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

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SCALE Code System

Analysis enabling nuclear technology advancements

SCALE 6.2 – SCALE 7.0

2016 – present:

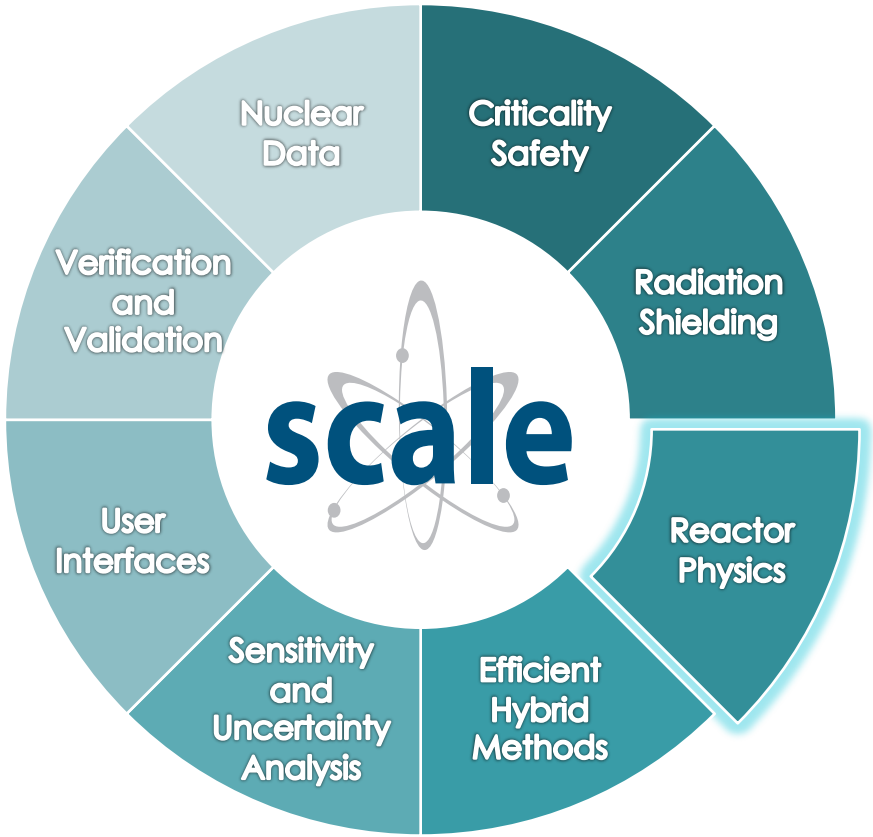
Increased Fidelity, Infrastructure Modernization, Parallelization, Quality Assurance

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

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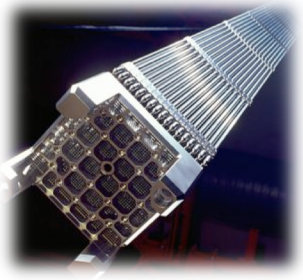
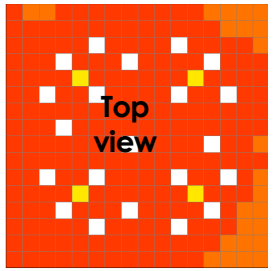
SCALE Code System

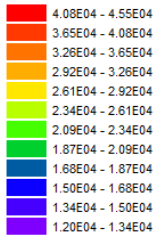
Reactor physics and used fuel characterization

