Molten Salt Reactor Safeguards: The Necessity of Advanced Modeling and Simulation to Inform on Fundamental Signatures

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Abstract

Oak Ridge National Laboratory (ORNL) has identified a number of previously reported[1,2] technical factors impacting the implementation of safeguards for Molten Salt Reactors (MSRs), which include: (1) the homogeneous mixture of fuel, coolant, fission products (FPs), and actinides; (2) continuous variation of isotopic concentrations in the fuel salt, including removal (passive or active) of FPs, rare earth elements, and noble metals; (3) the potential for online reprocessing whereby some fraction of the inventory can be removed while the reactor is operational; (4) unique refueling schemes, including the ability to continuously feed the core with fresh fissile or fertile material; and (5) the need for measurements to occur in high-radiation, high-dose, high-temperature environments. These factors necessitate the use of advanced modeling and simulation for tracking the isotopic masses and signatures (i.e., chemical, elemental, isotopic, and radiation) throughout the reactor and associated auxiliary processing, and importantly, tracking must be accomplished as a function of time as the fuel salt evolves during reactor and fuel cycle operations. Determining what needs to be measured, what can be observed, and where to make the measurement(s) are the first steps towards the development of the safeguards technology for the MSR family of reactors.

This paper presents insight into the necessity of advanced modeling and simulation methods and tools, highlighting the tight coupling between the reactor and fuel cycle operations and the resulting fuel inventory and associated signatures. This paper also demonstrates the importance of a comprehensive understanding of the MSR and fuel cycle technologies, as well as the safeguards approaches and technologies that need to be applied. Using ORNL-developed tools designed to model dynamic, complex systems such as salt-fueled MSRs (e.g., source term accountancy), several scenarios are presented that demonstrate the data and modeling fidelity required and highlights the physical behavior of the critical factors identified above, illustrating the need to capture the tight coupling between MSR behavior and safeguards assessments. A preliminary evaluation of the implications for safeguards technology development is also presented.

1. INTRODUCTION TO MOLTEN SALT REACTORS

Molten salt reactors (MSRs) represent a broad and diverse *class* of reactors that involves the use of a liquid salt (typically a fluoride salt or a chloride salt) either as (1) a *coolant* used with a solid fuel (as in fluoride salt–cooled high-temperature reactors) or (2) a *fuel dissolved in liquid salt* that also serves as the coolant material. In liquid-fueled MSRs, the salt can be processed further online or in a batch mode to allow for removal of fission products (FPs) and for the introduction of fissile fuel and fertile materials during reactor operation. Unless stated otherwise, the liquid-fueled MSRs are discussed, and results are presented herein.

MSR concepts have been developed with both thermal and fast neutron spectra and with uranium, thorium, and plutonium fuels. A defining characteristic of some MSR designs is the use of liquid salt as both fuel and coolant. While the use of a liquid fuel allows consideration of many reactor design features not possible with solid fuel, these features also introduce potential new challenges for safeguards. Examples of these distinctive potential features include:

(a) Negative reactivity feedback through fuel expansion from the critical region
(b) Progressive online refueling with adjustable fissile/fertile composition
(c) Online chemical processing
(d) Alternate decay heat removal concepts, such as draining the core to a passively cooled configuration

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Along with their applicability to a large number of fuel cycle variants, MSRs have the potential to offer additional benefits over other advanced reactor concepts. These benefits include high-temperature heat application, as well as closing the fuel cycle, which would lead to improved resource utilization. For these and other potential benefits claimed (such as safety and economic performance), the MSR has been selected as a Generation IV system. After the early development and demonstration of MSRs at Oak Ridge National Laboratory (ORNL), which was followed by some decades of relative inactivity, interest in these concepts has resurged in recent years.

ORNL first proposed MSRs shortly after World War II to provide a means to power military aircraft as part of the Aircraft Nuclear Propulsion (ANP) program. The civilian MSR program started in the mid-1950s and continued until the mid-1970s with the development of progressively more advanced reactor concepts. These efforts included research and development on high-temperature materials, salt chemistry, and separation sciences. ORNL operated two MSR test reactors: the aircraft reactor experiment in November 1954, and the Molten Salt Reactor Experiment (MSRE) from 1965–69. The MSRE successfully operated for more than 26,000 hours, including an 8,000-hour uninterrupted run.

US MSR designs of the 1950s to 1970s focused on optimizing the thorium fuel cycle to achieve a high level of breeding performance by online chemical processing. The Molten Salt Breeder Reactor (MSBR) program relied on separating ^{233}Pa from the fuel salt as a central element in obtaining a net breeding gain. The ^{233}Pa was then allowed to decay to ^{233}U outside the reactor core. The denatured MSR (DMSR) concept was initially developed following the cancellation of the MSBR program. Research on the DMSR concept pursued nonproliferation improvements by avoiding separating fissile material onsite. While gaseous FPs were extracted via sparging and the noble and semi-noble metals were plated out into filter systems, the fissile materials were not separated from the remainder of the primary salt. DMSRs would be refueled by adding sufficient low enriched uranium (LEU) to overcome FP poisoning. Once the salt had become so loaded with FPs that criticality could no longer be maintained, the entire salt inventory would be processed as waste.

