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 estimate
- **Potentially heterogeneous samples**
- **Strong radioactive source terms**
  - Creates challenges when carrying out measurement

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**

\[ ID_t = (\sum_{t-1}^{t} \text{inputs}) - (\sum_{t-1}^{t} \text{outputs}) - (\text{inventory}_{t-1} - \text{inventory}_t) \]  

- 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
- Continuous 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**

\[ ID_t = \text{inventory}_{\text{measured}, t} - \text{inventory}_{\text{calculated}, t} \]  \hspace{1cm} (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**

\[
ID_t = \text{inventory}_{\text{measured},t} - \text{inventory}_{\text{calculated},t}
\]

\[
ID_t = \hat{M}_{\text{salt}}(\hat{C}_{\text{meas}} - \hat{C}_{\text{calc}})
\]
MSDR material balance under normal operation

- SEID (standard error of inventory difference, $\sigma_{ID}$) 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 \( \approx 1SQ \ll SEID \)
- Large inventory of Pu implies small fraction of material needed to obtain 1SQ
MSDR (average) material balance under loss conditions

Average ID and SEID during material loss

- ID
- ID for loss scenario
- \( \pm 2\sigma_{ID} \)
- Diversion window
MSDR material balance (single run) under loss conditions

Single ID and average SEID during material loss

- ID
- ID for loss scenario
- $\pm 2\sigma_{ID}$
- Diversion window
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 $\sigma$ 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.