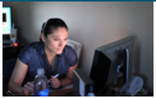
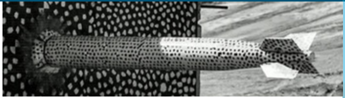
MSR Safeguards Modeling





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Objective

Explore traditional safeguards methods for molten salt reactors (MSRs) and determine limits imposed by measurement and computational uncertainties.

Key Questions

- Are traditional safeguards approaches used for large throughput facilities effective for MSRs?
- What is the lower limit of detector performance (statistical) that is required to hit future regulatory targets?
- Are novel approaches required to safeguard MSRs?

Traditional Safeguards Principles

Traditional safeguards that attempt to directly quantify actinides of interest require several key properties:

- Establishment of material balance areas
- Periodic material balance calculation
- Statistical tests and transforms for detection of material loss
- Low uncertainty measurements

Unique MSR Challenges

MSRs:

- Fuel is in bulk form
  - Will likely require near real time accounting (NRTA) principals
- Constant feed and removals
- Constant depletion and decay
  - Is inventory loss due to nuclear losses or adversarial theft?
  - Requires incorporation of burnup calculations for material accountancy
- Salt volume estimation
  - Salt concentration from NDA or DA will be combined with salt volume estimate for total actinide inventory

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)

Inventory Difference (ID) calculation

ID calculation

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

- Fresh fuel salt from online refueling
- Continuous removal (FP, noble metals)
- **Nuclear gains**
- **Nuclear losses**
- **Current MSR inventory**

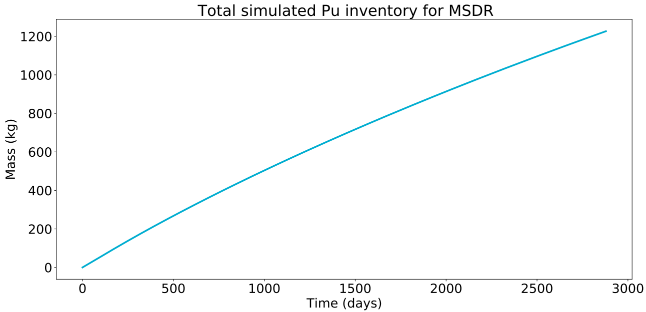
Use case: Molten Salt Demonstration Reactor (MSDR)

Wide range of MSR designs creates the need for a reference design with common MSR features. MSDR was designated by ORNL as a baseline design for this purpose.

- 750 MW_{TH} / 350 MW_e
- LiF - U fuel salt - 5% enriched
- Continuous fission product gas removal
- Continous removal of some noble metals
- Continuous feed of LEU
  - Flow optimized to maintain ^{238}U inventory
- Salt lifetime assumed to be eight years

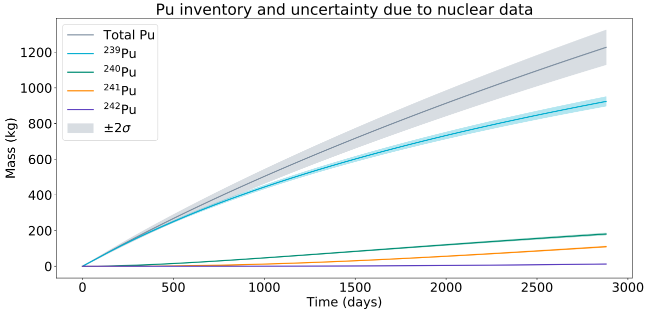
General observations: inventory growth

- Total plutonium inventory grows over time
- Equilibrium not reached within salt lifetime
- Static safeguards criteria present challenges
    - Normal metrics for beginning-of-life result in impossible targets for end-of-life (low thresholds)
    - Normal metrics for end-of-life result in poor targets for beginning-of-life (high thresholds)
- Need safeguards criteria that change with time?



Uncertainty in isotopic prediction due to nuclear data

- Uncertainties for individual Pu isotopes are relatively small
  - Maximum of 3% for ^{242}Pu
  - Minimum of 1.12% for ^{239}Pu
  - Depends on isotope and burnup
  - Independently confirmed via work from PSU
- Combined (total Pu) uncertainty can be more sizable at end of cycle at $\approx 4\%$.



Constructing the MSDR material balance

- Inputs and outputs should be zero for the Pu material balance (MB)
  - Continuous feed (input) only applies to U
  - Continuous removal (output) only applies to FP and noble metals
- Assume periodic measurements of concentration and salt mass are possible
- Assume reasonable ability to measure reactor conditions to enable good depletion estimates

MSDR ID calculation

$$\mathrm{ID}_t = \mathrm{inventory}_{\mathrm{measured},t} - \mathrm{inventory}_{\mathrm{calculated},t} \tag{2}$$

Follows the usual ID conventions that ID should be zero and that ID deviations from 0 should be caused by measurement and/or calculation error. Even when restarting burnup calculations to account for different reactor conditions this approach should capture loss (i.e. a mean shift in ID will still occur).

