HTGR Technology Course for the Nuclear Regulatory Commission

May 24 – 27, 2010

Module 6b
Pebble Bed HTGR Nuclear Design

Pieter Venter
Pebble Bed Modular Reactor (Pty) Ltd.
Outline

- Pebble bed nuclear design characteristics
- Nuclear design considerations
- Analytical tools
Pebble Bed Nuclear Design

Core Neutronics / Thermal Hydraulics
Analyze Neutronic Design for feedback to both engineering and safety
Steady-State (VSOP, MCNP) and Transient (TINTE) Analysis
Input to engineering on core component temperatures, power profiles etc.
Input to safety on maximum fuel temperatures, control rod worth etc.

Shielding and Activation
Analyze Shielding and Activation of core structures and surrounding
Monte Carlo Analysis (MCNP) or simplified transport analysis (MicroShield)
Input to engineering on core component activities for maintenance / decommissioning
Input to safety for worker dose

Fission Product Releases
Determine Fission Product Releases for both normal operation and accident scenarios
Input to the rest of the source term analysis chain

Dust Generation and Activation
Graphite and metallic dust generation in the core and fuel handling system and activation of the dust

Fuel Source Term
Neutron and photon sources from spent and used fuel
Key Pebble Bed Nuclear Characteristics

- Continuous fueling provides core design flexibility to introduce different fuel cycles online
- Burnup measurement of each sphere instead of calculations reduces core design uncertainty
- No reload analyses are required and approach to criticality is only required for initial core loading or after reflector replacement is performed
Fuel Cycle Flexibility

- Pebble bed can also be used for U-Th, Pu disposition and MOX
- AVR experience demonstrated core operation with between 4 and 14 different fuel elements
  - Heavy metal loadings ranging from 5g to 20g
  - Enrichments ranging from 5% to 93% U-235
- Different fuel cycle can be introduced on-line and the reactivity effect can be monitored continuously during the transition period
Outline

• Pebble bed nuclear design characteristics
• Nuclear design considerations
• Analytical tools
Key Considerations

- Equilibrium core parameters
- Excess reactivity
- Neutron control and shutdown
- Temperature coefficients
- Xenon stability
- Power distribution
- Neutron flux
- Fuel temperatures
- Burnup
- Decay heat
## Typical Equilibrium Core Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>PBMR-400MW</th>
<th>PBMR-250MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>MW</td>
<td>400</td>
<td>250</td>
</tr>
<tr>
<td>Core diameter (inner/outer)</td>
<td>m</td>
<td>2.0/3.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Core height (average)</td>
<td>M</td>
<td>11.0</td>
<td>10.5</td>
</tr>
<tr>
<td>Helium coolant temperatures (Inlet/Outlet)</td>
<td>°C</td>
<td>500/900</td>
<td>250/750</td>
</tr>
<tr>
<td>U-235 enrichment</td>
<td>wt%</td>
<td>9.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Number of average fuel sphere cycles</td>
<td></td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Average residence time in core</td>
<td>Days</td>
<td>~ 930</td>
<td>~ 1080</td>
</tr>
<tr>
<td>Average discharge burn-up</td>
<td>MWd/t</td>
<td>91 450</td>
<td>81 565</td>
</tr>
<tr>
<td>Number of Fuel Spheres (FS)</td>
<td></td>
<td>~ 452 000</td>
<td>~ 400 300</td>
</tr>
<tr>
<td>Average number of fresh fuel spheres to be loaded per day</td>
<td></td>
<td>~ 486</td>
<td>~ 438</td>
</tr>
<tr>
<td>Average number of fuel spheres recirculated per day</td>
<td></td>
<td>~ 2 913</td>
<td>~ 6 566</td>
</tr>
</tbody>
</table>
Load Following Requirement

Xenon Reactivity Effect Due To Power Changes

- Changes in reactor power causes Xe changes in core that affects the reactivity.
- This lowering of reactivity following a power change needs to be compensated for by adding excess reactivity.
Excess Reactivity

