OAK RIDGE National Laboratory

MC&A for MSRs

Michael Dion

dionmp@ornl.gov

Scott Greenwood, Karen Hogue, Sean O'Brien, Logan Scott, Steve Skutnik, Greg Westphal

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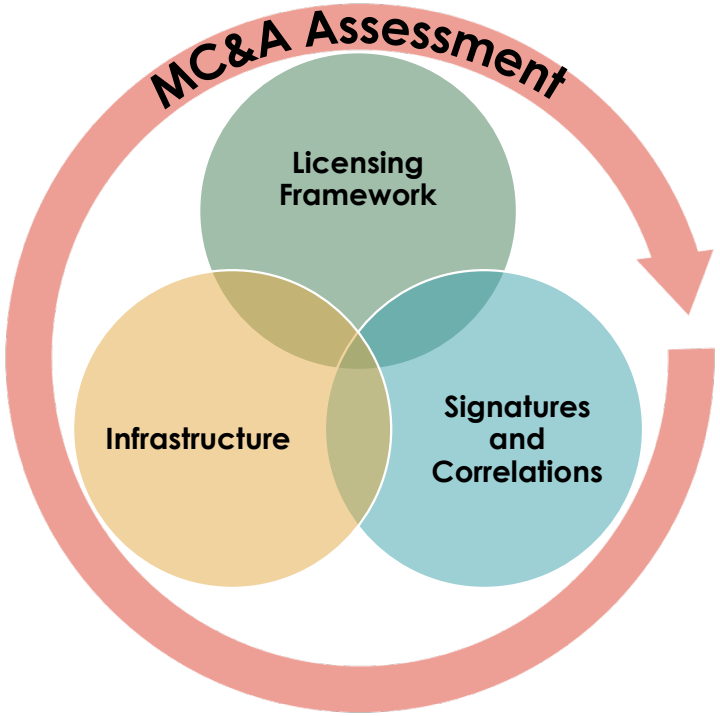
U.S. DEPARTMENT OF ENERGY

Objective, Tasking → Content

Perform a material control and accounting (MC&A) assessment for (salt-fueled) molten salt reactors.

1. **Licensing Considerations** – with NRC input, develop a framework to assist in MC&A and licensing for MSR technologies.
2. **Supporting Infrastructure** – identify potential gaps in safeguards approaches or technologies that require a test bed or infrastructure investment(s).
3. **Develop a Monitoring Approach** – understand signatures and correlations through system-level modeling.



