NOVEL STRATEGIES FOR SAFEGUARDING MOLTEN SALT REACTORS

PROCEEDINGS OF THE INMM ANNUAL MEETING
MAY 22-26, 2023

Nathan Shoman[*]
Sandia National Laboratories[†]
nshoman@sandia.gov

Pat Moosir
Sandia National Laboratories[†]
mhiggin@sandia.gov

ABSTRACT

There is a continued global interest in advanced nuclear power as a solution for reliable clean energy. However, new nuclear facilities are capital intensive, which is a significant barrier to future growth. Careful consideration during the design phase can reduce upfront costs to avoid expensive, future retrofits that might be required to reach regulatory goals. One key component of the licensing process for nuclear facilities is the material control and accountancy (MC&A) plan. Liquid-fueled molten salt reactors (MSR), one of the proposed advanced nuclear power designs, is a significant departure from contemporary light water reactors due to several unique design features, which could impact the MC&A plan. Prior work has shown that large fissile inventories can make it difficult, if not impossible, to rely solely on material accountancy of the liquid-fueled MSR core alone as an effective MC&A strategy. Potential solutions include a focus on input and output transfers, which would involve discrete item counting, or a performance-based MC&A approach. This work considers the latter by investigating changes in process monitoring signals from liquid-fueled MSRs under material loss conditions. Material losses are shown to induce transitions from a baseline state to a different post-loss state. However, future work is needed to investigate several shortcomings in this process-based approach.

1 Introduction

Advanced nuclear facilities continue to see significant levels of attention globally. Large expansions in nuclear fuel cycle facilities will lead to an increased burden on regulatory stakeholders. Consequently, it is important to design optimize systems that meet regulatory requirements while avoiding future retrofits and minimizing capital expenditures. Material control and accountancy (MC&A) is a notable part of regulatory requirements for power reactors that may change significantly from existing plans for conventional light water reactors (LWRs). LWRs' MC&A plans are relatively straightforward to secure given that the core is sealed under normal operation, requires special equipment to open, fuel is contained within discrete fuel elements, and robust reactor physics tools for burnup estimation are available. MC&A for these facilities involve straightforward item accountancy with robust containment and surveillance measures. Liquid-fueled molten salt reactors (MSRs), which in this work are referred to as simply "MSRs" while noting not all MSRs are liquid-fueled, have significant design differences that complicate the MC&A strategy.

MSRs in contrast often have several design specific features that prohibit direct implementation of strategies used for LWRs. These features include continuous feeds and removals, a bulk fuel form, and continual nuclear transmutation. Material accountancy for MSRs is further complicated by the heterogeneous landscape of proposed designs. This makes it difficult to develop a one-size-fits-all material accountancy strategy as unique design features will impact system performance. Unique MSR design features emphasizes the need to consider MC&A during the design phase.

---

[*] Corresponding author

[†] Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2023-02675C

Past work has shown that large fissile inventories present during operation creates a challenging environment to estimate the nuclear material [1, 2]. Material accountancy alone will likely be insufficient to detect loss, of significant quantities of material. This work specifically focuses on one of the proposed solutions; a performance-based MC&A system, by considering the process monitoring responses of a liquid-fueled MSR under loss conditions.

The goal of this work is to analyze the process monitoring responses of a liquid-fueled MSR system under material loss conditions. Specifically, this preliminary work uses existing tools to estimate responses of system reactivity, temperature, and flow during material loss to determine if these signals could play a role in a performance-based MC&A approach. This work complements other existing work investigating different MC&A strategies for liquid-fueled MSRs. There are two key focuses of this work:

- **Extension of existing tools to support material loss analysis (Section 3.1):** Existing tools such as SCALE [3], the MSDR dynamic depletion model [4], and models from Betzler [5–8] are combined and extended to support the calculation of process signals during material loss conditions. Specifically, a pipeline is created that automatically calculates material loss and substitution fractions, collects point kinetics parameters, estimates reactivity changes, and gathers problem-dependent process monitoring signals.
- **Analysis of state transition from material loss (Section 4):** Using the pipeline that ties together SCALE [3] and the MSDR dynamic depletion model [4], several material loss scenarios are calculated. Signals from the dynamic model are analyzed using Principle Component Analysis (PCA) [9]. Relative comparisons between different loss initiation times and durations are made.

