Idaho National Engineering and Environmental Laboratory

Prismatic Core VHTR Analysis using RELAP5-3D/ATHENA

Paul D. Bayless

August 28, 2003
Outline

• Analysis objectives
• VHTR description
• RELAP5-3D/ATHENA input model description
• Benchmarking results
• Scoping calculation results
• Code implications
VHTR Analysis Objectives

• Near term
  – develop a representative model of the reactor vessel
  – perform scoping analyses to establish basic operating parameters

• Longer term
  – develop an independent analysis capability for DOE to use during the plant design and licensing phases
What is the VHTR?

- One of the six selected Generation IV reactor concepts
- Helium cooled, graphite moderated, thermal neutron spectrum reactor
- Passively safe
- Reactor vessel coolant outlet temperature of 1000°C
- Will be used for generating both electricity and hydrogen
VHTR Plant Schematic
Reactor Vessel Cross Section
Fuel Element Cross Section
Model Overview

- A simplified RELAP5-3D/ATHENA system model is being used, in which the balance of plant has been neglected thus far.
- Reactor vessel with helium coolant
- Reactor cavity with water coolant and dry noncondensible air
- Reactor cavity cooling system with water coolant and dry noncondensible air
Reactor Vessel Model

- Coolant active and stagnant volumes
- Structures in the core region
  - inner and outer reflectors
  - upper and lower reflectors
  - core barrel
  - upper plenum shield
  - reactor vessel wall and upper head
- Structures below the core are being ignored
- Boundary conditions
  - coolant inlet temperature
  - coolant outlet pressure
  - inlet flow rate adjusted during steady state to provide desired outlet temperature
VHTR Vessel Hydraulic Nodalization
Ex-vessel Model

- Containment air volume
- Reactor cavity cooling system (RCCS)
  - Inlet plenum/downcomer piping
  - Lower distribution plenum
  - Riser/outlet plenum
  - Riser, downcomer, and outer metal walls
- Containment concrete wall and surrounding soil (behind RCCS downcomer)
- Other structures/walls neglected
VHTR Reactor Cavity Nodalization
Heat Transfer Modeling with Original RCCS Model

Axial conduction in core and reflectors

- Core
  - Inner reflector
    - Conduction
  - Outer reflector
    - Convection
  - He coolant
    - Convection

- Reactor vessel
  - Convection
  - Radiation

- RCCS inner wall
  - Convection
  - Radiation

- RCCS interior wall
  - Convection
  - Radiation

- Containment wall
  - Radiation
Heat Transfer Modeling with Revised RCCS Model

- Core
  - Inner reflector
    - Axial conduction in core and reflectors
  - Outer reflector
  - He coolant
    - Radiation

- Reactor vessel
  - Convection, radiation
  - Convection
  - Convection

- RCCS riser wall
  - Radiation

- RCCS downcomer wall
  - Convection
  - Radiation

- Containment wall
Reactor Cavity Radiation Modeled
GT-MHR Benchmarking

• The model is being benchmarked against calculations performed for the gas turbine-modular helium reactor (GT-MHR) by General Atomics.

• The steady state conditions for the VHTR model are adjusted to match the GT-MHR values (outlet temperature of 850°C, lower inlet temperature, higher flow rate).

• High and low pressure conduction cooldown (loss of forced flow) transients are modeled.
The 3-structure riser model has improved the RCCS modeling.

<table>
<thead>
<tr>
<th>Case</th>
<th>Concrete max T (K)</th>
<th>RV outer wall T (K)</th>
<th>RCCS max wall T (K)</th>
<th>RCCS outlet air T (K)</th>
<th>RCCS flow rate (kg/s)</th>
<th>RCCS power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target (GA)</td>
<td>322</td>
<td>719</td>
<td>596</td>
<td>547</td>
<td>14.3</td>
<td>3.30</td>
</tr>
<tr>
<td>Scoping analysis model</td>
<td>347</td>
<td>706</td>
<td>527</td>
<td>450</td>
<td>19.1</td>
<td>2.90</td>
</tr>
<tr>
<td>Current model</td>
<td>321</td>
<td>698</td>
<td>621</td>
<td>545</td>
<td>14.2</td>
<td>3.31</td>
</tr>
</tbody>
</table>
*Reduced decay heat has improved the transient benchmark.*