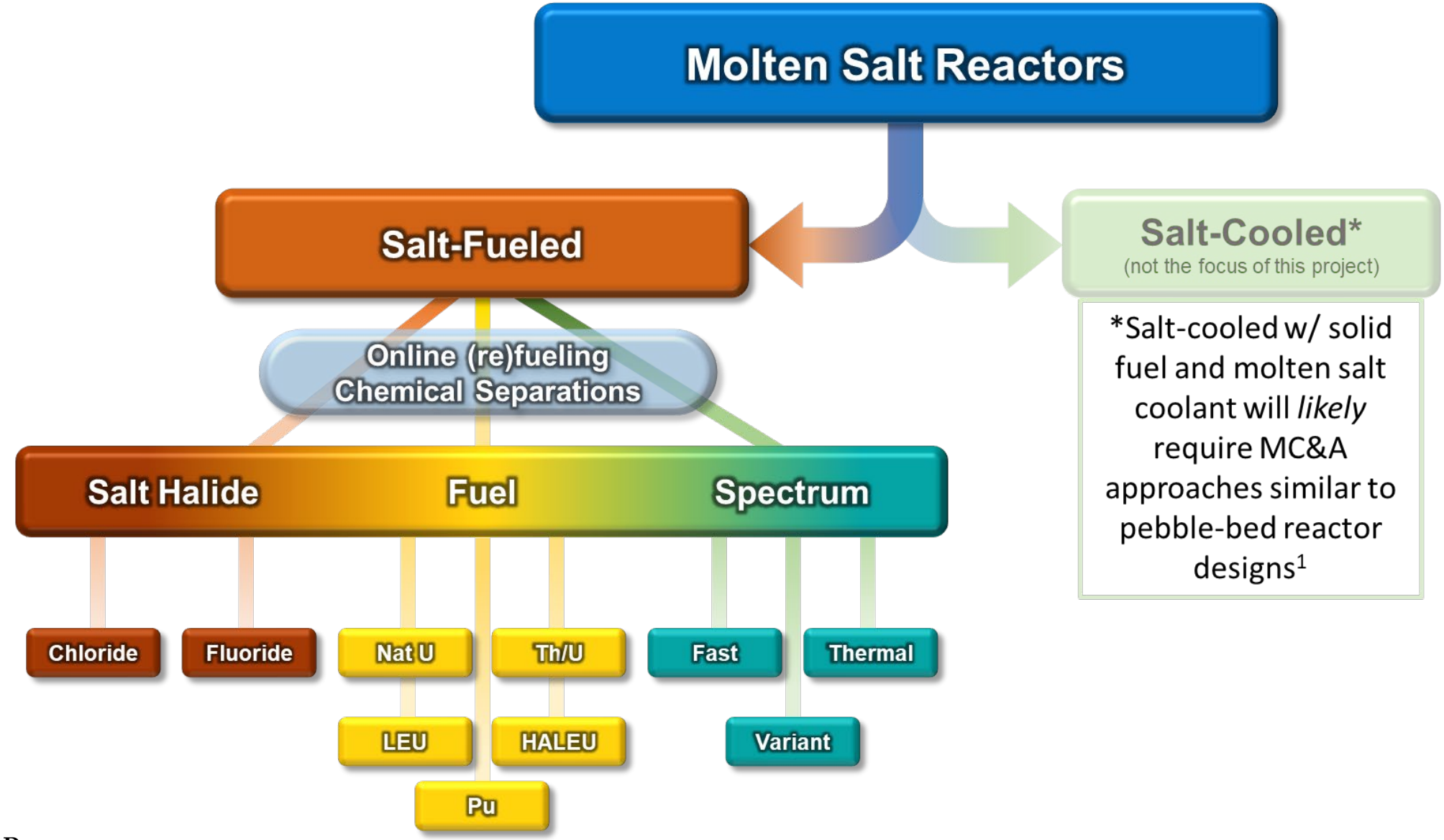
MSR MC&A Challenges

MSR design concepts can include a wide range of features and characteristics (compared to LWRs).

- **Salt-fueled** – fissile and fertile nuclear material dissolved in molten salt.
  - Flowing salt designs and molten salt in fixed geometry (tubes).
- **Salt-cooled** – solid-fueled (TRISO) with molten salt coolant.

This research is focused on salt-fueled → domestic investments and novel MC&A challenges.

MSR Design Variability



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[1]Kovacic D., Gibbs, P., Scott, L., "MC&A Program Performance Assessments for Pebble Bed Reactors", ORNL/SPR-2019/1175.

Domestic Safeguards MC&A Considerations

- Regulations in 10 CFR Parts 70 and 74 – licensee must develop, present, (and maintain) a nuclear MC&A program to receive license(s).
  - Should consider MC&A and broader safeguards during the design process.
- SNM (Pu, ^{233}U, enriched U in 233 or 235) falls in 3 main categories:
  - Strategic SNM (CAT I)
  - Moderate Strategic Significance (CAT II)
  - Low Strategic Significance (CAT III)
- Other factors to determine the MC&A requirements:
  - Material dose, accessibility, concentration of SNM.