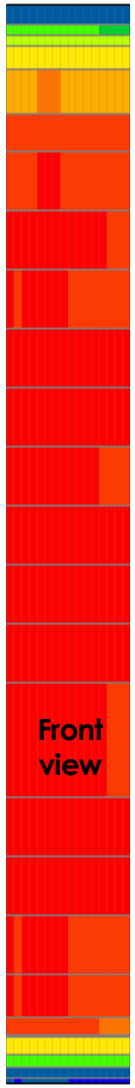


Pin-by-pin burnup and radioactive source terms

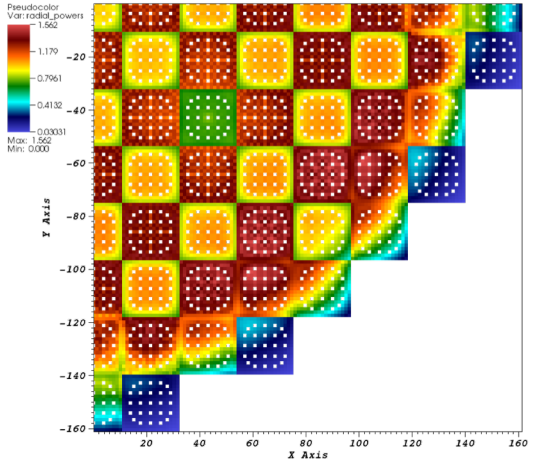


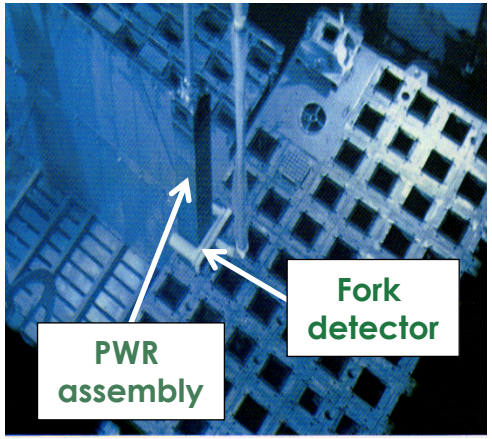
Burnup (MWd/MTU)