There are currently numerous MSR design variants being developed around the world for potential deployment within the next decade or two, and many of these variants are based on ORNL's early designs. For example, startups in the United States have not only expanded on the original ORNL MSRE design, but they have also developed options to consider using spent nuclear fuel (SNF), uranium-plutonium, transuranics, fast spectrum designs, and the original thorium-based concepts. However, in many of the new MSR concepts, active chemical reprocessing is no longer considered, so there are no pure fissile streams being separated and recycled in the MSRs. Instead, mechanical, nonchemical removal of some of the FPs, rare earth elements, and noble metals is deployed. This removal is often a passive process that will occur naturally, but it must be controlled for operational and safety considerations. Figure 1 shows the proposed technologies in relation to their main design characteristics (solid fuel vs. liquid fuel, fast vs. thermal spectrum, etc.). The figure highlights several key aspects of MSR designs, in particular the diversity of technologies (reactor and fuel cycle), and as a result underlines the likely diversity in future safeguards challenges and needs. MSRs encompass a diverse family of reactor types, with no single concept being a full representation of the reactor type. The fuel content (fertile and fissile), fuel processing (chemical or mechanical), and fuel cycle (e.g., open vs. closed) are also widely varying and are likely to require new safeguards approaches.

2. SAFEGUARDS CHALLENGES FOR MOLTEN SALT REACTORS

Many MSR features require a potential paradigm shift in the safeguards approaches and technologies deployed compared to the present light water reactor fleet, for example; hence a complete and thorough safeguards evaluation is needed for MSRs. Understanding and addressing these differences and needs is the objective of several specific programs at ORNL and is a key part of the future development of MSR safeguards activities. A summary is provided here, with further specific research needs/gaps outlined below in more detail:

- **Continuously flowing material.** The fuel salt (or the pebble fuel in the case of some fluoride high temperature reactor designs) is continuously moving in and out of the core and in and out of processing tanks or storage areas; this movement occurs while power is being generated in the reactor core.

- **Continuously changing material.** The salt and its content are continuously changing; this includes changes in the form of the salt, which is solid prior to reactor loading, liquid during normal operations, but once it is discharged, it is liquid for an extended period of time due to decay heat, but solidifies again. The isotopics are also continuously changing due to breeding of fissile material such as ^{239}Pu and ^{233}U and resulting signatures, including potentially new unique signatures to explore due to the short decay times of fission products, for example. Understanding, predicting, and measuring these variations is key.
- **Measurement environment.** Some measurements will occur in high-radiation, high-dose, high-temperature environments. Unlike commercial reactors or reprocessing facilities, in MSRs, there is virtually no decay time between irradiation and the measurement being taken.
- **Accessibility.** After the first day of irradiation, the entire containment and associated infrastructure of the MSR will be contaminated and likely inaccessible for extended periods. The reactor and fuel cycle processes will also be within containment, making inspections and measurements more challenging, and likely remote and unattended.

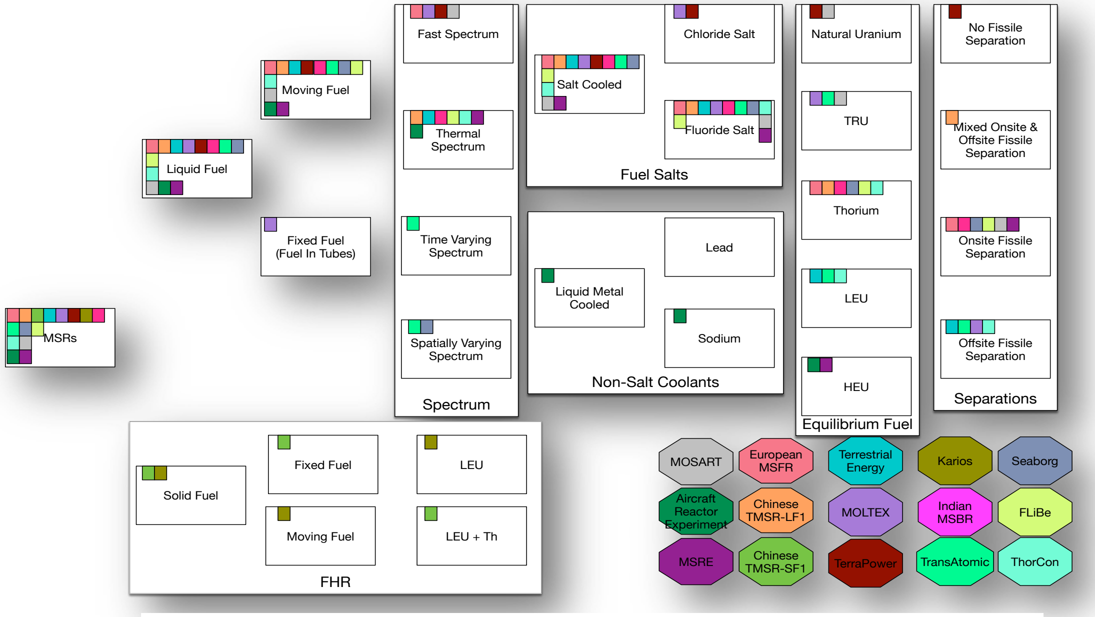


FIG. 1. Main design characteristics of representative MSR concepts.

Recently, safeguards have been evaluated for other advanced, future facilities including pyro-reprocessing. Although there are some similarities between MSRs and pyro-reprocessing (mainly around the salt form), as outlined above, there are a greater number of unique MSR elements requiring a new safeguards approach; for these issues, lessons learned from pyro-processing will likely have limited benefit. As the International Atomic Energy Agency (IAEA) noted regarding MSRs:

> *Designers should be aware that such reactors cannot be considered item facilities. Beyond pebble bed reactors, which have countable numbers of semi-distinguishable items, more stringent nuclear material accountancy measures will likely be required to verify the quantities, locations and movements of the nuclear material. These measures can include, but are not limited to, fuel flow monitors, seals, video surveillance, the use of sensors to trigger other sensors, more accurate [nondestructive assay] NDA measurements and sampling plans that select additional items for verification. Most of this instrumentation does not yet exist and a significant R&D effort can be expected* [3].