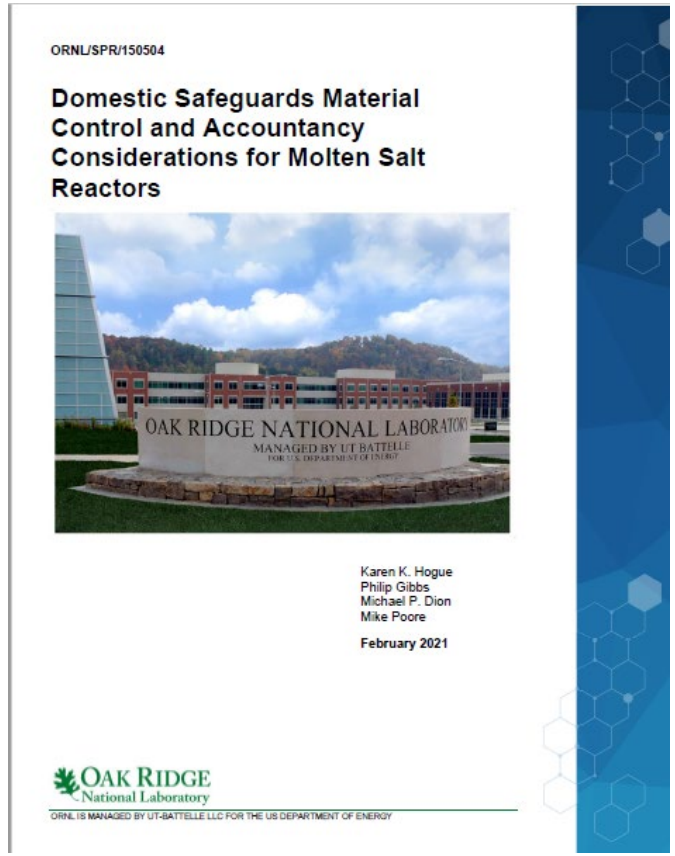
MSR MC&A Considerations

- Potential MC&A Approaches
  1. Black box (material in ↔ material out at some boundary)
  2. Process monitoring (terminology explicitly for CAT I, strategic SNM)
     - Processing monitoring could be proposed for Cat II or III SNM.
- Components of item-level MC&A combined with CFR Part 74 requirements typically used for bulk handling facilities (e.g., fuel fabrication in the U.S.).
- Ensure the MC&A program can identify theft of certain amounts within statistical uncertainties and time periods.

> - …NRC favors a *modified* MC&A approach utilizing process monitoring techniques for salt-fueled MSRs.
> - …new NRC requirements will likely be developed.

MSR MC&A Considerations

- Operations that influence MC&A plan:
  - Access to SNM while operational
    - **CHALLENGE:** High rad and temp, considered online inventory (similarities to enrichment plants).
  - Inventory of SNM during shutdown/drain
    - **CHALLENGE:** SNM will need to be quantified (in place) and/or flushed from system and then quantified.
  - Inventory and confirmation of online (re)fueling
    - **CHALLENGE:** SNM during refueling will require methods for quantification.
  - Chemical processing and/or separations
    - **CHALLENGE:** Timely detection cannot only rely on material balance and surveillance - NDA or direct measurements (volumes, tank levels, etc.) are needed.



Proposed MC&A Recommendations

- Fresh and end-of-life material/structure/component
  - Quantify SNM in fresh fuel upon arrival
    - Verify S/N, container (tare) weights, intact TID (leverage item counting methods)
  - Incorporate monitoring (e.g., camera surveillance, in situ NDA) to account for all fuel added to the system
    - Direct sampling for DA analysis (in coordination w/ primary loop sampling)
- Online Physical Inventories→Potential Measurement Locations:
  - Drain tank – confirm quantities and material inventory
  - Off-gas system – determine removal efficiency, identify potential SNM or progeny accumulation (e.g., I, Cs, Sr)
    - *Progeny isotopes* should be considered in maintenance plan
- Accumulation Points:
  - Off-gas system, salt & air filtration, heat exchanger, pipe baffles, etc.

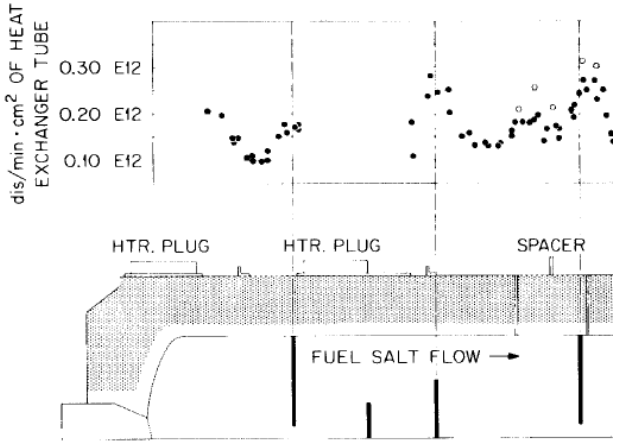


Image of isotope activity variation influenced by MSRE pipe geometry. Image reproduced from ORNL-TM-3151.

