Idaho National Laboratory
Reactor Analysis
Applications of the Serpent Lattice Physics Code

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Outline

• Intra-Pin Power and Flux Distribution for BISON Fuel Performance Calculations.
• Takahama Benchmark Validation Analysis
• TREAT Core Analysis
• Multi-SERTTA Experiment modeling
• NRAD facility modeling
• Wish List
Intra-Pin Power and Flux distribution for BISON.

- Most fuels performance codes have surrogate models for the “external” physics.
  - Example: Limited (Material dependent models such as the UO$_2$ Lassmann model) depletion models to produce the intra-pin power density

- The goal is to show a higher fidelity fuel performance calculation where the surrogate models are replaced with the relevant physics.
  - Replace the internal BISON depletion model with neutronics

- Produce a coupled system of codes that is easily maintainable and tested regularly.
  - Each application is a application is based on MOOSE and has their own tests.

- A goal is to be able to analyze different fuel types without having to invent new surrogate models for the external physics. (i.e. U$_3$Si$_2$)

- A goal is to be able to analyze conditions where the intra-pin power distribution is not axi-symmetric (azimuthal dependence).
**Intra-Pin Power and Flux Distribution for BISON**

- The master application is MAMMOTH:
  - BISON: fuels performance
  - Rattlesnake: neutronics
- Serpent: intra-pin fuel, cladding, and water region cross sections.
- Macroscopic cross section are tabulated over intra-pin burnup (MWd/kgHMI) and temperature (K).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Pin Radius</td>
<td>4.09575 (mm)</td>
</tr>
<tr>
<td>Fuel Pin Initial Temperature</td>
<td>600 (K)</td>
</tr>
<tr>
<td>Outer Cladding Thickness</td>
<td>0.5715 (mm)</td>
</tr>
<tr>
<td>Initial Gap Thickness</td>
<td>0.08255 (mm)</td>
</tr>
<tr>
<td>UO2</td>
<td>4.45 wt.</td>
</tr>
<tr>
<td>Cladding Initial Temperature</td>
<td>600 (K)</td>
</tr>
<tr>
<td>Water Temperature</td>
<td>585 (K)</td>
</tr>
<tr>
<td>Pitch</td>
<td>12.5984 (mm)</td>
</tr>
<tr>
<td>Linear Heat Rate</td>
<td>19.2 W/m</td>
</tr>
</tbody>
</table>
Rattlesnake reads in the Serpent cross tabulation.

At each “time” step Rattlesnake performs a macroscopic depletion calculation over the fuel portion of the quarter pin cell.

At each depletion step MAMMTOH calls BISON to perform a fuels performance calculation.

Temperature, Fast Flux, Intra fuel pin power density etc. are exchanged between BISON and Rattlesnake.
Intra-Pin Power and Flux Distribution for BISON
The Takahama Benchmark is an isotopic analysis of high burnup PWR spent fuel samples from the Takahama-3 reactor.

Original codes for validation: SAS2 and HELIOS.

Validation of MAMMOTH tool set

Provide BISON (fuel performance) tools with reasonable power history and coupled spatial distributions (power density, fast neutron flux, etc.) distribution during normal operation.

DATA: specification of power history at different rod axial levels, boron let down, and end of life isotopic content.

Serpent calculated pin homogenized cross sections at each depletion point.
Reactor Physics Analysis: Takahama Benchmark SF97

Serpent Isotopic Results SF97

SF97-4: 385 Days

RMS = 0.34%, Max = 1.05%, Min = -0.85%
**Takahama Benchmark SF97 Analysis**

**SF97-4: 875 Days**

**SF97-4: 1343 Days**

RMS = 0.47%, Max = 1.34%, Min = -1.38%  
RMS = 0.50%, Max = 1.01%, Min = -2.09%
TREAT Core Analysis

- Transient Reactor Test (TREAT) resuming operations ***very soon*** in order to support fuel safety testing and other transient science
- Zircaloy-clad graphite/fuel blocks comprise core, cooled by air blowers
  - 120 kW steady state, 19 GW peak in pulse mode
  - Virtually any power history possible within 2500 MJ max core transient energy
  - No reactor pressure vessel/containment, facilitates in-core instrumentation
- Experiment design
  - Reactor provides neutrons, experiment vehicle does the rest
  - Tests typically displace a few driver fuel assemblies (each 10cm square, 122cm L)

