Development of CTFFuel for use in VERA

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Purpose

• Fuel thermal feedback is currently handled in VERA using lookup tables pre-generated by Bison
• Fuel temperature is a function of local burnup, power, and coolant temperature
• Lookup table benefits:
  1. Fast estimation of fuel temperature for given burnup and power
  2. Captures many of the physics predicted by high-fidelity Bison model
• Lookup table drawbacks:
  1. A separate set of tables must be generated for each fuel type (VERA can only use one type currently)
  2. Not valid for transients

• CTFFuel development undertaken to achieve the following goals:
  1. Fast-running in core-scale models (Tens of thousands of pins)
  2. Suitable modeling fidelity for thermal feedback to MPACT
  3. Applicable to transients and depletions
  4. Applicable for multiple fuel types
Introduction
CTFFuel

• CTFFuel is the name given to the fuel rod solver in CTF after adding new models and performing validation and verification testing
• CTFFuel was built from the pre-existing fuel rod modeling capability in CTF
Introduction
CTFFuel

• State of initial CTF fuel rod modeling capability:
  – Dynamic gap model including effects of thermal expansion, pressure-driven gap closure, pellet relocation and densification
  – Gap heat transfer including effects of gas mixture thermal conductivity, radiative heat transfer, and pellet/clad contact
  – Temperature dependent thermal conductivity
  – No testing
  – No burnup effects

• Development of CTFFuel in CASL:
  – Addition of burnup-dependent thermal conductivity models, burnup-dependent clad creep, burnup-dependent relocation, burnup-dependent pellet swelling
  – Improvements to existing models and numerical stability
  – Coupling to VERA for depletion and transients with intra-pin data transfer and restart capability
  – Creation of separate interface to CTF fuel model through executable and input deck
  – Solution and code verification studies performed
  – Validation testing for RIA and depletions
# Overview of CTFFuel Capabilities

<table>
<thead>
<tr>
<th>Modeling Feature</th>
<th>CTF</th>
<th>BISON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal conduction:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel conductivity</td>
<td>Yes (temperature- and burnup-dependent)</td>
<td>Yes (temperature- and burnup-dependent)</td>
</tr>
<tr>
<td>Cladding conductivity</td>
<td>Yes (temperature-dependent)</td>
<td>Yes (temperature-dependent)</td>
</tr>
<tr>
<td>2D/3D conduction</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Coupled energy deposition</td>
<td>Yes (axial and radial)</td>
<td>Yes</td>
</tr>
<tr>
<td>Coupled burnup dependence</td>
<td>Yes (axial and radial)</td>
<td>Yes</td>
</tr>
<tr>
<td>Discrete pellets</td>
<td>No</td>
<td>Yes (dish and chamfer)</td>
</tr>
<tr>
<td><strong>Gap Conductance:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic gap conductance</td>
<td>Yes (three-term model: gas, contact, radiative)</td>
<td>Yes (three-term model: gas, contact, radiative)</td>
</tr>
<tr>
<td>Cladding plasticity</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Composition-dependent gas conductivity</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Gap gas composition</td>
<td>Yes (user-defined)</td>
<td>Yes (user-defined/calculated)</td>
</tr>
<tr>
<td>Fission gas release</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Transient Fission gas release</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Gas pressure calculation</td>
<td>Yes (function of gas volume and temperature)</td>
<td>Yes (function of gas volume, temperature, and fission gas release)</td>
</tr>
<tr>
<td>Internal gas volume calculation</td>
<td>Yes (includes plenum, no dish and chamfer; function of radial/thermal fuel and cladding expansion)</td>
<td>Yes (includes plenum, dish, and chamfer; function of radial/thermal fuel and cladding expansion)</td>
</tr>
</tbody>
</table>
## Overview of CTFFuel Capabilities

<table>
<thead>
<tr>
<th>Modeling Feature</th>
<th>CTF</th>
<th>BISON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel dimensional changes:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel thermal expansion</td>
<td>Yes (radial and axial)</td>
<td>Yes (radial and axial)</td>
</tr>
<tr>
<td>Fuel densification</td>
<td>Yes (burnup-dependent)</td>
<td>Yes (burnup-dependent)</td>
</tr>
<tr>
<td>Fuel swelling</td>
<td>Yes (burnup-dependent)</td>
<td>Yes (burnup-dependent)</td>
</tr>
<tr>
<td>Fuel relocation</td>
<td>Yes (burnup- and LHR-dependent)</td>
<td>Yes (burnup- and LHR-dependent)</td>
</tr>
<tr>
<td><strong>Cladding dimensional changes:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cladding thermal expansion</td>
<td>Yes (radial and axial)</td>
<td>Yes (radial and axial)</td>
</tr>
<tr>
<td>Cladding creepdown due to irradiation</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cladding expansion due to differential pressure</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cladding plastic deformation</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Cladding ballooning</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Work this FY