MSDR MB - bulk mass

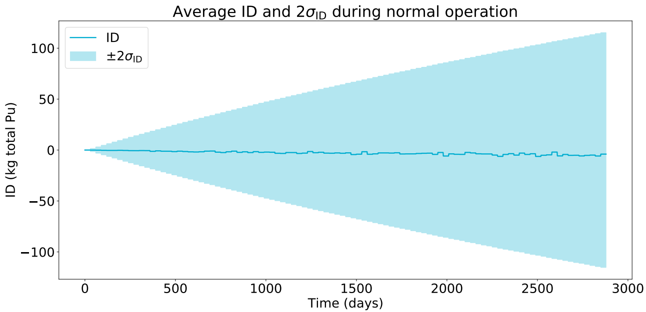
Calculation of the MSDR material balance will require two measurements; a concentration measurement derived from DA/NDA and a bulk salt estimate.

MSDR ID calculation with salt estimate

$$\begin{aligned} ID_t &= \text{inventory}_{\text{measured},t} - \text{inventory}_{\text{calculated},t} \\ ID_t &= \hat{M}_{\text{salt}}(\hat{C}_{\text{meas}} - \hat{C}_{\text{calc}}) \end{aligned} \quad (3)$$

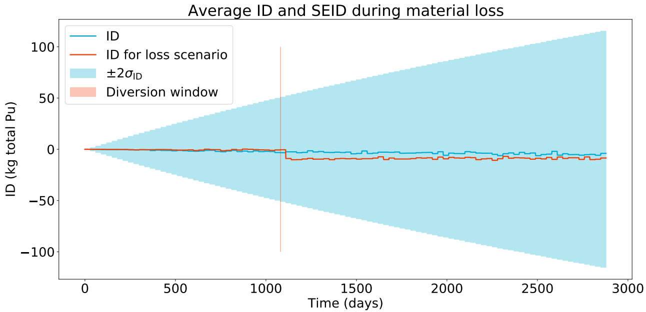
MSDR material balance under normal operation

- SEID (standard error of inventory difference, σ_{ID}) is significant, particularly at end of salt life
  - Assumed 30 day balance period (no impact on SEID due to ID formulation)
  - Assumes $\approx 4\%$ uncertainty in calculated concentrations from burnup calculation
  - Assumes $\approx 1\%$ uncertainty (R,S) in measured concentrations
  - Assume $\approx 1\%$ uncertainty (R,S) in measured salt mass

