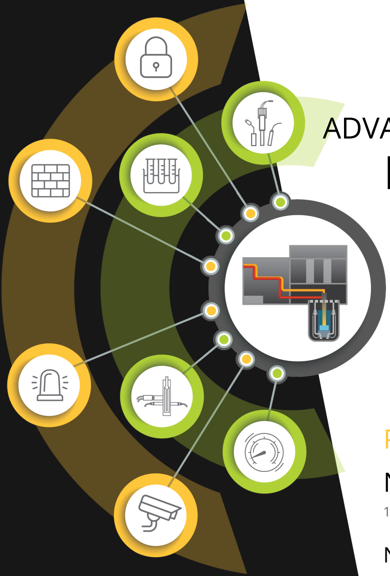
ADVANCED REACTOR SAFEGUARDS

MSR Safeguards Modeling

FY23 Status Update



Presented by:

Nathan Shoman[1]

[1]Sandia National Laboratories

November 2, 2023

Contact: nshoman@sandia.gov

SAND NO. 2023-11902PE

Unique MSR features necessitate NMA strategies that differ from LWRs

MSRs:

- Fuel is in bulk form
- Constant feed and removals
- Constant depletion and decay
- Salt volume estimation
- Potentially heterogeneous samples
- Strong radioactive source terms

Conventional Nuclear:

- Fuel is in discrete items
- No feeds and removals outside of outages
- Many fuel assemblies with potentially different burnup and enrichment
- Factors that impact burnup well characterized (axial and radial effects)
- Have methods to ensure spent fuel is present when too hot to measure (i.e. Cherenkov)

Material balances are key NMA components at bulk facilities

- Material balance (MB) is used to quantify nuclear material for accountancy
- Sometimes called Inventory Difference (ID) or Material Unaccounted For (MUF)
- Basis for more complex statistical tests
- Since liquid-fueled MSRs have bulk fissile material, bulk techniques are appropriate

MB calculation

$$MB_t = (\Sigma_{t-1}^{t} \text{inputs}) - (\Sigma_{t-1}^{t} \text{outputs}) - (\text{inventory}_{t-1} - \text{inventory}_t) \quad (1)$$

MB for MSRs can be formulated using time-differenced measured and observed values

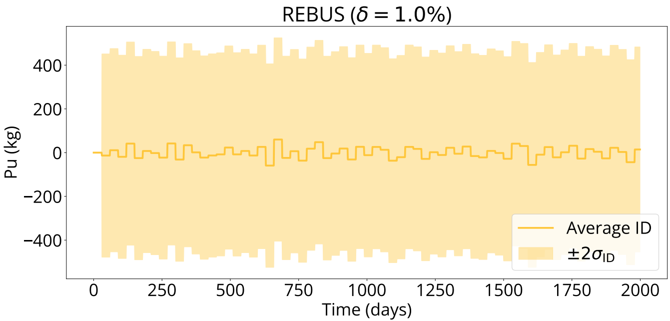
MSR material balance

$$\mathrm{MB}_t = \left(\sum_{i=1}^{n_\mathrm{I}} I_{i,t-1} + \cancelto{0}{\sum_{i=1}^{n_\mathrm{in}} Tin_{i,t}} - \cancelto{0}{\sum_{i=1}^{n_\mathrm{out}} Tout_{i,t}} \right) - \sum_{i=1}^{n_\mathrm{I}} I_{i,t} \tag{2}$$

$$\begin{aligned}\mathrm{MB}_t &= \left(I_{m,t} - I_{m,t-1} \right) - \left(I_{c,t} - I_{c,t-1} \right) \\ &= \left(C_{m,t}B_t - C_{m,t-1}B_{t-1} \right) - \left(C_{c,t}B_t - C_{c,t-1}B_{t-1} \right)\end{aligned}$$

Where $I_{m,t}$ is the measured quantity and $I_{c,t}$ is the calculated quantity, terms C and B refer to the concentration and bulk measurement respectively.