Potential Technologies for MC&A

Existing Technology for MSR MC&A:

- HPGe/Gamma Sensors – heavily collimated for online in-operation measurements OR traditional lab grade setup
- HKED (Hybrid K-Edge Densitometry) – Applied to molten salt samples or 'bypass' loop for actinide concentration measurements
- NPP instrumentation – in-core, out-of-core neutron detectors, contamination monitors, etc.
- Methods and techniques from the Uranium Cylinder Verification System (UCVS), CANDU online fuel bundle verification systems, and reprocessing/pyroprocessing facility designs.

Technology Under Development (*ARS*):

- *Ultra high resolution (low energy) (TES) - SOFIA @ LANL (M. Croce)*
- *Neutron methods – LANL High Dose Neutron Detector (HDND – D. Henzlova)*
- *UV/Vis/Raman – PNNL (A. Lines)*
- Flow measurements
  - *Electroanalytical sensors & modular test bed (ANL – N. Hoyt)*

  (Radiometric? – coolant loop activation or elsewhere)
- New materials for high-rate n/g discrimination @ temp – SBIR Radiation Monitoring Devices

Infrastructure Assessment: *What is available?*

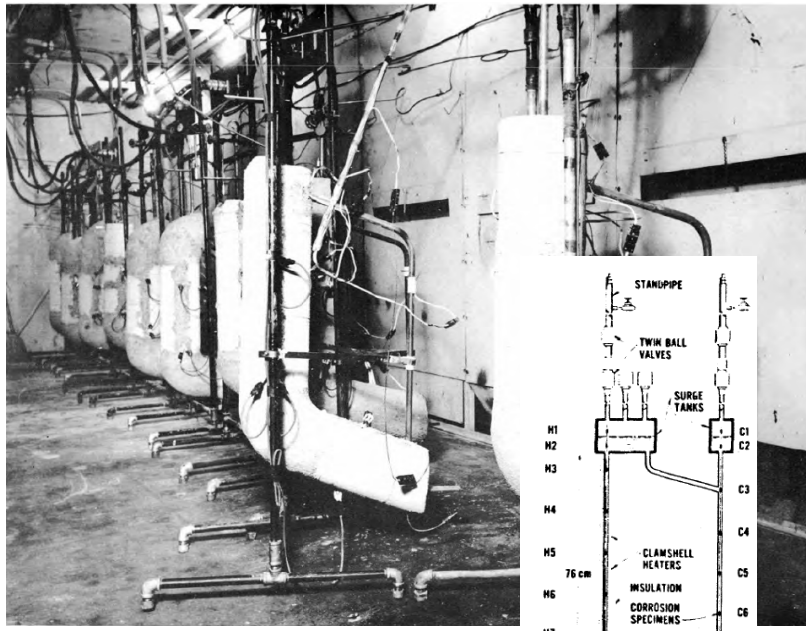
- Infrastructure needed to support testing, licensing, and technology development for commercial MSRs.
  - Molten Salt Reactor Experiment – '65-'69, >600 reports
  - Molten Salt Test Loops – convection and forced flow
  - NEXT Lab
  - Versatile Test Reactor
  - Molten Chloride Reactor Experiment
- Potentially support R&D for several advanced reactors

Commercially available forced flow loop from Copenhagen Atomics.