• Add and improve models to account for irradiation and thermal effects (e.g., swelling and clad creep)
• Improve fidelity of data transfers
• Add ability to use in depletions and restarts
• Improve on fidelity of direct energy deposition
• Benchmark against Bison with new models
• Add depletion modeling capability to the CTFFuel user interface
• Perform VERA demonstration
• Develop an interface between CTF and CTFFuel
  – Can be used to couple other fuel solvers to CTF in place of CTFFuel
Addition of depletion capability to CTFFuel User Interface (UI)

• Capability was added for solving depletion simulations
  – User specified depletion irradiation time evolution
  – Needed after improving clad creep burnup modeling and for benchmarking against Bison and performing validation testing

• CTFFuel UI now supports modeling of
  – Steady-state
  – Transient
  – Depletions (string of connected steady-state solves)

Example of CTFFuel UI input file
Modeling improvements

• Added clad creep model with creep being accumulated over burnup steps
• Improved models to calculate fuel swelling due to solid and gaseous fission products
  – Modified the Frapcon model in CTF to account for gaseous fission product swelling
• Added the NFIR model for fuel thermal conductivity and improved that model for Gd rods
  – Added an empirical Gd content threshold to prevent unphysical conductivity increase with Gd content (when the content is slightly above zero), which is the case in Bison
• Improved the gas pressure calculation in the gap and plenum
  – More accurately accounting for changes in the volume and thermal conditions of the gas
• Added a model to calculate the thermal expansion in the fuel while accounting for elastic strains due to the thermal gradient along the radius
Benchmarking against Bison Lookup Tables

Initial Benchmark

Addition of clad creep and pellet swelling

CTF with CladCreep (solid lines, escore, mod_nfr_falcon,variGasP); BISON (dash lines)

CTF: solid lines
Bison: dotted lines
Benchmarking against Bison

• Used the latest code version of CTFFuel that accumulates clad creep over burnup steps.
• For each LHR case, only one input file is needed for CTFFuel for all burnup steps using the latest depletion interface.
Integration into VERA

• Add data transfers to the coupling interface
  - Fast flux (passed for each pin+level)
  - Volume average burnup (passed for each pin+level)
  - Total irradiation time
• Add method to CTFFuel for setting solution checkpoints and rewinding for modeling of depletions
• Add method for getting/setting fuel rod restart data

Flowchart:
- MPACT
  - Coupled convergence?
    - Yes: Advance State
    - No: CTF:
      - Rewind to checkpoint
      - Fluid+solid solve
      - Set checkpoint
      - Temperature, temperature shape
      - Power, burnup, fast flux, irradiation time, burnup shape, power shape
- Begin State
Improvement of VERA coupling fidelity

- Improve fidelity of coupling
  - Zernike polynomials are used to do the mesh transfer
  - MPACT → CTF: Radial burnup shape for each pin+level
  - MPACT → CTF: Radial power shape for each pin+level
  - CTF → MPACT: Radial temperature shape for each pin+level
Development of fuel solver interface

- The interface between CTF and CTFFuel was formalized so that an external fuel solver can be coupled to CTF.
- CTF (fluid side calculation) continues to call class procedures for setting boundary conditions and getting solution data, unaware of who does the fuel solve.
- A template fuel solver class has been written in CTF.
- The external solver needs to fill out the template class procedures with calls to its own solver.

```
class :: FuelRodExt
  procedure :: init
  procedure :: solve
  procedure :: setCheckpoint
  procedure :: rewind
  procedure :: setRestart
  procedure :: getRestart
```
VERA model of Watts Bar Unit 1

- CTFFuel generally predicts lower temperatures than lookup tables
- Discrepancy early in cycle may be due to modeling differences
- Coupling verification assessment is being performed

Comparison of volume average fuel temperature

Comparison of volume average fuel temperature differences
VERA model of Watts Bar Unit 1

- Critical boron concentration prediction at HZP remains essentially unchanged between two approaches

Comparison to critical boron measurements (ARO)

