GCFR-PROTEUS EXPERIMENTAL PROGRAM CORE 11- NOMINAL CORE CONFIGURATION BENCHMARK

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Special Thanks

• This project was supported by the U.S. Department of Energy, NEUP program.
Purpose

- Re-evaluate experiments of GCFR Core designs performed in the 1970s at the PROTEUS reactor.

- Preserve decades old integral nuclear data.

- Enable the validation of thorium, neptunium, plutonium, and uranium cross sections.
Purpose of the ICSBEP and IRPhEP
Benchmark Process General Overview

1. Identify Experiment
2. Evaluate Experiment
   a. Prepare Benchmark Report
3. Internal Review of Benchmark Report
4. Submit Benchmark Experiment to ICSBEP/IRPhEP
5. Independent Review of Benchmark Report
6. Distribution of Benchmark Report to Technical Review Group
7. Technical Review Meeting
8. Resolve Action Items
PROTEUS

- Lifetime: February 1968 - April 2011
- Thermal Power Rating: 1 kilowatt.
- Driver Region Dimension: 3.5m diameter/3.5m height.
- Driver Fuel: 1m length UO$_2$ at 5 w/o.
- Central Cavity Dimension: 1.2m diameter/10m height.
- Central Cavity Fuel: Variable
PROTEUS
GCFR-PROTEUS

- April 1972 to April 1979 – Benchmark Experiments in PROTEUS to validate Neutronics calculations in GCFR core
- Increased interest in GFR concepts & Th\(^{232}\)/U\(^{233}\) fuel cycle in the 70’s
- Experiments required for accurate measurement of basic neutron cross section data, supplementing design calculations
- Initial cores – MOX cores (U\(^{238}\)/Pu\(^{239}\) fuel cycle)
- Latter cores dedicated to Th\(^{232}\)/U\(^{233}\) fuel cycle, homogeneous & heterogeneous distributions of Thorium
- C8/F9, F8/F9, C2/F9 etc, characterised breeding ratio, power distribution, neutron spectrum, axial & radial profiles etc.
- Experimental results compared with deterministic calculations
Proteus GCFR Configuration

1. GRAPHITE REFLECTOR
2. GRAPHITE DRIVER
3. D_2O-DRIVER
4. BUFFER (U-METAL)
5. FAST ZONE (PuO_2/UG_2)
6. TEST COLUMN
7. CONTROL ROD
8. MODERATOR TANK
9. REMOVABLE GRID PLATE
Proteus GCFR Configuration
Measurement Techniques

• Spectral Indices: Foil activation / fission chambers

• γ-counting : Twin Ge(Li) or NaI detectors
## Foil Measurements

### Experiment Values and Uncertainties

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Experiment</th>
<th>$1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c8/f9</td>
<td>1.33E-01</td>
<td>1.463E-03 (1.1%)</td>
</tr>
<tr>
<td>f8/f9</td>
<td>3.11E-02</td>
<td>4.043E-04 (1.3%)</td>
</tr>
<tr>
<td>f5/f9</td>
<td>1.01E+00</td>
<td>1.414E-02 (1.4%)</td>
</tr>
<tr>
<td>c2/f9</td>
<td>2.00E-01</td>
<td>2.600E-03 (1.3%)</td>
</tr>
<tr>
<td>f2/f9</td>
<td>8.06E-03</td>
<td>1.612E-04 (2.0%)</td>
</tr>
<tr>
<td>f3/f9</td>
<td>1.52E+00</td>
<td>1.976E-02 (1.3%)</td>
</tr>
<tr>
<td>(n,2n)2/c2</td>
<td>6.84E-03</td>
<td>1.710E-04 (2.5%)</td>
</tr>
<tr>
<td>c7/f9</td>
<td>8.26E-01</td>
<td>1.8998E-02 (2.3%)</td>
</tr>
<tr>
<td>f7/f9</td>
<td>2.27E-01</td>
<td>4.086E-03 (1.8%)</td>
</tr>
</tbody>
</table>

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### Foil Locations

- **UO$_2$-Blanket**
- **PuO$_2$/UO$_2$-Brennstoff**
- **Kote 1400**
- **Kote 1104**
- **Streuung der Grenzlinie in der Kolonne ± 1 mm**
  - (Über 37 Stäbe)
Core 11 MCNP Model

1 – Test Zone (MOX lattice)
2 – Blanket Zone (UO2 lattice)
3 – Buffer zone
4 – D2O zone
5 – Graphite Driver Zone
6 – Grid plates
7 - Reactor support plates
8 – Steel Shielding
Core 11 Energy Profile & Axial Flux Distribution

- 3D Model

- Top Blanket
- MOX Region
- Bottom Blanket

Flux/Lethargy vs. Energy (MeV) and Total Flux
Model Techniques

- Volume Averaging
- \( RR = F4 \times XS \)
- *Spectral Index* = \( \frac{RR_x}{RR_y} \)
- Ratio allows for direct comparison between foil and model volumes
Summary of experimental uncertainties in GCFR-PROTEUS Core 11

