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GFR Context

- GFR is a reactor concept for the GEN-IV initiative
- Integrated in the EU FP5 to 7 projects
- Challenges:
  - Heat removal
  - Core neutronics with Pu and MA
  - Materials at high temperature
  - Fuel type CERCER/CERMET, Carbide, Nitride, Oxide
- FAST Code system at Paul Scherrer Inst.
- Past efforts (70s to 00s) with evolutionary concepts – Pu oxides with metal cladding and limited temperature
• PROTEUS zero power research reactor (1968-2011)
• Power ~ 1kW
• Driven system
• Large test zone at the center
• Buffer region to adjust spectrum
• Driver regions
  • D₂O and graphite regions
  • Safety and control rods
  • Instrumentation
GCFR Program (1970’s)

- Investigate GCFR with PuO$_2$/UO$_2$
  (15% Pu, air cooled, $E \approx 185$keV)

- Investigate Thorium cross sections in fast spectra

- Radial and axial blankets
  - U depleted
  - ThO$_2$ / Th metal

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GCFR Measurements

• Axial / radial reaction rate distributions (activation foils / fission ch.)
  • Capture in $^{238}\text{U}$, $^{232}\text{Th}$
  • Fission in $^{239}\text{Pu}$, $^{238}\text{U}$, $^{235}\text{U}$, $^{233}\text{U}$, $^{232}\text{Th}$

• Spectral indices
  • C8/F9, F8/F9, F5/F9,
  • C2/F9, (n,2n)2/C2, F3/F9
  • C7/F9, F7/F9

• Small sample reactivity worth

• Neutron spectrum measurements
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  - $\text{C2/F9}$, $(n,2n)2/C2$, $\text{F3/F9}$
  - $\text{C7/F9}$, $\text{F7/F9}$

- Small sample reactivity worth

- Neutron spectrum measurements
- Deterministic Calculations
  - SN 1-D, DIFF-1D
  - DIFF-2D

- Cross-Section Libraries
  - ENDF/B-IV
  - FGL5

- Cross-Sections prepared with GGC-4 and MURLAB cell codes
GCFR New Calculation Models

- Monte Carlo Calculations (MCNPX)
  - 2D lattice equivalent cell model
  - 3D whole-reactor core model

- Cross Section Libraries
  - JEFF-3.1 and 3.1.1,
  - ENDF/B-VII.0 and VII.1
  - JENDL-3.3 and 4.0

- Configurations
  - Homogeneous PuO₂/UO₂ lattice
  - Mixed PuO₂/UO₂-ThO₂ lattice
Representativeness of the PROTEUS Lattice
• Spectral indices correction factors (ENDF/B-VII.0)
  
  \[
  \begin{align*}
  C8/F9 & : 0.988 \ (0.2\%), \\
  F8/F9 & : 0.978 \ (0.2\%), \\
  C2/F9 & : 1.028 \ (0.5\%), \\
  F2/F9 & : 0.978 \ (0.3\%), \\
  C7/F9 & : 1.033 \ (0.2\%), \\
  (n,2n)2/C2 & : 0.965 \ (1.5\%)
  \end{align*}
  \]
Calculated Reaction Rate Comparisons

