OECD/NEA Transient Benchmark Analysis with PARCS - THERMIX

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OECD/NEA PBMR Workshop
Paris, France
June 16, 2005
Introduction

• Motivation of the benchmark
  – Code-to-code comparisons.
  – Analysis of transient behavior of PBMR (Application of analytic models).

• Original OECD/NEA PBMR benchmark was based on the PBMR-268, but has since been updated to the PBMR-400.

• Results here will first be shown for the original PBMR-268 design, and then initial analysis of the PBMR-400 will be presented
PBMR-268 Design

- Power = 268 MW\textsubscript{th}
- Dynamic Central reflector
- $P_{\text{sys}} = 7$ MPa
- $T_{\text{in-out}} = 500-900^\circ\text{C}$
Some Simplifications of the Model

- Flattening of the pebble bed’s upper surface
- Flat bottom reflector (removal of the bottom cone and discharge tube)
- Flow channels within the pebble bed are parallel and at equal speed
- Dynamic central column and mixing zone widths are constant over the axial height
- Control rods in the side reflector are assumed as a cylindrical skirt with a given B-10 concentration
Code Descriptions: PARCS

- PARCS (Purdue Advanced Reactor Core Simulator) is the U.S. NRC Code for Best Estimate neutronics analysis.
- Nodal (ANM-NEM), Multi-group SP3, FMFD
- Cartesian, Hexagonal, Cylindrical geometries in 3D
- Coupled to RELAP5 and TRACE
- Extensively verified for PWR, BWR, and ACR applications
PARCS for PBMR

• In 2002 U.S. NRC contracted Purdue/PSU to upgrade PARCS for PBMR analysis
• Cylindrical (r-Θ-z) neutronics by FMFD (fine mesh finite difference) kernel was added.
• NRC support was suspended after Exelon withdrew its PBMR license application.
• Work was continued anyway, most recently for T/H feedback. The THERMIX code was implemented as a subroutine into PARCS.
THERMIX

• For PBMR analysis in 2D (r-z)
• Combination of THERMIX and DIREKT

THERMIX

– Solves SS and TR heat transfer in porous medium and conduction in pebble.

DIREKT

– Perform gas flow field and temperature calculation for SS and TR.
Coupling of PARCS-THERMIX

1. PARCS
2. Power Profile
   - Core Geometry
3. Interface Routine
   - Transmits power from neutronics meshes to T/H meshes
4. T/H Power Profile
5. THERMIX
6. Average Mesh Temperature
7. Interface Routine
   - Transmits average temperatures from T/H meshes to neutronics meshes
8. Update Macro X-sections
9. Converged?
   - NO
   - YES → Exit
   - PARCS
Application to PBMR-268: Ejection All 24 Rods at CZP
PARCS-THERMIX Results

Graph 1: Reactivity (\(\delta\)) over time (sec)
- Time axis: 0 to 12 sec
- Reactivity axis: -0.5 to 2
- HZP

Graph 2: Power over time (sec)
- Time axis: 0 to 12 sec
- Power axis: 0 to 16
- HZP
PARCS-THERMIX: Fuel Temp

![Fuel Temperature Over Time Graph](image)

- **FUEL** (red line)
- **SURFACE** (green dashed line)

- **Y-axis:** Temperature (°C)
- **X-axis:** Time (sec)

The graph shows the temperature change over time for fuel and surface conditions.
Analysis of CRE w/ Simplified Prompt Kinetics Model (Nordheim-Fuchs)

- Control Rod Ejection (CRE) analysis at zero power.
- Application of the “Linear Energy Feedback Model” with prompt kinetics approximation.
- Basis to assess PARCS-THERMIX results and to design benchmark cases.
Linear Feedback Model

• The maximum power rise in linear feedback model*

\[ P_m = P^0 - \frac{\rho_{p1}^2}{2\Lambda \gamma_e} \]

* Karl. O. Ott, Robert J. Neuhold “Nuclear Reactor Dynamics”
\[ P^0 = \frac{\rho_1}{\rho_1 - \beta} P_0 \]

\[ \gamma_e (\text{Energy Coefficient}) = C_{IT} \frac{\partial \rho}{\partial T} \]

\[ C_{IT} = \frac{\dot{q}}{\rho_d c_p} \]

\[ C_{IT} = \begin{array}{ll}
400 \text{ K/fp-s} & \text{for FBR} \\
40 \text{ K/fp-s} & \text{for BWRs} \\
13.6 \text{ K/fp-s} & \text{for PBMR}
\end{array} \]
\[ \frac{\partial \rho}{\partial T} = \begin{cases} 
-0.02$/K & \text{for LWRs (Ott)} \\
-0.002$/K & \text{for FBRs (Ott)} \\
-0.0072$/K & \text{for PBMR} 
\end{cases} \]

\[ \gamma = \begin{cases} 
-0.8$/fp-s & \text{for FBRs and LWRs (Ott)} \\
-0.098$/fp-s & \text{for PBRs} 
\end{cases} \]

\[ \beta = 0.00759 \quad \text{for PBMR} \]