<table>
<thead>
<tr>
<th>Spectral Indices</th>
<th>Measurement Uncertainty (Δ/Mean)</th>
<th>Evaluated Experimental Uncertainty (Δ/Mean)</th>
<th>Total Experimental Uncertainty (Δ/Mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c8/f9</td>
<td>1.4630E-03 (1.100%)</td>
<td>1.476E-04 (0.112%)</td>
<td>1.470E-03 (1.106%)</td>
</tr>
<tr>
<td>f8/f9</td>
<td>4.0430E-04 (1.300%)</td>
<td>7.427E-05 (0.235%)</td>
<td>4.111E-04 (1.322%)</td>
</tr>
<tr>
<td>f5/f9</td>
<td>1.4140E-02 (1.400%)</td>
<td>6.774E-04 (0.066%)</td>
<td>1.416E-02 (1.402%)</td>
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<tr>
<td>c2/f9</td>
<td>2.6000E-03 (1.300%)</td>
<td>1.058E-03 (0.514%)</td>
<td>2.807E-03 (1.404%)</td>
</tr>
<tr>
<td>f2/f9</td>
<td>1.6120E-04 (2.000%)</td>
<td>1.855E-05 (0.244%)</td>
<td>1.623E-04 (2.013%)</td>
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<tr>
<td>f3/f9</td>
<td>1.9760E-02 (1.300%)</td>
<td>1.288E-03 (0.086%)</td>
<td>1.980E-02 (1.303%)</td>
</tr>
<tr>
<td>(n,2n)2/c2</td>
<td>1.7100E-04 (2.500%)</td>
<td>1.018E-04 (1.333%)</td>
<td>1.990E-04 (2.910%)</td>
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<tr>
<td>c7/f9</td>
<td>1.8998E-02 (2.300%)</td>
<td>1.321E-03 (0.160%)</td>
<td>1.904E-02 (2.306%)</td>
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<tr>
<td>f7/f9</td>
<td>4.0860E-03 (1.800%)</td>
<td>3.072E-04 (0.135%)</td>
<td>4.098E-03 (1.805%)</td>
</tr>
</tbody>
</table>

Perturbations
Type: Density, isotope fraction, composition, impurities

Scaling Factors: MCNP limitations 10 to 100

Materials: Fuel, structural materials (steel/aluminum), D2O, graphite
## Comparison of ENDF Cross Sections Core 11

<table>
<thead>
<tr>
<th>Spectral Indices</th>
<th>Calculated (ENDF-8B3)</th>
<th>Benchmark</th>
<th>(C/E)-1</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>σ</td>
<td>Value</td>
</tr>
<tr>
<td>c8/f9</td>
<td>1.31E-01</td>
<td>4.69E-04</td>
<td>1.330E-01</td>
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<tr>
<td>f8/f9</td>
<td>3.09E-02</td>
<td>1.64E-04</td>
<td>3.11E-02</td>
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<tr>
<td>f5/f9</td>
<td>1.02E+00</td>
<td>2.67E-03</td>
<td>1.01E+00</td>
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<tr>
<td>f2/f9</td>
<td>2.04E-01</td>
<td>2.72E-03</td>
<td>2.00E-01</td>
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<tr>
<td>f3/f9</td>
<td>7.37E-03</td>
<td>4.12E-05</td>
<td>8.06E-03</td>
</tr>
<tr>
<td>f7/f9</td>
<td>2.25E-01</td>
<td>7.68E-04</td>
<td>2.270E-01</td>
</tr>
</tbody>
</table>

### Graph

- **Diagrams** showing percent deviation from benchmark values for different spectral indices.
- The graph compares data from ENDF-7.1, ENDF-7.0, and ENDF-8B3.
- The percent deviation is plotted on the y-axis ranging from -15% to 15%.
- The spectral indices are labeled on the x-axis.
Comparison of Cross Sections Core 11

Percent Deviation from Benchmark Values

Spectral Index

c8/f9  f8/f9  f5/f9  c2/f9  f2/f9  f3/f9  (n,2n)/c2  c7/f9  f7/f9

ENDF-7.1
ENDF-7.0
JEFF-3.1
JEFF-3.1.1
JEFF-3.2
JENDL-4.0
ENDF-8B3
Core 15 Model
Comparison of Cross Sections

Percent Deviation from Benchmark Values

Spectral Indices

- c8/f9
- f8/f9
- c2/f9
- f2/f9
- f3/f9
- (n,2n)2/c2

- JENDL-4.0
- JEFF-3.2
- JEFF-3.1.1
- JEFF-3.1
- ENDF-7.0
- ENDF-7.1
- ENDF-8B2
Questions?

"Good place to set a benchmark"
Fission U238

Reaction rate ratio w.r.t center vs. Axial Distance (cm)
Capture U238

Reaction rate ratio w.r.t center vs. Axial Distance (cm)

- Calculations
- Experimental

In-set image: Diagram of a reactor core with labeled sections.
Fission Pu239

Reaction rate ratio w.r.t center vs Axial Distance (cm)

- Calculations
- Experimental