<table>
<thead>
<tr>
<th>Case</th>
<th>Peak Fuel T (°C)</th>
<th>Peak Vessel T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steady</td>
<td>HPCC</td>
</tr>
<tr>
<td>Target (GA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scoping analysis model</td>
<td>964</td>
<td>1504</td>
</tr>
<tr>
<td>Lower decay heat model</td>
<td>971</td>
<td>1285</td>
</tr>
<tr>
<td>Lower pressure transient</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Scoping Transient Calculations

• **Objectives**
  – Provide feedback to the neutronics development on the effects of different core geometries
  – Determine modeling sensitivities
• **High pressure conduction cooldown**
  – 60-s flow coastdown
  – Steady state operating pressure maintained
• **Low pressure conduction cooldown**
  – 10-s blowdown to atmospheric pressure
  – Air ingress precluded
# Core Configuration Calculations

<table>
<thead>
<tr>
<th>Fuel rings</th>
<th>Core height (blocks)</th>
<th>Reactor vessel dP (kPa)</th>
<th>Peak Fuel T (°C)</th>
<th>Peak Vessel T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Steady</td>
<td>HPCC</td>
</tr>
<tr>
<td>6-8</td>
<td>10</td>
<td>71</td>
<td>1119</td>
<td>1596</td>
</tr>
<tr>
<td>6-8</td>
<td>11</td>
<td>75</td>
<td>1112</td>
<td>1535</td>
</tr>
<tr>
<td>6-8</td>
<td>12</td>
<td>79</td>
<td>1107</td>
<td>1481</td>
</tr>
<tr>
<td>5-7</td>
<td>11</td>
<td>92</td>
<td>1064</td>
<td>1707</td>
</tr>
<tr>
<td>7-9</td>
<td>10</td>
<td>56</td>
<td>1113</td>
<td>1457</td>
</tr>
<tr>
<td>7-9</td>
<td>12</td>
<td>62</td>
<td>1102</td>
<td>1360</td>
</tr>
</tbody>
</table>
HPCC Peak Fuel Temperatures

![Graph showing temperature trends over time for different fuel blocks and rings. The graph includes multiple curves representing different conditions and block configurations.](image-url)
**HPCC Peak Vessel Temperatures**

![Graph showing temperature versus time for different vessel sections](image-url)
LPCC Peak Fuel Temperatures

![Graph showing LPCC Peak Fuel Temperatures](image)
LPCC Peak Vessel Temperatures
# Modeling Sensitivity Calculations

<table>
<thead>
<tr>
<th>Case</th>
<th>Reactor vessel dP (kPa)</th>
<th>Peak Fuel T (°C)</th>
<th>Peak Vessel T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Steady</td>
<td>HPCC</td>
</tr>
<tr>
<td><strong>Base</strong></td>
<td>71</td>
<td>1119</td>
<td>1596</td>
</tr>
<tr>
<td><strong>Coolant channel diameter reduced</strong></td>
<td>79</td>
<td>1125</td>
<td>1628</td>
</tr>
<tr>
<td><strong>Flat axial and radial power profiles</strong></td>
<td>71</td>
<td>1094</td>
<td>1530</td>
</tr>
<tr>
<td><strong>Inner reflector heat capacity increased</strong></td>
<td>71</td>
<td>1119</td>
<td>1522</td>
</tr>
<tr>
<td><strong>0.1 mm He gap around fuel</strong></td>
<td>71</td>
<td>1133</td>
<td>1604</td>
</tr>
<tr>
<td><strong>Bypass channel in inner reflector</strong></td>
<td>61</td>
<td>1170</td>
<td>1547</td>
</tr>
<tr>
<td><strong>Bypass channel in outer reflector</strong></td>
<td>61</td>
<td>1180</td>
<td>1549</td>
</tr>
<tr>
<td><strong>Decay power reduced 15%</strong></td>
<td>71</td>
<td>1119</td>
<td>1483</td>
</tr>
<tr>
<td><strong>New RCCS model</strong></td>
<td>71</td>
<td>1119</td>
<td>1574</td>
</tr>
</tbody>
</table>
Code Results Summary

- The code and model appear to be able to provide reasonable results for the VHTR loss of flow transients.
- Thermal-hydraulic analyses indicate that changes in the core configuration may be helpful.
- Decay power and power distribution may have large impacts on the calculated transient fuel temperatures.
Code Improvement Possibilities

- Axial conduction capability (outside of reflood) for the heat structures
- Air ingress modeling (molecular diffusion)
- Extend/improve the decay heat model to account for the epithermal neutron spectrum in gas reactors
- Extend the material property definition options available to the user
- Allow SCDAP structures to participate in RELAP5 radiation/conduction enclosures