Bulk material balances are never zero



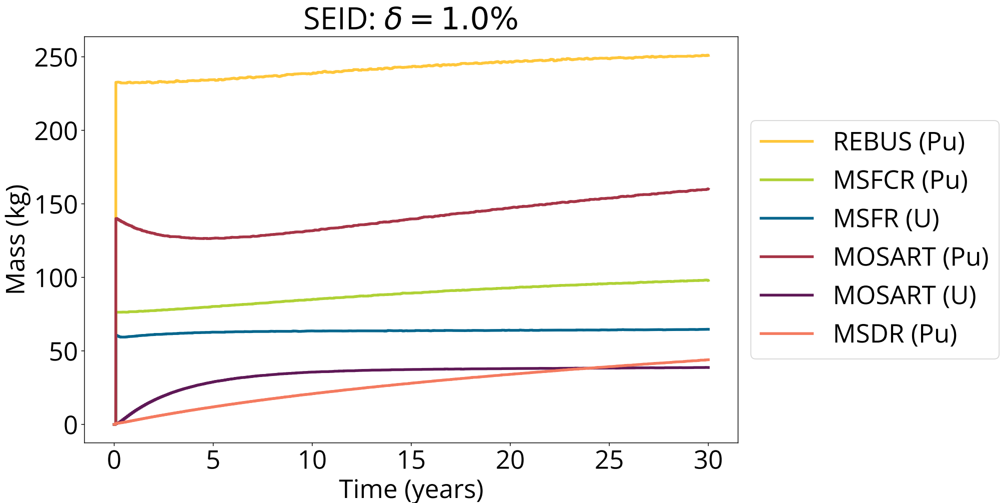
Measurements are never perfect

Measurements are never perfect which lead to non-zero material balances. Consequently, the material balance uncertainty plays an role in the ability of techniques to detect potential material loss.

Prior work considered several different designs

MSR parameter summary					
Parameter	**MSDR**	**MOSART**	**REBUS**	**MSFR**	**MCSFR**
Th Pwr (MWth)	750	2400	3700	3000	6000
F Salt Comp (mol%)	LiF-BeF_2-ThF_4-UF_4 (71.5-16-12-0.5)	LiF-BeF_2-ThF_4-$TRUF_3$ (69.72-27.1.28)	NaCl + (0.711% ^{235}U + 16.7 at.% TRU)Cl_3 (55-45)	LiF-ThF_4-$^{233}UF_4$ (77.5-19.9-2.6)	NaCl-UCL_3-$^{239}PuCl_3$ (60-36-4)
F Feed	3.08%^{235}U	0.711%^{235}U + TRU	0.711%^{235}U	^{233}U + ^{232}Th	0.711% ^{235}U + Pu
F Mass (MTIHM)	121.0	28.83507	114.62944	43.33535	67.78803
B Salt Comp	-	-	-	LiF-ThF_4 (77.5-22.5)	NaCl-UCl_3 (60-40)
B Feed	-	-	-	^{232}Th	0.711% ^{235}U
B Mass (MTIHM)	-	-	-	17.57098	133.76272
Fuel Cycle	U/Pu	U/Pu+Th/U	U/Pu	Th/U	U/Pu
Spectrum	Thermal	Fast	Fast	Fast	Fast

Large inventories create material accountancy challenges

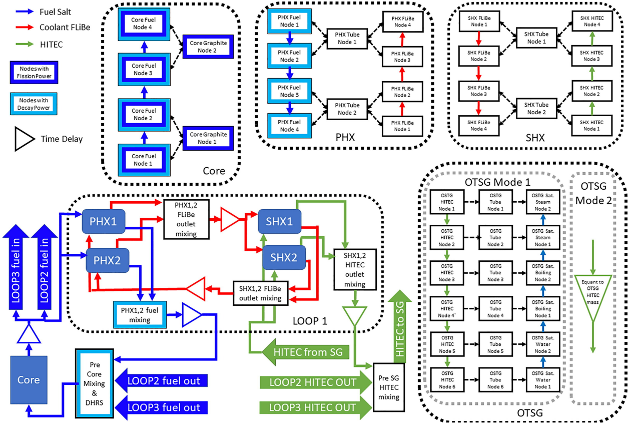


Could process signals be used to indicate signs of material loss?

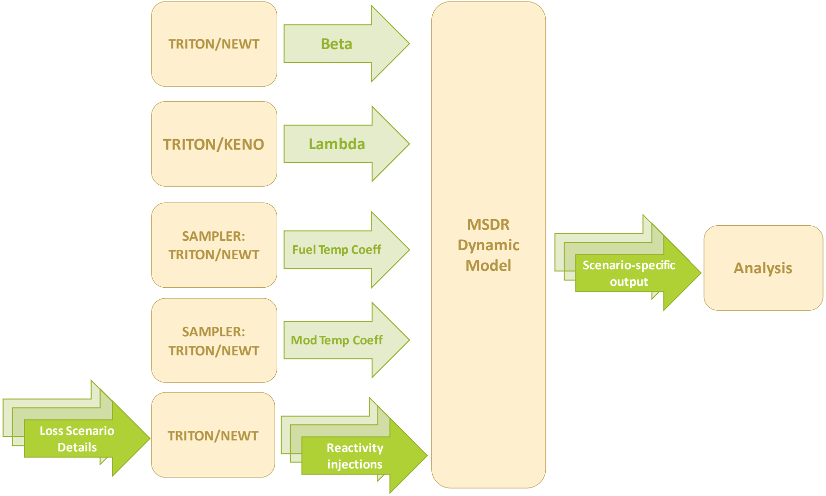
- Signals such as temperature, pressure, and flow must be monitored for operational purposes
- Material loss will likely have some impact on neutronics, and consequently, thermohydraulic parameters
- Build upon existing work considering novel strategies for improved MC&A of MSRs
  - Soares et al. (Impact of nuclear data uncertainty on detection probability)
  - Dunkle et al. (Feasibility for monitoring off-gas streams for material loss detection)
  - Kovacevic et al. (Potential gamma emitters that could indicate material loss)
  - Wheeler et al. (Sinusoidal reactivity insertion to monitor frequency response)