<table>
<thead>
<tr>
<th>Reaction</th>
<th>B70/B71</th>
<th>J31/B71</th>
<th>JN33/B71</th>
<th>J311/B71</th>
<th>JN40/B71</th>
</tr>
</thead>
<tbody>
<tr>
<td>F5</td>
<td>1.000</td>
<td>1.002</td>
<td>0.999</td>
<td>1.002</td>
<td>0.990</td>
</tr>
<tr>
<td>F8</td>
<td>1.000</td>
<td>0.996</td>
<td>1.004</td>
<td>0.996</td>
<td>0.999</td>
</tr>
<tr>
<td>F9</td>
<td>1.000</td>
<td>0.997</td>
<td>1.002</td>
<td>0.997</td>
<td>1.005</td>
</tr>
<tr>
<td>(n,2n)2</td>
<td>1.002</td>
<td>1.020</td>
<td>0.851</td>
<td>1.020</td>
<td>0.987</td>
</tr>
<tr>
<td>F2</td>
<td>0.976</td>
<td>1.046</td>
<td>1.042</td>
<td>1.046</td>
<td>1.059</td>
</tr>
<tr>
<td>C8</td>
<td>0.999</td>
<td>1.003</td>
<td>1.028</td>
<td>1.003</td>
<td>1.002</td>
</tr>
<tr>
<td>C2</td>
<td>0.994</td>
<td><strong>0.976</strong></td>
<td>0.916</td>
<td><strong>0.976</strong></td>
<td><strong>0.983</strong></td>
</tr>
<tr>
<td>F3</td>
<td>1.000</td>
<td>1.005</td>
<td>1.005</td>
<td>1.005</td>
<td>1.006</td>
</tr>
<tr>
<td>F7</td>
<td>1.000</td>
<td>1.001</td>
<td>1.001</td>
<td><strong>0.963</strong></td>
<td>0.992</td>
</tr>
<tr>
<td>C7</td>
<td>1.002</td>
<td><strong>0.960</strong></td>
<td><strong>0.960</strong></td>
<td><strong>0.972</strong></td>
<td><strong>0.974</strong></td>
</tr>
</tbody>
</table>

- $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{233}\text{U}$ fissions and $^{238}\text{U}$ captures are consistent
- $^{237}\text{Np}$ captures 3-4% higher for B71 than other libraries
- $^{232}\text{Th}$ reaction rates larger differences between libraries
From JEFF-3.1 to JEFF-3.1.1

• Cross section changes
  • Np-237 (n,γ) value was underestimated by 10% at thermal energy in JEFF-3.1 and has been corrected in JEFF-3.1.1
  • Pu-239 cross sections revised to account for the overestimation of the Plutonium-solution-thermal criticality experiments

• Reaction rate changes in the GCFR spectra
  (using full core MCNPX model with Flux calculated with ENDF/B-VII.1)

<table>
<thead>
<tr>
<th>Reaction Value (J311/J31)</th>
<th>F7</th>
<th>C7</th>
<th>F9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.963</td>
<td>1.012</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>
\(^{237}\text{Np fissions with JEFF-3.1 and 3.1.1}\)

\[J311/J31 = 0.963\]
$^{237}$Np captures with JEFF-3.1 and 3.1.1

Np-237 capture rate in center of GCFR Core 11

$J_{311}/J_{31} = 1.012$
$^{232}$Th fissions with ENDF/B-VII.0 and VII.1

Th-232 fission rate in center of GCFR Core 11

$B71/B70 = 1.024$
• $^{235}$U and $^{233}$U fissions and $^{238}$U captures are well predicted
• $^{238}$U fissions is well predicted except for JN33 (corr. in JN40)
• $^{237}$Np captures tend to be underestimated in all but B70 and B71
• $^{237}$Np fissions are well predicted except for J311
### Spectral Indices Agreement with Exp. (2/2)