MSRE Technology…

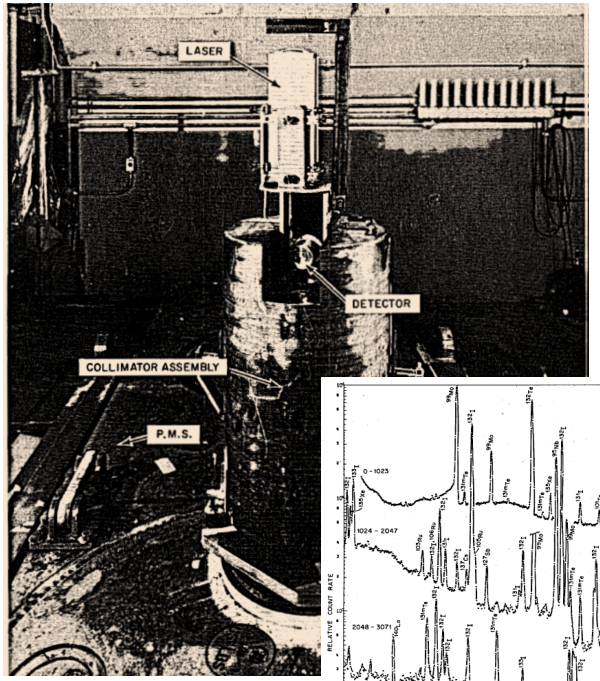
During operation equipment was designed and installed in various stages

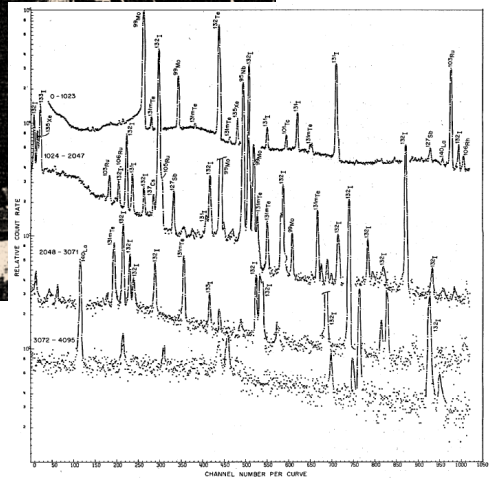
Convection loops helped understand corrosion and longevity



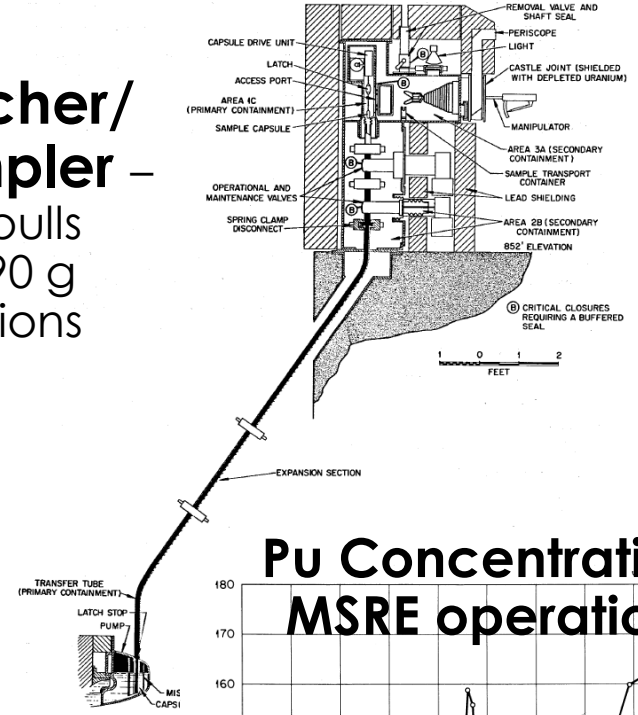
'65 MSRE critical

Portable Gamma Spectrometer – ONLY measurements of off-gas radioactivity





Fuel Enricher/ Sampler – 10 g pulls and 90 g additions



Pu Concentration MSRE operation

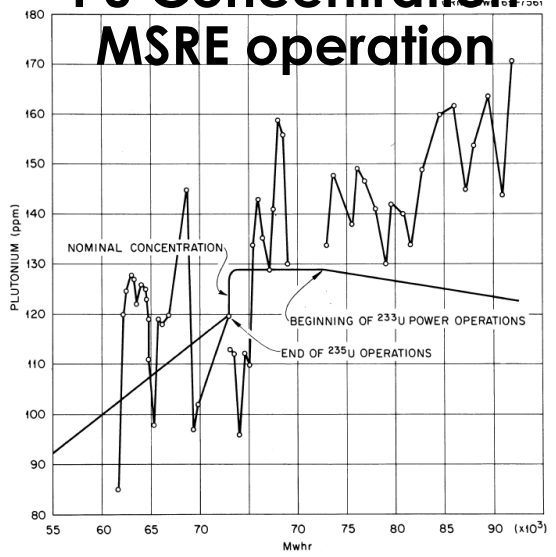


Fig. 1 Comparison of Nominal and Analytical Values for the Concentration of Pu in the MSRE Fuel Salt.

