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Adjustment Study in JAEA

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Objective and History of Adjustment
Study for FBR

1. Objective
To improve the prediction accuracy of FBR core nuclear design, the adjusted cross-section set, which combined integral experimental information with differential nuclear data, is being developed in Japan.

2. History
1) 1989 – 1991: A cooperative study between JAEA and JAPC was performed to create the ADJ91 set based on JENDL-2 --> Applied to the design study of the Demonstration FBR.
2) 1992 – 1995: JAEA, Hitachi and Osaka Univ. developed the sensitivity method and analytical system for the burnup characteristics and Doppler reactivity.
   --> Being used in the future FBR project (FS and FaCT).
## Main Features of Adjusted Cross-section Sets

<table>
<thead>
<tr>
<th></th>
<th>ADJ91</th>
<th>ADJ2000</th>
<th>ADJ2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nuclear parameters to be adjusted</strong></td>
<td>$\sigma_{\infty}$ of 11 nuclides (32 reactions), $\chi$ of 2 nuclides, $\beta$ of 6 nuclides</td>
<td>$\sigma_{\infty}$ of 11 nuclides (41 reactions), $\chi$ of 2 nuclides, $\beta$ of 6 nuclides, self-shielding factors of U-238</td>
<td>In addition, MA nuclides</td>
</tr>
<tr>
<td><strong>Nuclear data covariance</strong></td>
<td>Rough estimation from difference between measured values and JENDL-2</td>
<td>Covariance data file of JENDL-3.2, evaluated by the Japan Sigma Committee</td>
<td>Covariance data file of JENDL-4</td>
</tr>
<tr>
<td><strong>Integral experimental data</strong></td>
<td>82 data from JUPITER experiment</td>
<td>237 data from JUPITER, FCA, JOYO, BFS, MASURCA and Los Alamos, including burnup and Doppler data.</td>
<td>In addition, MA irradiation data, ZEBRA, SEFOR, Monju</td>
</tr>
</tbody>
</table>
Theory of Cross-section Adjustment


- Based on the Bayes theorem, i.e., the conditional probability estimation method
  
  $J(T) = (T-T_0)^t M^{-1}(T-T_0) + [Re-Rc(T)]^t[Ve+Vm]^{-1}[Re-Rc(T)]$
  
  Minimize the function $J(T)$. → $dJ(T)/dT = 0$

- The adjusted cross-section set $T'$, and its uncertainty (covariance), $M'$
  
  $T' = T_0 + MG'[GMG'+Ve+Vm]^{-1}[Re-Rc(T_0)]$
  $M' = M - MG'[GMG'+Ve+Vm]^{-1}GM$

- Prediction error induced by the cross-section errors

Before adjustment: $GMG'$

After adjustment: $GM'G'$

Where, $T_0$: Cross-section set before adjustment
$M$: Covariance before adjustment
$Ve$: Experimental errors of integral experiments
$Vm$: Analytical modeling errors of integral experiments
$Re$: Measured values of integral experiments
$Rc$: Analytical values of integral experiments

$G$: Sensitivity coefficients, $(dR/R)/(dσ/σ)$

If $GMG'\ll Ve+Vm$, $T'\approx T_0$ and $GM'G'\approx GMG'$
If $GMG'\gg Ve+Vm$, $GM'G'\approx Ve+Vm$
If $GMG'\approx Ve+Vm$, $GM'G'\approx 1/2 \times GMG'$
Sensitivity Coefficient of Doppler Reactivity


- Conventional sensitivity method treats only infinitely-diluted cross-sections. → Impossible to evaluate Doppler reactivity.

- Doppler reactivity: \[ R = \frac{1}{k_{\text{eff,low}}} - \frac{1}{k_{\text{eff,high}}} \]

- Relationship of effective cross-sections with temperature:
  \[ \sigma_{\text{eff,high}} \approx \left( f_{\text{low}} + \left( \frac{df}{dT} \right) \Delta T \right) \sigma_{\text{eff,low}} = (1 + f' \Delta T) \sigma_{\text{eff,low}} \]
  where,
  \[ f' = \frac{1}{f_{\text{low}}} \left( \frac{df}{dT} \right) = \alpha \]

- Introduction of pseudo-cross-sections, \( df/dT (=f') \):
  \[ S_{f'} = \frac{dR / R}{df'/f'} = \left( \frac{\sigma_{\text{eff,high}} - \sigma_{\text{eff,low}}}{\sigma_{\text{eff,high}}} \right) \times \frac{1}{R} \times \frac{S_{k_{\text{eff,high}}}}{k_{\text{eff,high}}} \]
  where,
  \[ S_{k_{\text{eff,high}}} = \frac{dk_{\text{eff,high}} / k_{\text{eff,high}}}{d\sigma_{\text{x,high}} / \sigma_{\text{x,high}}} \]
  (Merits) 1) Easily calculated from the sensitivity of criticality, \( S_{k_{\text{eff}}} \)
  2) No influence to the self-shielding factors at room temperature.
Sensitivity for Sample Doppler Reactivity (ZPPR-9 Core)

- The df/dT of U-238 capture has largely positive sensitivity at keV energy region.

- Sensitivity of Pu-239 fission is negative, since it increases the denominator of perturbation.