Using existing tools to improve analysis pipeline: MSDR dynamic model

- Process model is required to analyze process monitoring signals under material loss conditions
- Existing first order MSDR dynamic system based in MATLAB Simulink utilized (Pathirana et al. 2022)
  - Transient progression
  - Depletion dependency
  - Steam generator modeled
  - Utilizes modified point kinetics equation



Process-based response analysis requires several analytical steps



Overview of scenarios for process-based response analysis

- Scenarios divided into initiation time and duration
- Later losses generally decrease in reactivity
- Sign change in reactivity due to spectrum hardening
- Longer removals lead to smaller reactivity swings

Initiation Scenarios				
Scenario	**Initiation (years)**	**Duration (days)**	**Total removal (kg)**	**Reactivity (pcm)**
1	0.10x	y	8.748	-253.989
2	0.50x	y	8.315	-4.937
3	x	y	7.963	20.256
4	2x	y	8.168	34.887
5	2.5x	y	7.877	28.727

Duration Scenarios				
Scenario	**Initiation (years)**	**Duration (days)**	**Total removal (kg)**	**Reactivity (pcm)**
6	x	y	7.963	20.251
7	x	2y	7.950	21.324
8	x	4y	7.941	16.496
9	x	6y	8.038	10.626

Two approaches were utilized to analyze data

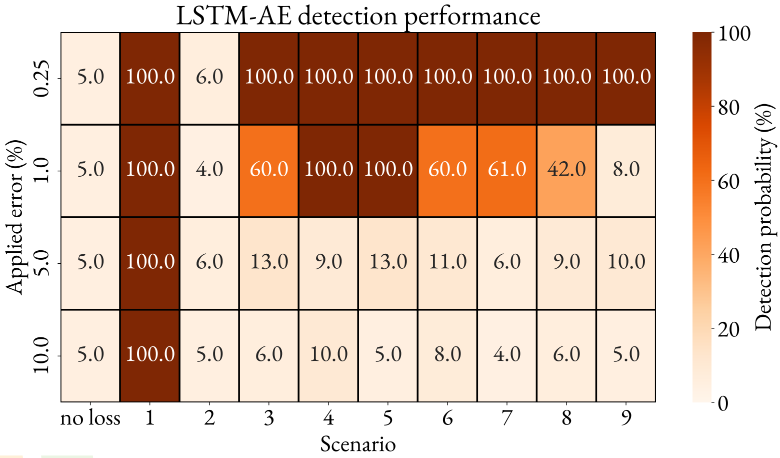
Parameterized model: Long short-term memory auto encoder

- Autoencoder neural network
- Trained on 83 features from dynamic model
- Should have low error on known patterns, high error on unknown/unseen patterns

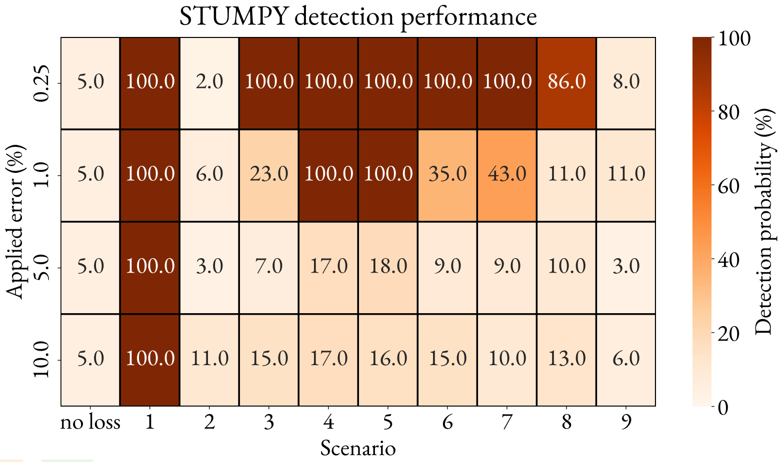
Non-parametrized model: Matrix profile

- Time-series motif matching
- Requires no training, works on streaming data if needed
- Rare behavior should have large amounts of time between events and low similarity