2 Related Work

Material accountancy of bulk facilities has been considered since at least the 1980s. The majority of this literature focuses on the develop and application of “near-real-time” accounting [10, 11] wherein statistical evaluations are made in regular intervals throughout the year rather than a single yearly evaluation. The most common approach to material accountancy for bulk facilities involves the calculation of Material Unaccounted For (MUF) [12, 13] and the associated uncertainty. Simple control charts and thresholds can be used to detect abnormal operation for smaller facilities. However, larger facilities often employ more complex statistical tests such as a combination of the standardized independent transformed material unaccounted for (SITMUF) [14], Page’s trend test [15–20] and GEMUF [21].

Analysis presented in this work is motivated by a potential performance-based MC&A system design, which would use process monitoring. Process monitoring has been considered since the late 1970s and is defined to a series of systems that support material accountancy by detecting anomalous conditions that might be indicative of material loss. These signals are not usually direct measurements of nuclear material, but instead provide information as to the operational status of a facility [22]. Although process monitoring has historically been used for process control, there has also been work to consider the application to material accountancy on the system level by integrating data streams [23–25] and by using data analytics [26–34, 34–37]. While several of these studies have shown the potential effectiveness for process monitoring, it has not been widely used for material accountancy in practice. These studies are often proof-of-concept in nature and would require expensive retrofits to existing facilities. The analysis presented here is being proposed early within the design cycle for many liquid-fueled designs, which would reduce costs by eliminating retrofits.

MSRs have some notable design differences from facilities considered in the traditional safeguards literature mentioned above (i.e., bulk processing facilities), that necessitates the inclusion of additional tools and techniques. Reactor physics tools such as SERPENT [38–40] and SCALE [5–8] have been used to model MSR fissile material evolution and consider the contribution of nuclear data uncertainty to MC&A performance. Other tools such as TRANSFORM [41], NERTHUS [42], and the MSDR dynamic model [4] have been used to model the thermophysical behavior of MSRs.

Literature focused on material accountancy strategy for MSRs dates back to 2020 and is relatively small. Initial work has been focused on exploring potential signatures for facility misuse, as these may vary from existing bulk facilities, and determining larger facility material accountancy strategy. Several key findings in the initial literature include the following:

- Representative MSR designs considered in literature often have large inventories leading to challenges detecting material loss when relying solely on material accountancy and statistics due to a large material balance uncertainty [1, 2].
- Nuclear data uncertainty contributes to material accountancy performance. This contribution is large compared to the relative isotopic change due to loss (i.e., nuclear data uncertainty increases difficulty of potential process monitoring) [43].

- Nuclear data uncertainty is largely insignificant compared to inventory measurement error (i.e., has little contribution to material balance performance) [1,2].
- Cumulative changes in fission product inventories, even for large material losses, could be difficult to detect [44]
- Facility-level material accountancy approach can be designed to rely more on input and output transfers to lessen the impact of large MSR core inventory uncertainties [45,46].
- Consideration should be given to the MSR fuel salt activity and fissile concentration, which could have significant impacts on overall security strategy [46].

3 Methodology

This work considers the process monitoring response of the Molten Salt Demonstration Reactor (MSDR) [47]. The MSDR was chosen as it is the most prevalent design in the wider body of material accountancy literature and features several characteristics common to most MSR designs. The goal is to consider the response of various process monitoring signals to a material loss and determine their ability to flag potential anomalous conditions. This is achieved through a multi-step process outlined in Figure 1 below.

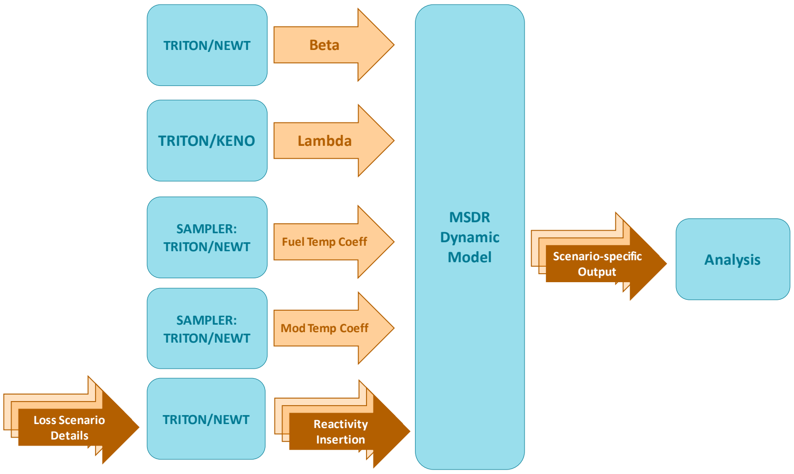

Figure 1: Computational flow overview.

The MSDR dynamic model developed and described in [4] is ultimately used to generate scenario-specific signals such as temperature and pressure. This model, based in MATLAB SIMULINK, is a nonlinear dynamic model designed to simulate transients for safety-related tasks. The model features a modified point kinetics equation, a decay heat removal system, and depletion dependency. An overview from the model is shown in Figure 2 below [4].