\[ \Lambda = 2.23 \times 10^{-3} \]
\[ P^0 = \frac{\rho_1}{\rho_1 - \beta} P_0 = 2.4P_0 \]

\[ P_m - P^0 = -\frac{\rho_{p1}^2}{2\Lambda \gamma_e} = \frac{0.5 \times (0.736)^2 \times 0.00759}{2.23 \times 10^{-3} \times 0.098} = 9.4P_n \]

\[ P_m = 11.8P_0 \]

\[ t_m = \frac{\Lambda}{\rho_{p1}} \left( \ln 4 \frac{p_m}{p_0} \right) \]

\[ t_m = 16.5 \frac{\Lambda}{\rho_{p1}} \quad \text{for} \quad p^0 \square p_m \]

\[ t_m = 16.5 \frac{2.23e - 3}{0.736 \times 0.00759} = 6.5 \text{ sec} \]
Comparison of Results

<table>
<thead>
<tr>
<th>Method</th>
<th>$t_{max}$ (sec)</th>
<th>$P_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytic “Nordheim-Fuchs”</td>
<td>6.5</td>
<td>11.8</td>
</tr>
<tr>
<td>PARCS-THERMIX</td>
<td>6.0</td>
<td>14.5</td>
</tr>
</tbody>
</table>
Conclusions of CRE analysis at HZP.

- The generation time calculated with PARCS is reasonable when compared to the PROTEUS experimental results which are performed with 16% enriched uranium fuel.
- Long neutron generation time results in slower CRE transients than those in the LWR.
- With the use of kinetics data available, the analytic results calculated by PKA with Linear Feedback Model are in reasonable agreement with those obtained by PARCS-Thermix coupled code, so this gives confidence for further analysis with other cores (e.g. PBMR-400)
Further Analysis of CRE

• Transient Response for Different Initial Power levels
  – $1 \times 10^{-6} P_0$ (Zero Power)
  – $1 \times 10^{-3} P_0$
  – $0.1 P_0$
  – $0.5 P_0$
  – $1.0 P_0$ (Full Power)
PARCS-THERMIX: Reactivity
PARCS-THERMIX: Power

\[ t_m = 16.5 \frac{\Lambda}{\rho_{p1}} \]
PARCS-THERMIX: Max. Fuel Temperature

![Graph showing temperature over time for different HOT P scenarios.](image)
Conclusions Cont …

• At full power the control rod worth is significantly higher than that at low powers, primarily because of the bottom peaked axial flux profile resulting from the high temperature difference between top and bottom at full power conditions.

• The transient response with different power levels suggests that the CRE accident at full power is more appropriate for benchmark analysis (i.e. at lower power conditions transients are much slower).
OECD / NEA PBMR-268: Benchmark Case 5

Case B: ejection of all control rods corresponding to a symmetric superprompt transient of more than 2$ of reactivity

Case C: ejection of a single CR corresponding to an asymmetric subprompt critical transient

Case D: ejection of four control rods corresponding to an asymmetric superprompt critical transient
Control Rod Positioning

• The total of 24 CRs are placed into two groups of 12 which are inserted in a “staggered” configuration in the side reflector.
  – Bank 1 (Group 1) is inserted to the bottom part of the core.
  – Bank 2 (Group 2) is inserted to the top part of the core.

• Group 1 is used for the reactivity control during normal operations.
CR positions

- Complete Withdrawal
- Standard Position
- Full Insertion
PARCS CR Modeling Capability

• PARCS can define different types of control rods and assign them to the related banks.

<table>
<thead>
<tr>
<th>Crb_def</th>
<th>1</th>
<th>1</th>
<th>582.3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>0     582.3</td>
</tr>
</tbody>
</table>

| Crb_type | 1 | 2 | 1 |

Type 1

Type 2
Case B: Ejection of All Rods

Initial Condition
- Steady – state full power
- All 24 CRs are inserted 2m from the top of the core.

Sequence of events
- $t = 0$ second to $t = 0.1$ second:
  - Withdrawal of all 24 CRs over 0.1 second.
- $t = 0.1$ second to $t = 60$ seconds:
  - Transient phase completed.
PARCS-THERMIX: Reactivity

![Graph showing reactivity over time](image)
PARCS-THERMIX: Power
PARCS-THERMIX Results

CRE in 0.1 s  ALL CRs IN(200cm)-OUT

- POWER
- REACTIVITY
- MAX. FUEL TEMP.
Summary of Case B Results

– Power level rises up to 80 times the nominal value in 0.7 seconds (HZP).

– The amount of reactivity inserted is about 3$ (HZP).

