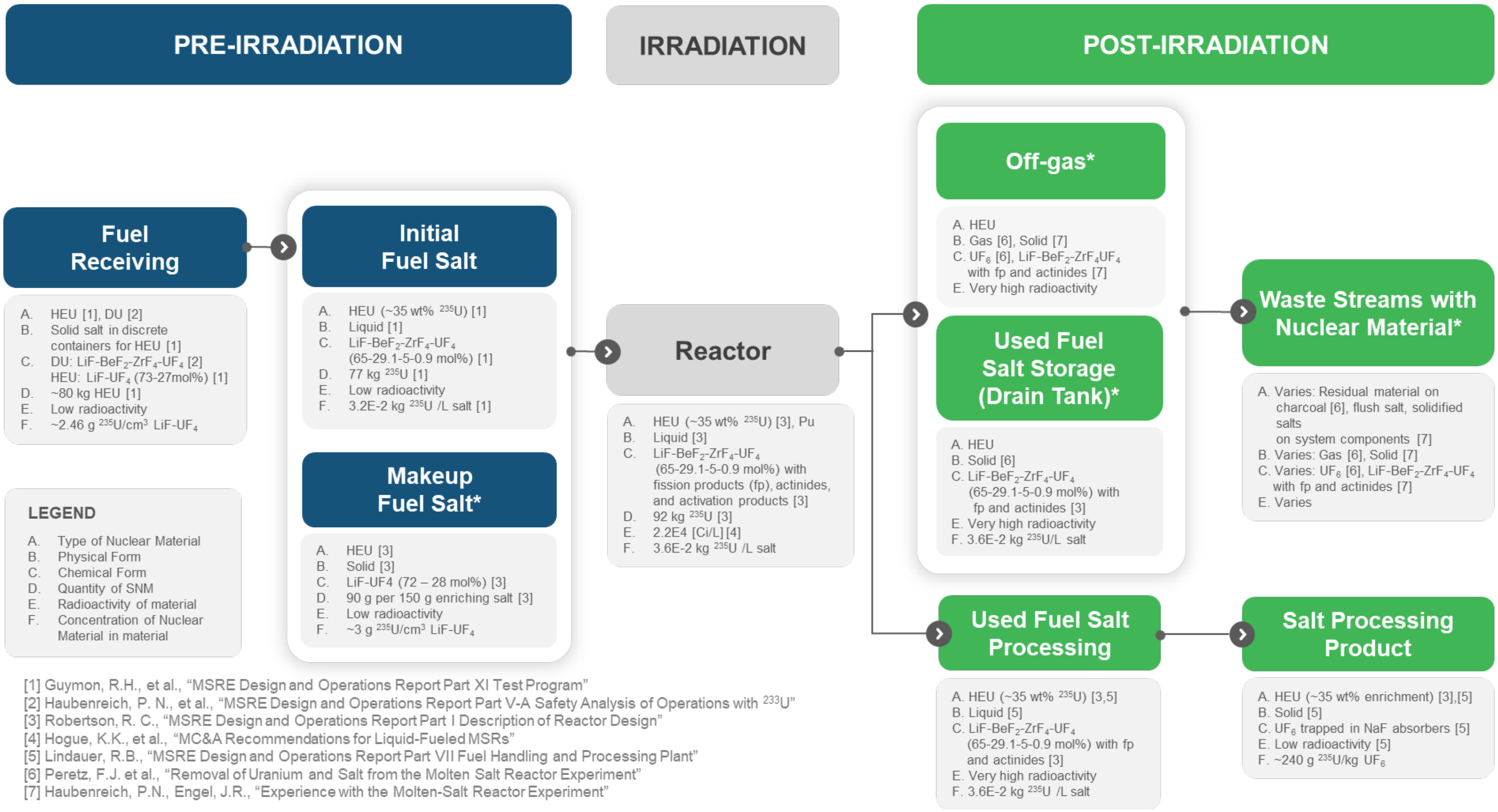
Figure 3 shows an example of how a fluid-fueled MSR developer or future license applicant could track MC&A-relevant design parameters across their specific design. The example uses the Molten Salt Reactor Experiment (MSRE)that operated at Oak Ridge National Laboratory in the 1960s. MC&A-relevant parameters, as noted in the legend, are described for various processes across the facility. A diagram like this could help a developer engage with the NRC (and other organizations like the IAEA) and convey the MC&A-relevant aspects of its design as the design evolves. Figure 3 includes activity per volume, represented by item E (radioactivity of the material). When a design has specific geometries, a better value to include would be the expected dose rates of the material at 1 m unshielded. This value will help determine how accessible the material is, which affects the credibility of theft scenarios and the feasibility of different measurement techniques, some of which are not compatible with high-radiation environments. Note that a material's self-protection is only relevant to domestic safeguards or security considerations of theft and does not credibly prevent diversion of nuclear material by a state actor, as considered by the IAEA under international safeguards obligations.

Table 2. Liquid-fueled MSR design features and their relevance to US MC&A requirements

Design feature category	Design feature	Description	Relevance to US MC&A requirements
Fuel	Fissile material content (type, quantity, enrichment) in fresh fuel salt and irradiated fuel salt	Designs include different fissile material in the fresh fuel, including <5 wt % ^{235}U, 10–20 wt % ^{235}U, ^{232}Th, Pu, and other actinides.	Quantities of U and Pu and enrichment of U defines the strategic significance category; LEU that is >10% enriched has different regulations than LEU that is <10%
	Fertile material content (type, quantity) in fresh fuel salt entering the reactor	Fertile material (^{238}U, ^{232}Th) is present in the salt in either the primary salt loop or a separate blanket salt loop.	U_{total} inventories are reported to the NRC via NMMSS. If computational physics codes are used to generate predicted inventories of irradiated salt, accurate knowledge of fertile material fed into the reactor is necessary.
Operations	Inventory of fresh fuel salt held at the facility	Facility operators will likely expect to store different amounts of fresh fuel on-site.	Inventories, containment, and surveillance of this material will require MC&A resources.
	Method and frequency initial and makeup salt are added	Designs will likely incorporate different practices for loading initial and makeup salt.	MC&A systems will likely require either surveillance or measurements to verify that no SNM is diverted during refueling. If computational physics codes are used to generate predicted inventories, the quantities of fissile and fertile material added to the system will be key parameters to these codes.
	Frequency reactor components are replaced	Components within liquid-fueled MSR designs will have to be replaced periodically (e.g., in thermal spectrum liquid-fueled MSRs, the graphite moderator blocks will likely have to be replaced every few years). When reactor components are replaced, fuel salt may be drained and stored in one or more storage tanks.	MC&A systems should incorporate elements to ensure no diversion of SNM during replacement of reactor components.

Table 2. Liquid-fueled MSR design features and their relevance to US MC&A requirements (continued)

Design feature category	Design feature	Description	Relevance to US MC&A requirements
Reactor physics	Power of the reactor	Some liquid-fueled MSR designs are expected to be significantly smaller (e.g., <300 MW_{th}) than large, commercial LWRs (~1,000 MW_{th}); other designs exist for larger (~1,000 MW_{th}) liquid-fueled MSRs.	The power of the reactor affects the throughput of fissile material, which affects the total quantity of fissile material on the site.
	Breeding ratio (correlated to neutron energy spectrum)	The breeding ratio determines how effectively the reactor is transmuting fertile material into fissile material.	The breeding ratio will impact the total quantity of fissile material within the reactor over the core lifetime.
	Neutron energy spectrum (correlated to breeding ratio)	The neutron energy spectrum, in which the reactor primarily operates, impacts how much fissile material is produced.	Thermal energy spectrum liquid-fueled MSRs will typically have lower amounts of Pu in their irradiated salt; Pu waste characterization will likely be a part of a facility's MC&A systems.
Auxiliary systems	Chemical processing of salt to separate fissile material and reuse as makeup fuel.	Some liquid-fueled MSR designs (especially those with high breeding ratios) plan to separate fissile material from the salt and use it as makeup feed to refuel the reactor during operation.	Nuclear material in this recycle stream, where fissile material is separated, stored, and returned to the reactor as makeup fuel, may need to be accurately quantified.
	Off-gas system	Some designs include an off-gas system to actively filter out gaseous fission and activation products. These systems sometimes include decay tanks.	Online measurements could occur in the off-gas system to provide data relevant to MC&A. Any SNM in waste streams from the off-gas system need to be quantified.



[1] Guymon, R.H., et al., "MSRE Design and Operations Report Part XI Test Program"
[2] Haubenreich, P. N., et al., "MSRE Design and Operations Report Part V-A Safety Analysis of Operations with ^{233}U"
[3] Robertson, R. C., "MSRE Design and Operations Report Part I Description of Reactor Design"
[4] Hogue, K.K., et al., "MC&A Recommendations for Liquid-Fueled MSRs"
[5] Lindauer, R.B., "MSRE Design and Operations Report Part VII Fuel Handling and Processing Plant"
[6] Peretz, F.J. et al., "Removal of Uranium and Salt from the Molten Salt Reactor Experiment"
[7] Haubenreich, P.N., Engel, J.R., "Experience with the Molten-Salt Reactor Experiment"

Figure 3. An example of MC&A relevant design parameters for the Molten Salt Reactor Experiment

3.2 Defining MC&A Objectives

Once the MC&A-relevant parameters have been identified, the MC&A objectives need to be clearly defined so that MC&A program elements can be selected and documented in the MC&A plan. MC&A program elements are individual devices or measures (e.g., seals, cameras, scales, spectrometers) that are used to implement the MC&A approach. The specificity of the MC&A objectives, the conditions of the measurement environment, and the MC&A-relevant parameters of the design will affect which options are useful as MC&A elements.

For example, one objective could be to ensure that SNM is not removed from an area, whereas another objective could be to quantify the mass of the SNM after or before some event occurs, such as after receiving or before packaging material. The MC&A program elements required to ensure these two objectives would be very different. If the objective is to ensure no SNM is removed from an area, then tags, seals, cameras, or other similar program elements may be useful. If the objective is to quantify the mass of SNM, program elements may include scales, spectrometers, or other nondestructive assay (NDA) instrumentation. The selection of these elements is constrained by the measurement environment, which could include high-radiation fields, corrosive materials, high temperatures, or other limiting factors.

Table 3 illustrates how, for different areas of the facility (fresh salt storage, confinement, irradiated salt storage), the MC&A objectives, MC&A-relevant parameters (SNM type, physical form), and the measurement environment affect the selection of the MC&A program elements.

Table 3. MC&A objectives, measurement environment, and MC&A elements to meet objectives for MSRs

	MC&A objectives	SNM in area	Physical form of SNM	Measurement environment	MC&A elements
Area #1: Fresh fuel salt storage	Quantify SNM upon receipt of material	May be LEU, HALEU, Pu	SNM is within salt in a solid form at room temperature	Salt components or salt eutectic in containers, low radiation	Unique identifiers (serialized tags) on each container for tracking
					Weigh fuel salt containers upon receipt, during inventories, and after salt is removed and added to reactor confinement
	Ensure no SNM is removed from containers stored on-site except when entering confinement				Confirm integrity of TIDs on containers upon receipt and during inventories at facility
					Camera surveillance of material added to reactor confinement
					TIDs or surveillance on any valves that could be manually opened to allow access to the system
	Quantify SNM entering reactor confinement		Fuel salt may be heated to a liquid before entering reactor confinement (e.g., in a furnace) but could potentially be added as a solid		Measurements on fuel salt as salt enters confinement
Area #2: Reactor confinement	Ensure no SNM is removed from reactor confinement outside expected operations	May be LEU, HALEU, Pu entering Area #2	SNM will likely be in a salt eutectic as a liquid	Extremely high radiation because of fission products and actinides	TIDs on all potential access points to confinement.
					Potentially measure actinide concentrations in fuel salt using NDA or destructive analysis and total salt volume
		Dynamic amounts and concentrations of SNM as ^{235}U is depleted and Pu is produced from neutron interactions, ^{233}U if MSR fuel salt contains Th	When the reactor is sufficiently cooled down, the salt eutectic will solidify	Salt is at high temperatures (>500C), ambient temperature within confinement would likely be high; material is difficult to physically access	Camera surveillance on all access points to detect removal of SNM

Table 3. MC&A objectives, measurement conditions, and elements to meet objectives for the MSDR model (continued)

	MC&A objectives	SNM in area	Physical form of SNM	Measurement environment	MC&A elements
Area #3: Irradiated fuel salt and waste storage	Quantify SNM in salt leaving reactor confinement	May include LEU, HALEU, Pu, ^{233}U	SNM is in salt eutectic either as a liquid or solid, depending on temperature and pressure	Irradiated fuel salt is likely in tanks or shielded containers and highly radioactive if co-located with fission products and actinides	In situ NDA techniques or destructive analysis sampling from tanks, processing monitoring for indications of diversion
					TIDs placed on storage tanks or containers containing irradiated fuel salt, waste streams, or reactor equipment with residual material
	Ensure no SNM is removed from tanks, waste streams, containers, or equipment stored on-site		SNM may be in solid, liquid, or gaseous form depending on chemical form and temperature and pressure within waste and containers		Assay material being removed from containment to containers, NDA and destructive analysis: gamma spectroscopy, optical spectroscopy, electrochemical sensors, mass spectrometry, hybrid k-edge densitometer, and so on
					TIDs placed on equipment entry points (e.g., waste reactor vessel closure)
					NDA holdup measurements and imaging techniques to characterize and quantify material
	Measure holdup of SNM in equipment removed from reactor confinement		SNM may be in a solid form within equipment		Camera surveillance on entry and exit points to storage areas
					Weigh containers during inventories or upon changes to content

3.3 Recommended Approach for Liquid-Fueled MSRs

This section describes the recommended approach for developing a practical liquid-fueled MSR MC&A approach that is consistent with NRC guidance and regulations. The authors' recommended approach will be referred to in this paper as an inventory-monitor containment-inventory (IMCI) approach. We recommend this approach be used because it relies on inventorying material when it is accessible[G], but it relies on monitoring for diversion while the material is contained and inaccessible. The IMCI approach was developed by the authors following discussions with the NRC MC&A group, focused on the intended purpose of MC&A and domestic safeguards and awareness of practical considerations. The intended purpose of nuclear material accounting as a component of an MC&A program is to prepare and maintain accounting records, perform measurements, and analyze the information for confirming the location and quantities of nuclear materials and for detecting potential theft, loss, or diversion of nuclear materials that trigger an appropriate response [12]. The IMCI approach satisfies this intended purpose and acknowledges the uniqueness of a liquid-fueled MSR, being both a nuclear reactor and a bulk facility.

3.3.1 Alternative Liquid-fueled MSR MC&A Approaches that are Not Recommended

The IMCI approach was developed after exploring alternative approaches to liquid-fueled MSR MC&A that we do not recommend. Those approaches are described in general terms here to identify their limitations and demonstrate the need for an acceptable approach to MC&A.

3.3.1.1 Not Recommended: Approach Liquid Fueled MSR MC&A as Bulk Fuel Cycle Facility MC&A

A possible approach to liquid-fueled MSR MC&A is to treat liquid-fueled MSRs like enrichment or fuel fabrication facilities and directly apply 10 CFR Part 74 requirements. Part 74 MC&A requirements are currently tailored to types of facilities that have previously submitted license applications to the NRC and have SNM in bulk form, including fuel fabrication and enrichment plants. To inventory SNM in bulk form, the mass or volume of the SNM must be measured, which contrasts with SNM in item form (individual items can be inventoried. Measuring the total salt volume at any given time across the entirety of the MSR process flow with varying temperatures and salt conditions is likely to be considerably more difficult than measuring the material present in an individual fuel fabrication process or the UF_6 flow across a single enrichment cascade.

Title 10 CFR Part 74 relies heavily on accounting of SNM. Material balance evaluations are performed such that each strata (i.e., type) of SNM is measured during periodic inventories and reported in NMMSS. The difference between the expected (i.e., book values plus additions and minus any removals from each item control area) and measured quantities of each strata of SNM after each inventory is documented as the inventory difference (ID). In facilities with purposes like fuel fabrication and enrichment, this accounting strategy works well. In facilities like reactors, where the quantities of SNM are rapidly changing through transmutation and depletion as the material is undergoing irradiation, material balances are inherently challenging. Material balances in reactors are not as simple as accounting for movement of SNM through different process streams (and potentially small removals due to decay, as uranium has a long half-life). In reactors, you must

---

[G] Title 10 CFR 74.4 defines *accessible location* as "a process location at which SSNM could be acquired without leaving evidence of the acquisition, i.e., without tools or other equipment to obviously violate the integrity of the containment."

account for the predicted addition and removal terms of each strata of SNM through computational codes (e.g., SCALE) [13]. These codes include uncertainties, such as in the nuclear data (e.g., cross sections for reactions, fission yields). For LWRs, these codes have been validated and experiments have been tailored to reducing uncertainties that are relevant to nuclear reactors that have operated for decades. For new types of reactors, and especially liquid-fueled MSRs, these computational codes have not yet been validated, and uncertainties currently cannot be accurately quantified. Nuclear data that are relevant for LWRs are often different from nuclear data relevant for MSRs. For example, Cl cross sections are highly relevant in MSRs using a chloride-based carrier salt but not generally relevant for LWRs. Therefore, it is difficult to quantify the expected uncertainties in computational codes that would be needed to generate expected inventories of SNM in material undergoing irradiation within MSRs. Completing inventories of SNM that is in process and undergoing irradiation (i.e., in a system in an operational reactor with a notable thermal power) will likely be so challenging in the near-term that it prevents material balances from being an effective tool for liquid-fueled MSR MC&A. Inventories of SNM that are not in process in an at-power reactor could likely be performed, and traditional material accounting and material balance approaches could apply.