3.1 Models

In this work, rather than relying on pre-generated values provided by the authors, problem-dependent point kinetics parameters are recalculated using SCALE to more accurately reflect the specific depletion time scales of interest and material flows. Scenario specific reactivity changes were also calculated in order to represent material loss scenarios as process transients to the model.

The six group delayed neutron constants, β, mean neutron generation lifetime, Λ, fuel temperature feedback coefficient, α_f, and moderator temperature feedback coefficient, α_m were calculated using various SCALE routines which are shown in Figure 1. In the cases where SAMPLER is used, 400 cases were run to provide good estimates of the parameters of interest.

Parameters β, Λ, α_f and α_m were calculated for normal conditions and were not modified based on material loss conditions as the impact is anticipated to be low. In contrast, individual reactivity changes, λ, were calculated for each material loss scenario considered which can vary significantly.

In all cases where SCALE is used to generate the point kinetic parameters described above, a MSDR unit cell approximation is used. The unit cell is a doubly-symmetric, quarter assembly model that was developed by ORNL [5–8] based

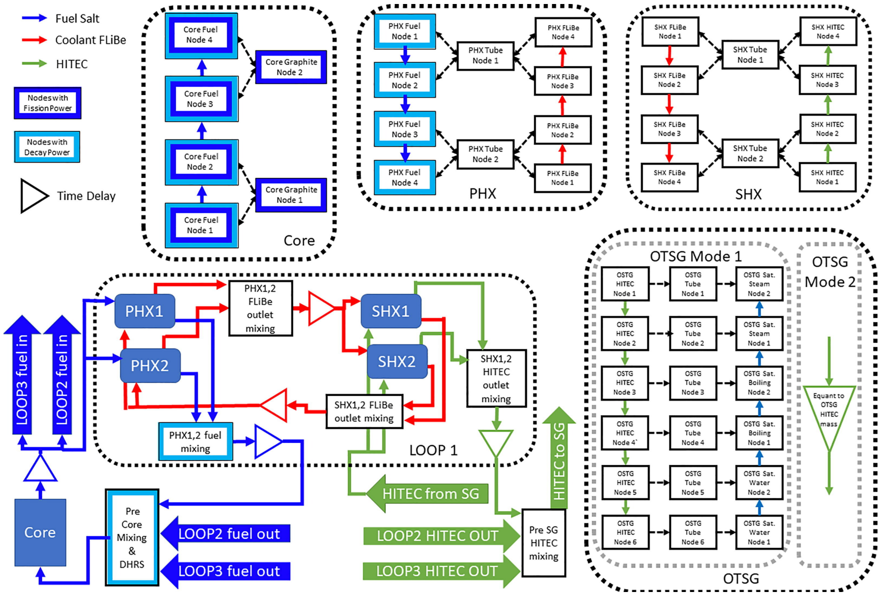

Figure 2: Overview of the MSDR dynamic model, reproduced from [4]

on the MSDR [47] but utilizes a modified salt described in [48]. A salt lifetime of $30t_0$ years is assumed and feeds were optimized to maintain a constant fissile inventory, however, it is noted that other optimization targets could be chosen.

3.2 Data

Several different diversion scenarios were considered to determine the limits of a process-based approach to improving MC&A for MSRs. Nine scenarios are split into two different categories: one category varies loss initiation time and the other varies loss duration. These scenarios are summarized in Table 1. Both the initiation time and loss duration are expressed in arbitrary units expressed as t_0 and t_1 respectively.

In all cases, approximately the same amount of material is removed and replaced with an equal mass of surrogate material (feed material). This loss modality, often referred to as substitution loss, is chosen over the direct loss wherein no material is replaced, because substitution losses are often the more difficult case. This is largely due to the use of high precision process monitoring methods (e.g., tank level measurements) that can be used to detect direct losses.

It is important to note that the timescales commonly associated with material losses are much larger than timescales associated with transient analysis. The MSDR dynamic model used to generate process outputs from the scenarios above is simulated on the order of seconds where as the input parameters generated from SCALE and the loss itself is on the order of days. A simplifying assumption is made by injecting the final reactivity change at the end of the material loss as an instantaneous reactivity change in the MSDR dynamic model when it has reached steady state conditions. This reactivity insertion is continued for the duration of the dynamic model simulation period. While both the material loss induced reactivity change and the MSDR dynamic model inputs can be expressed as on the same timescale, doing so would require a significantly larger computational overhead as the MSDR dynamic model would need to be simulated over much longer periods of time. This simplification is not expected to have a significant impact on the work presented here, but further consideration is a target for future work.