– The maximum fuel temperature of 1436 ºC is reached at about 2.7 seconds.
### HFP Cases: CR Positions

<table>
<thead>
<tr>
<th>Core Condition</th>
<th>CR insertion Depth</th>
<th>(k_{\text{eff}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>BANK 1&lt;br&gt;BANK 2</td>
<td>425 cm&lt;br&gt;OUT</td>
</tr>
<tr>
<td>Single Rod out</td>
<td>BANK 1(N-1)&lt;br&gt;BANK 1(1)&lt;br&gt;BANK 2</td>
<td>425 cm&lt;br&gt;OUT  OUT</td>
</tr>
<tr>
<td>4 – Rods Out</td>
<td>BANK 1(N-4)&lt;br&gt;BANK 1(4)&lt;br&gt;BANK 2</td>
<td>425 cm&lt;br&gt;OUT  OUT</td>
</tr>
</tbody>
</table>
Case C: Single Rod Ejection (HFP)
Case C: SRE Power
Case C: SRE Max. Fuel Temperature
Case D: Four Rods Ejected (HFP)
Case D: 4 Rods Ejected HFP
Case D: 4 Rods Ejected Max. Fuel Temperature
Conclusions

• The proposed extensions to CASE-5 were analyzed to complement the current Case A:
  – Case B: ejection of all control rods corresponding to a **symmetric superprompt** transient of more than 2$^\circ$ of reactivity.
  – Case C: ejection of a single CR corresponding to an **asymmetric subprompt** critical transient
  – Case D: ejection of four control rods corresponding to an **asymmetric superprompt** critical transient

• The Benchmark specifications were modified to include Cases C and D
• The Cases will be reanalyzed for the PBMR-400
OECD/NEA/NSC
PBMR-400 COUPLED
NEUTRONICS/THERMAL
HYDRAULICS TRANSIENT
BENCHMARK
# PBMR-400 vs. PBMR-268

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PBMR-268</th>
<th>PBMR-400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Power (MW)</td>
<td>268.0</td>
<td>400.0</td>
</tr>
<tr>
<td>System Pressure (MPa)</td>
<td>7.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Mass Flow Rate (kg/s)</td>
<td>129.0</td>
<td>192.7</td>
</tr>
<tr>
<td>Central reflector</td>
<td>Dynamic with graphite pebble</td>
<td>fixed centre graphite reflector column</td>
</tr>
<tr>
<td>Core outer diameter (m)</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Core effective height (m)</td>
<td>8.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Reserve Shutdown System</td>
<td>in outer reflector</td>
<td>in inner reflector</td>
</tr>
</tbody>
</table>
Core Layout of PBMR-400
PBMR-400 Reactivity Control System

- 24 Absorber Rods in the Side Reflector
  – 12 Control Rods
  – 12 Shutdown Rods
- Rod effective height **6.5m**
- Moving depth
  – CR : 6.5m from the bottom of top refl.
  – SR : 10m from the bottom of top refl.
- Normal operation, 24 CR move together.
• STEADY STATE BENCHMARK CALCULATIONAL CASES
  – **CASE S-1**: Neutronics Solution with Fixed Cross Sections
  – **CASE S-2**: Thermal Hydraulic solution with given power / heat sources
  – **CASE S-3**: Combined neutronics thermal hydraulics calculation
    – starting condition for the transients

• TRANSIENT BENCHMARK CALCULATIONAL CASES
  – **CASE T-1**: Depressurised Loss of Forced Cooling (DLOFC) without SCRAM
  – **CASE T-2**: DLOFC with SCRAM
  – **CASE T-3**: Pressurised Loss of Forced Cooling (PLOFC) with SCRAM
  – **CASE T-4**: 100-40-100 Load Follow
  – **CASE T-5**: Reactivity Insertions by CRE
  – **CASE T-6**: Cold Helium Inlet
Case S-1: Simplified Cross-section Sets

- Extracted from VSOP equilibrium core calculation.
- 2-G, thermal cut-off 3.059eV.
- In order to compare neutronics calculations before going into the detailed feedback mechanisms.
## Preliminary Results for Case S-1

<table>
<thead>
<tr>
<th>CODE</th>
<th>k-eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSOP</td>
<td>1.00000</td>
</tr>
<tr>
<td>PARCS (VSOP mesh)</td>
<td>1.00048 (+48 pcm)</td>
</tr>
<tr>
<td>PARCS (fine mesh)</td>
<td>1.00272 (+272 pcm)</td>
</tr>
<tr>
<td>PARCS (VSOP mesh+DDDC)</td>
<td>0.99875 (-125 pcm)</td>
</tr>
</tbody>
</table>
Axial Thermal Flux
Radial Thermal Flux

The graph shows the thermal flux as a function of radial position. Two sets of data are plotted: VSOP (in red) and PARCS (in green). The thermal flux is measured in neutrons per cm² per second (n/cm²/sec). The x-axis represents the radial position in centimeters, ranging from 0 to 300 cm.
Axial Fast Flux

![Graph showing Axial Fast Flux with two curves representing VSOP and PARCS. The x-axis represents Axial position (cm) from TOP to BOTTOM, and the y-axis represents Fast Flux in particles per cm² per second, with values ranging from 0 to 7e+013.]
Axial Power (S.S. Full Power)
Summary / Continuing Work

• Calculations with simplified VSOP cross-sections gives good agreement in flux and power profiles. Some small discrepancies are observed in k-eff results.

• Continuing Work: S-2, S-3 and Transient Cases
• **STEADY STATE BENCHMARK CALCULATIONAL CASES**
  - **CASE S-1**: Neutronics Solution with Fixed Cross Sections
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THANKS