Molten Salt Reactor Fuel Cycle and Reactor Physics Analysis with SCALE/TRITON

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SCALE Code System
Analysis enabling nuclear technology advancements

2016 – present:
Increased Fidelity, Infrastructure Modernization, Parallelization, Quality Assurance
Solutions for extremely complex systems
High-fidelity shielding, depletion and sensitivity analysis in continuous energy
Modern, modular software design
Scalable from laptops to massively parallel machines

• Transport
  – Monte Carlo
  – Deterministic

• Point depletion
SCALE Code System
Reactor physics and used fuel characterization

Pin-by-pin burnup and radioactive source terms

Power distribution for AP-1000 reactor

Burnup (MWd/MT U)

User interface for facility-wide source term characterization
Liquid-Fueled Molten Salt Reactors
Extending methods for solid fuel reactors

- Solid fuel reactor characteristics
  - Fission products and actinides remain with fuel until reprocessing (if applicable)
  - Excess reactivity control occurs with soluble boron/burnable absorbers

- Liquid fuel reactor characteristics
  - Fuel flows with carrier material (delayed neutron precursor drift)
  - Includes continuous and batch chemical processes
Liquid-Fueled Molten Salt Reactors

Core designs using molten fuel salt

- Fast spectrum molten salt reactor (MSR) cores are usually large volumes of salt
- Thermal spectrum cores incorporate fixed moderator material
- Multiple fuel stream designs include
  - Different salt compositions
  - Fissile and fertile salt compositions
- Multiple spectrum zones include
  - Different fuel-to-moderator ratios
  - Driver and blanket zones for breeding

Motivation

Develop MSR modeling and simulation capabilities in SCALE

• Account for the flowing fuel materials in a liquid-fueled system
  – Model precursor drift and its effect on neutronics and depletion
  – Remove isotopes with specific rates or portions of the fuel salt

• Draw on reactor physics tools within the SCALE code system
  – Neutron transport and depletion
  – Strong quality assurance program

• Provide ORNL modeling and simulation tools applicable to liquid-fueled reactor problems
  – Assessment of MSR impact on fuel cycle outcomes
  – Fuel cycle and core optimization and design
Reactor Physics Analysis
Challenges in neutronic modeling and simulation

• Delayed neutron precursor drift occurs in flowing fuel
  – Delayed neutron precursors are radioactive fission products that release neutrons upon decaying
  – In solid fuel systems, the movement of these delayed neutron precursors is negligible
  – In liquid fuel systems, the precursors move away from their birth location and may decay outside the core, changing the neutron source distribution within the core

• Fission source calculated by standard lattice physics codes is biased
  – Prompt neutrons and some delayed neutrons are emitted in the liquid fuel while it is still inside the core
  – Some delayed neutrons are emitted after the liquid fuel leaves the core (coolant loop, chemical processing, etc.)
  – Effect on $k$ eigenvalue is on the order of a few hundred pcm
Reactor Physics Analysis
Challenges in depletion modeling and simulation

• Depletion with continuous and batch feeds and removals
  – Continuous processes in liquid fuel systems remove fission gases and potentially other elements during operation
  – In addition to continuous processes, material may be added to and removed from the liquid in batches at specific times

• Set of depletion equations describing the rate of change of nuclides

\[
\frac{dN_i}{dt} = \sum_{j=1}^{m} l_{ij} \lambda_j N_j + \Phi \sum_{k=1}^{m} f_{ik} \sigma_k N_k - (\lambda_i + \Phi \sigma_i + \nu_i) N_i
\]

- Decay rate of nuclide \( j \) into nuclide \( i \)
- Production rate of nuclide \( i \) from irradiation
- Loss rate of nuclide \( i \) due to decay, irradiation, or other means
Precursor Drift Model in SCALE/NEWT
Implementation, impact, and remaining work

• Developed a simple one-dimensional delayed neutron precursor drift model
  – Impact is severe in regions where delayed neutrons dominate the neutron source
• Remaining tasks
  – Finalize implementation of input at the sequence level
  – Coordinate with PARCS team on format for tabulation of broad group data
Continuous Feeds, Removals, and Tracking

Implementation and results

- Implemented removal and feed and waste tracking mechanisms within TRITON
  - New timetable input to access these capabilities

- Remaining tasks
  - Some numerical integration work on the feedback mechanism is required to conserve mass
  - Addnux nuclide mapping must be implemented
  - Write additional mass information to output
**Input**

- Typical SCALE/TRITON input of an assembly of the Molten Salt Demonstration Reactor
- New input block for continuous feed and removal
  - Fission product gases and noble metals
  - Power must be normalized to represent full salt amount
  - Must quantify processing systems for accurate results

**Output**

- Typical SCALE/TRITON output with additional mixtures provided on the *.ft71 file
- Run OPUS or convert the isotopic data file to generate isotopic composition in time

**Analysis**

- Outputs must be normalized to provide total amount in the system or relevant densities
- Relate these trends in terms of burnup or masses
Adapting SCALE Methods for MSR Analysis

Key points

• Developed a simple 1D model for calculating precursor distribution that is internal to SCALE
  – Used correction factors to generate flow-adjusted parameters to implement during neutron transport calculations

• Developed feed, removal, and tracking mechanisms available within SCALE/TRITON timetable inputs
  – Tested and used tools in several applications for fuel cycle, source term, and safeguards analyses
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