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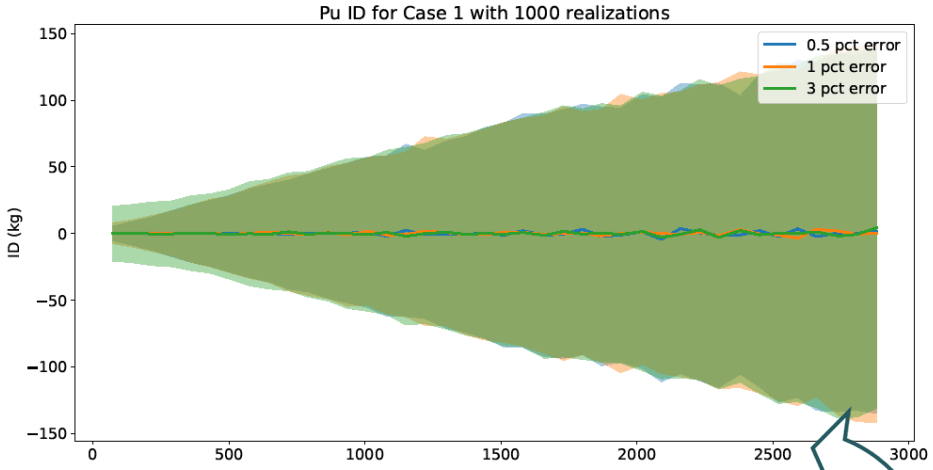
Infrastructure Assessment: NEEDS

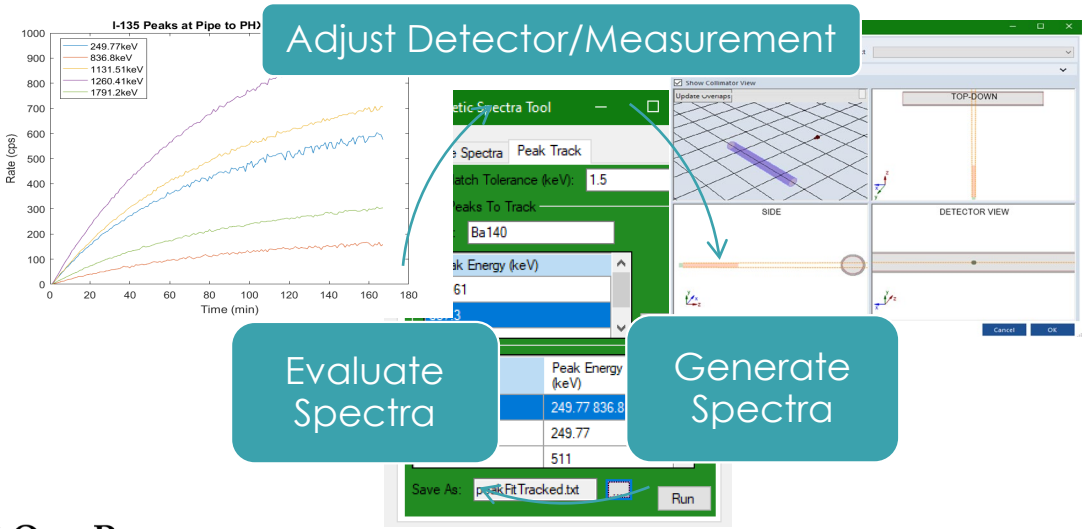
- Advanced Infrastructure Supports:
  - Corrosion/salt chemistry, physical properties of salts, instrumentation longevity tests
  - Online monitoring (assay) of fresh fuel
  - Maintenance and shutdown scenarios
  - Measurements of irradiated salts
  - Instrumentation for fuel monitoring and handling
  - Waste fuel, storage and associated monitoring