Fundamentally, MC&A plans for liquid-fueled MSRs could also rely on control of SNM. In principle, MC&A of SNM in nuclear reactors currently licensed by the NRC is based on control of SNM during irradiation. Currently, an NRC-licensed nuclear reactor reports SNM that enters the facility through NMMSS. This report includes the weight of enriched U in fresh fuel assemblies. When the assemblies are placed into the reactor vessel and sealed, MC&A relies on control in the form of containment within the reactor vessel. Inventories do not have to be performed while assemblies are in the reactor vessel. Once irradiated assemblies are removed from the reactor vessel and transferred to a spent fuel pool, U and Pu weights associated with those assemblies are reported to the NRC via NMMSS. Plutonium weights are reported to the NRC not based on measured values but based on computationally predicted values using reactor physics burnup codes. Essentially, though never stated explicitly, LWR license applicants are relying on the lack of access to the SNM while it is in the reactor vessel, high radioactivity of the fuel assemblies (self-protection), and the ability to detect diversion of the SNM from the large items: all aspects of material control opposed to material accounting.

In summary, MC&A practices like material balance evaluations are inherently and, in the near-term, prohibitively challenging to perform in reactors. SNM is in highly radioactive material and not accessible while in an operational reactor. Implementing an MC&A approach like what is done in a, for example, fuel fabrication facility with periodic inventories throughout all process streams would be (prohibitively) expensive to implement. Accurate material accounting of rapidly changing SNM inventories within a high-temperature, high-radiation, and highly corrosive environment may not be attainable with current measurement technologies. Finally, this approach is inconsistent with the NRC's approach for other reactors. It requires a high level of resources devoted to MC&A and is, in the author's opinion, both inefficient and not necessary to prevent or detect diversion, which is the overall goal of an MC&A program.

Regardless of design and fuel cycle choice, analysis by *Shoman and Higgins* shows that detection of material loss using traditional statistical tools alone is very challenging [14]. Detection of the most obvious abrupt material losses using commonly employed statistical tests is projected to require at or above current state-of-the-art destructive analysis levels of precision. This largely arises from the large fissile inventory present in many designs. A total of five different reference MSR designs were considered. Material accountancy for MSRs will likely have to account for unique design features, so the exemplar designs are chosen to cover a variety of neutron spectrums and fuel cycles. These designs included the MSDR [15], MOSART [16], REBUS [17], MSFR [18], and MCSFR [19]. The designs are summarized in Table 5. Figure 4 shows the U and Pu masses that equate to a representative 1% SEID[H], on irradiated salt for different times, assuming the reactor operated at full power and constantly. With current measurement techniques, it is unlikely that total measurement error for U and Pu mass could be reduced to below 1% and would likely be higher than 1%.

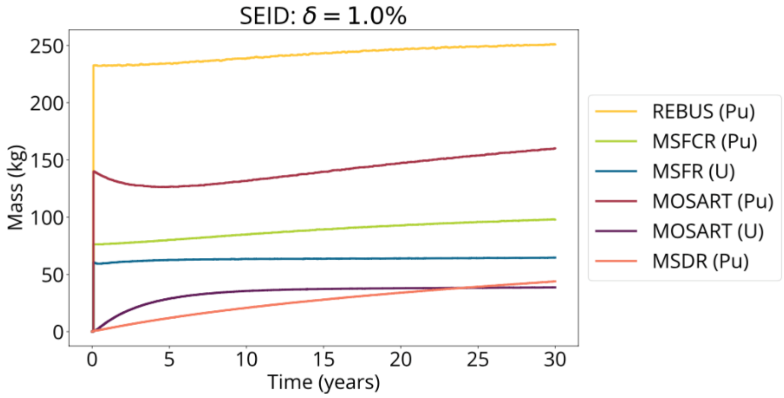


Figure 4. Nominal SEID liquid-fueled MSR designs

Designs shown in in Figure 4 have different nominal thermal power, so some difference in SEID between designs is expected given the variation in reactor size. Fissile inventory generally scales with thermal design power, however, some designs have lower fissile inventory per unit power than others. The MSFCR has the largest thermal power design at 6000 MW_{th}, but has a SEID that is lower than both the 3700 MW_{th} REBUS and 2400 MW_{th} MOSART.

Regardless of design, large fissile inventories create a challenging environment to detect material loss using statistical testing on material accountancy data alone. Generally, detection of material loss on the order of multiple significant quantities is difficult in MSRs using obtainable measurement errors. The inability to detect these losses are not a reflection of any particular design feature of MSRs themselves. Rather, the inventories of fissile inventory required for these large reactors lead to significant uncertainty in the material balance, even at extraordinarily low measurement uncertainties.

For each of the five designs, SCALE was used to carry out reactor physics calculations, estimate nuclear data uncertainty, and inform the probability of diversion detection. A wide range of different material losses were considered for each design, at least nine cases for each. Material losses were modeled as substitution losses; the removed actinide bearing salt is replaced with an equal mass of a surrogate material with the same composition as the salt makeup feed. Substitution losses were simulated as it is assumed that direct losses would be easier to detect through use of process monitoring and bulk measurements.

[H] SEIDs, as currently defined, are based on measured values. To determine a loss of SNM, the measured quantity is compared against an expected quantity (the book value), plus any additions and minus any losses. The concept of SEID is challenging to apply to an operating reactor because the addition and loss terms would be based on computational predictions, not measured values.

The impact of a large fissile inventory is shown in Table 4 where the average nominal SEID is reported for materials of interest for each of the designs considered. The lower limit of detection (LLD) (e.g., the required SEID for a 95% detection probability) is also provided. It is statistically impossible to detect even 10 times the IAEA-defined significant quantities[I] at high confidence levels in some scenarios when using DA-level measurement errors.

Table 4. Lower limits of detection based on current SEID values

Design	Design power (MW_{th})	Material	Average nominal SEID at 1.0% uncertainty (kg)	Lower limit of detection at 1.0% uncertainty (kg)
MSDR	750	Total Pu	26.11	85.65
MOSART	2400	^{233}U	33.60	110.22
MOSART	2400	Total Pu	141.164	463.02
MSFR	3000	^{233}U	63.20	207.29
REBUS	3700	Total Pu	242.08	794.05
MSCFR	6600	Total Pu	87.97	288.56

In summary, MC&A practices like material balance evaluations are inherently and, in the near-term, preventatively challenging to perform in reactors. SNM is in highly radioactive material and not accessible while in an operational reactor. Implementing an MC&A approach similar to what is done in a e.g., fuel fabrication facility with periodic inventories throughout all process streams would be (potentially prohibitively) expensive to implement. Accurate material accountancy of rapidly changing SNM inventories within a high temperature, high radiation, and highly corrosive environment may not be attainable with current technologies. Lastly, this approach is inconsistent with the NRC's approach for other reactors. It requires a high level of resources devoted to MC&A and is not necessary to prevent or detect diversion which is the overall goal of an MC&A program. This approach would not be efficient.

3.3.1.2 Not Recommended: Approach Liquid-Fueled MSR MC&A as Conventional LWR MC&A

Another possible approach is to treat a liquid-fueled MSR like an LWR and not submit an MC&A plan in the license application of a liquid-fueled MSR. Counter to what is described in 0, this approach would not be effective. SNM in liquid-fueled MSRs is not in large, heavy items that can be counted and for which diversion has arguably more obvious indicators from a nuclear security perspective. Although a liquid-fueled MSR is a reactor, it is also a facility with SNM in bulk form, and MC&A is important to track and verify SNM on-site. The NRC should have the opportunity to review a detailed plan before granting a liquid-fueled MSR facility's license to operate and ensure the plan is being effectively implemented throughout the facility lifecycle. Theft of SNM from material in bulk form is more credible than theft of SNM in large, heavy fuel assemblies.

3.3.2 The Recommended IMCI Approach to Liquid-Fueled MSR MC&A

The recommended approach to MC&A in a terrestrial-based liquid-fueled MSR includes separate internal control areas for SNM, where different MC&A approaches would apply. Figure 5 depicts a recommended approach, where SNM could be accounted for, periodic inventories could be applied, and material balances with IDs and SEIDs calculated in all material outside of the physical boundary

---

[I] A "significant quantity" is defined by the IAEA for international safeguards as 8 kg for total Pu and ^{233}U, 25 kg for LEU, and 75 kg for HEU.

encompassing the reactor system, where irradiation primarily occurs while the reactor is operational or at power. In Figure 3, MC&A in MBA 2 would primarily rely on control of the SNM. diversion path analysis could identify any potential paths to divert SNM from within reactor confinement (e.g., through a sampling port), as described in Section 2.2.1. 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 MC&A elements might incorporate measurements, confinement, or surveillance elements and should be described in the MC&A plan. Periodic inventories would not be performed on SNM within MBA 2.

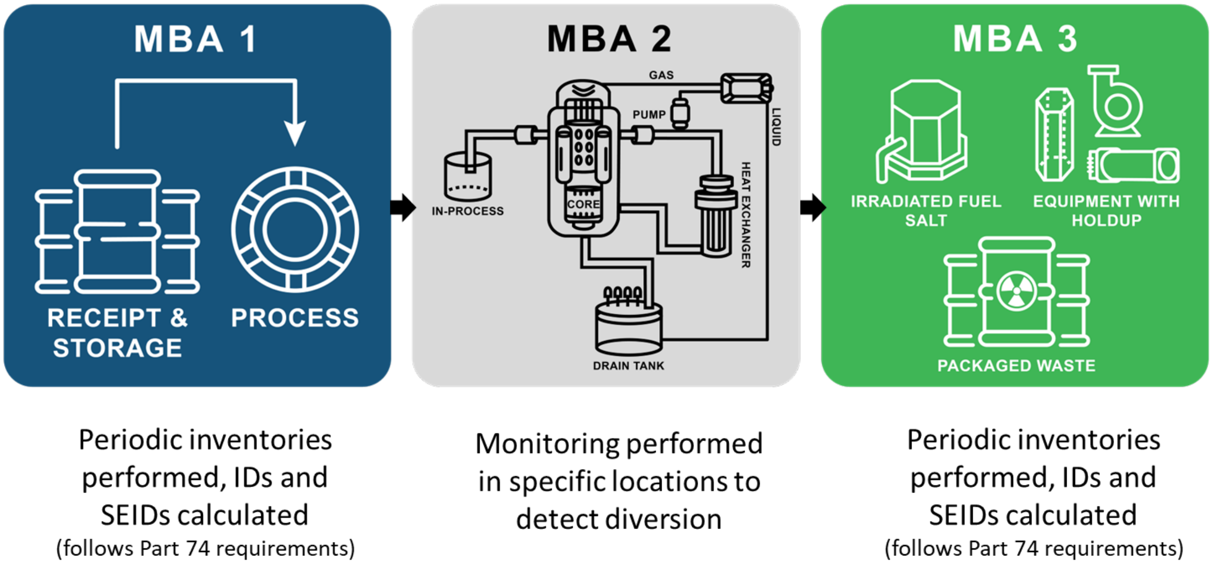


Figure 5. A proposed MBA structure for a terrestrial-based liquid fueled MSR

The license applicant could evaluate whether each of the internal control areas would be most effective and efficient as MBAs or ICAs, based on what form the SNM is and where the boundary lines are drawn. The boundary for the internal control area 2 (labeled in Figure 5 as *MBA 2*) should be consistent with a physical boundary, behind which physical access is limited, and that can be accessed only through known points that can be controlled through containment and surveillance.

Alternatively, a license applicant could ensure the first and third internal control areas only have items present in these areas. In this case, the boundaries would be immediately before (or, in the case of irradiated salt and equipment removal, after) the points in the process flow, where SNM changes form from item to bulk. Additionally, some applicants may plan to both feed and withdraw SNM from the system through the same access point. In this case, MBA 1 and 3 could potentially be combined into one MBA, but consideration would need to be made to enable effective and efficient accounting for different strata of SNM (e.g., LEU or HALEU entering the reactor as initial or makeup fuel salt, as opposed to Pu exiting confinement).

3.3.3 MC&A Plan Recommendations

In an MC&A plan, the applicant 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 confinement or physical barriers preventing access requires more significant material accounting efforts. Physical boundaries (e.g., defining a reactor confinement) coupled with radiological hazards and expected low concentrations of SNM 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, initial and makeup fuel salt entering the reactor core, process streams outside of reactor confinement that may contain SNM, and irradiated fuel salt or components leaving reactor confinement.

The MC&A plan should contain details of the transfer of irradiated fuel salt from reactor confinement to storage, transfer off-site, or a salt processing area (e.g., for conditioning into a stable waste form). Like the online fueling case, the applicant should consider how the irradiated fuel salt will be removed from the physical reactor confinement boundary and transferred to approved storage containers and storage tanks. The applicant should also consider whether the transfer will take place within reactor confinement, with a sealed container being transferred out of reactor confinement, or whether a pipe breach of confinement will be required to transfer irradiated fuel salt into an approved container outside of reactor confinement. The MC&A plan should incorporate the details of the proposed systems used to transfer fresh and irradiated SNM throughout the facility. The MC&A plan should also include details for measurements on all waste streams to determine whether SNM is present. Equipment removed from reactor confinement 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.

3.3.4 Future Transition to Process Monitoring

Many liquid-fueled MSR designs with fuel dissolved in salt will likely incorporate the ability for facility operators to monitor operational parameters to optimize operations and measure fuel salt thermochemical and thermophysical properties. This capability would help ensure that the parameters remain within the established limits necessary to satisfy the reactor safety bases or to perform fundamental safety functions (i.e., normal operations). For example, one approach could be to extract a small quantity of salt from the reactor environment through a sampling line. Analysis of the sample material could allow determination of the quantities of fissile materials and actinide concentrations in near real time. Destructive analysis (e.g., mass spectrometry) techniques, in situ nondestructive analysis gamma, or neutron detection systems could be used to determine the sample isotopic composition and extended to understand the composition and inventories within the process streams. Much of this operational parameter data could also provide relevant information to determine the material quantities and locations for MC&A purposes. This methodology is often referred to as *process monitoring*. However, 10 CFR Part 74 uses that terminology in a very specific context associated with the robust MC&A requirements mandatory for Category I SSNM.

Applying the technical approach of material accounting throughout the process streams would provide less overall uncertainty as to the location and quantities of the SNM within the facility. Additionally, the designs would likely already incorporate measurement systems to produce these data for other purposes. The NRC would benefit from more accurate and efficient MC&A implementation at liquid-fueled MSRs by encouraging the facility designers—especially those whose designs are liquid-fueled MSRs with fuel dissolved in salt—to incorporate the methodology of material accounting throughout the process streams, not necessarily requiring all of the obligations associated with the process monitoring used in 10 CFR Part 74 for Category I SNM (SSNM).

3.3.5 Examples of Potential Measurement Techniques to Meet MC&A Objectives

This section includes examples of measurement techniques that are under development and could be used to meet MC&A objectives. There is likely not a generic set of measurement techniques that can be applied to all liquid-fueled MSRs. Similar to Table 2, physical constraints, operational plans, SNM concentrations within process streams, materials used, and facility operator priorities and preferences will all factor into what measurement techniques a license applicant chooses to include in an FNMC plan to meet specific MC&A objectives. For example, designs with chloride-based fuel salts may have higher actinide concentrations than fluoride-based fuel salts. Nuclear reactions within the salts will be distinct based on the salt composition [20]. These factors, and others, will impact the feasibility of some measurement techniques. Thus, each license applicant must determine the measurement techniques most appropriate for their design. Notably, sensors incorporated in the design may provide data that is useful for applications beyond MC&A. This data may be useful to monitor salt chemistry, holdup to prevent criticality, and other safety- or operational-related purposes. The usefulness of these data for other purposes should also be considered when developing an MC&A plan.