<table>
<thead>
<tr>
<th>Cycle</th>
<th>BOC Exposure</th>
<th>Measured</th>
<th>Lookup</th>
<th>CTFFuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>1293</td>
<td>1294</td>
<td>1294</td>
</tr>
<tr>
<td>2</td>
<td>8.8</td>
<td>1443</td>
<td>1438</td>
<td>1437</td>
</tr>
<tr>
<td>3</td>
<td>12.8</td>
<td>1572</td>
<td>1603</td>
<td>1603</td>
</tr>
<tr>
<td>4</td>
<td>14.9</td>
<td>1761</td>
<td>1762</td>
<td>1765</td>
</tr>
</tbody>
</table>
VERA Model of Watts Bar Unit 1

- Flux map comparison using CTFFuel is in close agreement with Bison lookup tables
Farley Loss of Flow Transient

- LOF may result from a simultaneous loss of electrical supplies to all reactor coolant pumps (RCPs).
- Flow and power forcing functions for a 9 second transient
- System pressure and inlet temperature remain at nominal values
Farley Loss of Flow Transient

Equilibrium Cycle BOC Power Distribution

Fuel temperature response
### Transient testing

- **CABRI RIA experiments** were used to assess Bison and CTFFuel.
- **Tests** were performed with high burnup fuel (up to 64 GWD/MTU).

<table>
<thead>
<tr>
<th>Test (date)</th>
<th>REP Na-2 (6/94)</th>
<th>REP Na-3 (10/94)</th>
<th>REP Na-5 (5/95)</th>
<th>REP Na-10 (7/98)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Type</td>
<td>17x17 UO₂</td>
<td>17x17 UO₂</td>
<td>17x17 UO₂</td>
<td>17x17 UO₂</td>
</tr>
<tr>
<td>Cladding Type</td>
<td>Std Zy-4</td>
<td>Std Zy-4</td>
<td>Std Zy-4</td>
<td>Std Zy-4</td>
</tr>
<tr>
<td>Initial enrichment (²³⁵U/U %)</td>
<td>6.85</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Internal gas pressure (MPa, 20°C)</td>
<td>0.101</td>
<td>0.31</td>
<td>0.302</td>
<td>0.301</td>
</tr>
<tr>
<td>Active length (mm)</td>
<td>1004.9</td>
<td>440.8</td>
<td>563.5</td>
<td>559</td>
</tr>
<tr>
<td>Max. burnup (GWh/(tU))</td>
<td>33</td>
<td>53.8</td>
<td>64</td>
<td>63</td>
</tr>
<tr>
<td>Corrosion thickness (µm)</td>
<td>10</td>
<td>35-60</td>
<td>15-25</td>
<td>60-100</td>
</tr>
<tr>
<td>Pulse width FWHM (ns)</td>
<td>9.6</td>
<td>9.5</td>
<td>8.8</td>
<td>31</td>
</tr>
<tr>
<td>Energy deposit (J/g) [cal/g]</td>
<td>865 [207]</td>
<td>511 [122.2]</td>
<td>435 [104]</td>
<td>453 [108.3]</td>
</tr>
<tr>
<td>Cladding OD (mm)</td>
<td>9.51</td>
<td>9.55</td>
<td>9.51</td>
<td>9.51</td>
</tr>
<tr>
<td>Cladding thickness (mm)</td>
<td>0.637</td>
<td>0.596</td>
<td>0.578</td>
<td>0.575</td>
</tr>
<tr>
<td>Pellet OD (mm)</td>
<td>8.05</td>
<td>8.19</td>
<td>8.19</td>
<td>8.19</td>
</tr>
<tr>
<td>Pellet height (mm)</td>
<td>11.99</td>
<td>13.69</td>
<td>13.74</td>
<td>14.25</td>
</tr>
<tr>
<td>Diametral fuel-cladding gap (µm)</td>
<td>186</td>
<td>164</td>
<td>164</td>
<td>164</td>
</tr>
</tbody>
</table>
Conclusion and future work

- CTFFuel was developed from CTF’s fuel solver capability by adding new models, developing a standalone user interface, and testing for transients and depletion.
- CTFFuel is used for providing thermal feedback to MPACT in depletion and transient core-scale simulations.
- Further development was performed this FY by improving models, coupling to VERA for depletions, and improving the fidelity of data transfers.
- Assessments of code accuracy and numerical stability in coupled simulations are currently being performed.
- CTFFuel will become the default fuel temperature thermal feedback solver in an upcoming release of VERA.