• The excess reactivity is the additional reactivity available in the core during operating conditions by the loading of a fuel mixture that is more reactive (less burned) than what is required to keep the reactor critical at the full power operational conditions (temperatures and equilibrium fission products)

• The excess reactivity is balanced by the insertion of the control rods to keep the reactor critical

• The excess reactivity can be changed by changing the position of the control rods and the adjusting loading of fresh fuel into the core
Neutron Control and Instrumentation Requirements

- Provide two independent and diverse systems of reactivity control for reactor shutdown
- Each system shall be capable of maintaining hot subcriticality
- One system shall be capable of maintaining cold shutdown
- Provide neutron flux (low, intermediate and high range) and axial profile measurements
Typical Pebble Bed Neutron Control Systems

- Control rods are used for operational (ROT) control and hot shutdown
- Small absorber spheres (SAS) are used to achieve cold shutdown
- Control rods and SAS are located in reflectors (SR/SR or SR/CR)
- Control rods can be operated in banks
Rapid shutdown of reactor for two different control rod speeds

- 1 cm/s is the normal controlled insertion
- 50 cm/s is the scram speed when the power is cut to the CRDMs
When the coolant flow is stopped through the core, the sphere temperatures increase and the reactor is shutdown, even with no movement of the control rods.

This temperature coefficient effect has been successfully demonstrated in the AVR and HTR-10.
## Temperature Coefficients

<table>
<thead>
<tr>
<th>Temperature Coefficients</th>
<th>Unit</th>
<th>At Operating Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (Doppler coefficient of mainly $^{238}\text{U}$)</td>
<td>$\Delta \rho/^{\circ}\text{C}$</td>
<td>- 4.4 $\times 10^{-5}$</td>
</tr>
<tr>
<td>Moderator</td>
<td>$\Delta \rho/^{\circ}\text{C}$</td>
<td>- 1.0 $\times 10^{-5}$</td>
</tr>
<tr>
<td>Reflector regions (all together)</td>
<td>$\Delta \rho/^{\circ}\text{C}$</td>
<td>+ 1.8 $\times 10^{-5}$</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$\Delta \rho/^{\circ}\text{C}$</td>
<td>- 3.6 $\times 10^{-5}$</td>
</tr>
</tbody>
</table>

- The Doppler temperature coefficient acts promptly and stabilizes the nuclear chain reaction.

- The moderator coefficient acts promptly when temperature change of the moderator is the primary event, and causes a response in the neutron flux and fission rate.

- The reflector temperature changes are not so strongly coupled to power changes in the fuel. The side reflector temperature is dominated by the coolant temperature in the riser channel and combined with the large heat capacity will cause a considerable delay of effect of the reflector temperature coefficient.
Xenon Stability

• Xenon stability refer to the degree to which the spatial flux distribution varies for a specific reactor design due to spatial xenon dynamics

• The main question is whether the change in xenon concentration with time exhibits a damped or un-damped oscillatory behavior

• Previous studies on HTGR-specific xenon stability reported the following conclusions:
  – Un-damped axial xenon oscillations only occurred for HTR cores when the core height was increased to larger than 8 m, with a simultaneous power density increase to more than 20 MW/m³
  – No un-damped radial xenon oscillations were observed for cylindrical cores of up to 6.4 m in radius
Xenon Oscillation Results from 100%-40%-100% Power Variation

- Legend refers to different heights in the core with 100 being near the top of the bed and 1000 being at the bottom of the bed.
Power Shaping

- Pebble beds do not have to use fuel loading or burnable poison to affect power shaping.
- Fuel can be circulated faster through the core to flatten the axial power profile.
- Once equilibrium conditions are established control rods do not need to be moved to compensate for burnup.
Axial Power Distribution

- The power profile is biased towards the top of the core due to the lower fuel temperatures and fresh fuel.
- The top of the power profile is depressed due to the partially inserted control rods.
- Since no burnable poisons are used with on-line refueling, this power profile is representative of the greater part of plant operation.