3.3.5.1 Optical Spectrometry Based Approaches [21]

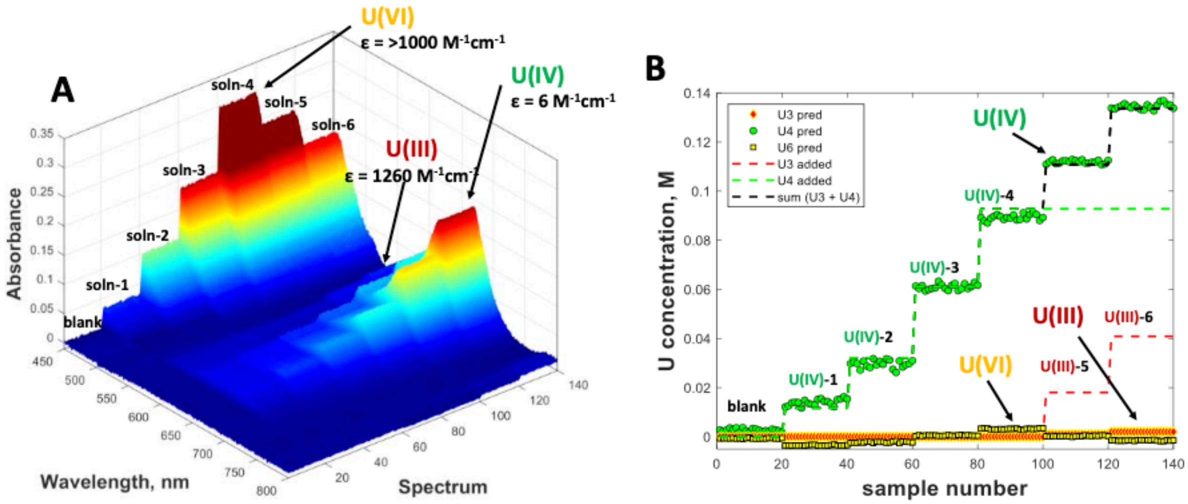


Figure 6. Validation set for U(III)/U(IV)/U(VI) in LiK-Cl salt eutectic. Indicates ability to account for U species originally added to matrix, and ability to account for complex chemistry within matrix.

A technology with potential for process monitoring of liquid fueled MSRs is optical spectroscopy, which can provide insight into chemical speciation, redox states, and concentrations. Both Raman and UV-vis spectra can be measured simultaneously to monitor U in different oxidation states and in the presence of interfering species. This information can be highly valuable in accurately accounting for actinides that display complex chemistry under molten salt conditions. Optical monitoring approaches can be combined with advanced analysis techniques such as chemometric modeling for the real-time and accurate analysis of optical data, but transitioning these technologies to molten salt systems requires key technology advances.

Uranium can assume multiple oxidation states and speciation forms within a given salt melt. Nominally, U in the 3+, 4+, and 6+ states is possible while speciation will depend on the background salt matrix and presence of interacting species. Several chloride salt eutectics were explored by *Lines et al.* to gain an understanding of the U fingerprint (Figure 6), though a wider range of focus was placed on the NaMg-Cl eutectic. Limits of detection were determined to be in the milimolar (mM) range for the various U oxidation states within the chloride melts explored. Representative industry salts were characterized and optical spectroscopy was found to provide valuable insight into salt composition. All data was used to build and validate models for the real-time characterization of U within salts. Uncertainties indicate high precision is possible with optical approaches, though values will still have trouble meeting 0.1% accountability targets, particularly after propagating errors from volume and density measurements. However, optical techniques still provide a highly valuable pathway to 1) monitoring for trends indicating short or protracted diversions and 2) identifying chemistry complexities that can indicate precipitated or plated out actinides are impacting material accounting; all in addition to general quantification with uncertainties in the neighborhood of 1% for U species.

3.3.5.2 Flow-Enhanced Sensors for Actinide Quantification in MSRs [22]

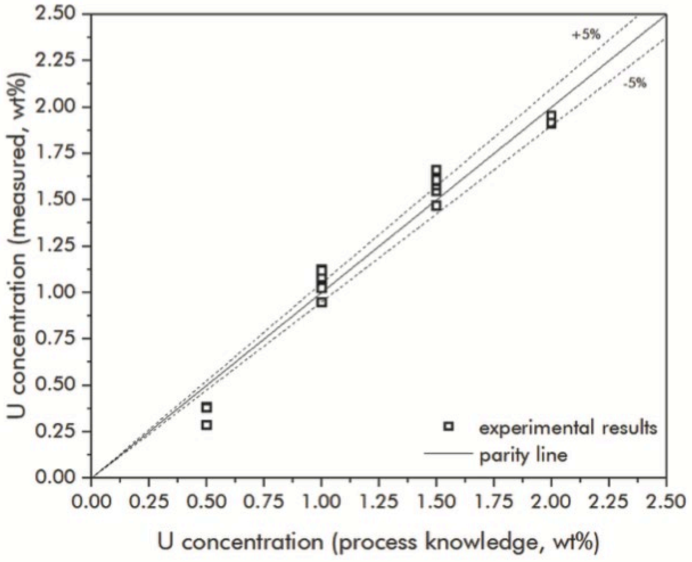


Figure 7. U concentration measured with flow sensor vs. U concentration from process knowledge. Dotted lines are parity plus or minus 5%.

Through extensive flow testing using UCl_3-bearing salts, *Moore et al.* has been able to show that flow-enhanced electrochemical sensors (FEES) are able to make good measurements of salt composition. Concentration measurements with a mean absolute error of 0.09 wt% have been achieved for representative fuel salt mixtures across a range of UCl3 loadings. Repeatability was also good, with the relative standard deviation from repeated measurements being less than 1.0%. These sensors have also been shown to be able to measure the flow rate of the salt within the flow system's transfer line. Although the performance of the sensors has been good, the MC&A requirements listed in 10 CFR 74 require extremely accurate measurements that the FEES were not able to achieve at this stage. 10 CFR 74 requires the SEID to be less than 0.1% of the AI for Category I SNM. The FEES has so far only been able to achieve relative errors of approximately 5.0% for concentration measurements (Figure 7). Most of this error resulted from loss of knowledge of the UCl_3 concentration within the flow system due to corrosion, alloying, and other processes that lead to the conversion of UCl_3 to non- electroactive species (e.g., UO_2 and U^0). With better long-term control of the salt composition, it is expected that the accuracy can be improved considerably.

Nonetheless, a 0.1% SEID criterion will likely be challenging to achieve. The use of multimodal sensors in concert with the FEES could help push the accuracy toward this needed level.

Alongside concentration measurements, the FEES has also been shown to be able to make flow rate measurements for radiological salts. This capability has been demonstrated for moderate flow rates using a combination of potential sweep and potential hold techniques. Further development of this approach, however, is required to fully delimit the accuracy that can be achieved. Beyond the FEES assessment, the modular flow instrumentation testbed (MFIT) at Argonne National Laboratory has shown itself to be an effective testbed for material accountancy and safeguards sensor development.

4. INTERNAL CONTROL AREA APPROACHES [23]

If an NRC license applicant will possess greater than 1 effective kg of SNM, the applicant must divide the facility into designated internal control areas. The internal control areas can be assigned as an MBA or ICA (if only items exist within the control area) [24]. Boundary areas should be developed and defined to minimize SNM loss and provide a means to locate material loss by measurements. Another consideration is developing 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 used or processed). The licensee is required to officially notify the NRC for SNM of moderate strategic significance (Category II facility) if (1) a SEID is greater than 0.125% of the active inventory (AI) or (2) an ID is greater than both 3× the SEID and either (a) 200 g of Pu, ^{233}U, (b) 300 g of ^{235}U in HEU, or (c) 9,000 g of ^{235}U in LEU.

The NRC does not advise the applicant or require a certain number or type of internal control areas that must be included in an FNMC plan. Each applicant must evaluate the current domestic regulations and determine the combination of MBAs and ICAs to provide the highest level or material control by reducing SEID, and that enables locating any loss of SNM. Generally, a good starting point for determining a facility's boundary and 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 MBA Approach

Previous research presented a simplified material balance for a liquid-fueled MSR based on the MSDR [25]. That plan was applied to the MSDR to develop an MC&A approach. The approach considered the entire plant as an MBA with three internal control areas. Control area no. 1 could be for fresh fuel storage, including receipt of containers with SNM for initial and/or makeup salt (either as fuel salt, fuel salt in concentrated form if fuel is synthesized on site, or other). Control area no. 2 could be reactor confinement, including the MSR process stream such as the reactor system, which would include the primary vessel, off-gas system, drain tanks, pumps, piping, heat exchangers, and chemical processing systems. Control area no. 3 could be for irradiated fuel salt and waste storage, including salt that has been removed from confinement, and any equipment that may have SNM on it or in it that was removed from confinement. Figure 5 depicts this MC&A approach.

A facility requires barriers between control areas—which can simply be a marking on the floor—but physical barriers are encouraged to localize material in the event of material loss or investigation. In this MC&A approach, each control area handles SNM, and the categorization of SNM in the control areas could vary by based on the material within the facility.

4.2 MBA and ICA Approach[J]

For some designs, the 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 an applicant who intends to process and synthesize fuel salt after receiving SNM in a different, shippable form (e.g., UF_6), the separation of control area no. 1 into two separate areas may provide a better means to localize material inventory (or loss), store the SNM as an item after receipt, and support distinct physical boundaries based on material type or processing. Moreover, a further-divided approach may better facilitate distinct SNM categories (e.g., Category III fresh fuel salt vs. Category II irradiated salt), so that more rigorous MC&A could be applied to material that had more strategic significance. Figure 8 depicts a MC&A approach that includes MBAs and ICAs.

4.2.1 Item 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.

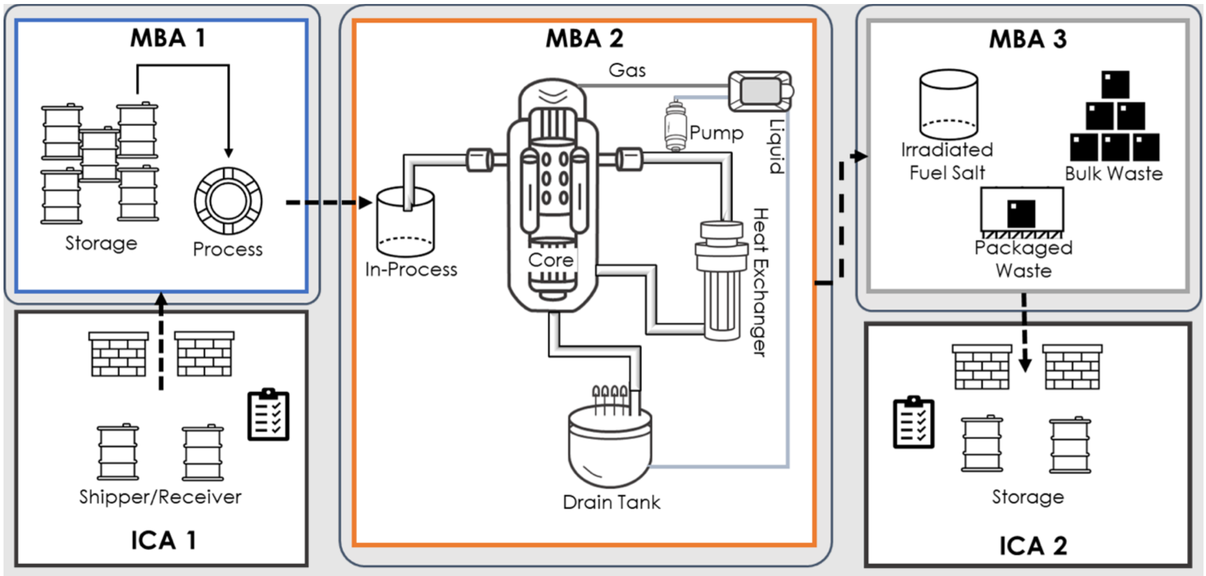


Figure 8. MBA and ICA MC&A approach for a liquid-fueled MSR [23]

[J] Adapted from [23].

4.2.2 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 (Section 1.2) and balanced against the feed rate to the primary loop via measurements (e.g., destructive analysis of fresh fuel salt samples or in situ nondestructive assay of fresh fuel and mass of fuel salt added to the system). MBA 1 requires ID and SEID calculations for each type of SNM during periodic inventories.

4.2.3 Material Balance Area 2: Reactor Loop and Core Confinement

Irradiated fuel salt is highly radioactive, and it is generally inaccessible within reactor confinement. It is disadvantageous and challenging to shut down or drain a liquid-fueled MSR on specified periodic time frames to support static periodical physical inventories for NRC MC&A requirements. SNM in MBA 2 is controlled via (1) containment and surveillance, (2) measurements of all SNM entering or leaving the MBA boundaries, and (3) surveillance monitoring to detect any diversion of material outside of the MBA. The following conditions should be met:

1. All physical access points to the MBA must be strictly controlled by using physical and administrative protections. All material entry and 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.

2. If fresh 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.

3. A diversion path analysis could identify any potential paths to divert SNM from within reactor confinement (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 maintained by the licensee by combining additions and removals from the MBA with quantities of SNM that are produced and depleted via fuel use, as estimated by the computational model of the reactor. The material balance for MBA 2 for each material balance period during operation would be zero, resulting in an 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 [2, 26].

Full inventory measurements could potentially be performed if a reactor, planned or unplanned, shuts down and is drained. License applicants may incorporate methods to quantify each type of SNM in the fuel salt if a reactor is drained. For example, drain tank levels could be measured and used for total volume calculations and combined with destructive analysis of fuel salt samples, or nondestructive assay measurement techniques could be used for in situ measurements to quantify SNM within the fuel salt [21, 22, 27]. 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 for Category II SNM).

4.2.4 Material Balance Area 3: Irradiated Salt, Waste Output, and Packaging

SNM in irradiated fuel salt and waste (e.g., used filters) removed from MBA 2 must be quantified. 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. Irradiated salt from sampling existing outside of MBA 2 should be placed in serialized containers with TIDs. No (re)measurements should be 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.

4.2.4.1 Item 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 material access.

5. DESIGN SPECIFIC CONSIDERATIONS

5.1 Design Impacts on Special Nuclear Material Concentration

To characterize MC&A-relevant parameters for different liquid-fueled MSR designs, SCALE 6.3.0 was used to model various classes of liquid-fueled MSRs and compare trends of MC&A-relevant design features across these reactors [13]. Specifically, previous models of thermal- and fast-spectrum liquid-fueled MSRs were adapted from Bae [28], Rykhlevskii [29], Betzler [30], and Shoman [31], who developed simplified 2D unit cell representations of higher fidelity Monte-Carlo models, which preserve the flux spectra and reaction rates. The designs analyzed are not necessarily representative of designs currently pursued by developers, but they are nonproprietary, openly available designs useful to demonstrate modeling and simulation to assess MC&A-relevant parameters of different designs. This analysis also demonstrates the wide variation in liquid-fueled MSR designs in parameters that are relevant to developing an MC&A plan, which is the reason a generic MC&A approach that includes recommendations for specific MC&A elements does not exist. The reactor designs considered here are summarized in Table 5.

Table 5. Reactor model parameters for different designs

Parameter		Molten Salt Demonstration Reactor (MSDR) [28]	Molten Salt Fast Reactor (MSFR) [32]	Molten Chloride Salt Fast Reactor (MCSFR) [33]	Reactor Burnup System (REBUS) [17]	Molten Salt Actinide Recycler and Transmuter (MOSART) [16]
Thermal power (MW)		750	3,000	6,000	3,700	2,400
Specific power (MW/MTHM$_{\text{initial}}$)		6.2	69.2	30.7	32.2	140.0
Neutron spectrum		Thermal	Fast	Fast	Fast	Fast
Fuel cycle		U / Pu	Th / ^{233}U	U / Pu	U + TRU / Pu	Th + TRU / ^{233}U + Pu
Fresh fuel salt	Chemical form of fuel	UF_4	ThF_4, UF_4	UCl_3, $PuCl_3$	UCl_3, $TRUCl_3$	ThF_4, $TRUF_3$
	Molten salt carrier (mol %)	LiF–UF_4 (72.5–27.5)	LiF–ThF_4–UF_4 (77.5–19.9–2.6)	NaCl–UCl_3–$PUCl_3$ (60–36–4)	NaCl–(U + 16.7 at % TRU)Cl_3 (55–45)	LiF–BeF_2–ThF_4–$TRUF_3$ (69.75–27.0–2.0–1.25)
	^{235}U (wt % enrichment)	19.75	0.0*	0.247	0.642	9.94

* The MSFR initial fissile load is entirely ^{233}U in this model. The initial ^{233}U is presumed to come from either another breeder reactor or previous cycles of the same reactor.

Additionally, a parametric study was performed, which incorporated periods of shutdown with durations of 0, 3, or 6 months every 5 years of operation to account for periods of maintenance. Periods of operation were modeled as constant operation at full power and periods of shutdown were modeled as a period of decay only. During shutdown, no makeup fuel was fed into the salt, but noble gas and metal removal was still assumed to occur at a rate consistent with normal operations.

5.1.1 Results

To consistently compare the different reactor designs, material masses were normalized by the specific power of each reactor. In Figures 9 through 11 show the power-normalized masses (plotted as solid curve, left axis) and mass densities (i.e., concentrations in the fuel salt, plotted as dashed curves, right axis) of various species of interest: Pu_{total}, ^{233}U, and ^{235}U. The results are shown for 6 months of down time each 5-year period of depletion, and 1.1.1.1APPENDIX B additionally shows the results for 0 months of down time for these species as well as ^{239}Pu and U_{total} for comparison.