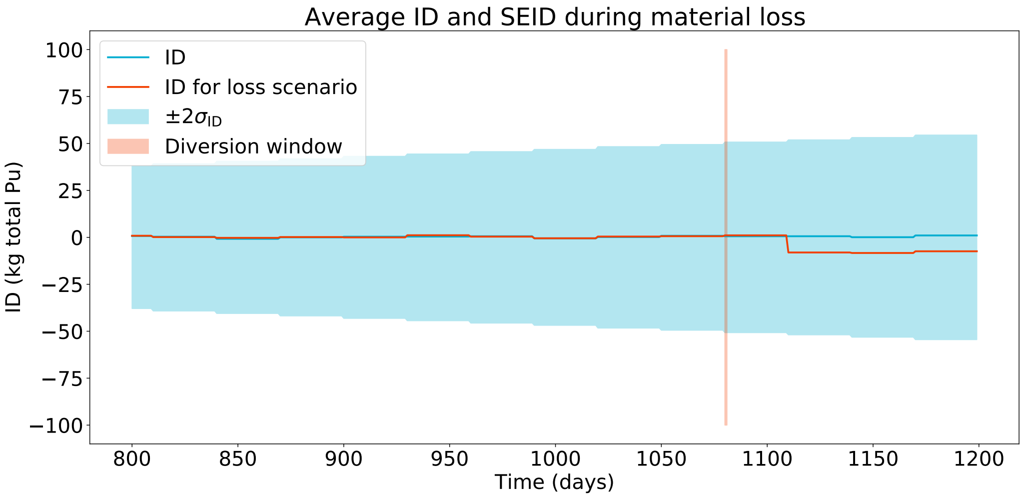


MSDR material balance under loss conditions

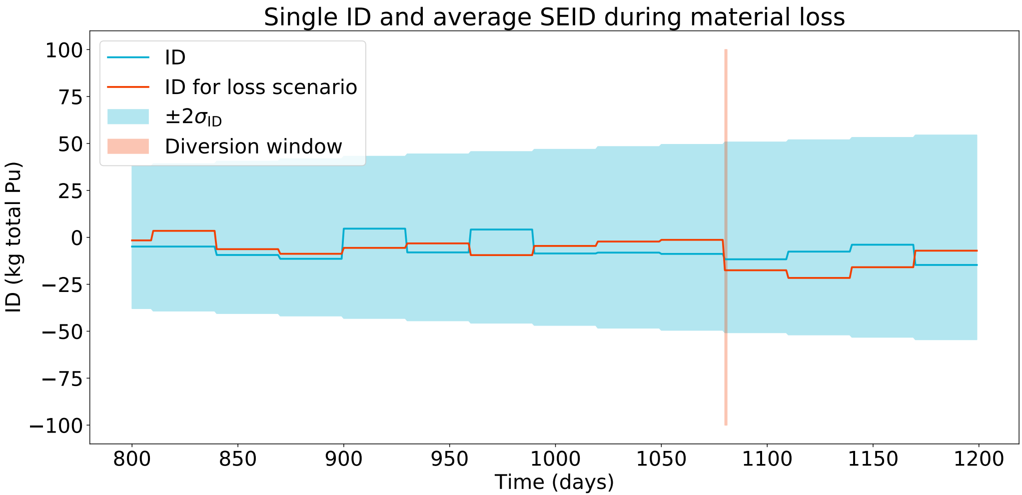
- Material loss not easily detected via ID
- Loss of $\approx$ 1SQ $<<$ SEID
- Large inventory of Pu implies small fraction of material needed to obtain 1SQ



MSDR (average) material balance under loss conditions

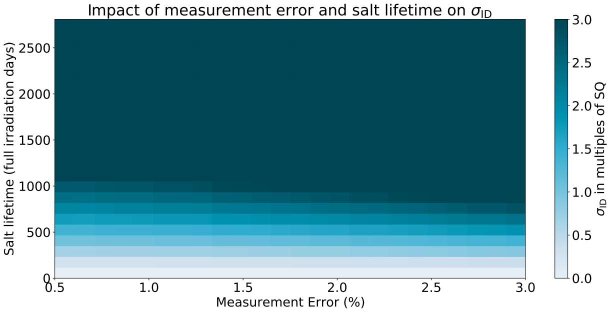


MSDR material balance (single run) under loss conditions



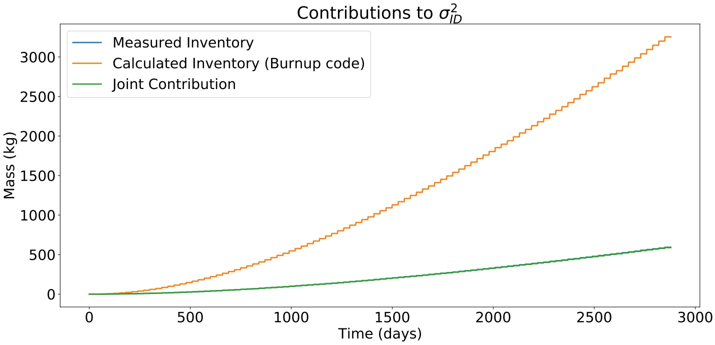
SEID vs measurement uncertainty

- Decreased measurement error doesn't buy much
  - Pu inventory is large
  - Lower uncertainty just buys more time before SEID is $>$ 3SQ
- Even destructive assay level errors will eventually lead to SEID $>>$ 3SQ
- Generously assumes computational error for estimated inventory only due to σ in nuclear data
  - Full knowledge of reactor state unlikely
  - Likely a few extra % of uncertainty due to model assumptions and simplifications



SEID error contribution

- Calculated inventory is dominant contributor to inventory error
- Computational uncertainty set conservatively (lower bound is nuclear data uncertainty at 4%)
- DA-level measurements may not represent a significant improvement in the inventory difference



FY22 outlook

- Strategies for improving the MB
  - Improved burnup tools and UQ
  - Novel strategies for designing the MB
  - Operational activities that could improve actinide quantification
- Strategies that do not rely on direct quantification and the MB
  - Increased containment and surveillance
  - Use of process monitoring measurements
  - Data science based methods
    - Unsupervised machine learning
    - Pattern recognition

Conclusions*, so far

- SEID is large
- Improving measurements will only improve statistics to some degree
- Uncertainty arising from computational sources (i.e. burnup calculations) remains challenging
- Alternative strategies to the material balance might be needed to implement effective safeguards
  - Credit for self-protecting nature of the material
  - Integration with process monitoring
  - Increased reliance on containment and surveillance

*Analysis presented here only considers a specific case of a thermal MSR with LEU-type fuel. Different designs and fuel cycles may have different conclusions.