Each scenario that is run using the MSDR dynamic model generates approximately 209 different features, not all of which would be directly observable. Unobservable signals are ignored and this work focuses attention on process monitoring signals from the primary and secondary loop such as temperatures and flows.

3.3 Algorithms

Truncating the MSDR dynamic model output to observable signals still results in a dataset that has 80 features. This dataset still retains a large number of features, which can be difficult to analyze and explore trends without secondary analytical tools. Principle component analysis (PCA) [9] is used in here to help reduce the dimensionality of the data from 80 to 2. Generally, PCA is a technique to project a high dimensionality dataset into a lower dimensionality by determining a new coordinate system where most of the variation in the data can still be described. PCA has some

test	**Initiation Scenarios**		
Scenario	**Initiation (years)**	**Duration (days)**	**Reactivity (pcm)**
1	t_0	t_1	-253.989
2	$5t_0$	t_1	-4.937
3	$10t_0$	t_1	20.256
4	$20t_0$	t_1	34.887
5	$25t_0$	t_1	28.727
Duration Scenarios			
6	$10t_0$	t_1	20.251
7	$10t_0$	$2t_1$	21.324
8	$10t_0$	$4t_1$	16.496
9	$10t_0$	$6t_1$	10.626

Table 1: Summary table of material loss scenarios.

limitations in that it is a linear transformation and cannot capture more complex non-linear relationships, but is still appropriate for this exploratory analysis.

Off-normal conditions that occur as a result of material loss will likely not be known a priori for any proposed advanced nuclear facility. Therefore, when PCA is used in this work, it is only fitted on the normal baseline dataset without knowledge of the most important features to use for describing changes induced by material loss.

4 Experimental Results

The results are divided into two major sections: **Section 4.1** shows the results based on the starting time of the material loss scenario, and **Section 4.2** shows the results based on the length of the material loss scenario.

4.1 Initiation Scenarios

The MSDR fuel salt composition evolves over time, which could impact the reactor response to a material loss. Several material losses with different initiation times ranging from a salt irradiation time of t_0 years up to a irradiation time of $25t_0$ years are considered. Previous work has shown that material losses that occur at higher salt irradiation have a lower probability of detection when traditional statistical tools for material accountancy are used. Process-based signals generated by the MSDR dynamic model behave in a similar manner; later initiation times (i.e., higher salt burnups) generally result in smaller system changes. Figure 3 below shows the baseline scenario (i.e., no loss case) and different initiation times embedded into a reduced space using PCA. Points closer to the baseline indicate a smaller overall system change than points further away.

The deviations from normal operating conditions in the reduced space, shown in Figure 3, directly correspond to the magnitude and sign of the injected reactivity change described in Table 1. This is expected as reactivity insertions cause temperature transients from the nominal state to a new state. This is clearly observable when examining a single scenario in the reduced space. For example, consider the loss initiated at a $10t_0$ year salt lifetime, which is projected into the reduce space in Figure 4 below. The initial state starts at roughly (0,0) in the reduced space and transitions to a new, non-zero coordinate state at the end of the loss.

Although initiation time of the loss has an impact on the overall change in the system, all cases showed some change from the baseline. The change in observable signals is not a linear function of salt lifetime, as is the case with traditional statistics for material accountancy. For example, the changes induced with loss initiation times of $10t_0$, $20t_0$, and $25t_0$ years are comparable to each other, but are between year t_0 and year $5t_0$ initiation times. Year $5t_0$ actually shows the

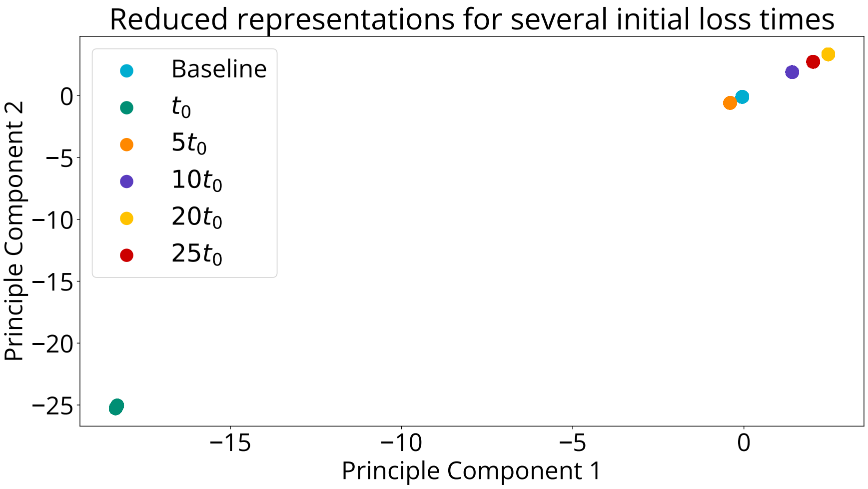

Figure 3: PCA embedding of MSDR dynamic model outputs under material loss for different initiation times.