The plots demonstrate that inventories of Pu_{total}, ^{235}U, and ^{233}U vary by multiple orders of magnitudes across different liquid-fueled MSR designs. Additionally, these inventories can vary over orders of magnitude over operating lifetime, as well. Plutonium, ^{235}U, and ^{233}U concentrations within the fuel salt also vary by orders of magnitude across liquid-fueled MSR designs and over operational lifetime. These factors make it difficult to develop a generic approach for MC&A in liquid-fueled MSRs.

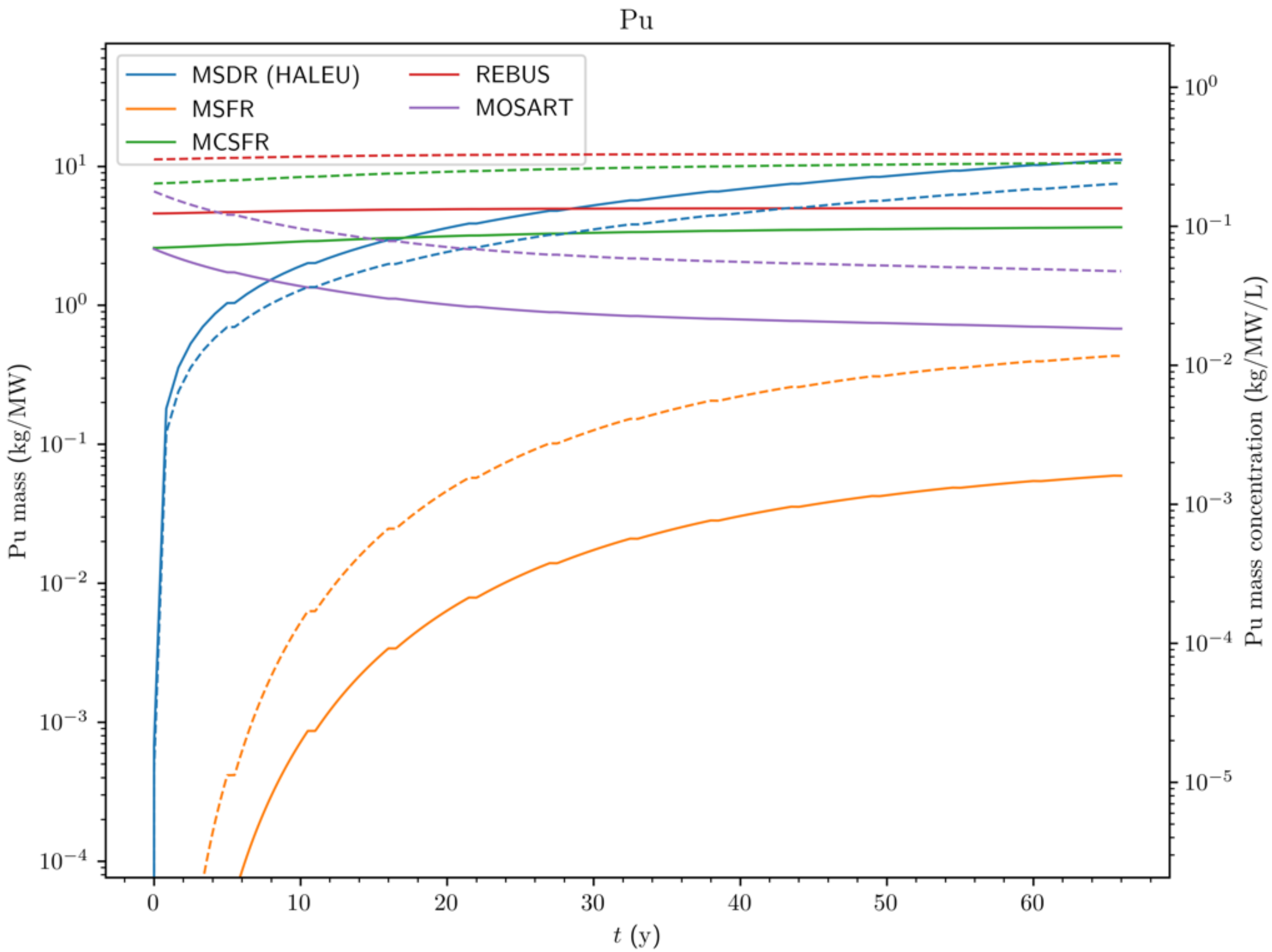


Figure 9. The power-normalized Pu_{total} mass and concentration over time for each reactor with 6 months of shutdown every 5 years

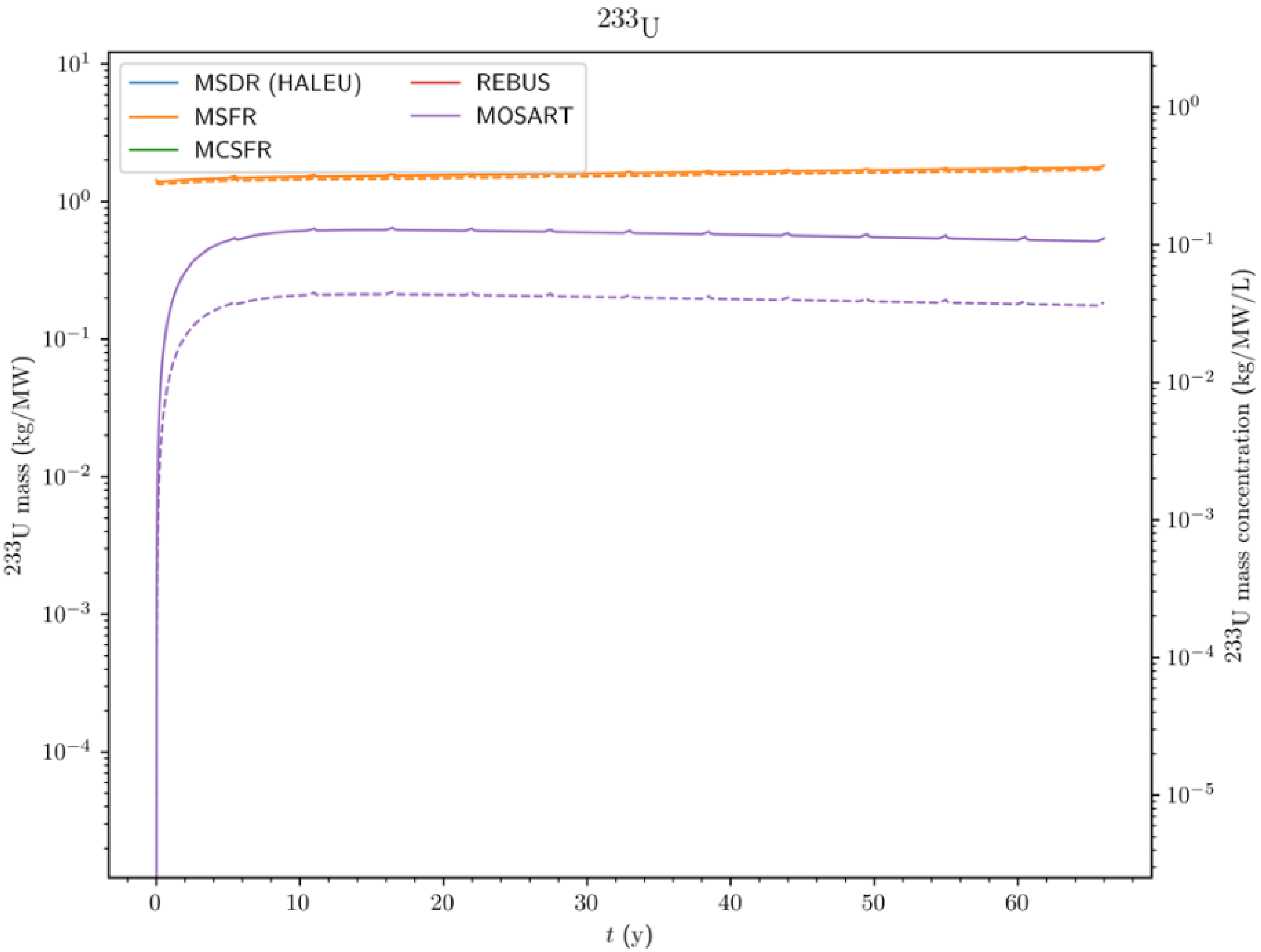


Figure 10. The power-normalized ^{233}U mass and concentration over time for each reactor with 6 months of shutdown every 5 years

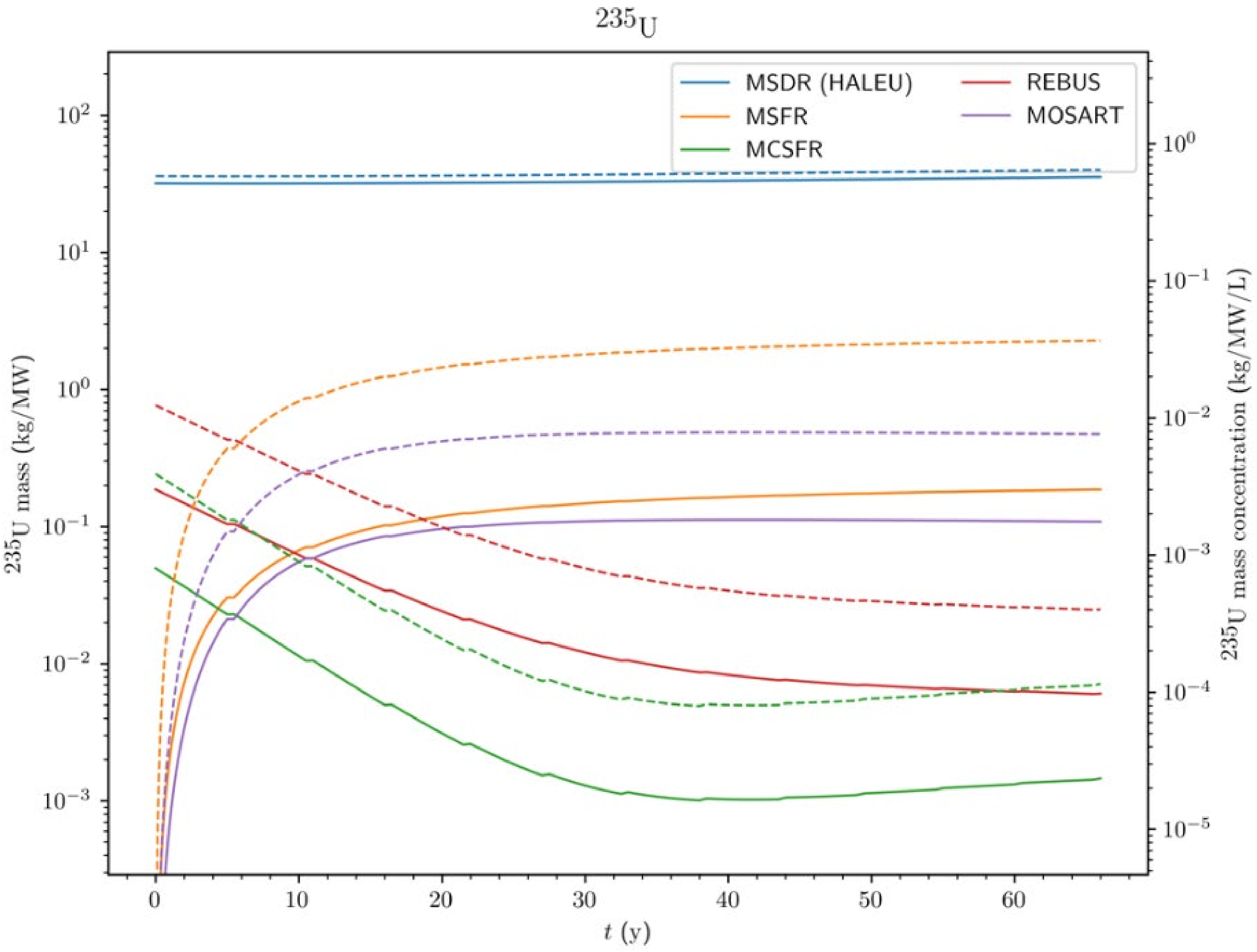


Figure 11. The power-normalized ^{235}U mass and concentration over time for each reactor with 6 months of shutdown every 5 years

5.2 Design Impacts on MC&A Parameters

Design decisions are driven by many factors, including safety, economics, and a variety of regulatory requirements. MC&A considerations should also affect design decisions. However, without subject matter expertise on these nuanced topics, it is difficult for developers to understand how a design decision might affect MC&A. The following examples demonstrate how design parameters can impact MC&A parameters.

5.2.1 Example 1: Effect of Fresh HALEU vs. LEU on SNM Inventories

The first example considers the effects of selecting HALEU (19.75 wt % ^{235}U) or LEU (4.95 wt % ^{235}U) as a fresh fuel on the type and quantity of SNM present in the irradiated fuel. This example uses the MSDR as a reference model [15]. The MSDR is a graphite-moderated reactor with a LiF (99.995% ^{7}Li) carrier salt. Although this study used the MSDR as a basis, the conclusions of the study are expected to hold broadly across the class of thermal spectrum liquid-fueled MSR designs.

A simplified model of a 2D quarter fuel channel unit cell with reflected boundaries was generated using the TRITON module in SCALE 6.3 [13]. The fuel salt material was depleted using a specific power of 6.197 MW/MTHM in both models with all materials at 625°C. In both cases, the fuel feed rate was assumed to be constant for simplicity. Gases (Kr, Xe, Ar, H, N, and O) and metals (Se, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Sb, and Te) are removed at a constant rate during the depletion. The fuel was depleted for 40 years at full power, and output of both models were processed to retrieve the mass of SNM in kilograms per metric ton initial heavy metal[K] over this period of operation.

This simplified model does not capture most of the design considerations of a real reactor. A real core would have finite dimensions, whereas this model has reflected boundaries. For two similar designs using different enrichments, a smaller core volume is possible with a higher enrichment. All other factors being equal, a smaller core volume would mean a lower mass of SNM is present, albeit at the greater enrichment of the fresh fuel. The two similar designs could be operated at the same power level, with different power densities, provided thermal limits or safety margins are not exceeded. These detailed MC&A-relevant design decisions are not considered in this example but should be considered during the design phase of a liquid-fueled MSR.

The simplified model illustrates a fundamental point of thermal spectrum reactors: fuels with lower enrichments generally produce more Pu per initial fuel mass because of the increased number density of ^{238}U. If a liquid-fueled MSR design initially used HALEU fresh fuel, it would be categorized as a Category II facility by the NRC. If the design was changed to use LEU fuel, the facility would instead be categorized as a Category III facility. Although there are MC&A and broader safeguards and security benefits, associated with use of LEU instead of HALEU because the fresh fuel enrichment has decreased, the irradiated fuel, both in process and as spent fuel, will have a greater concentration of Pu. In other words, there is a design tradeoff in fresh fuel enrichment versus used fuel SNM concentration when considering MC&A. A deeper analysis may find that certain designs with greater enrichment produces a lower Pu total mass (despite greater concentration) because of decreased core volume. Although this design may be possible, it may not be optimal because of economic, safety, or other design considerations.

[K] The term *heavy metal* includes all elements with atomic number greater than 89 (Th and beyond). For fresh fuel with U only, this is equivalent to metric tons of U.

Figure 12 and Figure 13 show the time-dependent ^{235}U and Pu concentrations in the salt over a total period of operation of 40 effective full power years (EFPY). The magnitude of the differences in SNM concentrations will depend on many factors, including the feed and removal rate of the salt, the initial enrichments, geometry, moderator parameters, and other features that modify the neutron spectrum. However, it is generally true that lower enrichments in the fresh fuel will produce greater concentrations of Pu in the irradiated fuel.

