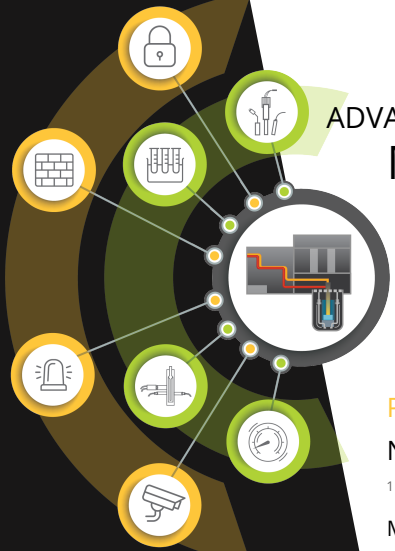

ADVANCED REACTOR SAFEGUARDS

MSR Safeguards Modeling

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Objective

Extend Nuclear Material Accountancy (NMA) concepts developed in FY22 for thermal spectrum MSRs to fast spectrum MSRs.

Key Questions

- How well does the previously developed material balance concept extend to fast reactors?
- Are there changes in the supporting reactor physics calculations that change the overall uncertainty?
- Is there an impact of having multiple fluids over a single fluid?

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
- Sometimes called Inventory Difference (ID) or Material Unaccounted For (MUF)
- Basis for more complex statistical tests

MB calculation

$$\mathrm{MB}_t = \left(\Sigma_{t-1}^{t}\,\mathrm{inputs}\right) - \left(\Sigma_{t-1}^{t}\,\mathrm{outputs}\right) - \left(\mathrm{inventory}_{t-1} - \mathrm{inventory}_t\right) \quad (1)$$

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

MSR material balance

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

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

Where $I_{m,t}$ is the measured quantity and $I_{c,t}$ is the calculated quantity.

Material balance can easily be extended to two fluid systems

- Assume single material balance area for reactor that includes both fluids
- Simply add terms for both primary and secondary salts
- No shared covariance as salts are independent
- Feeds and removals explicitly accounted for in calculated quantities
  - Feeds and removals also reflected in measured quantities
- MB should be zero for the no loss case

MSR material balance for two fluids

$$\begin{aligned} \mathrm{MB}_t = &\left(I_{mp,t} - I_{mp,t-1} \right) - \left(I_{cp,t} - I_{cp,t-1} \right) \\ &+ \left(I_{ms,t} - I_{ms,t-1} \right) - \left(I_{cs,t} - I_{cs,t-1} \right) \end{aligned} \tag{3}$$

Multiple exemplar designs modeled in SCALE

Parameter	MOSART	MCSFR	MSFR	REBUS
Thermal Power, MW	2400	6000	3000	3700
Fuel Salt Initial Comp	$LiF\text{-}BeF_2\text{-}ThF_4\text{-}TRUF_3$	$NaCl\text{-}UCl_3\text{-}^{239}PuCl_3$	$LiF\text{-}ThF_4\text{-}^{233}UF_4$	$NaCl\text{-}UCl_3\text{-}TRUCl_3$
Fertile Salt Initial Comp	-	$NaCl\text{-}UCl_3$	$LiF\text{-}ThF_4$	-
Fuel Cycle	$Th/^{233}U$	U/Pu	$Th/^{233}U$	U/TRU
Initial Inventory, t	9.637	9.400	7.726	18.061

Modeling methodology

- Started with templated developed by Rykhlevskii and Betzler
  - Unit cells used to approximate full core behavior
  - Controlled fuel-to-fertile salt ratio, k_{eff}, and neutron spectrum
- Added and/or tuned feed and removal rates to achieve proper inventory and reactivity

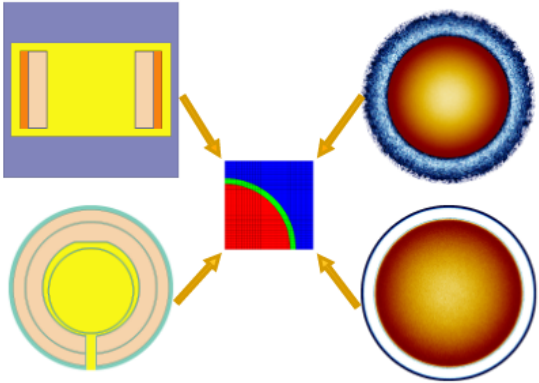


Figure: Fuel Cycle Performance of Fast Spectrum Molten Salt Reactor Designs, credit: Rykhlevskii, et al. (2019)

Uncertainty analysis

- Measurement error will be informed by specific measurement technology
- Assume best case scenario computationally
  - Sources of uncertainty only arising from nuclear data
  - Neglect uncertainty due to imperfect knowledge of modeling parameters (e.g., temperatures, current inventories, etc)
- Used SCALE/Sampler routine to understand computational uncertainty lower bounds

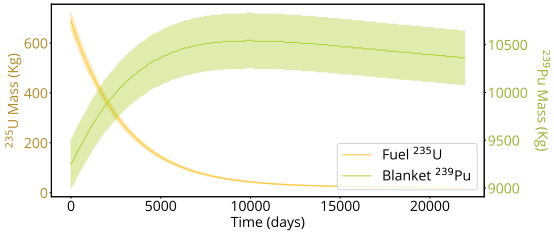
Importance of uncertainty

Increased uncertainty leads to greater uncertainty in the material balance. This results in a lower probability of detection for a fixed material loss.

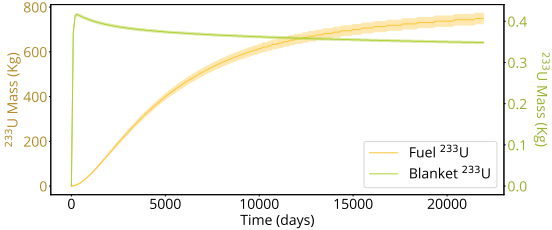
Preliminary uncertainty data

- Overall uncertainty dependent on total inventory and reactor design
- Most designs tuned for level inventories, but equilibrium values can change based from design to design

Simulated inventory evolution of REBUS



Simulated inventory evolution of the MSFR



Ongoing work

Remaining tasks

- Completing uncertainty analysis
- Performing material balance evaluations
- Conducting notional material loss scenarios
- Comparison of different design choices
  - Single vs multiple salt streams
  - Fuel cycle choices

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