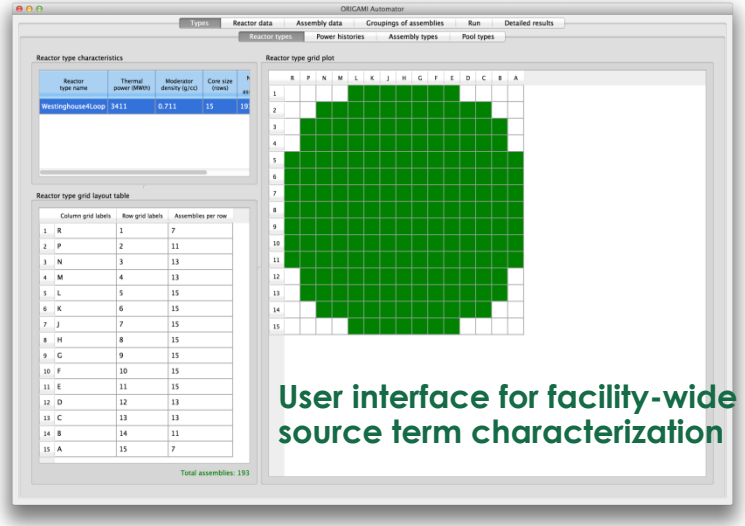




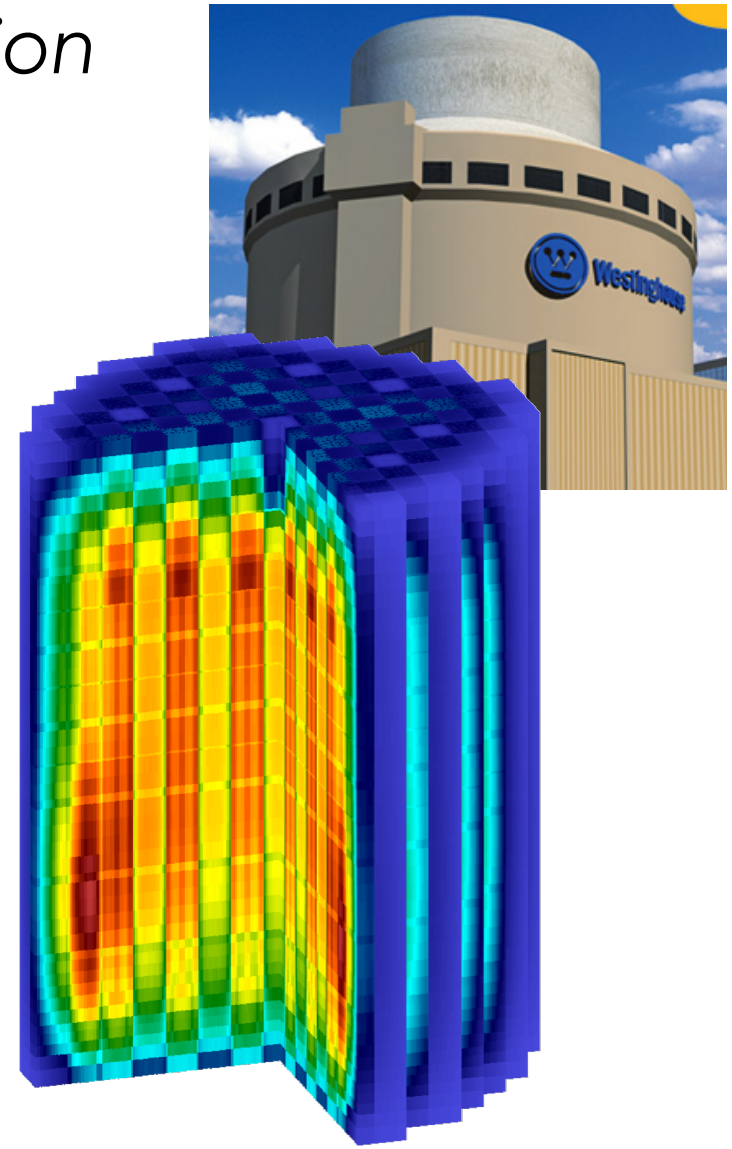
Power distribution for AP-1000 reactor







User interface for facility-wide source term characterization



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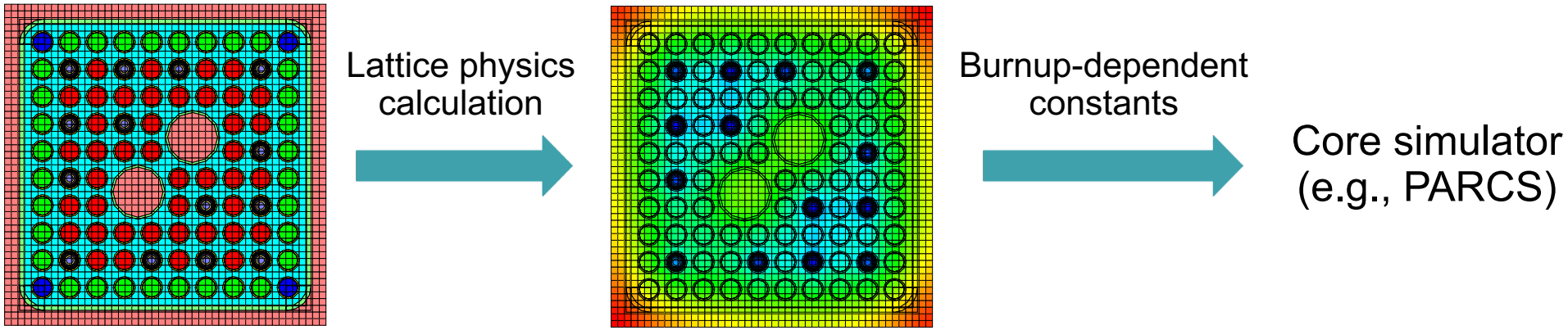
Liquid-Fueled Molten Salt Reactors

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

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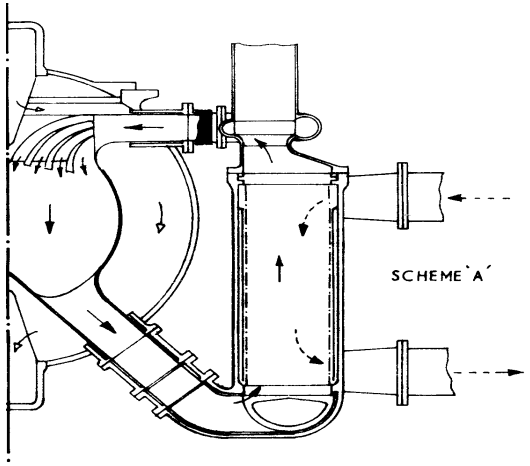
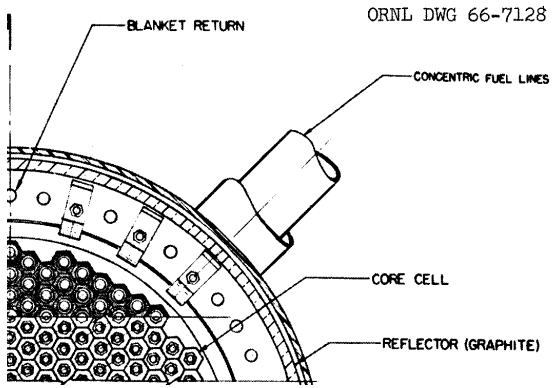
Liquid-Fueled Molten Salt Reactors

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



½-core fast spectrum



¼-core thermal spectrum design.[2]

[1] "An Assessment of a 2500MWe Molten Chloride Salt Fast Reactor" (1974).
[2] "Design Studies of 1000-MW(e) Molten-Salt Breeder Reactors" (1966).