To perform a complete safeguards evaluation of an MSR, several technical disciplines and assessments are required beyond those that traditionally fall under safeguards. These differences are driven by the unique nature of MSRs described above, their low level of design maturity, and the interdependency of the necessary disciplines. The disciplines required to complete a safeguards evaluation include policy and guidance requirements (domestic and international), reactor and fuel cycle technology options, modeling and simulation, safeguards approaches, nuclear material accountancy, and safeguards technology. This paper demonstrates the interplay and value in integrating these disciplines.

As noted by the IAEA, "*Each phase in the life cycle of the facility can benefit from consideration of safeguards. While safeguards implementation potentially has a small impact on project cost and schedule when considered early in the design process, failure to do so can result in a much larger impact than necessary, both in construction and during operation*" [3].

This underlines that a *safeguards by design* process early in the concept design stages can benefit reactor developers. Furthermore, noting the gaps in the technologies and safeguards approaches quoted above for MSRs, there is evidence that R&D in this area is needed, and there is merit to start that process as soon as possible. However, with such a large variation in reactor and fuel cycle concepts under the MSR class of reactors, and with limited final design information available, there may appear to be limited scope for early consideration of safeguards needs; however, this is where modeling and simulation is key and critical. Modeling and simulation is a fundamental part of the developer's tool kit when assessing the design feasibility and optimizing the design concept. But equally it is a vital part of the *safeguards* and *safeguards by design* toolkit, especially at the early concept stage of development. This includes an assessment of the inventories (masses, isotopics, source term, gamma and neutron signatures etc.), their locations in the core and associated fuel cycle, what drives and governs the isotopics and resulting gamma and neutron signatures, and safeguards approaches and instrumentation needs. However, as highlighted below, the modeling and simulation of MSRs requires new tools and new approaches to accurately reflect the continually flowing and changing salt composition. This is vital not only for reactor design and performance, but it is also key to the assessment of safeguards needs and challenges, and eventually it will be necessary when verifying the inventories versus those material declarations. The tools also provide an early insight not only into *what* can be measured, but potentially *where* that measurement can and should take place, as well as determining the *reactor operational measures* that could be used to inform safeguards and mass accountancy.

3. MODELING AND SIMULATION OF MOLTEN SALT REACTORS

3.1. Considerations and Approach for MSR Inventory Modeling

Within the MSR class of reactors, liquid-fueled MSRs in particular present unique challenges beyond the capabilities of typical modeling and simulation tools including those tools used for reactor physics (i.e., characterizing neutron behavior and time-dependent changes within the molten salt due to irradiation), fuel cycle assessment (i.e., characterizing mass flow rates of materials in and out of the molten salt), and systems analysis (i.e., characterizing the transport of material throughout the system and its impact on the behavior and safety of the reactor system). These challenges are primarily due to (1) the movement of fuel-bearing molten salt and (2) the potential for continuous feeds (fissile and fertile material) and removals (FPs, noble metals, etc.) to and from the molten salt. For common reactors in operation today, the fuel is designed to contain all FPs and transmutation chain isotopes; this is often an assumption within typical reactor modeling and simulation tools that prevents the application from characterizing the behavior of liquid-fueled nuclear reactor systems. Furthermore, the feed and in particular the removal rates can vary for different elements due to the passive or chemical means by which the elements are processed and managed. This results in the need to not only predict the isotopic composition of the salt at each time step, but also to be able to model the continual feed and removal of specific elements at different rates, keeping track of where they go in the system and what they eventually decay to become. For example, removal rates are specified using an element-specific *cycle time*, which is defined as the amount of time it takes to completely remove an element from the salt. These cycle times vary from seconds for volatile gases and noble metals to tens, hundreds, or thousands of days for semi-noble metals and rare earth elements, and the inventory calculation tools must be able to address this level of complication [4].

In addition to these characteristics, most of the fuel material in an MSR is loaded at initial startup, with smaller amounts of makeup material (with or without fissile isotopes) fed into the system over the course of the reactor's lifetime. This makes the reactor physics simulation itself more similar to a fuel cycle simulation. More information is required from fuel processing definitions; reactor physics simulations are far less accurate without considering material movement to and from the molten salt. However, regarding reactor physics, the prediction of isotopic composition of the molten salt is imperative. For fuel cycle characterization, it is necessary to track the material being removed or fed into the molten salt. This capability is functionally not difficult, but it introduces large approximations because it reduces physical processing schemes and efficiencies into simpler removal actions [5]. Another step further beyond this approach is to characterize the composition and spatial distribution of the molten salt within the core and primary loop. Characterizing material holdup due to molten salt constituent–primary loop material interactions (e.g., corrosion, FP attachment) requires further chemical characterization of the molten salt mixture. This level of fidelity is likely desired for safeguards analysis, as it provides the most accurate assessment of the location of materials within the MSR system.