<table>
<thead>
<tr>
<th>SI / Library</th>
<th>B70</th>
<th>B71</th>
<th>J31</th>
<th>J311</th>
<th>JN33</th>
<th>JN40</th>
</tr>
</thead>
<tbody>
<tr>
<td>C8/F9</td>
<td>0.995 (1.2%)</td>
<td>0.997 (1.2%)</td>
<td>0.993 (1.2%)</td>
<td>0.991 (1.2%)</td>
<td>0.993 (1.2%)</td>
<td>0.981 (1.2%)</td>
</tr>
<tr>
<td>F8/F9</td>
<td>1.009 (1.4%)</td>
<td>1.009 (1.4%)</td>
<td>0.992 (1.4%)</td>
<td>0.992 (1.4%)</td>
<td><strong>1.032 (1.4%)</strong></td>
<td>1.008 (1.4%)</td>
</tr>
<tr>
<td>F5/F9</td>
<td>1.012 (1.5%)</td>
<td>1.013 (1.5%)</td>
<td>1.012 (1.5%)</td>
<td>1.011 (1.5%)</td>
<td>1.009 (1.5%)</td>
<td>0.991 (1.5%)</td>
</tr>
<tr>
<td>F3/F9</td>
<td>0.987 (1.4%)</td>
<td>0.986 (1.4%)</td>
<td>0.992 (1.4%)</td>
<td>0.995 (1.4%)</td>
<td>0.990 (1.4%)</td>
<td>0.983 (1.4%)</td>
</tr>
<tr>
<td>C2/F9</td>
<td>1.015 (1.4%)</td>
<td><strong>1.032 (1.5%)</strong></td>
<td>0.985 (1.5%)</td>
<td>0.994 (1.6%)</td>
<td><strong>0.931 (1.6%)</strong></td>
<td>0.985 (1.5%)</td>
</tr>
<tr>
<td>F2/F9</td>
<td><strong>0.913 (2.1%)</strong></td>
<td><strong>0.935 (2.1%)</strong></td>
<td>0.965 (2.1%)</td>
<td>0.965 (2.1%)</td>
<td>0.996 (2.1%)</td>
<td>0.991 (2.1%)</td>
</tr>
<tr>
<td>(n,2n)2/C2</td>
<td><strong>1.084 (2.9%)</strong></td>
<td>1.054 (2.9%)</td>
<td><strong>1.112 (3.2%)</strong></td>
<td>1.051 (3.8%)</td>
<td>1.026 (3.8%)</td>
<td><strong>1.126 (3%)</strong></td>
</tr>
</tbody>
</table>

- $^{232}$Th captures underestimated in JN33 but corrected in JN40
- $^{232}$Th fissions underestimated in B70 and B71
- $^{232}$Th (n,2n) overestimated in B70, J31 and JN40
• MCNPX 3D whole reactor model of the GCFR experiments in the zero power reactor PROTEUS has been built

• PROTEUS configuration has been shown to be representative of an infinite lattice

• Spectral indices predictions with modern libraries and the 3D MCNPX model improve previous results (deterministic/old libraries)
Conclusions (2/2)

• General good agreement between predictions and experimental results is seen in the PuO$_2$/UO$_2$ lattice with the exception of:

<table>
<thead>
<tr>
<th>Library</th>
<th>F8/F9</th>
<th>C7/F9</th>
<th>C2/F9</th>
<th>F2/F9</th>
<th>(n,2n)2/C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENDF/B-VII.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.913 (2.1%)</td>
<td>1.084 (2.9%)</td>
</tr>
<tr>
<td>JEFF-3.1</td>
<td>-</td>
<td>0.951 (2.4%)</td>
<td>-</td>
<td>-</td>
<td>1.112 (3.2%)</td>
</tr>
<tr>
<td>JENDL-3.3</td>
<td>1.032 (1.4%)</td>
<td>0.953 (2.4%)</td>
<td>0.931 (1.6%)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ENDF/B-VII.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.935 (2.1%)</td>
<td>-</td>
</tr>
<tr>
<td>JEFF-3.1.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JENDL-4.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.126 (3%)</td>
</tr>
</tbody>
</table>

• Better agreement with the latest libraries (B71, J31 and JN40)
• All results are in good agreement with JEFF-3.1.1
• Some trends:
  • J31 -> J311: Capture in $^{237}$Np improved, Fission in $^{237}$Np worsen
  • B70->B71: Fission in $^{232}$Th improved
• PROTEUS GCFR experiments are rich
  • 20 configurations with axial / radial blankets
  • Oxide and metal thorium investigations
  • Several type of measurements – SI, reaction rate dist., react. worth

• Capitalize on the effort to construct a high fidelity whole core model of the GCFR experiments

• Extend the Spectral Indices validations to heterogeneous core configurations with thorium oxide and metal

• Investigate the axial and radial reaction rate distributions at the interface between PuO$_2$/UO$_2$ and thorium oxide and metal pins
Thanks are due to:

- *swissnuclear* for their constant support of the PROTEUS reactor and PROTEUS teams
- R. Capote and A. Trkov for their assistance with JENDL-4.0 and ENDF/B-VII.1