Note: channels are not physical but represent sphere flow regions for modeling with channel 1 towards the centre of the core and channel 5 towards the outside of the core.
The power produced per fuel sphere reduces with each pass through the core.
Neutron Flux Distribution (Radial)

Radial Flux Profile

Cylindrical, 250MW, 700°C

Flux [n cm⁻² s⁻¹]

Radial Distance (from center) [cm]

- > 0.1 MeV
- 0.1 MeV - 0.009 MeV
- 0.009 MeV - 130 eV
- 130 eV - 1.86 eV
- < 1.86 eV

INL Idaho National Laboratory
Neutron Flux Distribution (Axial)

Axial Flux Profile
(Center of Core)

Cylindrical, 250MW, 700°C

Flux [n cm⁻² s⁻¹]

Axial Distance (from top) [cm]

> 0.1 MeV
0.1 MeV - 0.009 MeV
0.009 MeV - 130 eV
130 eV - 1.86 eV
< 1.86 eV
Temperature Distribution for Equilibrium Core

Axial Fuel Temperature Distribution

Cylindrical, 250MW, 700°C

Axial Height (from top) [cm] vs Average Fuel Temperature [°C]

- Core Center
- Between Core Center and Side Reflector
- Near Side Reflector
Fuel Temperature Distribution

Temperature Distribution

- Average Pebble Surface Temperature
- Average Fuel (UO2) Temperature (Doppler)

Temperature Distribution for Cylindrical, 250MW, 700°C

Percentage of Spheres

Temperature [°C]

295 341 387 433 479 525 571 617 663 709 755 801 847 893 939
• Fuel spheres are circulated through the core continuously and each sphere is measured for burnup as it comes out of the core.

• Fuel spheres that have not yet reached target burn-up, or more specifically the burnup limit setpoint, can be reloaded and recycled continuously during normal reactor operation.

• Fuel spheres with higher burn-up as the setpoint are discharged from the refueling line, and replaced with a fresh fuel sphere. In practice some fuel may pass through the reactor less than the average number of passes while others may pass more times before reaching the setpoint burnup value.

• The Burnup Measurement System discriminates between spent and used fuel spheres by analyzing the gamma energy spectrum to determine the inventory of specific nuclides (specifically Cs-137).
Decay Heat

- German standard DIN is used to evaluate decay heat
- The standard provide the methodology to calculate the heat power generated by the decay of the fission products (valid for all kinds of thermal reactors) and rules concerning the additional sources of decay heat (activation) in the fuel of pebble-bed high temperature reactors

![Graph showing decay heat over time](Cylindrical, 250MW, 700°C)
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PBMR Nuclear Codes

• Analysis Codes
  – **VSOP99/5**: HTR core neutronics code including cell calculations, 2D and 3D reactor physics simulation, depletion and 2D quasi-static thermal-hydraulic
  – **T-REX**: 1-D transport solution used to model control rods for VSOP99/5
  – **TINTE**: HTR transient analysis tool based on 2-D spatial kinetics
  – **GETTER**: Metallic (long lived) fission product release calculation software for normal and accident conditions.
  – **NOBLEG**: Steady state gaseous (short lived) fission product release calculation software
  – **SCALE5**: Used for the calculation of the fuel source term and fuel depletion
  – **DAMD**: Calculation of radioactive source terms on the surfaces and in the coolant due to the plate-out of condensable atomic fission products released from the fuel in the core. The code also calculates the deposition of dust and the amount of dust circulating in the coolant.
  – **MCNP5**: Monte Carlo code for neutron, photon and electron transport and the calculation of criticality
  – **FISPACT**: Code for the calculation of neutron induced activation source terms
Summary

- The nuclear design of a pebble bed reactor is simple and straightforward.
- The on-line refueling provides significant flexibility to the core designer to choose a fuel cycle whilst reducing uncertainty in the core calculations.
- The core designer has well proven and validated nuclear design codes at his disposal to calculate the core behavior and characteristics.
Suggested Reading

- Plutonium Disposition in the PBMR-400 HTGR, E. Mulder, PHYSOR 2004, April 2004