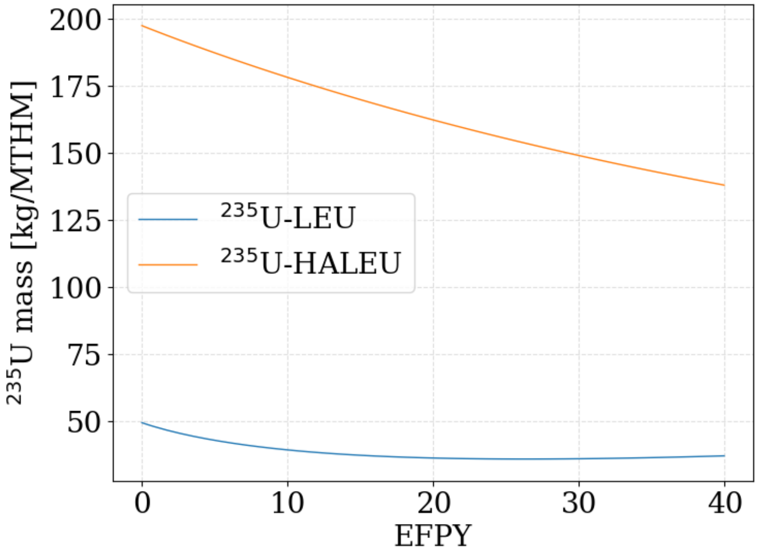


Figure 12. The ^{235}U mass in kilograms per metric tons of initial heavy metal over 40 EFPY

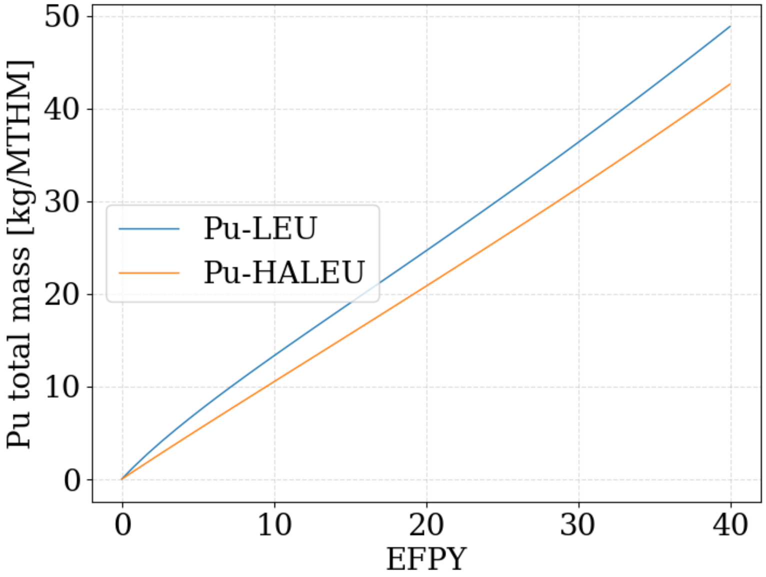


Figure 13. The Pu_{total} mass in kilograms per metric tons of initial heavy metal over 40 EFPY

5.2.2 Example 2: Assessment of Location of Storage of Makeup Fuel Salt

An assessment was performed to evaluate the effects of storing the makeup salt, either outside or inside of a confinement boundary. Table 6 describes the benefits and challenges of two practical options of storage of makeup salt to the reactor system. Each benefit or challenge is labeled with the primary topic it influences (e.g., operation, cost, MC&A, safeguards, security, safety, design). The overall recommendation is that Option 1 is selected in terrestrial-based operations where there is potentially significant benefit to having higher certainty in the quantity of makeup fuel salt that has been added to the reactor system. More confidence in those values would be beneficial from a perspective of validating computational models that the facility operators could be developing. Although this likely will not be a formal part of an MC&A plan in the near-term, as the computational models mature and are validated, MC&A plans could shift so that computational models and measurement techniques improve to enable inventories of SNM within the full reactor system. In this case, periodic measurements involving process monitoring or sampling could be used to check inventories against expected computational values for domestic safeguards purposes. In maritime applications (and potentially others, like operation in remote areas), sealed, integral units either without makeup fuel requirements or with all makeup fuel salt behind a physical barrier may be preferred.

- Option 1: Makeup salt is added as needed (either continuously or in batches) but stored outside the physical boundary defining the difficult to access area of the MSR (analogous to confinement; high radiation environment after reactor operation).

- Option 2: Makeup salt for the planned length of continuous operation (i.e., until the physical boundary will need to be opened to replace or perform maintenance on equipment components) is stored inside confinement (e.g., in a tank) and withdrawn from the tank (i.e., added as fuel) as needed.

Table 6. Benefits and challenges of two practical options for storing makeup fuel salt

Option 1: stored outside confinement		**Option 2: stored inside confinement**	
Benefits	**Challenges**	**Benefits**	**Challenges**
(MC&A, Safeguards) Improved ability to perform and accuracy of measurements to account for SNM added to the system (relevant if computational codes are used to track inventories of SNM within reactor)	(MC&A, Safeguards, Security) Increased physical access to SNM for potential diversion as it is being added to the system	(MC&A, Safeguards, Security) Significantly reduced access to fresh fuel after reactor is operational	(Cost) Cost of fuel up front
(MC&A, Safeguards) Potentially reduced quantities of SNM at the facility	(MC&A, Safeguards, Security) Increased physical access to SNM for potential diversion from storage (as fresh fuel)	(Safety) Potentially reduced probability for accident during fuel loading	(Operation) Potentially limited amounts of fuel salt available to procure at beginning of life in near-term deployments (e.g., if U is HALEU)
(Operation) Adaptability; allows ability to change techniques, equipment, replace or maintain any sensors used to monitor feed being added to system		(MC&A, Security) Potentially fewer penetrations into difficult to access areas	(MC&A, Safeguards) Potential impact on the ease of performing measurements and accuracy of quantifying SNM entering the system
(Operation) Allows for changing of composition/enrichment of makeup salt over time			(MC&A, Safeguards) Potentially larger amounts of SNM at the facility at one time
(Cost) Cost of fuel spread out over a longer time			(Design) Potential design issues with significant shielding required to keep fresh fuel unirradiated but behind a physical barrier

5.2.3 Example 3: Reflectors for Fast Chloride Liquid-Fueled MSRs

A technical analysis was performed to demonstrate methodology for assessing the effects of design decisions on MC&A-relevant parameters. This analysis assessed the effect of reflector material on MC&A-relevant parameters total uranium mass needed for operation, total plutonium mass needed for operation, and uranium and plutonium isotopic ratios. Three reflector materials were evaluated: HT9[L], Pb, and MgO. The following assessments were performed using a generic chloride molten salt fast reactor design and the design parameters listed in APPENDIX C and further described in [34].

The results are listed below, considering designs using similar salt, specific power, and neutron spectra:

- Lower total ^{235}U quantities are required (or lower enrichments) to achieve core criticality if using an MgO reflector, followed by Pb and HT9 (see Figure 14 and Tables 7–8).

- The best neutron economy is obtained using the Pb reflector, which allows the core to operate longer without any makeup fuel salt. HT9 and MgO would require addition of makeup fuel salt, with MgO requiring the largest total quantity (or highest feed rate) of makeup fuel salt (see Figure 15).

- The reflector material does influence the total plutonium produced in the reactor; however, the effect is not significant enough that it should be a major factor in the decision of the reflector material (see Table 9).

- Slightly lower total Pu is produced when using HT9 because of lower amounts of ^{238}U (due to a higher enrichment) and lower capture probability of ^{238}U in the reflector.

- The reflector material only minimally influences the ^{239}Pu/total Pu ratio and should not be a factor in the decision of the reflector material.

- The ^{239}Pu/total Pu ratio is slightly lower for the MgO reflector because the reaction probability of ^{239}Pu is higher due to the softer spectrum.

Table 7. Uranium-235 mass at the BOL and EOL for different reflector materials.

Reflector	^{235}U BOL [MTHM]	^{235}U EOL [MTHM]
HT9	5.029	4.701
Pb	4.526	4.200
MgO	4.137	3.804

[L] HT9 is a high chromium ferritic-martensitic steel (12Cr-1MoVW, in wt.%).

Table 8. Uranium-235 beginning of life enrichments required for a chloride molten salt fast reactor surrounded by different reflector materials

Reflector	^{235}U [wt%]
HT9	15.60
Pb	13.95
MgO	12.75

Table 9. Total plutonium masses after 10 EFPY for different reflector materials

Reflector	Pu [kg]
Pb	253.58
MgO	248.51
HT9	221.17

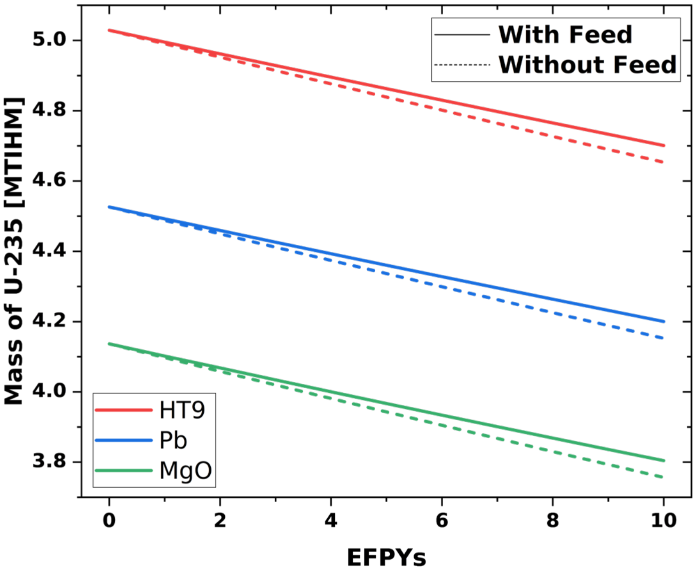


Figure 14. Uranium-235 mass with and without makeup fuel salt feed over 10 EFPY for different reflector materials

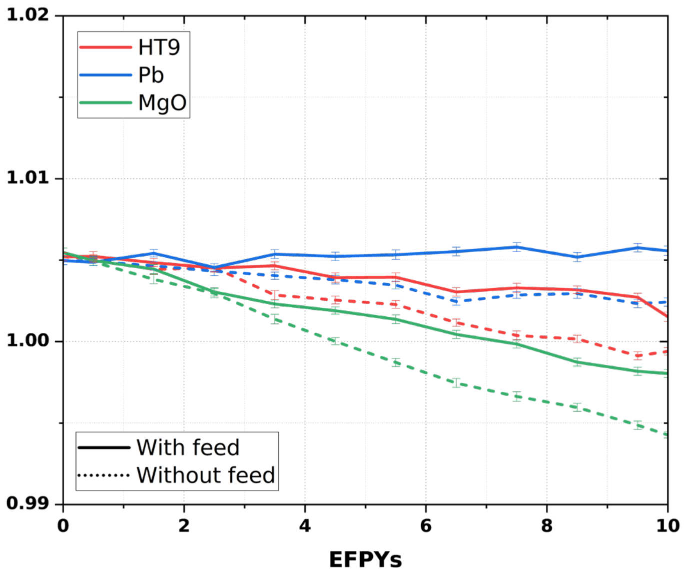


Figure 15. Multiplication factor, k_{eff}, for different reflector materials with and without makeup fuel salt feed

6. CONCLUSIONS AND RECOMMENDATIONS

MSR license applicants should consider safeguards (both domestic and international) and security throughout the design, including as early as preconceptual design phases. Because liquid-fueled MSRs are reactors with SNM in nondiscrete (or item) form, it is likely that the NRC will require liquid-fueled MSR license applicants to submit a formal MC&A program description or MC&A plan as a part of their license application for operation. The authors recommend that the license applicant, or MSR developers, develop an MC&A plan throughout the design lifecycle and plan to submit a MC&A plan to the NRC as a part of a license application. No MC&A plan template or guidance exists that is specific to liquid-fueled MSRs.

Because of the breadth of MSR designs, there is no single, universal, detailed MC&A plan that will work for every design. The wide variation of fresh fuel salts, method and frequency of loading fresh fuel, reactor system design components (e.g., tanks, filtration systems, chemical processing streams), and waste streams will determine the specific measurement locations and instrumentation that can best meet MC&A objectives throughout an MSR facility. Additionally, MSR designs are rapidly evolving, and new design features and deployment scenarios that will affect MC&A are being explored and pursued.

The recommended methodology for developing an MC&A approach for a liquid-fueled MSR is as follows:

- Develop a process flow diagram for the design tracking MC&A-relevant design parameters for each process step or flow.
- Identify the high-level MC&A objectives across the facility that would be necessary to prevent or detect diversion of material.

- Perform a diversion path analysis to identify potential specific paths of diversion from process streams.

- While considering constraints like the measurement environments and measurement technique limitations, identify specific MC&A elements (i.e., devices like TIDs, spectrometers, scales) to meet each MC&A objective and prevent or detect every plausible diversion path. There should be at least two independent elements to prevent or detect every diversion path.

These combined elements across the facility will be incorporated into the MC&A plan. Combined with descriptions of how the licensee will manage its MC&A program, this will form the basis of an MC&A program description or an FNMC plan that can be submitted to the NRC as a part of a license application.

Additionally, this report described a recommended MC&A approach for liquid fueled, terrestrial-based MSRs that uses periodic inventories in internal control areas outside of an area of the reactor facility that is difficult to access because of high-radiation and high-temperature environments (analogous to reactor confinement). Within the difficult to access area, periodic inventories would not be performed; however, every plausible diversion path would be identified through metrics for the diversion paths that could include quantities of SNM that could be diverted via the path and technical difficulty to successfully achieve diversion through the path. Further work is needed to create clear guidelines for performing an effective diversion path analysis as a tool consistent with the NRC's risk-informed, performance-based regulation approach. The results from a diversion path analysis could be used as justification to request exemptions from 10 CFR Part 74 requirements that cannot be met within the difficult to access area of the liquid-fueled MSR.

Finally, the report contains several technical analyses that demonstrate the use of modeling and simulation tools to enable consideration of MC&A and, more broadly, safeguards and security, in design decisions. A technical analysis of the MC&A-relevant design parameters of five different nonproprietary liquid-fueled MSR designs demonstrates that parameters like quantities of SNM and concentrations of SNM within material streams varies over multiple orders of magnitude across designs. Therefore, generic and specific solutions for MC&A do not exist that encompass all liquid-fueled MSR designs. Additionally, three examples demonstrate how both quantitative and qualitative technical analyses can be performed to assess how design decisions effect MC&A and can enable liquid-fueled MSR developers to consider safeguards and security throughout their design lifecycle.

REFERENCES

[1] D. Holcomb, *Module 2: Overview of MSR Technology and Concepts,* Washington, DC: Presentation to the U.S. NRC, 2017.

[2] M. P. Dion, M. S. Greenwood, K. Hogue, S. E. O'Brien, L. M. Scott and G. T. Westphal, "MC&A for MSRs: FY2021 Report ORNL/SPR-2021/2305," Oak Ridge National Laboratory, Oak Ridge, TN, 2021.

[3] International Atomic Energy Agency, IAEA Safeguards Glossary, 2022.

[4] U.S. Nuclear Regulatory Commission, "Standard Format and Content Acceptance Criteria for the Material Control and Accounting (MC&A) Reform Amendment: 10 CFR Part 74, Subpart E (NUREG-1280, Revision 1)," U.S. Nuclear Regulatory Commission, Washington, DC, 1995.

[5] United States National Archives and Records Administration, "eCFR :: 10 CFR Part 74 -- Material Control and Accounting of Special Nuclear Material," 23 Dec 2002. [Online]. Available: https://www.ecfr.gov/current/title-10/section-74.4. [Accessed 22 Dec 2023].

[6] U.S. Nuclear Regulatory Commission, "Part 70—Domestic Licensing of Special Nuclear Material," [Online]. Available: www.nrc.gov/reading-rm/doc-collections/cfr/part070/full-text.html. [Accessed 8 Janauary 2024].

[7] N. P. Kadambi, "Guidance for Performance-Based Regulation," United States Regulatory Commission, 2002.

[8] U.S. Nuclear Regulatory Commission, "SECY-98-144," 1 March 1999. [Online]. Available: https://www.nrc.gov/docs/ML0037/ML003753601.pdf.

[9] U.S. Nuclear Regulatory Commission, "Performance Based Regulation," 09 March 2021. [Online]. Available: https://www.nrc.gov/reading-rm/basic-ref/glossary/performance-based-regulation.html. [Accessed 22 November 2023].

[10] K. K. Hogue, P. Gibbs, M. P. Dion and M. Poore, "Domestic Safeguards Material Control and Accountancy Considerations for Molten Salt Reactors ORNL/SPR/150504," Oak Ridge National Laboratory, Oak Ridge, TN, 2021.

[11] K. K. Hogue and M. P. Dion, "Safeguards Material Control and Accountancy Considerations for Molten Salt Reactors," in *INMM & ESARDA Joint Virtual Annual Meeting*, 2021.

[12] Nuclear Regulatory Commission, "Nuclear Material Control and Accounting," 10 December 2021. [Online]. Available: https://www.nrc.gov/materials/fuel-cycle-fac/nuclear-mat-ctrl-acctng.html. [Accessed 2 October 2023].

[13] W. A. Wieselquist and R. A. Lefebvre, "SCALE 6.3.1 User Manual," Oak Ridge National Laboratory, ORNL/TM-SCALE-6.3.1, Oak Ridge, TN 37830, 2023.

[14] N. Shoman and M. Higgins, "Material Accountancy for Molten Salt Reactors: Challanges and Opportunities SAND2023-01845R," Sandia National Laboratories, 2023.

[15] E. S. Bettis, L. G. Alexander and H. L. Watts, "Design Studies of a Molten-Salt Reactor Demonstration Plant," Oak Ridge National Laboratory, 1972.

[16] V. V. Ignatiev, F. O., I. Gnidoi, A. Merzlyakov, V. Smirnov, A. Surenkov, I. Tretiakov and R. Zakirov, "Progress in Development of Li,Be,Na/F Molten Salt Actinide Recycler & Transmuter Concept," in *International Congress on Advances in Nuclear Power Plants*, 2007.

[17] A. Mourogov and P. M. Bokov, "Potentialities of the fast spectrum molten salt reactor concept: REBUS-3700," *Energy Conversion and Management,* vol. 47, no. 17, pp. 2761-2771, 2006.