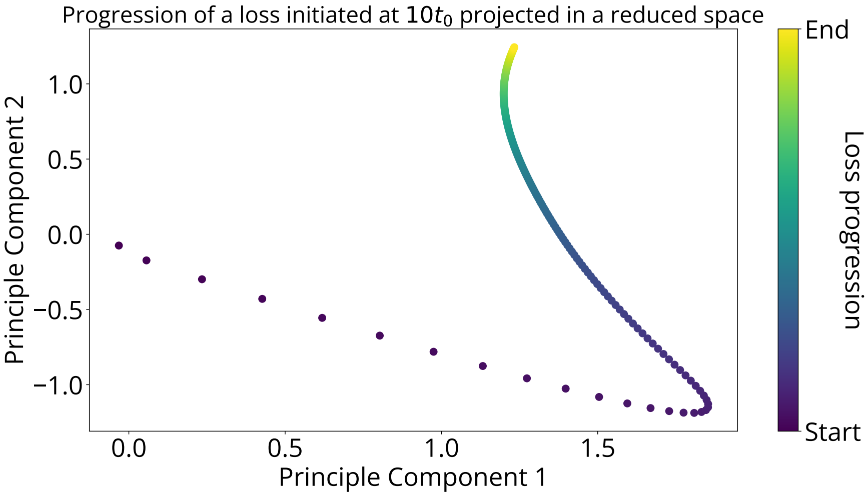

Figure 4: Progression of the MSDR state from a normal state to off-normal state during a loss-induced reactivity insertion.

smallest state change of any loss that is considered. This occurs as a result of neutron spectrum hardening that occurs as the fuel salt ages and the material addition assumed for a substitution loss.

4.2 Duration Scenarios

Increasingly protracted material losses have been difficult to detect for traditional material accountancy strategies due to statistical limitations. Therefore, it is important to consider increasingly protracted losses for a proposed process-based method to augment MC&A for MSRs. Here, the loss initiation time is fixed at $10t_0$ years and only the loss duration is varied. As shown in Figure 5 below, increasingly protracted losses also induce generally smaller system responses.

5 Discussion

All scenarios considered in this work induce a detectable change in system state. Figure 6 shows the system responses for most scenarios that are considered (scenario 1 omitted due to large scale of state change) divided by scenario type. All scenarios exhibit similar state transition paths regardless of material loss rate and initiation time. Later initiation scenarios have similar magnitude state changes, although earlier scenarios have a negative state change path owing to the negative reactivity insertion. Increased duration, which results in a reduced flow of material removed, generally

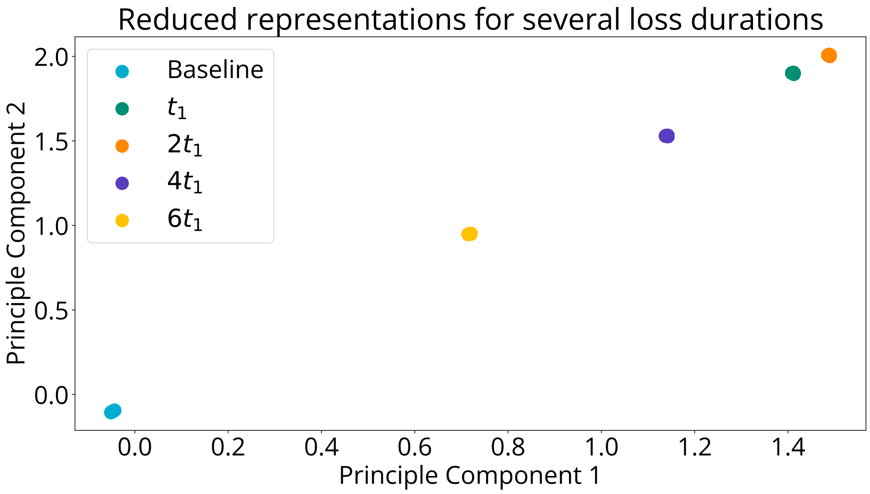

Figure 5: Dynamic MSDR signals simulated with increasingly protracted losses embedded into a reduced space.

results in a smaller state change. Similar to traditional accountancy, process based changes will be more difficult to detect for increasingly protracted losses.