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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

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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

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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

$$\frac{dN_i}{dt} = \sum_{j=1}^{m} l_{ij}\lambda_j N_j + \bar{\Phi}\sum_{k=1}^{m} f_{ik}\sigma_k N_k - (\lambda_i + \bar{\Phi}\sigma_i + \cancelto{0}{r_i})N_i$$

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

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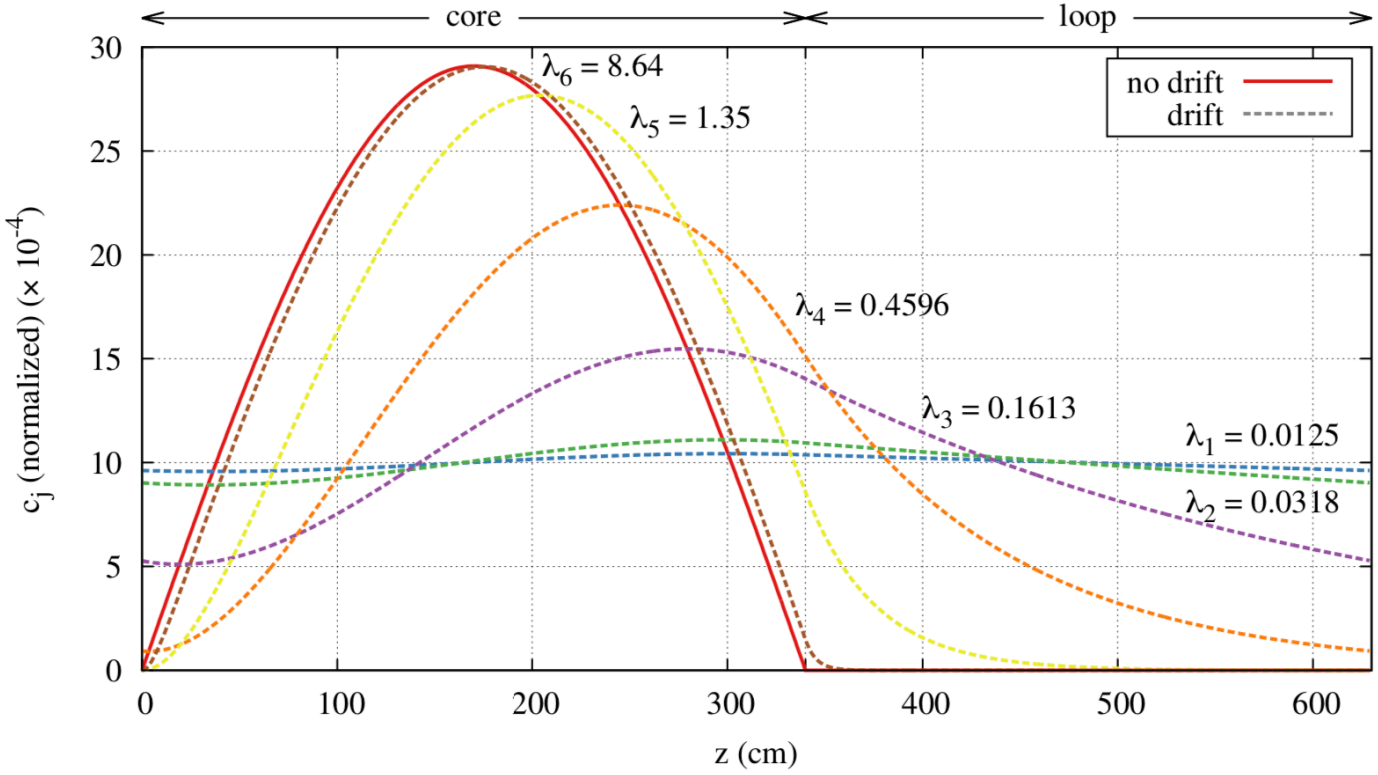
Precursor Drift Model in SCALE/NEWT