[18] Centre National De La Recherche Scientific (CNRS), "Final Report - EVOL (Evaluation and Viability of Liquid Fuel Fast Reactor System," 2012.

[19] R. C. Asher, G. Long, H. A. C. McKay and D. L. Reed, "An Assessment of a 2500 MWe Molten Chloride Fast Reactor," 1974.

[20] K. K. Hogue, "Feasibility Study of Fresh Fuel Feed Monitoring for Liquid-Fueled Molten Salt Reactor Safeguards," University of Tennessee, Knoxville, Dec 2023.

[21] A. M. Lines, S. A. Bryan, H. M. Felmy and S. D. Branch, "On-line Monitoring for Molten Salt Reactor MC&A: Optical Spectroscopy-Based Approaches PNNL-33367," Pacific Northwest National Laboratory, Richland, WA USA, 2022.

[22] C. E. Moore, W. H. Donigner and N. C. Hoyt, "Assessment of Flow-Enhanced Sensors for Actinide Quantification in MSRs ANL/CFCT-22/34," Argonne National Laboratory, Lemont, IL USA, 2022.

[23] M. P. Dion and K. K. Hogue, "Domestic MC&A Recommendatins for Liquid-Fueled MSRs ORNL/SPR-2022/2673," Oak Ridge National Laboratory, Oak Ridge, TN USA, 2022.

[24] U.S. Nuclear Regulatory Commission, "Acceptable Standard Format and Content for the Fundamental Nuclear Material Control Plan Required for Special Nuclear Material of Moderate Strategic Significance – Final Report (NUREG-2159, Revision 1)," Office of Nuclear Material Safety and Safeguards U.S. Nuclear Regulatory Commission, Washington, DC, 2022.

[25] M. P. Dion, M. S. Greenwood, K. K. Hogue, S. E. O'Brien, L. M. Scott and G. T. Westphal, "MC&A for MSRs: FY2021 Report ORNL/SPR-2021/2305," Oak Ridge National Laboratory, 2021.

[26] N. Shoman and M. Higgins, "FY22 Final Report on Molten Salt Reactor Safeguards Modeling SAND2022-11048 O," Sandia National Laboratories, Albuquerque, USA, 2022.

[27] H. B. Andrews and K. G. Myhre, "Quantification of Lanthanides in a Molten Salt Reactor Surrogate Off-Gas Stream Using Laser-Induced Breakdown Spectroscopy," *Applied Spectroscopy,* vol. 76, no. 8, 2022.

[28] J. W. Bae, B. R. Betzler and A. Worrall, "Molten Salt Reactor Neutronic and Fuel Cycle Sensitivity and Uncertainty Analysis," in *ANS Winter Meeting*, Washington, DC, 2019.

[29] A. Rykhlevskii, B. R. Betzler, A. Worrall and K. D. Huff, "Fuel Cycle Performance of Fast Spectrum Molten Salt Reactor Designs," in *International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2019)*, Portland, OR, 2019.

[30] B. R. Betzler, A. Rykhlevskii, A. Worrall and K. D. Huff, "Impacts of Fast-Spectrum Molten Salt Reactor Characteristics on Fuel Cycle Performance," in *Global 2019 International Fuel Cycle Conference*, 2019.

[31] N. Shoman and M. Higgins, "FY22 Final Report on Molten Salt Reactor Safeguards Modeling," Sandia National Laboratories, Tech. Rep. SAND2022-11048, Albuquerque, NM 87185, 2022.

[32] Euratom, "Final Report Summary – EVOL (Evaluation and Viability of Liquid Fuel Fast Reactor System)," Euratom, Tech. Rep. 249696, 2015.

[33] W. E. Simmons and J. Smith, "An Assessment of a 2500 MWe Molten Chloride Salt Fast Reactor," United Kingdom Atomic Energy Authority, Tech. Rep. AEEW-R956, 1974.

[34] D. Hartanto, D. Chandler, G. Westphal and K. K. Hogue, "Characterizing Impacts of Fast-Spectrum Molten Chloride Salt Reactor Design Choices on Safeguards-Relevant Parameters,"

Advances in Nuclear Nonproliferation Technology and Policy Conference, Washington, D.C., 2023.

[35] U.S. Nuclear Regulatory Commission, "Acceptable Standard Format and Content for Fundamental Nuclear Material Control (FNMC) Plan Required for Low-Enriched Uranium Facilities (NUREG-1065, Revision 2)," Division of Fuel Cycle Safety and Safeguards Office of Nuclear Material Safety and Safeguards U.S. Nuclear Regulatory Commission, Washington, DC, 1995.

[36] "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 (NUREG/CR-5734, K/ITP-415)," Division of Safeguards and Transportation Office of Nuclear Material Safety and Safeguards U.S. Nuclear Regulatory Commission, Washington, DC, 1991.

[37] U.S. Nuclear Regulatory Commission, "Frequently Asked Questions About the Fundamental Nuclear Material Control Plan," 14 August 2017. [Online]. Available: https://www.nrc.gov/security/domestic/licensing/fnmc.html#submit. [Accessed 3 October 2023].

[38] U.S. Nuclear Regulatory Commission, "Regulatory Guide 5.29, Revision 2," June 2013. [Online]. Available: https://www.nrc.gov/docs/ML1305/ML13051A421.pdf. [Accessed 3 October 2023].

[39] American National Standards Institute (ANSI), "ANSI N15.8-2009 Methods of Nuclear Material Control—Material Control Systems—Special Nuclear Material Control and Accounting Systems for Nuclear Power Plants," American National Standards Institute (ANSI), New York, 2009.

[40] U.S. Nuclear Regulatory Commission, "Instructions for the Preparation and Distribution of Material Status Reports (DOE/NRC Forms 742 and 742C) (NUREG/BR-0007, Revision 8) - Final Report," Office of Nuclear Material Safety and Safeguards U.S. Nuclear Regulatory Commission, Washington, DC, 2020.

[41] U.S. Department of Energy, "D-24 Personal Computer Data Input for Nuclear Regulatory Commission Licensees," United States Department of Energy, Washington, DC, 2016.

[42] U.S. Department of Energy and U.S. Nuclear Regulatory Commission, "NRC Form 741 - Nuclear Material Transaction Report," May 2021. [Online]. Available: https://www.nrc.gov/docs/ML1308/ML13083A296.pdf. [Accessed 3 October 2023].

[43] U.S. Nuclear Regulatory Commission, "Instructions for Completing Nuclear Material Transaction Reports: (DOE/NRC Forms 741 and 740M) (NUREG/BR-0006, Revision 8)," Office of Nuclear Material Safety and Safeguards U.S. Nuclear Regulatory Commission, Washington, DC, 2018.

[44] P. R. Bevington and D. K. Robinson, Data Reduction and Error Analysis for the Physical Sciences, 3rd ed., New York, USA: McGraw-Hill, 2002.

[45] Nuclear Science Committee, Nuclear Energy Agency (NEA), "PBMR Coupled Neutronics / Thermalhydraulics Transient Benchmark The PBMR-400 Core Design, vol. 1: The Benchmark Definition," NEA/NSC/DOC(2013)10, Paris, France, 2013.

[46] S. Skutnik and W. Wieselquist, "Assessment of ORIGEN Reactor Library Development for Pebble-Bed Reactors Based on the PBMR-400 Benchmark," Oak Ridge National Laboratory, ORNL/TM-2020/1886, Oak Ridge, TN 37830, 2021.

[47] W. A. Wieselquist, R. A. Lefebvre and M. A. Jessee, "SCALE Code System, Version 6.2.4," Oak Ridge National Laboratory, ORNL/TM-2005/39, Oak Ridge, TN 37830, 2020.

[48] The International Organization for Standardization, *ISO 2859,* 1999.

[49] The International Organization for Standardization, *ISO 3951,* 2013.

[50] L. C. Huberts, M. Schoonhoven, R. Goedhart, M. D. Diko and R. J. Does, "The Performance of x-bar Control Charts for Large Non-Normally Distributed Datasets," *Quality Reliability Engineering International,* pp. 979-996, 2018.

[51] A. Mukherjee, P. Qiu and M. Marozzi, "A Comprehensive Distribution-Free Scheme for Tri-Aspect Surveillance of Complex Processes," *Applied Stochastic Models in Business and Industry,* pp. 1157-1181, 2021.

[52] A. N. Petit, "A Two-Sample Anderson-Darling Rank Statistic," *Biometrika,* pp. 161-168, 1976.

[53] B. M. Boyerinas, "Determining the Statistical Power of the Kolmogorov-Smirnov and Anderson-Darling Goodness-of-Fit Tests via Monte Carlo Simulation," CNA, 2016.

[54] U.S. Nuclear Regulatory Commission, "Standard Format and Content Acceptance Criteria for the Material Control and Accounting (MC&A) Reform Amendment: 10 CFR Part 74, Subpart E (NUREG-1280, Revision 1)," Division of Fuel Cycle Safety and Safeguards Office of Nuclear Material Safety and Safeguards U.S. Nuclear Regulatory Commission, Washington, DC, 1995.

[55] International Atomic Energy Agency, "The Physical Protection of Nuclear Material (INFCIRC/225)," International Atomic Energy Agency, Vienna, Austria, 1975.

[56] U.S. Nuclear Regulatory Commission, "Domestic Safeguards," 11 March 2020. [Online]. Available: https://www.nrc.gov/security/domestic.html.

[57] U.S. Nuclear Regulatory Commission, "Frequently Asked Questions About the Fundamental Nuclear Material Control Plan," 19 September 2023. [Online]. Available: https://www.nrc.gov/security/domestic/licensing/fnmc.html#submit.

[58] D. Hartanto, W. A. Wieselquist, S. Skutnik, D. N. Kovacic and P. Gibbs, "Uncertainty Quantification of Pebble's Discharge Burnup and Isotopic Inventory using SCALE," *American Nuclear Society Winter Meeting,* 2022.

7. APPENDICES

APPENDIX A. FNMC PLAN AND MC&A REPORTING AND RECORDKEEPING REQUIREMENTS

A.1 FNMC Plan Format and Requirements

Most Fundamental Nuclear Material Control (FNMC) plans reviewed by the US Nuclear Regulatory Commission (NRC) are for fuel fabrication facilities and enrichment plants, and no suitable FNMC plan template exists for liquid-fueled molten salt reactors (MSRs). Material control and accounting (MC&A) for liquid-fueled MSRs will be significantly different from those for fuel fabrication and enrichment facilities because the quantities of special nuclear material (SNM) in the liquid-fueled MSR facility will change significantly because of fission, transmutation, and decay. The NRC's acceptance criteria for FNMC plans and related information is found in the following documents, which do not directly address 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 [24]

- NUREG-1065, Acceptable Standard Format and Content for Fundamental Nuclear Material Control Plan Required for Low-Enriched Uranium Facilities [35]

- NUREG-1280, Standard Format and Content/Acceptance Criteria for the Material Control and Accounting Reform Amendment [4]

- 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 [36]

The approval and implementation of an FNMC plan allows the licensee to change the FNMC plan without NRC approval if changes do not degrade the plan's effectiveness. The licensee should notify the NRC of any changes. However, if any proposed changes to the plan reduce the effectiveness of the MC&A program, then NRC approval is required before implementing the change [39]. Alternatively, the NRC can contact the licensee and request changes to the FNMC plan. The changes may be required in the event of an MC&A alarm or if an NRC inspection deems a plan to be ineffective. The licensee is obligated to consider any such requests and must revise and resubmit its FNMC plan.

The category of SNM licensed at a facility directly influences the MC&A requirements. Applicants are required to submit an FNMC plan that meets the following graded performance objectives.

- Category III: Low strategic significance (10 CFR 74.31) requirements are designed for licensees that possess more than 1 effective kilogram SNM of low strategic significance, excluding sealed sources, production and utilization facilities licensed pursuant to part 50 or 70, or waste disposal. Special requirements exist for uranium enrichment facilities (10 CFR 74.33).
    - Requires confirming the presence of special nuclear material
    - Requires resolving indications of missing material
    - Requires aiding in the investigation and recovery of missing material

- Category II: Material of moderate strategic significance (10 CFR 74.41) requirements are designed for licensees that possess SNM of moderate strategic significance or SNM in a quantity exceeding 1 effective kg of strategic special nuclear material (SSNM), excluding sealed sources, nuclear reactors licensed pursuant to part 50, reactor irradiated fuels or waste disposal.

    - Requires maintaining accurate, current, and reliable information on, and confirming, the quantities and locations of SNM in possession
    - Requires conducting investigations and resolving any anomalies indicating a possible loss of SNM
    - Requires rapid determination of whether an actual loss of a significant quantity of SNM
    - Requires aiding in the investigation and recovery of missing SNM in the event of an actual loss
- Category I: SSNM (10 CFR 74.51) requirements are designed for licensees that possess SSNM, excluding nuclear reactors licensed pursuant to 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 prompt investigations of anomalies potentially indicative of SSNM losses
    - Requires timely detection of the possible abrupt loss of five or more formula kilograms of SSNM from an individual unit process (process monitoring)
    - Requires rapid determination of whether an actual loss of five or more formula kilograms (alarm resolution)
    - Requires ongoing confirmation of the presence of SSNM in assigned locations (item monitoring)
    - Requires timely generation of information to aid in the recovery of SSNM in the event of an actual loss

A.2 MC&A Reporting and Recordkeeping Requirements (10 CFR Part 74, Subpart B)

For both 10 CFR Parts 50 and 52 applicants, 10 CFR Part 74, Subpart B, excluding 10 CFR 74.17, contains the appropriate MC&A general reporting and recordkeeping requirements. The applicant for a liquid-fueled MSR facility should present information about the MC&A program to the NRC even if the applicant may be exempted from submitting an MC&A plan. An adequate application submittal would describe the applicant's MC&A program elements that will meet certain applicable requirements of 10 CFR Part 74, "Material Control and Accounting of Special Nuclear Material." Applicants that expect to possess, transfer, or receive SNM in a quantity of 1 g or more will be subject to the general reporting and recordkeeping of 10 CFR Part 74, Subpart B (excluding 10 CFR 74.17), "General Reporting and Recordkeeping Requirements."

US NRC Regulatory Guide 5.29 declares American National Standards Institute (ANSI) publication N15.8-2009 is an acceptable approach for an applicant complying with the NRC's regulations for MC&A requirements in Subpart B of 10 CFR Part 74 at nuclear reactor plants [38], [40]. This approach results in an MC&A description that provides assurance that the implemented program will meet the performance requirements of 10 CFR Part 74, Subpart B, excluding 10 CFR 74.17. Note, however, that ANSI N15.8-2009 is intended for LWRs that uses low-enriched uranium oxide fuel. Applicants for liquid-fueled MSRs should consider how their individual reactor design and operation will differ from that described in ANSI N12.8-2009 and Regulatory Guide 5.29 in ways that may affect MC&A of SNM. A framework for these considerations is included in Section 2 of this report. NUREG -1537, "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors – Part 1 – Format and Content," and Part 2 – "Standard Review Plan and Acceptance Criteria" is available, but these documents are outdated and need to be revised and updated with respect to the MC&A review.

The following requirements of Subpart B apply to liquid-fueled MSR applicants:

- 10 CFR 74.11, "Reports of Loss or Theft or Attempted Theft or Unauthorized Production of Special Nuclear Material," requires the applicant to notify the NRC Operations Center in the event of any lost, stolen, or unlawfully diverted SNM, including attempts, within 1 hour of discovery.

- 10 CFR 74.13, "Material Status Reports," requires the applicant to prepare material balance reports concerning SNM that the licensee has received, produced, possessed, transferred, consumed, disposed of, or lost.

- 10 CFR 74.15, "Nuclear Material Transaction Reports," requires the applicant who transfers or receives SNM in certain quantities or adjusts its SNM inventory to submit a nuclear material transaction report.

- 10 CFR 74.19, "Recordkeeping," requires the applicant to maintain and retain records of the receipt, inventory, acquisition, transfer, and disposal of all SNM. This section also requires applicants to establish, maintain, and follow written MC&A procedures that are sufficient to enable the applicant to account for the licensed SNM in its possession. This section also requires the applicant possessing certain quantities to take a physical inventory of all SNM in its possession at intervals not to exceed 12 months.

A.2.1 Reports of Loss or Theft or Attempted Theft of SNM

The regulations in 10 CFR 74.11 require the applicant to notify the NRC Operations Center in the event of any lost, stolen, or unlawfully diverted SNM, including attempts, within 1 hour of discovery.

The applicant should describe actions that will be taken if a loss, theft, or diversion of SNM is discovered or suspected. The applicant describes how indicators of a possible loss, theft, or diversion of SNM, whether arising from errors or deliberate actions, will be investigated and resolved. The applicant should have well-defined procedures for promptly investigating and resolving indications of possible missing SNM and procedures for promptly determining whether an actual loss of SNM has occurred. Resolving a loss indicator means that the licensee has determined that loss, including possible diversion or theft, has not occurred, and is not occurring. Any investigation of an indication of a loss or theft should provide, whenever possible, (1) an estimate of the quantity of SNM involved, (2) the material type or physical form of the material, (3) the type of unauthorized activity or event detected, (4) the time frame during which the loss or activity could have occurred, (5) the most probable cause(s), and (6) recommendations for precluding reoccurrence.