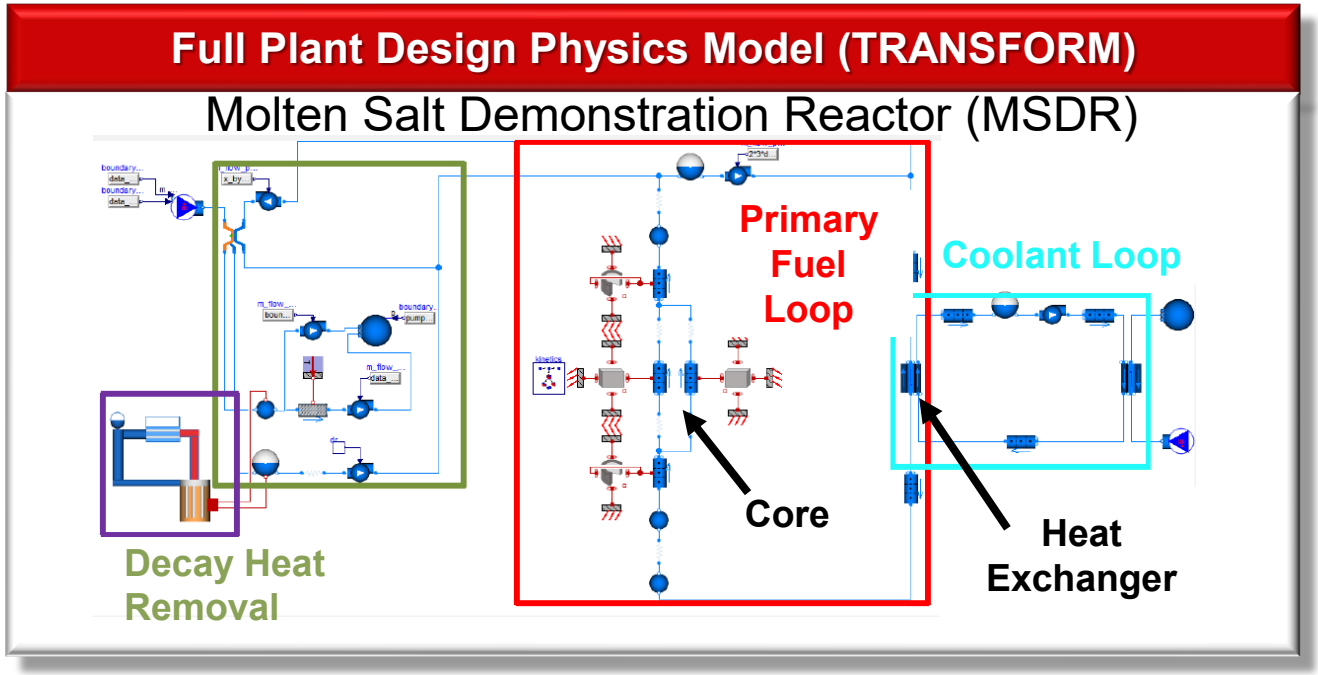


- *Advanced modeling and simulations* for fuel-salt (actinide) chemistry, isotopic inventories, and safeguards assessments.
  - *Statistical tools to evaluate measurement uncertainty goals – SNL (N. Shoman)*
  - *Dynamic modeling and simulation methods to support MC&A and licensing for MSRs – ORNL (M. Dion)*

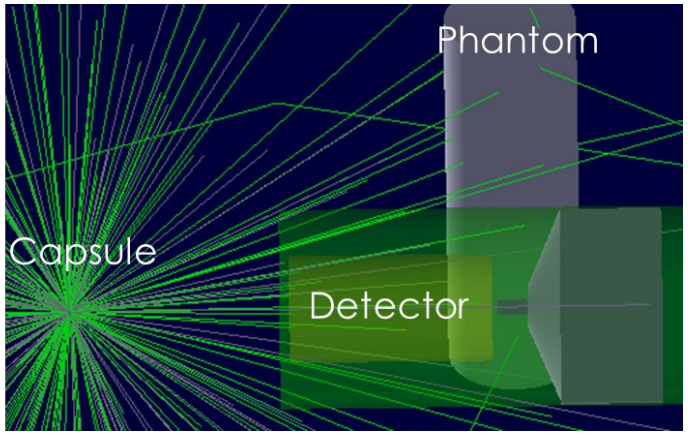
Dynamic, System-Level Reactor Modeling

- Transient Simulation Framework of Reconfigurable Modules (TRANSFORM*) – Extract time-dependent radioisotope concentrations from MSR component (e.g., pipes, tanks)
- Evaluate passive gamma detection, sampling (10 g) – dose and spectra





- High Fidelity transport modeling:
  - Evaluate dose, complex geometries etc.