This work considers many observable signals, however, monitoring a few key signals (e.g., reactivity and core temperatures) would likely be sufficient to capture these state changes. While a direct comparison between traditional accountancy and this process-based strategy is yet to be conducted, there are several potential weaknesses in this new approach that are already readily apparent. First, the MSDR dynamic model does not capture normal process variation or measurement error. This can make it difficult to assess a level of detectability for the transitions shown in Figure 6 as it is reasonable to assume state transitions below some threshold are undetectable.

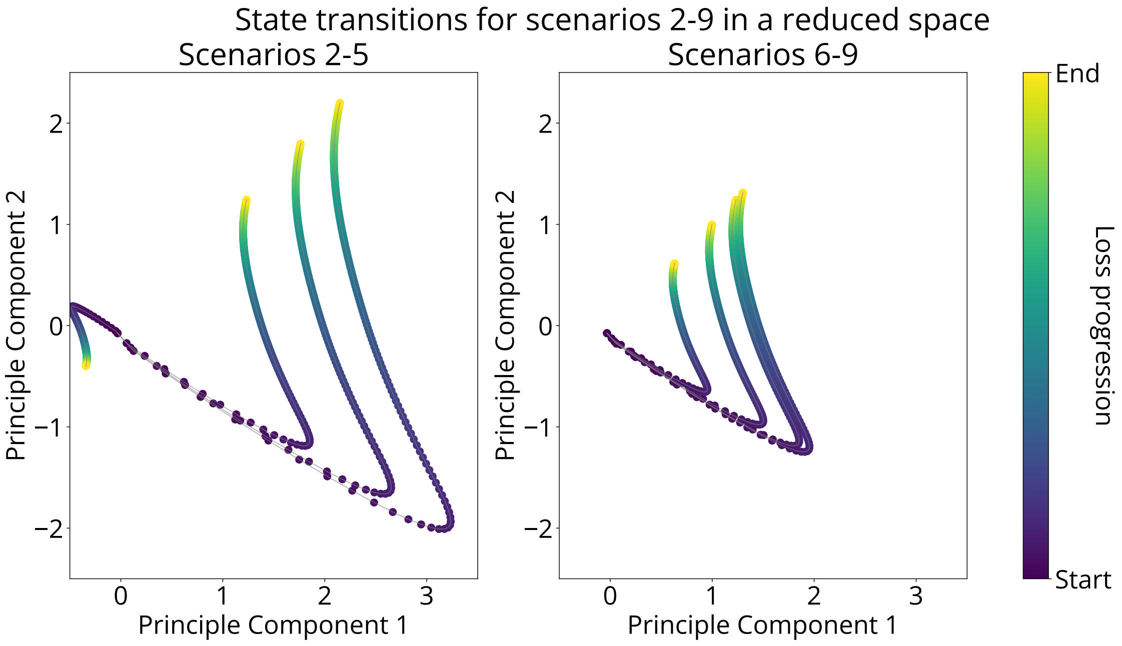

Figure 6: Response of MSDR dynamic model for a variety of material loss durations and initiation times embedded into a reduced space.

Second, as a result of substitution material insertion and neutron spectrum hardening, the loss-induced reactivity changes sign from negative to positive. Although the exact point is not quantified in this work, this implies that there is a loss initiation time wherein the loss-induced reactivity is zero, which would result in no state change. There could also be an entire “dead-zone” region where certain combinations of loss rates and initiation times result in a zero reactivity change. As this is a serious potential vulnerability and is a target for future work.

Finally, changes in state might not be unique to material loss as there are external events, both intended and unattended, that could impact the normal operational state. For example, some MSR designs could be designed with load-following in mind, which would involve state changes. Safety accidents, both large and small, could also result in state changes. A process monitoring based system would need to discriminate between state changes induced by material loss and other conditions mentioned above.

6 Conclusion

This work provides a preliminary analysis that considers the change in state of the MSDR that is induced by various material losses. More protracted material losses and losses initiated at higher salt burnups generally result in smaller state changes. No loss scenarios considered resulted in no state change, however, this could be a result of model simplifications (e.g., lack of process variation and measurement error). Experiments varying the loss initiation time suggests that there is at least one material loss that would result in no state change. Future work will consider:

1. A direction comparison between loss-induced state changes and traditional material accountancy
2. The potential “dead-zones” wherein certain combinations of loss initiation times and loss rates result in zero state change
3. Working with industry partners to estimate expected variation in key signals during normal operation

The state change monitoring described in this work could play an important role in a performance-based MC&A strategy for liquid-fueled MSRs, which prior work has shown will be difficult to monitor using material accountancy alone.