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



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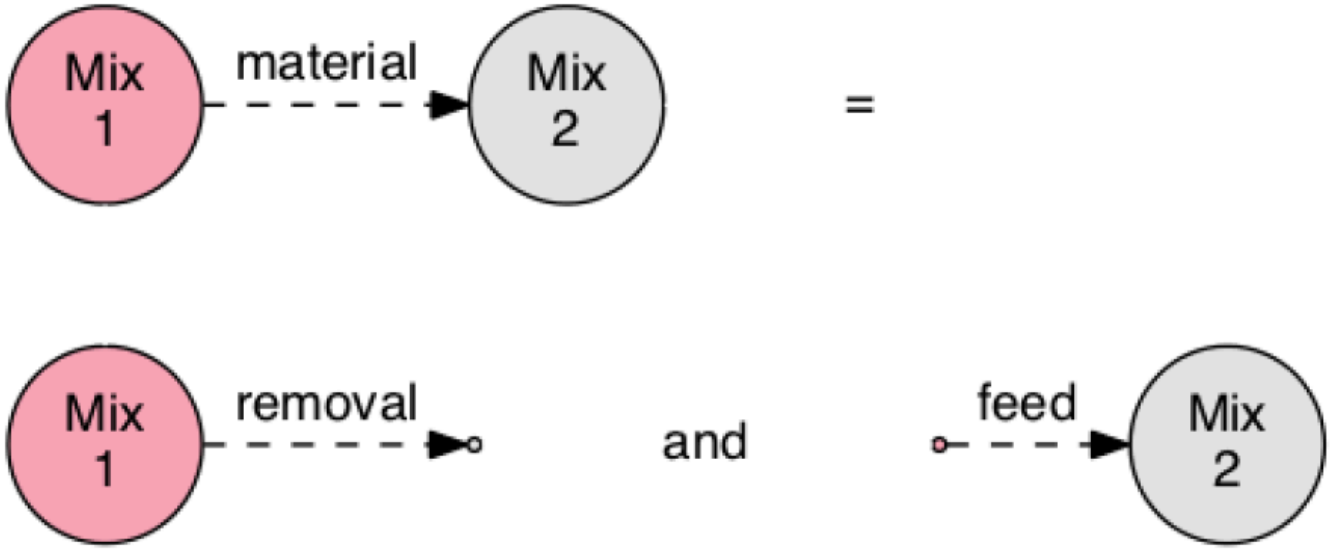
Continuous Feeds, Removals, and Tracking

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



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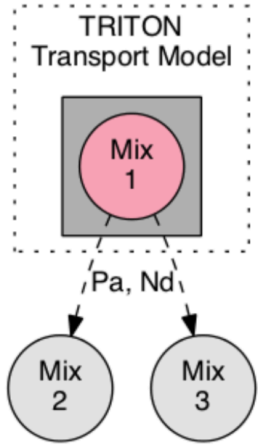
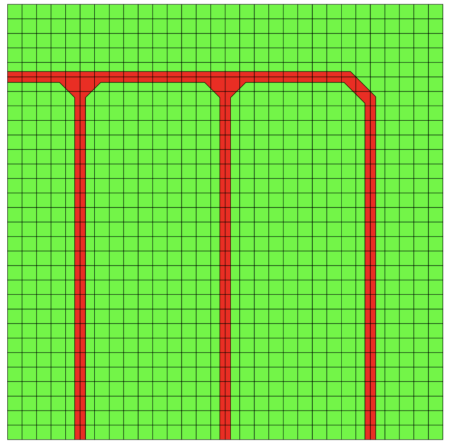
Example TRITON problem used for simulating fueling and removals

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





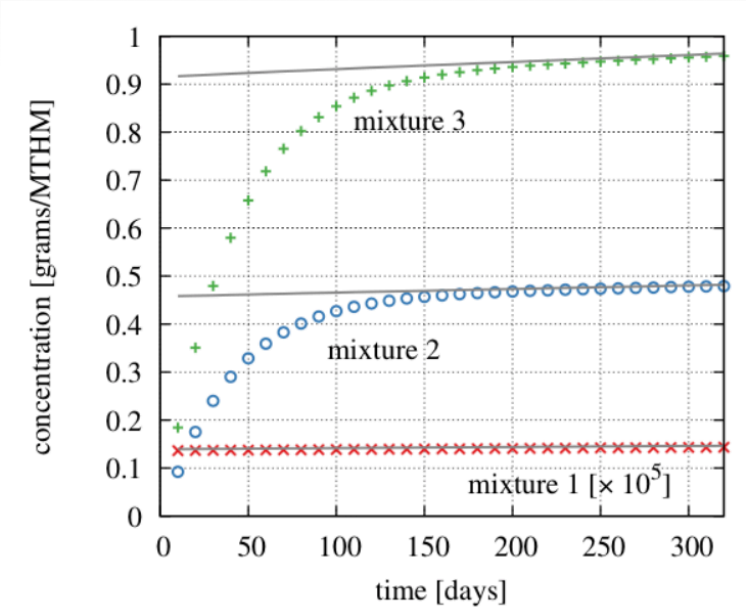
Output

- 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

```
read timetable
' gaseous fission product removal
   flow
      from 1
      to 7
      type continuous
      units pers
      nuclides Kr Xe end
      constant 3.3012E-01 3.3012E-01 end
      time 0.0 end
      factor 1.0 end
   end flow
' thorium feed
   flow
      to 1
      type continuous
      units gpers
      nuclides u-238 u-235 end
      constant 0.65  0.35  end
      time 0.0 end
      factor 3.632558145E-04 end
   end flow
end timetable
```

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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