Traditional reactor physics tools are optimized for solid fuels generate rates of fission, transmutation, and decay to characterize the change in the fuel material (e.g., buildup of plutonium). Computationally, these rates are used to build a large matrix, which is then solved. For a liquid fuel salt with material additions and removals, either (1) material must be removed and added in between these solves, or (2) material removal and feed rates must be added to the matrix. ORNL has developed a suite of tools as an extension to the SCALE suite of analysis tools that accounts for each of these issues and phenomena [6]. SCALE is a comprehensive modeling and simulation suite for nuclear safety analysis and design developed and maintained by ORNL under contract with the US Nuclear Regulatory Commission, the US Department of Energy, and the National Nuclear Security Administration to perform reactor physics, criticality safety, radiation shielding, and spent fuel characterization for nuclear facilities and transportation/storage package designs. The former approach developed in SCALE for MSRs uses a tool called ChemTriton and has been shown to perform well in characterizing the fuel salt isotopic composition in time [7] where fuel material such as LEU and FPs such as noble gases and noble metals are removed from fuel salt compositions according to cycle times and processing system definitions (see Figure 2). For the latter, elemental- or isotope-specific removal rates are added to the solution matrix, providing a more accurate representation of continuous processes and generating mass flow rates for removed materials [8] (see Figure 3).

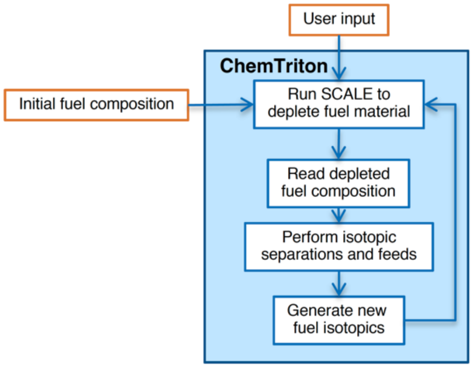


FIG. 2. Methodology used in the ChemTriton tool for updating material compositions.

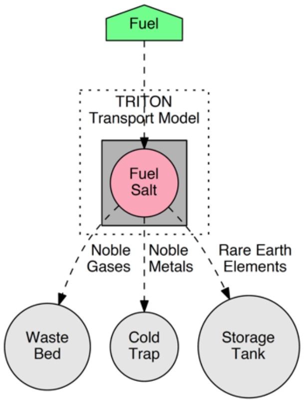


FIG. 3. Latest approach deployed in SCALE, providing a more accurate representation of continuous processes.

For MSRs, the reactor operations and resulting fuel isotopics and fuel cycle are tightly coupled. This means that any change in reactor operations (e.g., change in power, flow rate of fuel salt), or a change in the fuel cycle operations (e.g., addition of fertile or fissile material, rate of removal of FPs) will have a direct, almost immediate effect on the nuclear material inventory in the core, as well as on the reactor itself. This further underlines the importance of developing tools like those used at ORNL not only for reactor analysis, but also for ensuring that the tools accurately capture the evolution of the fuel salt isotopics, allowing for the ability to predict accurately the nuclear material content in the core.

Although SCALE has been enhanced for MSR analyses, classic inventory calculational tools have no spatial awareness/dependency and hence no representation. Therefore, to capture not only the reactor core, but also the system inventory, associated mass flows and responses, and timescales for movement and responses, ORNL has developed a system level code. The TRANSient Simulation Framework Of Reconfigurable Modules (TRANSFORM [9]) is an ORNL-developed component library created using the Modelica programming language for the investigation of dynamic thermal-hydraulic systems and other multi-physics systems. The TRANSFORM library has been successfully used for a variety of nuclear applications, including investigations into the performance of nuclear hybrid energy systems and gas-cooled reactors. Recent enhancements to TRANSFORM have been added specifically for MSRs, such as modified point kinetics models that account for FP transport. An example of the application of TRANSFORM and the insight it provides is illustrated below.

3.2. Modeling and Simulation Results for MSR Concepts and Early Safeguards Insights

In the absence of actual operating MSRs or extensive, publicly available design information, simulations have been performed on updated historical reactor design concepts developed at ORNL. These designs are representative and indicative of the modern MSR concepts being developed by private industry today. In the examples provided below, this is primarily the Molten Salt Demonstration Reactor (MSDR), a large commercial-scale MSR with extensive design details and physical plant layout information available, and the design is representative of many of the MSR designs under development today. The models have been developed to ensure that they are not only representative, but also are viable in terms of their fuel cycle performance to maintain criticality throughout operations, to ensure that salt compositions are realistic, and to ensure that the lifetimes of the cores are consistent with those being developed today. Several examples of the use of these models to inform safeguards needs are presented below. These models and results have been generated using the SCALE code package that includes the series of new enhanced capabilities outlined above and developed at ORNL specifically to enable MSRs to be modeled more accurately, as well as the TRANSFORM tool that has additional MSR functionality included. The following examples provide further insight into the safeguards challenges outlined above: continuously flowing and changing material, measurement environment, and accessibility.

3.2.1. Isotopic Prediction and Evolution Throughout the Reactor

As detailed above, a major challenge for the accurate prediction of nuclear material inventories in MSRs is the continuing evolution of the isotopics caused by the addition and removal of elements throughout the life of the reactor. This not only includes the ability to track these changes in the core, but also the ability to remove and track those elements removed during salt processing and normal operations. This requires traditional reactor physics tools to perform more like fuel cycle modeling tools. To demonstrate this, results from a high-burnup MSR fueled with 5 wt% ^{235}U are presented in Figure 4. Although the trends are similar to those seen for LWR fuel, the timescales should be noted; monitoring of the changing salt in the core is required for 25–30 years compared with the typical 3–5 years of irradiation for a pressurized water reactor (PWR) assembly. The plutonium inventory continues to change throughout the life of the core, so it is necessary be able to accurately predict the inventory for an extended period of time. Furthermore, there is also a continual addition of ^{235}U to the salt to replace that which has been fissioned.