For indications that a loss or theft may have occurred, the resolution process should include (1) thoroughly checking the accountability records and source information, (2) locating the source of the problem, (3) isolating the exact reason for the problem within the area, (4) determining the amounts of SNM involved, and (5) determining that the indication is or is not resolved. If an investigation of an indicator results in a conclusion that the indication is true, such a conclusion must be reported to the NRC within 1 hour of its determination in accordance with 10 CFR 74.11. Procedures should identify all documentation requirements associated with reporting, investigating, and resolving missing SNM indicators. The applicant should identify facility positions responsible for implementing these notification and reporting requirements.

A.3 Material Status Reports

The regulations in 10 CFR 74.13 require the licensee to prepare material balance reports and physical inventory listings concerning SNM that the licensee has received, produced, possessed, transferred, consumed, disposed of, or lost. US Department of Energy (DOE)/NRC Form 742, "Material Balance Report," and DOE/NRC Form 742C, "Physical Inventory Listing," is the means for submitting reports of material balance and physical inventory listing data to the Nuclear Materials Management and Safeguards System (NMMSS), which is the national database used for tracking certain nuclear material. DOE/Form 742 is used to report a summary of activity for a specified material within a material balance reporting period, as specified in 10 CFR 74.13. The report conveys beginning and ending inventory balances; activities such as shipment and receipts involving other facilities; decay and transmutation; and production calculations. DOE/NRC Form 742C is used to report a facility's physical inventory listing as of a specified date.

The applicant should generally describe how material status reports are prepared and submitted to NMMSS. Reports must be submitted for each reporting identification symbol, which can only be obtained after the NRC license is issued. Once the license is issued, the licensee should contact the NRC's Office of Nuclear Material Safety and Safeguards, Division of Fuel Management, to request an reporting identification symbol. Processing the request for a reporting identification symbol will require the NRC license number, the address where the material will be used and stored, the business address of the licensee, and the name and telephone number of a contact person.

The applicant should have well-defined procedures for preparing and submitting reports in a computer-readable format in accordance with the detailed instructions contained in NUREG/BR-0007, "Instructions for the Preparation and Distribution of Material Status Reports (DOE/NRC Forms 742 and 742C)," and in NMMSS Report D-24, "Personal Computer Data Input for Nuclear Regulatory Commission Licensees" [40, 41]. The procedures should ensure that reports are made and filed within the required time periods, as defined in 10 CFR 74.13. If it possesses US government-owned material, the applicant should also have procedures in place to ensure that it will meet the DOE-reporting requirements for all receipts, transfers, and inventories of US government-owned, loaned, or leased material, as specified in NUREG/BR-0007 as well [40].

In the case that a liquid-fueled MSR facility has materials that are nationally tracked sources, the applicant should have procedures in place to ensure reporting to the National Source Tracking System, which is a secure web-based database designed to track Category I and II radioactive sources regulated by the NRC and the agreement states. Applicants with less than a critical mass and plutonium sources (less than 16 Ci) or Pu/Be sources should report them to the National Source Tracking System.[M]

If the applicant is subject to the requirements in 10 CFR Part 75, "Safeguards on Nuclear Material—Implementation of Safeguards Agreements between the United States and the International Atomic Energy Agency," it should describe how it will submit the required material status reports in accordance with 10 CFR 75.35, "Material Status Reports."

A.3.1 Nuclear Material Transaction Reports

The regulations in 10 CFR 74.15 require the licensee who transfers or receives SNM in certain quantities or who adjusts its inventory of SNM to submit that information to NMMSS. DOE/NRC Form 741, "Nuclear Material Transaction Report," is how licensees submit transaction data to NMMSS [43]. DOE/NRC Form 741 is used to report physical transfers of nuclear materials between facilities and to report exchanges of foreign obligations on material between facilities even when no physical transfer occurs. The form is also used to report on-site transactions, such as inventory corrections that otherwise increase or decrease foreign obligation balances or nuclear material categories within a facility.

The applicant should generally describe how it will track licensed materials from "receipt to disposal" to ensure accurate accounting records and that possession limits listed on the license are not exceeded. The applicant should describe how it prepares nuclear material transaction reports and submits them to NMMSS. The applicant should have well-defined procedures for preparing and submitting reports in a computer-readable format, in accordance with the detailed instructions contained in NUREG/BR-0006, "Instructions for Completing Nuclear Material Transaction Reports (DOE/NRC Forms 741 and 740M)," and in NMMSS Report D-24 [43, 41]. If the applicant intends to possess US government-owned material, the applicant should also have procedures in place to ensure that it will meet the DOE-reporting requirements for all receipts, transfers, and inventories of US government-owned, loaned, or leased material, as specified in NUREG/BR-0006 as well [43]. If the applicant will be subject to the requirements in 10 CFR Part 75, it should describe how it will submit the required inventory change reports in accordance with 10 CFR 75.34, "Inventory Change Reports."

A.3.2 Recordkeeping

A.3.2.1 Receipt, Inventory, Acquisition, Transfer, and Disposal

The regulation in 10 CFR 74.19(a) states that the licensee is not subject to 10 CFR 74.31, 10 CFR 74.33, 10 CFR 74.41, or 10 CFR 74.51 are subject to the recordkeeping requirements in 10 CFR 74.19(a)(1)–(4), which require a licensee to maintain records of receipt, inventory, acquisition, transfer, and disposal of all SNM in its possession. Each record relating to MC&A that is required by this regulation or by license condition is to be maintained and retained in accordance with the appropriate regulation or license condition. If a retention period is not specified, the licensee shall retain the record until the NRC terminates the license.

[M] Information about the National Source Tracking System can be found on the NRC's public website at http://www.nrc.gov/security/byproduct/ismp/nsts.html.

The applicant should generally describe the recordkeeping system used to maintain records of receipt, use, transfer, and disposal (as waste) of all licensed material. Table 9 lists each type of record and how long the record must be maintained. Other records, such as transfer records, could be linked to radioactive material inventory records. Receipt records should also document cases the licensee found excessive radiation levels or radioactive contamination on packages or containers of material received and describe the action taken.

Table 10. Types of records and how long the record must be maintained

Type of Record	Record Maintenance Duration
Receipt	For as long as the material is possessed until 3 years after transfer or disposal.
Acquisition	
Physical inventory	
Transfer	For 3 years after the transfer.
Disposal	Until the NRC terminates the license.

Receipt, transfer, and disposal records typically contain the following information:

- Radionuclide, quantity, and date of measurement of SNM
- For each sealed source, the manufacturer, model number, location, and, if needed for identification, serial number and, as appropriate, manufacturer and model number of the device containing the sealed source
- Date of the transfer and name and license number of the recipient, and description of the affected radioactive material (e.g., radionuclide, quantity, manufacturer's name and model number, serial number)
- For licensed materials disposed of as waste, the radionuclide, quantity, date of disposal, and method of disposal (e.g., decay, sewer)

A.3.2.2 Written MC&A Procedures

The regulation in 10 CFR 74.19(b) states that each licensee authorized to possess SNM in a quantity exceeding 1 effective kilogram shall establish, maintain, and follow written MC&A procedures that are sufficient to enable the licensee to account for the SNM in its possession under license. The applicant should indicate that procedures will be established, maintained, and followed to account for SNM and describe the written procedures established to ensure all the applicable MC&A requirements are met. The applicant should provide specific examples addressing, at a minimum, the following: organization, records and reporting, notification of events, receiving and shipping, internal transfers, physical inventory, element and isotopic calculation method, and identification of SNM and non-SNM items to preclude loss. The applicant should indicate that provisions are made for the written approval of procedure revisions.

A.3.2.3 Physical Inventories

The regulation in 10 CFR 74.19(c) states that each licensee not subject to 10 CFR 74.31, 10 CFR 74.33, 10 CFR 74.41, or 10 CFR 74.51 and authorized to possess SNM in a quantity greater than 350 g of contained ^{235}U, ^{233}U, or Pu, or any combination thereof, shall make a physical inventory of all SNM in its possession under license at intervals not to exceed 12 months. The applicant should have well-defined procedures for the planning, conducting, assessing, and reporting the physical inventories. The applicant should generally describe how it performs physical inventories of its SNM. The inventory description should address the regulatory requirement for conducting a physical inventory at intervals not to exceed 12 months and for maintaining and retaining associated inventory records, although the results of the physical inventories need not be reported to the NRC. Concerning the physical inventory requirement, the applicant should define the term *physical inventory*, identify the overall responsibility for the implementation of physical inventories, and address other inventory topics such as conduct, coverage, inventory procedures, inventory methods for fuel types, fuel components, fuel inside the reactor, fuel outside the reactor, storage of fuel and non-SNM fuel, inventory reconciliation, and documentation. The applicant is required to submit reports about the physical inventory in accordance with the requirements in 10 CFR 74.13. The applicant should describe how it maintains and retains inventory records in accordance with 10 CFR 74.19.

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

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

Therefore, liquid-fueled MSR licensees must perform physical inventories and submit related accounting reports to the NRC based on the material categorization. Although liquid-fueled MSR operators will likely need to shut down the reactor and perhaps drain the irradiated salt at some periodicity to perform maintenance, the frequency for maintenance is extremely unlikely to be ≤12 months [2]. A few liquid-fueled MSR designers have spoken publicly on the subject suggest plans for equipment replacement at a frequency of ≥4 years [11]. 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.

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*), *AI*, and the standard error of the inventory difference (*SEID*) for SNM in the defined internal control areas.[N] The *ID* is the book inventory minus the inventory determined during physical inventory:

$$ID = BI + A - R - EI, \tag{A1}$$

where *BI* is the beginning/book inventory, *A* are additions (receipts), R are removals (shipments, discards, or both), 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

---

[N] References by the International Atomic Energy Agency and others may include the term *material unaccounted for* (MUF). MUF is equivalent to ID in definition and mathematical formulation.

random), material holdup, and other unmeasured material loss. The *ID* is calculated per inventory period based on individual measurements of each type of SNM.

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

$$AI = BI + A + R + EI - C, \tag{A2}$$

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

The SEID is the variance of 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 [45]. According to rules for error propagation, variances are summed regardless of the sign and their effect on the *ID* calculation:

$$\sigma^2(ID) = \sigma^2(BI) + \sigma^2(A) + \sigma^2(R) + \sigma^2(EI) \tag{A3}$$

Modeling was performed to evaluate the *ID* and *SEID* of irradiated fuel salt in reactor confinement for thermal and fast-spectrum MSRs. A diversion analysis (removal of fuel salt from the primary fuel loop) was also performed [46]. The models were based on bulk measurements taken during periodic inventories. Because of the large amounts of material in the primary fuel loop, the probability of detecting the diversion solely by using process monitoring measurements of SNM in the fuel salt is low, even considering a very low measurement error (0.01%). However, diversion of fuel salt from the primary fuel loop (in amounts needed to equate to SNM loss of interest) is highly 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 MSRs 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 confinement during reactor operations do not have a high probability of detecting theft or diversion, multiple other elements can prevent, detect, or prevent and detect theft of the fuel salt in reactor confinement.

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

- Category I: SSNM
  - *SEID* ≥0.1% of *AI*
  - *ID* exceeds both three *SEID* and 200 g of (Pu or ^{233}U), or 300 g of ^{235}U in highly enriched uranium
  - 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 highly enriched uranium, or 9,000 g ^{235}U in low-enriched uranium

- 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*

A.3.2.4 Records Access and Storage

The regulation in 10 CFR 74.19(d) requires licensees to ensure that the recordkeeping system can produce clear and legible copies of records after storage for the period specified by the regulations. The section also states that the licensee should maintain adequate safeguards against tampering with and loss of records. The applicant should describe how it stores records and how it controls its access to records to meet the requirement in 10 CFR 74.19(d). The applicant should define the term *MC&A records* and provide examples of various types of records such as SNM receipt, acquisition, internal transfer, measurement and calculation, reconstitution, inventory, shipment, and disposal. The applicant should identify the organization responsible for maintaining records for the SNM in the facility's possession. The applicant should indicate that adequate controls against tampering with and losing records will be maintained and that periodic review and assessment of records will be documented. In terms of the record retention requirements, the applicant should indicate that SNM records and reports will be retained as required.

A.3.3 Additional Applicable Subparts of 10 CFR Part 74

As previously noted, applicants that intend to possess certain amounts and types of SNM not in sealed sources may be subject to additional MC&A requirements in 10 CFR Part 74 other than those in Subpart B. A license to possess SNM of low strategic significance (Category III), SNM of moderate strategic significance (Category II), or SSNM (Category I) not in sealed sources, may be subject to requirements in 10 CFR Part 74, Subparts C, D, and E, respectively.

APPENDIX B. ADDITIONAL PLOTS FOR DESIGN CONSIDERATIONS STUDY

In Figure 16 to Figure 20 we show the power-normalized mass and concentration of ^{239}Pu, total Pu, ^{233}U, ^{235}U, and total U without a period of down time during the entire 60 years modeled of reactor operation. The overall behavior without shutdown is quite like that with the short periods 3-6 months of shutdown, except for some small transients during these periods of shutdown.

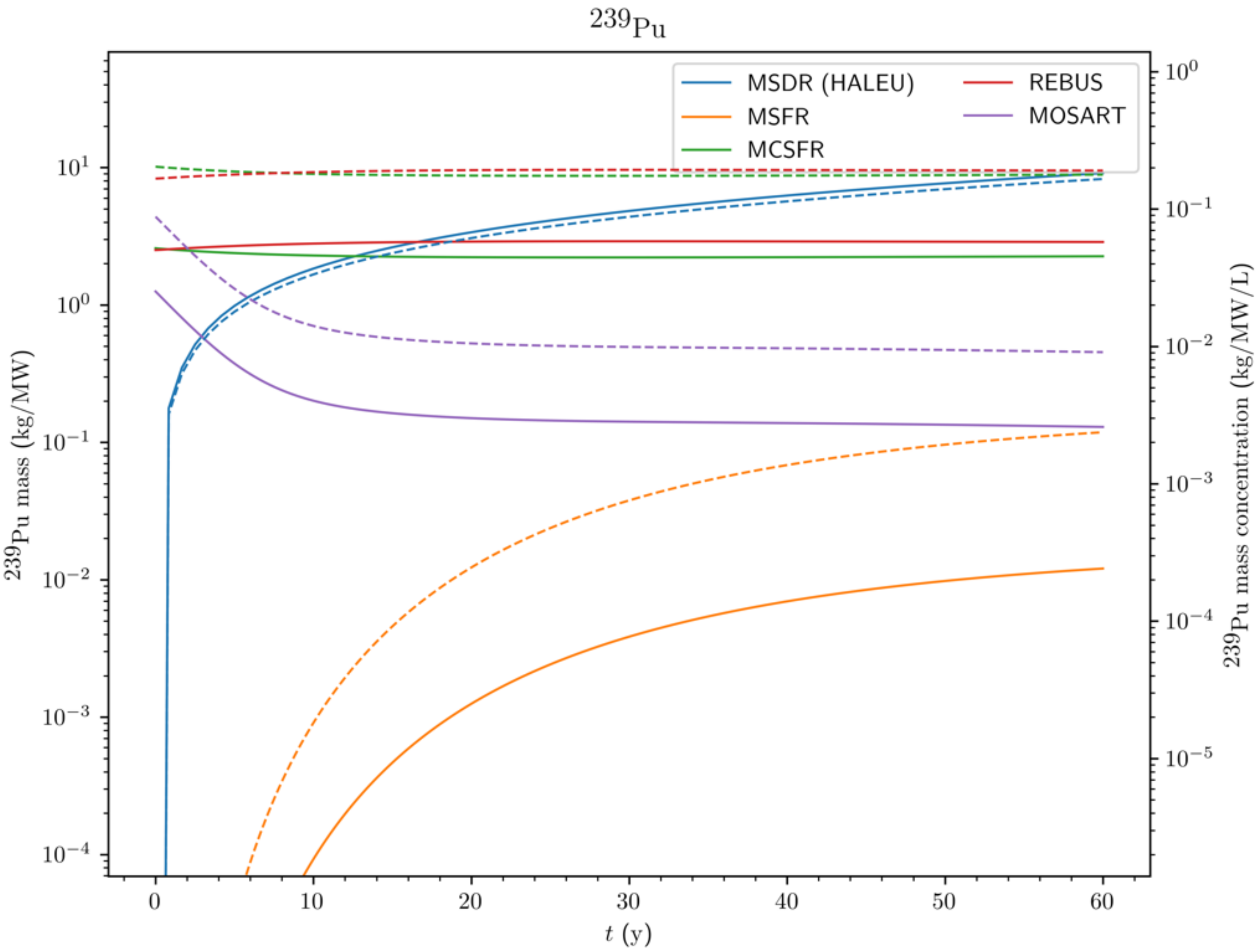


Figure 16. The power-normalized ^{239}Pu mass and concentration over time for each reactor with no period of shutdown