7 Acknowledgements

This work was funded by the Department of Energy Office of Nuclear Energy’s Advanced Reactor Safeguards program. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

References

[1] N. Shoman and M. Higgins, “Fy21 final report on molten salt reactor safeguards modeling,” *SAND Report*, vol. SAND2021-10928R, 2021.

[2] N. Shoman and M. Higgins, “Fy22 final report on molten salt reactor safeguards modeling,” *SAND Report*, vol. SAND2022-11048O, 2022.

[3] W. A. Wieselquist, R. A. Lefebvre, and M. A. Jessee, “Scale code system,” tech. rep., Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States), 2020.

[4] V. Pathirana, O. Chvala, and S. Skutnik, “Depletion dependency of molten salt reactor dynamics,” *Annals of Nuclear Energy*, vol. 168, p. 108852, 2022.

[5] B. R. Betzler, J. J. Powers, and A. Worrall, “Fuel cycle and neutronic performance of a spectral shift molten salt reactor design,” *Annals of Nuclear Energy*, 2017.

[6] B. R. Betzler, S. Robertson, E. E. D. (nee Sunny), J. J. Powers, A. Worrall, L. Drewan, and M. Massie, “Fuel cycle and neutronic performance of a spectral shift molten salt reactor design,” *Annals of Nuclear Energy*, 2018.

[7] P. Jr Vicente Valdez, B. R. Betzler, W. Wieselquist, and M. Fratoni, “Modeling molten salt reactor fission product removal with scale,” 3 2020.

[8] J. W. Bae, B. R. Betzler, and A. Worrall, “Molten salt reactor neutronic and fuel cycle sensitivity and uncertainty analysis,” 11 2019.

[9] I. T. Jolliffe, *Principal Component Analysis and Factor Analysis*, pp. 115–128. New York, NY: Springer New York, 1986.

[10] T. Speed and D. Culpin, “The role of statistics in nuclear materials accounting: issues and problems,” *Journal of the Royal Statistical Society: Series A (General)*, vol. 149, no. 4, pp. 281–300, 1986.

[11] A. S. Goldman, R. R. Picard, and J. P. Shipley, "Statistical methods for nuclear materials safeguards: an overview," *Technometrics*, vol. 24, no. 4, pp. 267–274, 1982.

[12] A. Goldman, R. Picard, and J. Shipley, "Statistical methods for nuclear materials safeguards: An overview," *Technometrics*, vol. 24, no. 4, pp. 267–275, 1982.

[13] J. Doyle, *Nuclear safeguards, security and nonproliferation*. Oxford, England: Butterworth-Heinemann, Jun 2008.

[14] B. Jones, "Near real time material accountancy using SITMUF and a joint page's test: comparison with MUF and CUMUF tests," 1988.

[15] B. Jones, "Calculation of diversion detection using the sitmuf sequence and page's test: application to evaluation of facility designs," in *Proceedings of the 7th ESARDA Symposium on Safeguards and Nuclear Material Management*, 1985.

[16] B. Jones, "Calculation of diversion detection using the sitmuf sequence and page's test," in *Nuclear safeguards technology 1986*, 1987.

[17] B. Jones, "Comparison of near real time materials accountancy using sitmuf and page's test with conventional accountancy," in *Proceedings of the 9th ESARDA Symposium on Safeguards and Nuclear Material Management*, 1987.

[18] B. Jones, "Near real time materials accountancy using sitmuf and a joint pages test: improvement of the test," *ESARDA Bulletin*, vol. 16, pp. 13–19, 1989.

[19] E. S. Page, "Continuous inspection schemes," *Biometrika*, June 1954.

[20] T. Burr and M. S. Hamada, "Revisiting statistical aspects of nuclear material accounting," *Science and Technology of Nuclear Installations*, March 2013.

[21] R. Seifert, *The GEMUF test: A new sequential test for detecting loss of material in a sequence of accounting periods*. IAEA, 1987.

[22] J. M. Cavaluzzi and P. W. Gibbs, "Safeguards inventory and process monitoring regulatory comparison," 6 2013.

[23] B. B. Cipiti, "Process monitoring considerations for reprocessing.," 6 2015.

[24] B. B. Cipiti and O. R. Zinaman, "The integration of process monitoring for safeguards.," 9 2010.

[25] T. Burr, M. S. Hamada, L. Ticknor, and J. Sprinkle, "Hybrid statistical testing for nuclear material accounting data and/or process monitoring data in nuclear safeguards," *Energies*, vol. 8, no. 1, pp. 501–528, 2015.