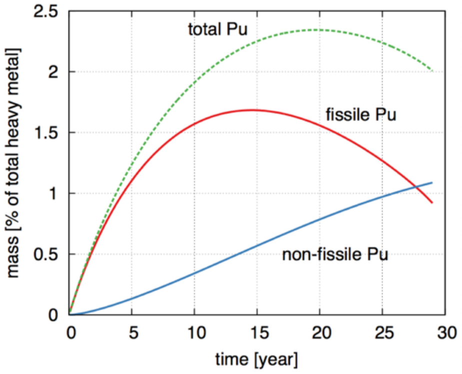


FIG. 4. Simulated plutonium concentrations in the fuel salt for a thermal spectrum MSR.

Unlike PWRs, MSRs are not constrained by traditional fuel performance limitations or by a fixed amount of fissile material that can be loaded at a given interval. Therefore, MSR fuels can be irradiated to much higher burnups: 60 GWd/tHM as is typical for PWRs compared with anything up to 200–300 GWd/tHM for fast spectrum MSRs. For lower burnups such as 40 GWd/tHM, some of the MSR models have ~3 times as much Pu than a PWR per unit fuel mass and ~4 times as much at a burnup of 60 GWd/tHM. Based on the simulations of a representative fast spectrum concept, a large MSR produces on the order of ~0.5 MT Pu each year, and it contains up to 4 MT of Pu in its core. This type of analysis, in which the evolution of plutonium and other nuclear material is accurately modeled, provides insight not only into the overall content of material in the core and in other parts of the fuel salt processing systems, but it also provides insight into the volume or mass of salt needed to divert 1 significant quantity of nuclear material. This amount can be as little as less than 1% of the total core salt volume. This also begins to inform on the accuracy of measurement needs for safeguards instruments and inspection frequencies.

The complex addition and removal of all materials generated (e.g., FPs, transuranics), must be modeled and tracked throughout irradiation, as the materials move throughout the reactor system, as they are removed by mechanical or chemical processing, and as they are subsequently stored and/or sent for disposal. This assists the safeguards assessments by informing on mass flows, locations, diversion scenarios, and key measurement points, including waste disposal, filters, as well as in the fuel salt. Figure 5 illustrates how not only the content of the fuel salt in the reactor is modeled and tracked within the code, but also the materials that are being removed and stored during operations. This information is required, as each of the streams could be processed and stored in a different way and may require safeguards. The data can also provide important details on key measurement points. The details of the FPs also must be modeled and tracked, as they will either plate out in the reactor or come out of solution.

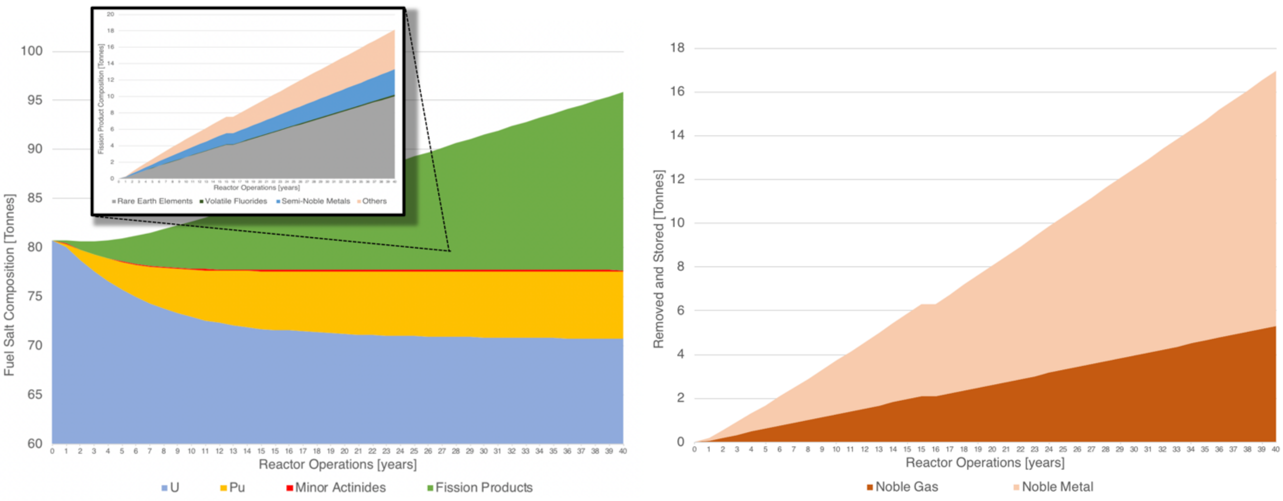


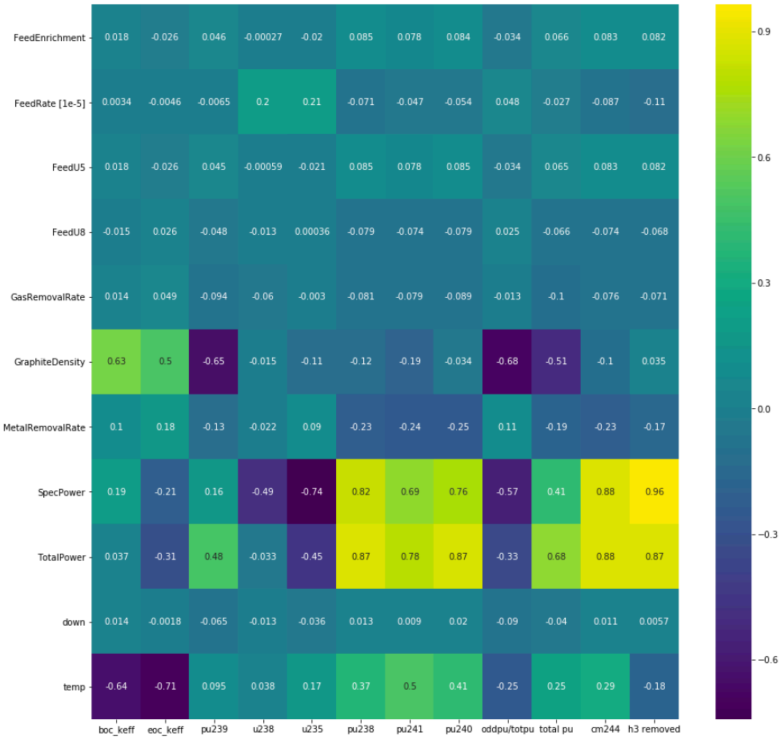
FIG. 5. Simulated inventories in the core (left) and processed and in storage (right).