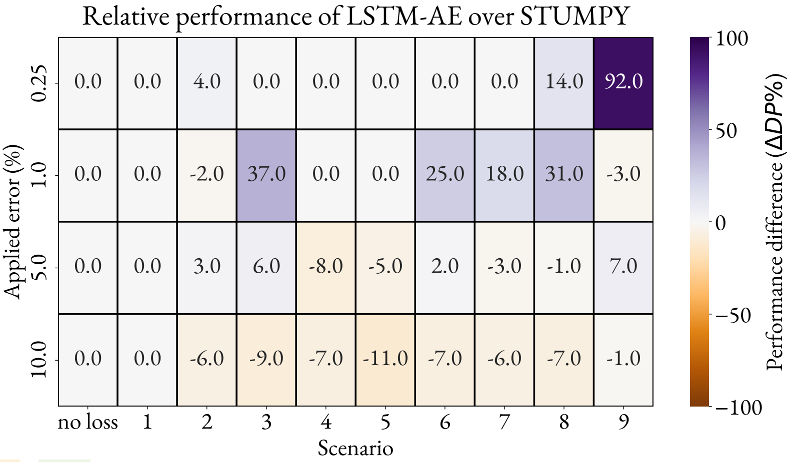
Parameterized model performs well at lower measurement uncertainities; result of overfitting



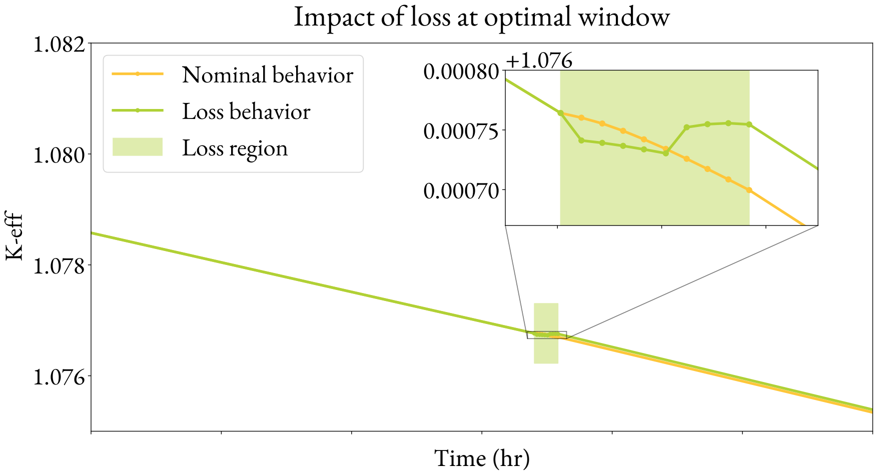
Non-Parameterized offers better generalized performance, but worse at lower uncertanities



Relative comparison highlights weakness of methodology; simple model signals



Reactor specific behavior can result in undetectable losses



Viability of approach is unclear; further tool development required

Opportunities

- Material losses do cause a reactivity swing
- Transitions from pre-loss and post-loss states are observable
- Existing signals likely monitored by operators can indicate material loss
  - Temperatures, reactivity, etc.

Challenges

- Existence of sign change in reactivity insertion implies the existence of a loss with no reactivity change
- Changes in process monitoring signals might not be unique to material loss
- Simplified model doesn't capture normal operational variation
  - How much change is expected under normal operation? Will a material loss exceed that variation?

Currently no technique to reliably detect loss of significant quantity in liquid-fueled MSRs with large fissile inventory

- SEID alone, even with conservative uncertainty estimates, is multiple times larger than a significant quantity
- Few fission product indicators are available to detect large losses of material
  - This holds true even when only considering a single uncertainty source at a time (e.g., nuclear data uncertainty or counting statistics)
- Neutronics-based techniques could be viable for relatively large losses of material
- Other process signals (e.g., temperature and pressure) might be viable at 1% measurement uncertainty levels
  - Full study points out several limitations that would need to be resolved before a conclusive evaluation could be undertaken
- Performance-based approach might be more effective for large, liquid-fueled MSRs
  - Consideration of radioactivity of fuel, fissile density, accessibility of area, etc.

Acknowledgements

This work was funded through the U.S. Department of Energy's Office of Nuclear Energy (DOE-NE), Advanced Reactor Safeguards and Security (ARSS) campaign.

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.