Insert Experiment Here (or anywhere else really)

Example Transient Shapes
TREAT Core Analysis

- Serpent generated cross sections for the homogenized fuel elements from an eigenvalue calculation.
- Use core isothermal fuel temperature states and transient CR position for the tabulation.
- Tensor Diffusion Coefficients (TDC) are computed in optically thin regions with Rattlesnake 1st order $S_N$.
- Superhomogenization method is employed for equivalence calculations to prepare the final cross section tabulation.
MAMMOTH Core Results

- MAMMOTH is used for transient analysis with an adiabatic fuel model.
- PKE: (Point Kinetics), SD: Spatial Dynamics
- Comparison of temperature limited transient (safety case without rod re-insertion) with PKE vs. SD.
Multi-SERTTA (PWR-condition static water, fresh fuel)  
One of many vehicles as part of the Accident Tolerant Fuel (ATF) program

- Impressive instrument array (including fast-response temperature and boiling detection)
- 4X vessels filled with one 10-pellet PWR rodlet each
- Filled with static PWR-condition water (280C, 16MPa)

- Current efforts to prepare for construction and irradiation of a water-filled nuclear mockup in 2019
- Quite relevant for PWR-condition transient boiling, but these tests not likely until well into 2020
Multi-SERTTA experiment

- The cross sections for the multi-SERTTA were developed using a source calculation in Serpent from the various core isothermal fuel temperature states saved at the experiment vehicle surface.

- Developed cross section tabulations as a function of local fuel temperature, average core fuel temperature near experiment and CR position.
- Calculated fuel temperature approach melting point for UO$_2$.
- First time a dynamic power coupling factor (DPCF) has been computed. Shows effects from the rod withdrawal on all units.
Neutron Radiography (NRAD) Facility

- Similar to X-ray, neutron radiography provides images of structures that X-rays cannot penetrate.
- Neutron radiographs:
  - Significantly reduce the time and cost for conducting examinations of irradiated samples
  - Allow researchers to see inside them to evaluate features for further study
- Irradiated specimens to be radiographed are:
  1. Mounted in custom-designed fixtures
  2. Lowered in an elevator from the main HFEF hot cell down into the east beam line
Neutron Radiography (NRAD) Facility

- 300-kilowatt TRIGA (Training, Research, and Isotopes, General Atomics) research reactor

**Motivation:** to study differences between transient simulations using a Point Reactor Kinetics (PRK) model versus a spatial dynamics model for the NRAD core with MAMMOTH.

- Serpent used to generate reference solution and cross section for the core.

### Prompt Fuel Temperature Coefficient of Reactivity

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>k-eff</th>
<th>Δ rho / °C</th>
<th>Temp. (°C)</th>
<th>k-eff</th>
<th>Δ rho / °C</th>
<th>% Diff.</th>
</tr>
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<tbody>
<tr>
<td>23</td>
<td>1.02109</td>
<td>5.36E-05</td>
<td>23</td>
<td>1.01291</td>
<td>5.58E-05</td>
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<td>200</td>
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<td>200</td>
<td>1.00287</td>
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<td>-7.1</td>
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<tr>
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<td>700</td>
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<td>1000</td>
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<td>1.32E-04</td>
<td>1000</td>
<td>0.92498</td>
<td>1.10E-04</td>
<td>16.9</td>
</tr>
</tbody>
</table>
MAMMOTH Transient Results

- Comparison of MAMMOTH Spatial Dynamics (SD) vs. PKE with two different values of mean generation time.
- The SD model predicts a peak power of 600.0 MW, whereas both PRK results are approximately at 855 MW.
Wish list

- More flexibility in cross section generation:
  - Overlay grid for cross section generation and burnup regions.
  - Radial and azimuthal regions for pins.
  - Compute a local burnup value.

- More memory efficient functionalization of temperature dependence of cross sections.

- Robust and well tested variance reduction techniques for cross section generation.

- Integrated isotope dependent and energy dependent heating values.

- For detectors, use local isotopes at current conditions instead of providing redefining the isotope.
  - e.g.: det 1 du 1007 dr -8 92235

- Cumulative Migration Method (MIT?)
  - Improve diffusion coefficients both isotropic and directional.
QUESTIONS ?