3.2.2. Key Reactor Operational Parameters Effecting Isotopic Content and Composition

As noted above, in MSRs there is a tight coupling between the reactor and fuel cycle operations e.g., feed and removal rate of fuel into the core, and removal of FPs during salt processing. Therefore, from a safeguards perspective, this indicates that there is likely to be a need to monitor the reactor and fuel cycle operations in greater detail than in traditional commercial reactors. This monitoring must be accomplished in an integrated manner, ensuring that all uncertainties are captured. From a safeguards measurement perspective, isotopes and elements of interest include fissile and fertile materials, but they also include those isotopes used in classical non-destructive assay (NDA) techniques such as ^{244}Cm and certain FPs that indicate reactor operating powers. As such, before addressing the details of instrument development and needs, the reactor and fuel cycle factors with the greatest impact on these key isotopes in the core should be determined and analyzed to discern whether those factors can themselves be easily measured.

This approach provides an insight into the operational parameters that also need to be known as part of the safeguards declarations, as these will affect directly the inventories.

A scoping analysis was performed on selected reactor and fuel cycle parameters to understand the impact of variations/uncertainties in these parameters on specific metrics. A series of parameters and their uncertainties were selected through a literature review, and while these elected parameters are not intended to be exhaustive, they do demonstrate the value and insight from this analysis capability, and they identify the most significant parameters. Uncertainties in these design parameters either represent physically known uncertainties or general unknowns (e.g., in processing system efficiency and design). Parameters investigated include reactor power, fuel loading (initial and during operations), moderator density, fission gas and noble metal removal rates, temperature, and enrichment (uranium and lithium in the salt). Responses include key isotopes and core reactivity. Figure 6 shows the statistical correlation between parameters and responses. Three major parameters that have large correlations with responses are graphite density, power (burnup), and reactor temperature, as shown by the lighter/brighter colors in the heatmap below. Graphite density is positively correlated with criticality due to increased thermalization of neutrons, and it is negatively correlated with plutonium generation for the same reason. Reactor (and local) power is directly proportional to burnup, and higher burnups increase ^{244}Cm and ^{3}H generation, as well as decrease the ^{235}U at the end of operations. Feed rates of the fuel salt also have an impact on the isotopic content, but the gaseous FP removal has a minor effect.



	boc_keff	eoc_keff	pu239	u238	u235	pu238	pu241	pu240	oddpu/totpu	total pu	cm244	h3 removed
FeedEnrichment	0.018	-0.026	0.046	-0.00027	-0.02	0.085	0.078	0.084	-0.034	0.066	0.083	0.082
FeedRate [1e-5]	0.0034	-0.0046	-0.0065	0.2	0.21	-0.071	-0.047	-0.054	0.048	-0.027	-0.087	-0.11
FeedU5	0.018	-0.026	0.045	-0.00059	-0.021	0.085	0.078	0.085	-0.034	0.065	0.083	0.082
FeedU8	-0.015	0.026	-0.048	-0.013	0.00036	-0.079	-0.074	-0.079	0.025	-0.066	-0.074	-0.068
GasRemovalRate	0.014	0.049	-0.094	-0.06	-0.003	-0.081	-0.079	-0.089	-0.013	-0.1	-0.076	-0.071
GraphiteDensity	0.63	0.5	-0.65	-0.015	-0.11	-0.12	-0.19	-0.034	-0.68	-0.51	-0.1	0.035
MetalRemovalRate	0.1	0.18	-0.13	-0.022	0.09	-0.23	-0.24	-0.25	0.11	-0.19	-0.23	-0.17
SpecPower	0.19	-0.21	0.16	-0.49	-0.74	0.82	0.69	0.76	-0.57	0.41	0.88	0.96
TotalPower	0.037	-0.31	0.48	-0.033	-0.45	0.87	0.78	0.87	-0.33	0.68	0.88	0.87
down	0.014	-0.0018	-0.065	-0.013	-0.036	0.013	0.009	0.02	-0.09	-0.04	0.011	0.0057
temp	-0.64	-0.71	0.095	0.038	0.17	0.37	0.5	0.41	-0.25	0.25	0.29	-0.18

FIG. 6. Correlated heatmap. Responses are listed on the x-axis, and the parameters varied are listed on the y-axis.