[26] C. R. Orton, S. A. Bryan, J. M. Schwantes, T. G. Levitskaia, C. G. Fraga, and S. M. Peper, "Advanced process monitoring techniques for safeguarding reprocessing facilities," 11 2010.

[27] N. Shoman, J. Coble, and D. Meier, "Experimental performance of the multi isotop process monitor," in *Transactions of the American Nuclear Society*, vol. 113, pp. 483–485, 2015.

[28] J. Coble and D. Meier, "Monitoring aqueous reprocessing systems for detection of facility misuse," *IEEE Transactions on Nuclear Science*, vol. 66, 2 2019.

[29] N. Shoman and T. Burr, "Impact of safeguards measurement errors on deep neural networks.," 8 2021.

[30] N. Shoman, B. Cipiti, T. Grimes, B. Wilson, and R. Gladen, "Insights from applied machine learning for safeguarding a purex reprocessing facility.," 8 2021.

[31] N. Shoman, P. Honnold, and B. Cipiti, "Pattern and motif recognition for improved enrichment safeguards," *SAND Report*, vol. SAND2021-11235, 2021.

[32] R. Gladen, T. Grimes, B. Wilson, J. Dermigny, B. B. Cipiti, and N. Shoman, "Neural assessment of non-destructive assay for material accountancy," in *Annual Meeting Proceedings of the Institute of Nuclear Material Management*, 2021.

[33] N. Shoman and P. Honnold, "Limitations for data-driven safeguards at enrichment facilities," in *Annual Meeting Proceedings of the Institute of Nuclear Material Management*, 2022.

[34] T. Burr, M. Hamada, M. Skurikhin, and B. Weaver, "Pattern recognition options to combine process monitoring and material accounting data in nuclear safeguards," *Statistics Research Letters*, vol. 1, no. 1, pp. 6–31, 2012.

[35] H. Garcia, W.-C. Lin, and R. Carlson, "Evaluating safeguards benefits of process monitoring as compared with nuclear material accountancy," 7 2014.

[36] H. E. Garcia, "Integrated process monitoring based on systems of sensors for enhanced nuclear safeguards sensitivity and robustness," 7 2014.

[37] T. L. BURR, C. A. COULTER, J. HOWELL, and L. E. WANGEN, "Solution monitoring: Quantitative and qualitative benefits to nuclear safeguards," *Journal of Nuclear Science and Technology*, vol. 40, no. 4, pp. 256–263, 2003.

[38] J. Leppänen, *Serpent: a Continuous-energy Monte CarloReactor Physics Burnup Calculation Code*, 18 ed., June 2015.

[39] A. Rykhlevskii, J. W. Bae, and K. D. Huff, "Modeling and simulation of online reprocessing in the thorium-fueled molten salt breeder reactor," *Annals of Nuclear Energy*, vol. 128, pp. 366–379, 2019.

[40] L. Seifert, A. Wheeler, and O. Chvála, "Material flows and on-line reprocessing in serpent," November 2021.

[41] M. S. Greenwood, B. R. Betzler, A. L. Qualls, J. Yoo, and C. Rabiti, "Demonstration of the advanced dynamic system modeling tool transform in a molten salt reactor application via a model of the molten salt demonstration reactor," *Nuclear Technology*, vol. 206, no. 3, pp. 478–504, 2020.

[42] N. J. Dunkle, "Dynamic modeling of thermal spectrum molten salt reactors," 2022.

[43] A. V. Soares, B. Kovacevic, A. Johnsen, A. Lintereur, B. Betzler, M. Dion, N. Shoman, and W. Walters, "The impact of nuclear data uncertainty on identifying plutonium diversion in liquid-fueled molten salt reactors," *Nuclear Physics B*, 2022 (in-press).

[44] B. Kovacevi, A. V. Soares, A. Lintereur, W. Walters, and A. Johnsen, "Gamma-ray signatures for identifying plutonium diversion in molten salt reactors," *Nuclear Physics B*, 2022 (in-press).

[45] 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*, September 2021.

[46] M. P. Dion and K. K. Hogue, "Domestic mc&a recommendations for liquid-fueled msrs," *ORNL/SPR-2022/2673*, September 2022.

[47] E. S. Bettis, L. Alexander, and H. L. Watts, "Design studies of a molten-salt reactor demonstration plant," *ORNL-TM-3832*, June 1972.

[48] B. R. Betzler, S. Robertson, E. E. Davidson (née Sunny), J. J. Powers, A. Worrall, L. Dewan, and M. Massie, "Fuel cycle and neutronic performance of a spectral shift molten salt reactor design," *Annals of Nuclear Energy*, vol. 119, pp. 396–410, 2018.