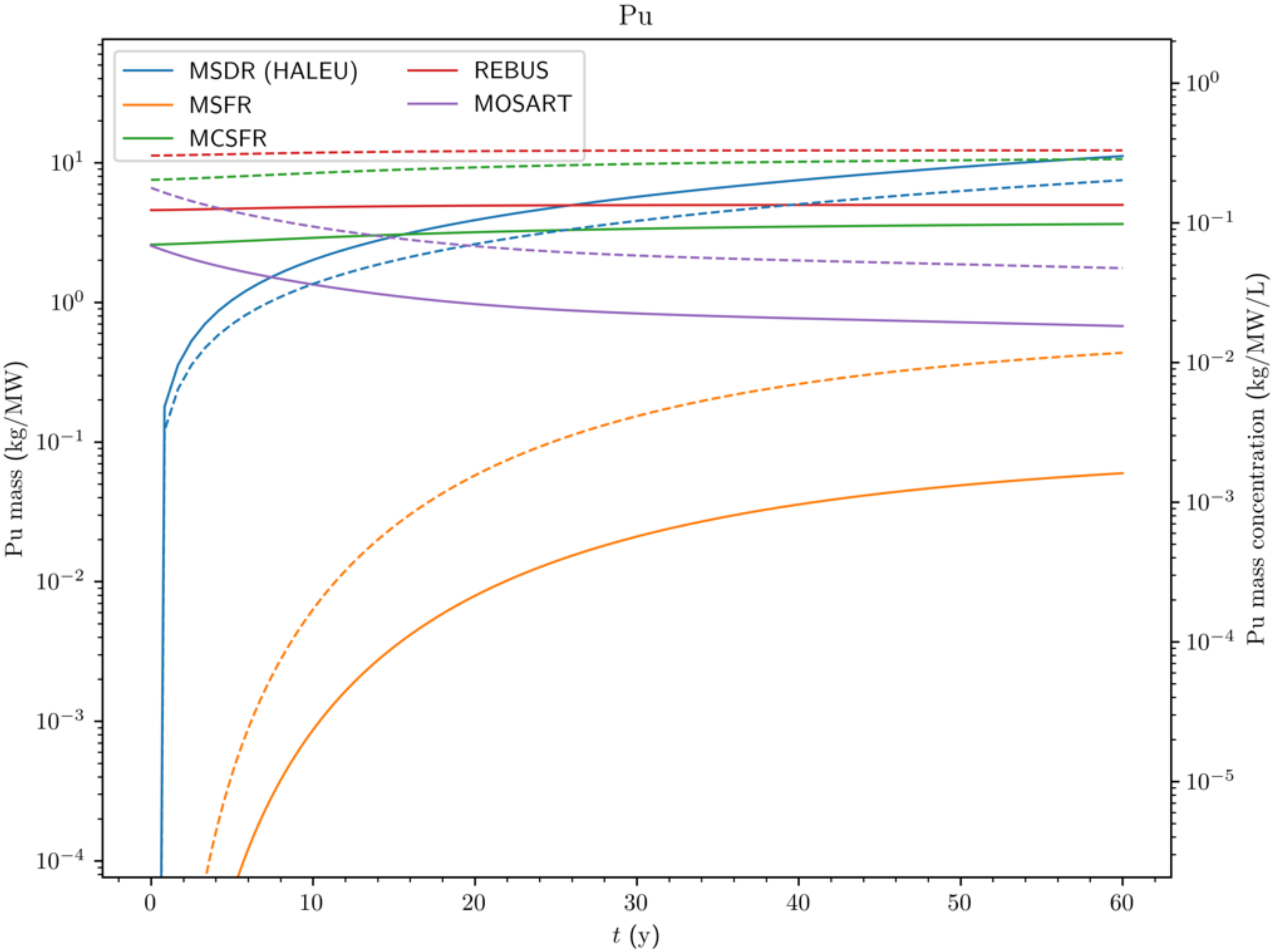


Figure 17. The power-normalized $\mathrm{Pu_{total}}$ mass and concentration over time for each reactor with no period of shutdown

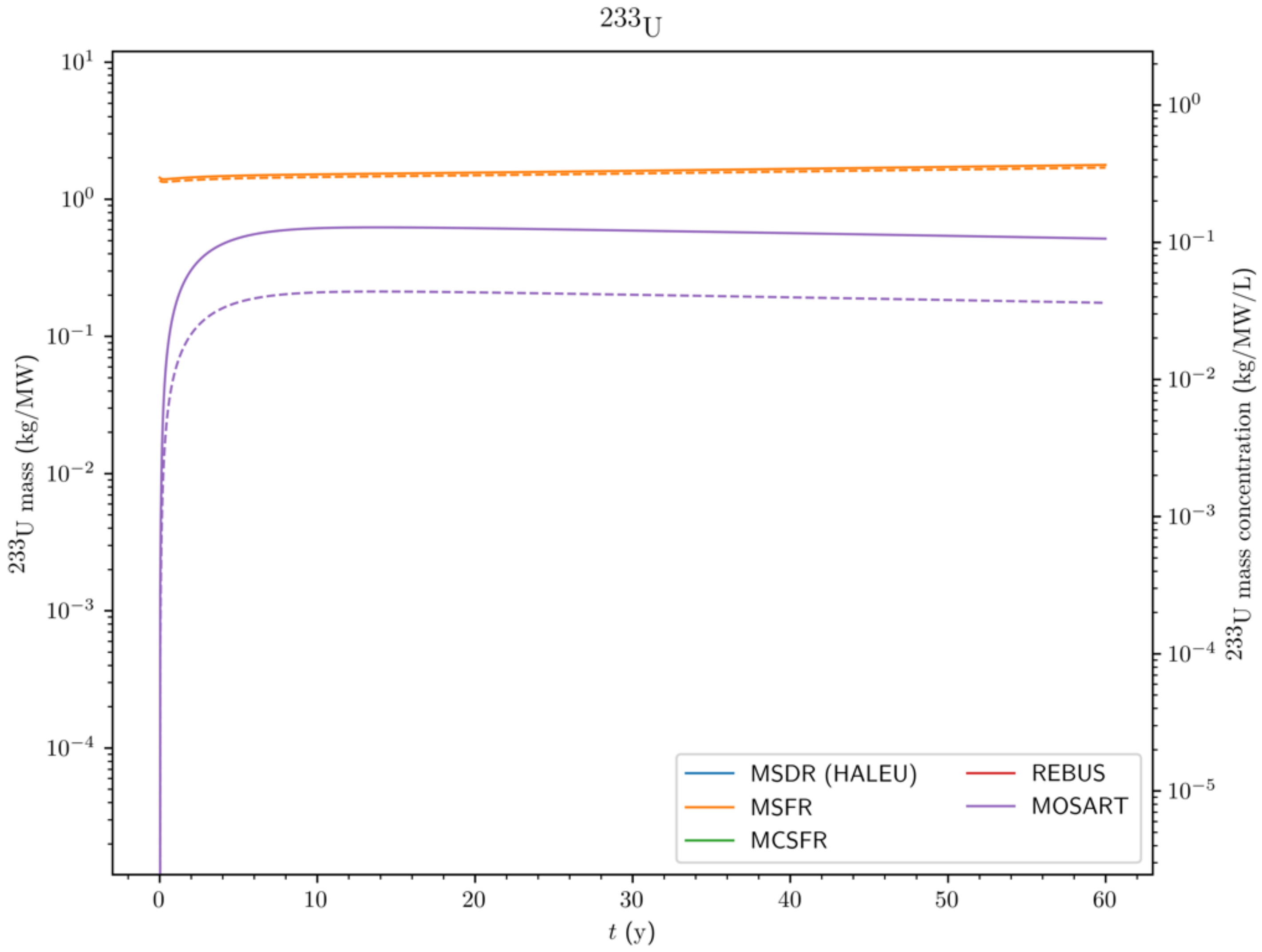


Figure 18. The power-normalized ^{233}U mass and concentration over time for each reactor with no period of shutdown

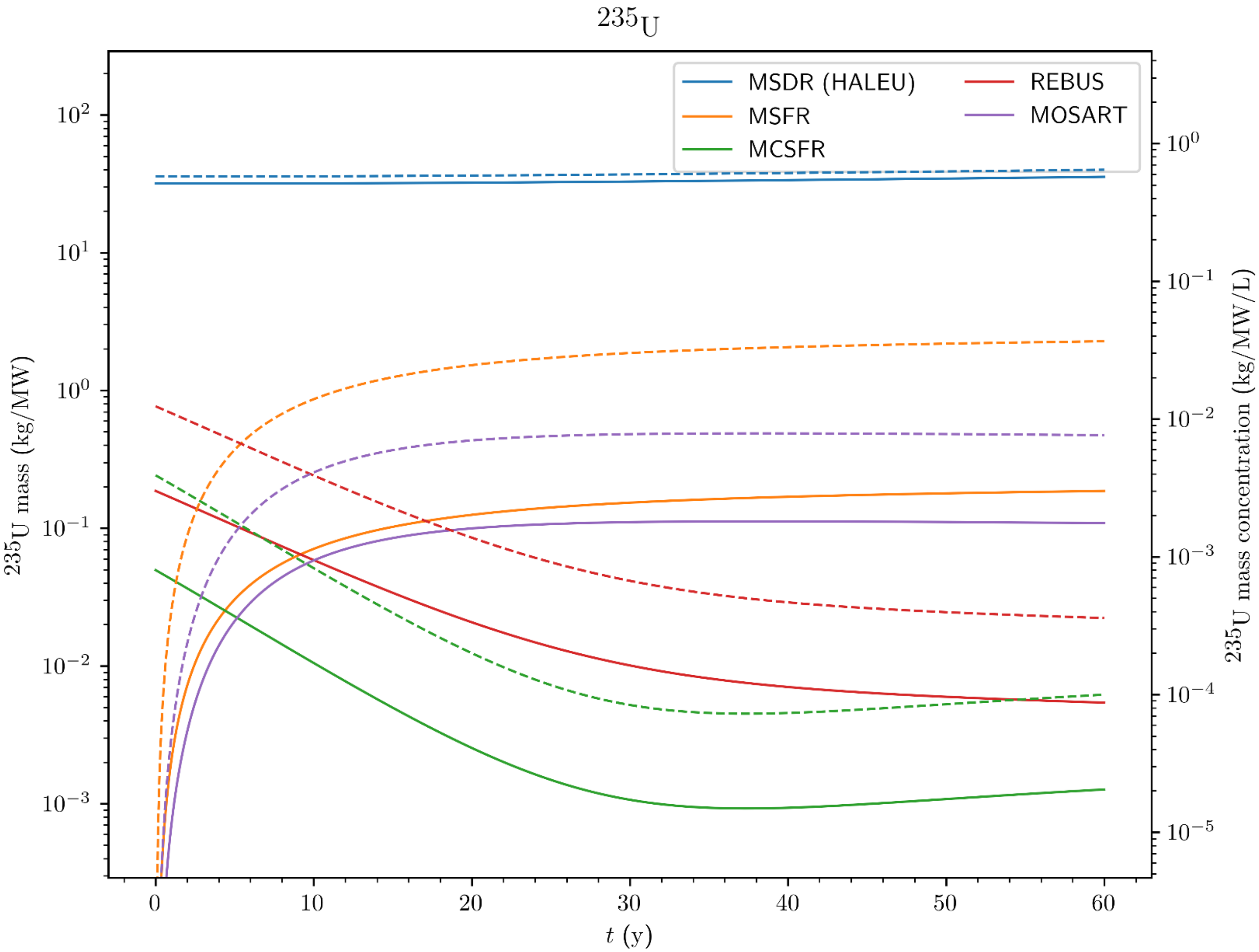


Figure 19. The power-normalized ^{235}U mass and concentration over time for each reactor with no period of shutdown

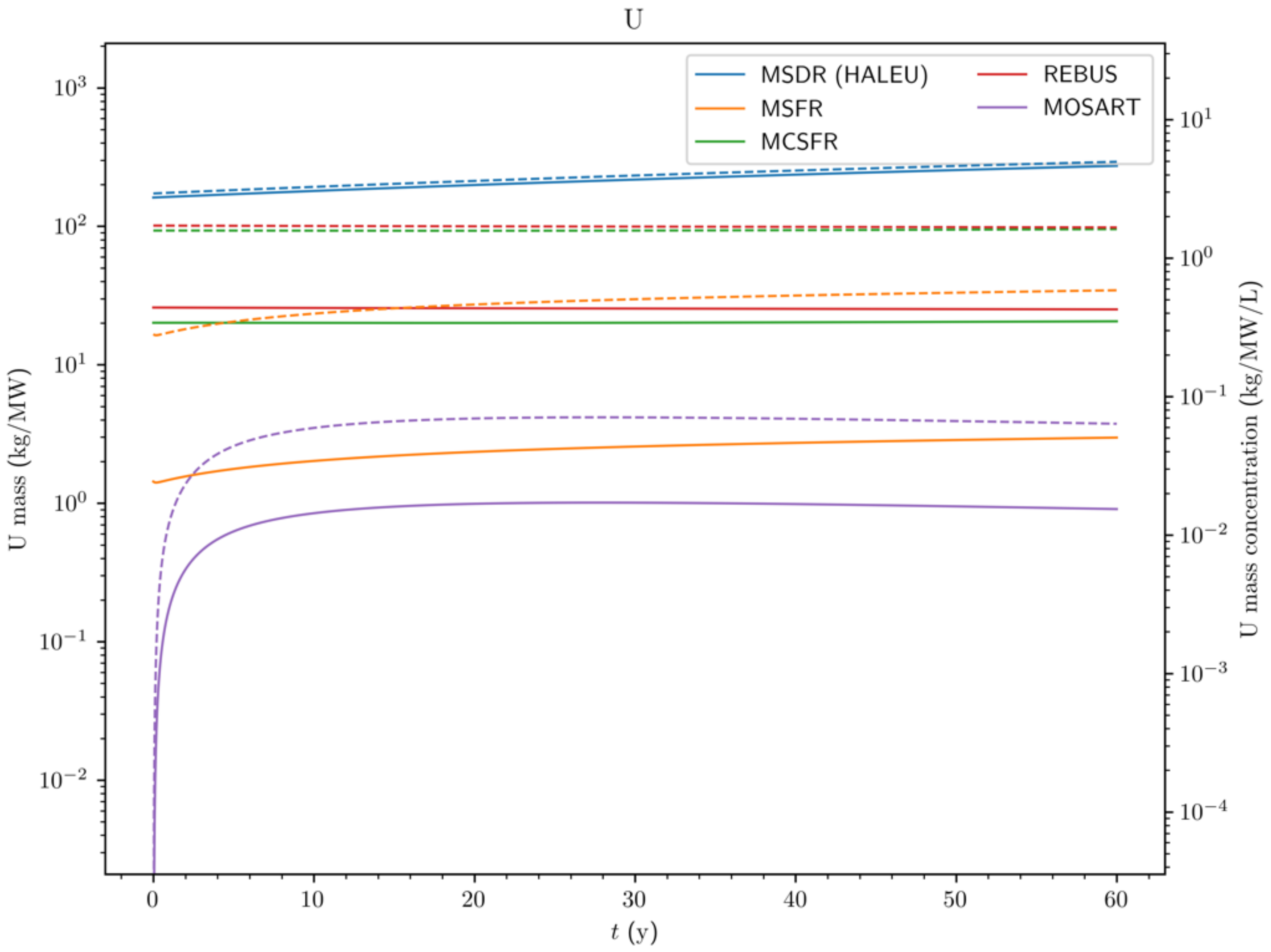


Figure 20. The power-normalized U_{total} mass and concentration over time for each reactor with no period of shutdown

APPENDIX C. FAST-SPECTRUM MOLTEN CHLORIDE REACTOR PARAMETERS

A generic molten chloride fast reactor was modeled with the following assumptions:

- The reactor would operate continuously for 7 years.
- The sparging system continuously removes the noble gases and volatile fission products.
- The noble metals and insoluble fission products are continuously removed through mechanical filtration.
- Uniform removal rates of fission products were applied for the sparging system and the mechanical filtration.
- The makeup fuel salt contains uranium with an enrichment of 19.75 wt %, and it is continuously fed at a rate of 0.767 mg uranium/s into the core.
- The feed rate was obtained by looking at the concentration of heavy metals at the beginning and at the end of cycle for the case without makeup fuel feed.
- In the feed simulation, only U was fed as makeup salt.
- In the depletion simulation, the total power of the core is scaled down to consider the total volume of fuel salt in the system (both core and loop). The total volume of the salt is assumed to be two times the salt volume in the core region.

Table 11. Generic molten chloride fast reactor design parameters assumed in model development

Parameter	Value
Power	180 MW_{th}
Active core radius	150 cm
Active core height	276 cm
Fuel salt	66% NaCl–34% UCl_3
Fuel salt density	3.251 g/cm^3
Fuel salt temperature	900 K
Reflector material candidates	HT9/MgO/Pb
Reflector density	7.70/2.86/10.4 g/cm^3
Reflector temperature	800 K
Reflector thickness	50 cm
Target core lifetime	10 years
Fission products' removal time	30 s