One of the concerns often raised regarding MSRs is the ability to remove fuel salt during operations with the potential to divert the nuclear material from that salt. The ability to detect salt removal during operations could be a key requirement for the safeguards approach for MSRs. From a reactor operations perspective, the removal or change in salt composition is likely to have an impact on the core, and therefore TRANSFORM was used to determine whether such changes could be observed at the more macroscopic core level, as well as in the more refined isotopic level, as outlined above. The TRANSFORM model incorporates FP mass accountancy throughout the reactor system, including primary, secondary, and auxiliary systems (e.g., off-gas). The model also includes the coupled behavior of the movement of the FPs with reactor kinetics and thermal hydraulics. Three variations of a scenario were simulated using TRANSFORM in which the operator removes used fuel salt from the reactor:

A. A *step change* in salt removal/addition, but with *no reactivity control* (e.g., no control rod movements) of the core to compensate

B. A *periodic change* in salt removal/addition, but with *no reactivity control* of the core to compensate

C. A *periodic change* in salt removal/addition, but *with reactivity control* of the core to hold power constant

In each case, the salt addition was adjusted to match the salt removal rate such that the total flow rate through the system remained constant. The salt feed and removal rate were chosen arbitrarily for illustration purposes. The TRANSFORM results can be seen below in Figures 7, 8, and 9.

These illustrative assessments demonstrate how as the fueled salt is removed, including all FPs, a distinct change to the reactor system may be observed, in particular changes in power and reactivity. Figures 7 and 8 show (1) how the total core power and reactivity could be monitored to determine a change in salt addition/removal, whilst at the same time shows that, (2) when using additional reactor maneuvers (case C) with control systems (such as control rods), the effects can be ameliorated. However, Figure 9 shows that other parameters such as FPs (shown here is Xe concentrations monitored in the off-gas system) provide an additional unequivocal indication of the changes in the reactor power, with Xe concentrations clearly varying for case C, even when there was less of a change seen in reactor power or reactivity.

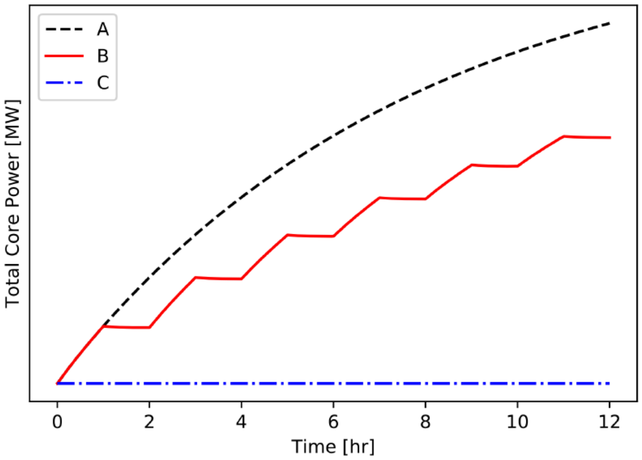


FIG. 7. Total reactor power within the core as a function of time.

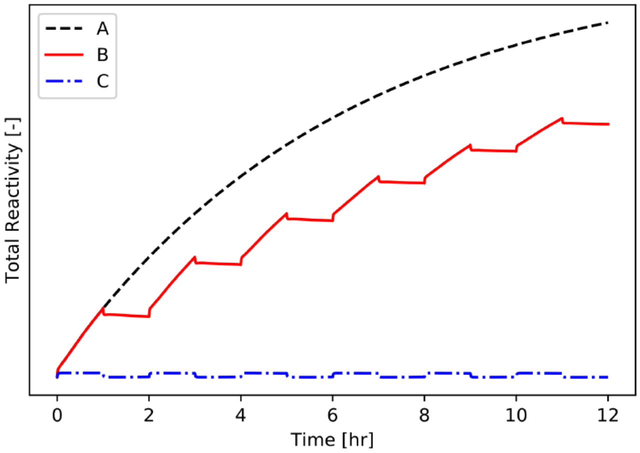


FIG. 8. Total reactivity in the core as a function of time

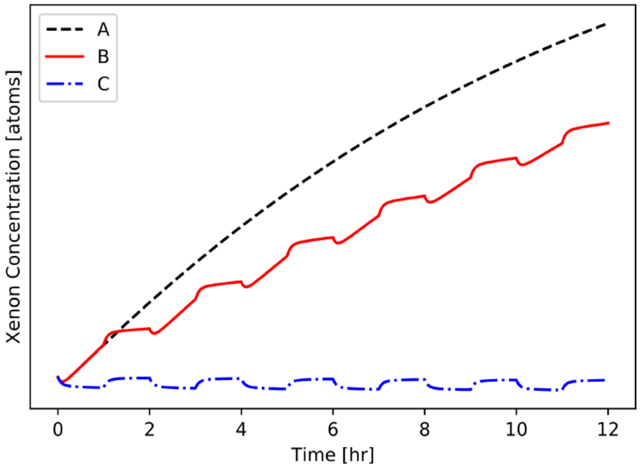


FIG. 9. Concentration of ^{135}Xe as a function of time in off-gas stream.

Regardless of the scenario, the tightly coupled nature of molten salt reactors such as the MSDR means that there is a high degree of likelihood that when perturbations occur within the salt composition, there will be evidence of the disturbance in a variety of ways. This feature opens a wide array of mechanisms for safeguard applications. However, the measurement environment itself could be a challenge for the safeguards of MSRs, and the early analysis using advanced techniques can provide an insight into those challenges.

3.2.3. Measurement and Inspection Environment

The fuel salt and resulting isotopics in an MSR flow from the core, through heat exchangers, and into and through a number of other processing or storage tanks. During normal operations in each of these systems, the short-cooled (minutes to hours) fuel salt will contain a variety of short-lived FPs and minor actinides that emit a significant radiation field, including neutrons and high energy gammas. Therefore, regardless of the specific location or instrumentation for safeguards, a number of measurements must occur in high-radiation, high-dose, high-temperature environments. For example, based on SCALE calculations, the total gamma rate for a short-cooled MSR salt will be approximately two orders of magnitude greater than for commercial PWR fuel, which is more typically cooled for 1 year or more. The ability of the modeling and simulation tools to accurately capture the inventories and resulting gamma and neutron signatures is key to being able to design the safeguards instruments and determine their requirements in terms of accuracy, response, and lifetime.