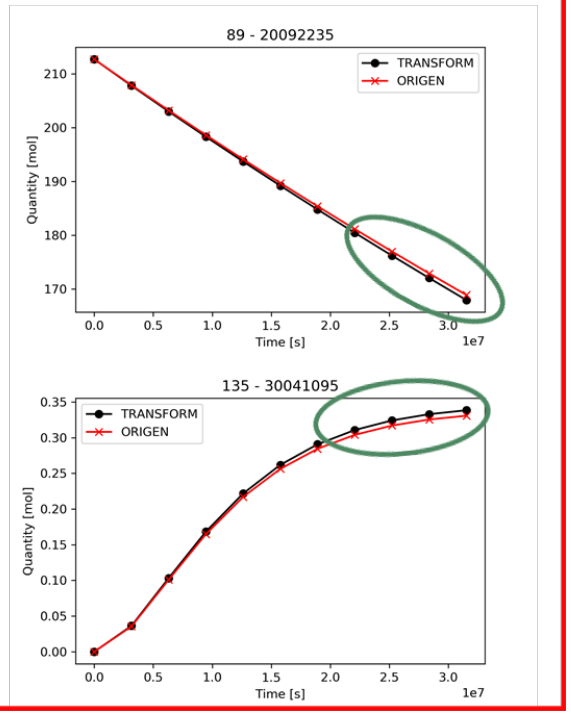
*TRANSFORM was funded and developed under the DOE-NE MSR Campaign

TRANSFORM Status – Safeguards MC&A support

- Developed primarily for core reactivity and equilibrium confirmation
- Problem:
  - Tracking all fission product isotopes (2000+) is computationally expensive
- Solution:
  - Reduced sets of isotopes (100s) of isotopes will drastically improve the ability of TRANSFORM to be used for these analysis.
  - Still expected to be adequate for the near-term needs of safeguards analysis
  - **SCALE/ORIGEN integrated w/ TRANSFORM**

"fixed-fuel" simulation w/ reduced isotopic inventory

Parameter	Value
Power (MW)	25
Number of Tracked Groups	268
Simulation Length (year)	1
Initial Composition	
SIZZZAAA ID	20092235, 20093238
Common Name	U-235, U-238
Mass Fraction (-)	0.05, 0.95
Total Mass (kg)	1



Progress & Future Work

- Report on MC&A Considerations complete
  - Infrastructure Assessment, and Signature Evaluations being developed.
- Software and other data analysis tooling developed to provide ways to evaluate model data
- TRANSFORM being expanded to support safeguards of MSRs
  - Non-fixed fuel simulations and larger fission product inventories underway
- Continue to explore signature evolution (e.g., photon spectra) during operation, dose studies, etc.

ARS is developing technology and utilizing modeling and simulation to support MC&A for MSRs.

Conclusions and Takeaways

…NRC favors a *modified* MC&A approach utilizing process monitoring techniques for salt-fueled MSRs.

➢ MC&A Key Points

- ➢ Quantification of fresh fuel additions will likely be needed.
- ➢ "Dual use" physical inventories during operation.
  - e.g., determine off-gas removal eff + confirm or deny presence of SNM.
- ➢ Minimizing accumulation points (in design) could reduce potential salt/SNM holdup.

❑ Infrastructure

- ❑ Needed to validate modeling efforts AND provide critical testing structures.
- ❑ Provides a test platform for MC&A technology (what works/what doesn't).

❖ Dynamic Modeling

- ❖ System-level dynamic modeling is needed to understand the MSR fuel cycle and related signatures.
- ❖ Inform and support MC&A measurement plan including frequency (direct and sampling), dose, technology evaluation, process monitoring, …