Determining the distribution of the radiation field through the primary loop and accounting for shielding from pipes, civil structures, etc., are also important considerations for determining instrumentation locations, and they are also crucial factors when considering access for safeguards inspections. The ORNL modeling and simulation toolkit has been expanded to enable a dose calculation to be conducted under normal and off-normal operations, such as for a dose from activated piping and structural materials when the fuel salt is drained from the reactor core and stored in tanks during an outage (Figure 10). Under the current program of work, the radiation exposure and dose to instruments, electronics, and inspectors is being assessed, and will be used to inform on the development of safeguards technology and inspection regimes.

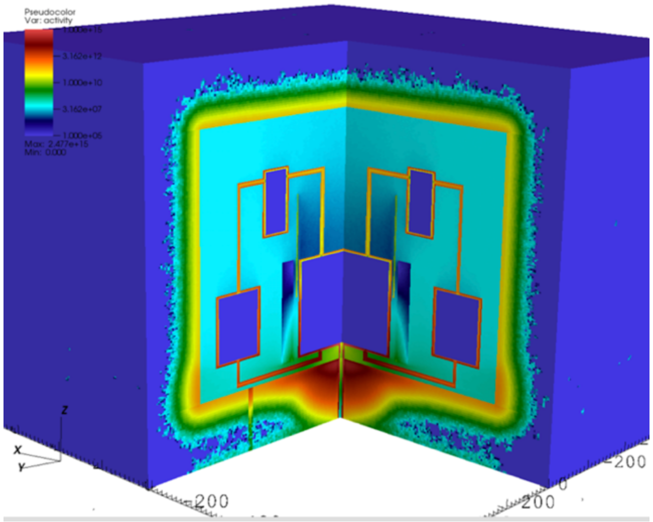


FIG. 10. Structural activation source of a notional MSR concept after 7 years of full power irradiation at 10 days after shutdown.

4. SUMMARY AND CONCLUSIONS

Following a period of limited research and investment, development of a diverse variety of MSRs has commenced over the last ten years around the world. These include a broad spectrum of technologies supported by national governments, but the majority of investment is being provided by private capital. The diversity in reactors, fuels, and fuel cycle approaches and technologies presents a principal challenge to the evaluation of the proposed MSRs from a safeguards perspective. Furthermore, due to the diversity in reactor designs and fuel cycles, it is unlikely that one safeguards approach or technology will accommodate all MSR designs.

MSRs with fuel dissolved in liquid salt (which also acts as the coolant) require a potential paradigm shift in the safeguards approaches and technologies deployed, compared to, for example, the present light water reactor fleet, and hence a comprehensive, broad safeguards evaluation is needed. Understanding and addressing these differences and needs is part of programs of work at ORNL and is a key part of the future development of MSR safeguards activities. The key features of liquid-fueled MSRs that are driving the need for evaluations include continuously flowing fuel (which includes fissile and fertile material, as well as transuranics and FPs), continuously changing material (e.g., form, irradiation, fertile material added, and FPs and noble metals being removed), the measurement environment (high radiation, dose, and temperature), and accessibility (processes will also be inside containment, making inspections and measurements more challenging). These features necessitate the development and use of sophisticated modeling and simulation tools for tracking the isotopic masses and signatures throughout the reactor and associated auxiliary processing, and as a function of time as the fuel salt evolves. As part of its ongoing MSR activities, ORNL continues to actively engage in the development of the modeling and simulation, and science and technology of MSRs, including leading and managing the related US national programs. The programs include evaluation of associated safeguards challenges and opportunities, and this paper presents insights into how some of that work is beginning to inform on safeguard needs for MSRs.

Modeling and simulation provides a fast, inexpensive insight into the important factors in reactor operations for safeguards, as well as instrument requirements (such as accuracy, signature to measure, lifetime in measurement environment, etc.), and safeguards approaches. Since the MSR designs are relatively immature, and detailed physical layouts are not available, modeling and simulation is vital at this early stage of the design process. Furthermore, the use of a modeling and simulation toolkit specifically focused on safeguards application ensures that applying a *safeguards-by-design* process early in the concept design stages can benefit reactor developers and domestic and international regulators. The analysis and results presented above indicate the types of insight that can be provided by application of advanced modeling and simulation techniques for MSRs: (1) nuclear material content in the core and in the fuel cycle as a function of time, reactor operations, and location throughout the system, (2) development of new correlations for radiological signatures for use in safeguards instruments, and complementary measurements such as those from reactor operations (power, reactivity etc.), (3) instrumentation requirements, and (4) measurement environment. Furthermore, the sensitivity analysis presented herein underlines the importance of the Design Information Verification (DIV) to ensure that design and material properties are as initially defined. The paper also demonstrates the importance of a comprehensive understanding of the MSR and fuel cycle technologies, as well as the safeguards approaches and technologies that need to be applied.

Future work includes assessments of specific MSR concepts, including determining (1) key reactor and fuel cycle parameters that change the inventory and potential measurement signatures, (2) instruments needed to monitor and measure these changes, (3) where to locate the instruments in the reactor system, and (4) the accuracy and delay time prior to the detection of those changes. This includes a tight coupling between the MSR physics/inventory tools to safeguards tools, including an evaluation of the detector responses in the system. ORNL continues to lead the development of MSR modeling and simulation and other areas and is working with its reactor, fuel cycle, and safeguards and instrument experts to resolve the challenges presented by MSRs and to identify opportunities for improving the safeguards of these new advanced concepts.

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