- There is also a certain sensitivity to space-related reactions, since it also has the characteristics of local sample reactivity.
Generalized Perturbation Theory for Burnup characteristics


- Needs: 1) Use of power reactor data such as burnup reactivity loss or composition changes of fuel nuclides
- 2) Evaluation of FBR nuclear design accuracy

- Net sensitivity: \( S(\sigma^g_x) = \frac{dR / R}{d\sigma^g_x / \sigma^g_x} = \sigma^g_x \times \left\{ S_D + S_N + S_\phi + S_\phi^* + S_P \right\} \)

\[
S_D = \sum_{i=1}^{l_i} \left[ \int_{t_i}^{t_{i+1}} dt \frac{\partial R}{\partial \sigma^g_x} \right]_{E,V} \quad \text{: Direct term}
\]
\[
S_N = \sum_{i=1}^{l_i} \left[ \int_{t_i}^{t_{i+1}} dt \left( N^* \frac{\partial M}{\partial \sigma^g_x} N \right) \right]_{E,V} \quad \text{: Atomic number density term} \quad \frac{\partial}{\partial t} N(t) = M \times N(t) \quad \text{: Burnup equation}
\]
\[
S_\phi = \sum_{i=1}^{l_i} \left[ \Gamma_i^* \frac{\partial B}{\partial \sigma^g_x} \phi_i \right]_{E,V} \quad \text{: Normal flux term} \quad P_i = \int_{E,V} dEdV [\kappa \sigma_f N \phi] \quad \text{: Reactor power}
\]
\[
S_\phi^* = \sum_{i=1}^{l_i} \left[ \Gamma_i \frac{\partial B}{\partial \sigma^g_x} \phi_i^* \right]_{E,V} \quad \text{: Adjoint flux term} \quad P^* : \text{Adjoint power}
\]
\[
S_P = \sum_{i=1}^{l_i} \left[ P_i^* \frac{\partial P}{\partial \sigma^g_x} \right]_{E,V} \quad \text{: Power normalization term} \quad N_i^* : \text{Adjoint atomic number density}
\]
Sensitivity for Burnup Reactivity Loss
( JOYO Mk-I Core )

- **Direct term** is negative because it increases Denominator.
- **Atomic number density term** is positive since it accelerates the decrease of Pu-239.
- **Power normalization term** is negative because it lowers the neutron flux level.

Net sensitivity of Pu-239 fission is slightly negative because of these cancellation.
Group-structure Covariances

(Comparison of Pu-239 Fission Cross-section)

Integral Data for Fast Reactors (1/4)

**JUPITER Critical Experiment**
- Cooperative study of DOE and JNC in 1978～1988, using ZPPR facility at ANL, USA.
- The largest FBR mockup experiment in history, 4,600 – 8,500 liters.
- Various core concepts, sizes, and structures:
  - 600～800MWe-class two-region homogeneous cores,
  - 650MWe-class radially-heterogeneous cores,
  - 650MWe-class axially-heterogeneous cores,
  - and, 1000MWe-class homogeneous cores with enriched uranium regions.
- Many kinds of measured parameters.

As-built experimental information is available for the public.

ZPPR Critical Assembly (ANL)
Integral Data for Fast Reactors (2/4)

- **FCA Critical Experiment**
  - Fast Critical Assembly at JAEA, Japan.
  - To simulate small FBR cores with plutonium and enriched uranium fuels.
    - FCA X-1 Core (1982) - 130 liters.

- **Experimental Reactor JOYO**
  - First Japanese FBR (1st Criticality in 1977)
    - Burnup, pin-wrapper structure.
      - Mixed one-region plutonium and enriched uranium core with 240 liter-size.
      - Criticality, fuel-blanket replacement reactivity, and burnup reactivity were adopted.
  - JOYO Mk-I Core (JAEA) (Minimum critical core)

As-built experimental information is available for the public.
Integral Data for Fast Reactors (3/4)

**BFS-1, 2 Critical Experiment**
- Fast Critical Assembly at IPPE, Obninsk, Russia.

**MASURCA Critical Experiment**
- Fast Critical Assembly at CEA, Cadarache, France.
  - ZONA2B Core (1996) — a 380 liter-size MOX fuel core with reflectors, which simulated Pu-burner.
Integral Data for Fast Reactors (4/4)

- **Los Alamos Small Core Experiment**
  - Sphere-shaped cores of approx. ten centimeter in diameter with metallic fuel consisted of Pu-239, or degraded Pu, or U-235.
  - FLATTOP-Pu, FLATTOP-25, JEZEBEL, JEZEBEL-Pu, GODIVA (1950s – early 60s)

Benchmark models have already opened.

- **Other Experiments**
  - **ZEBRA** (MOZART program, 1971-73, UK) - a 560 liter-sized single-region and a 1,800 liter-sized two-region MOX cores.
  - **SEFOR** (General Electric, 1969-72, USA) - a 20MWt fast power reactor core fueled with mixed PuO₂-UO₂ and cooled with sodium.
  - **Monju** (JAEA, 1st Criticality in 1994, Japan) - a 280MWe FBR with MOX fuel.

Los Alamos Small Core (JEZEBEL)
Determination of Experimental and Analytical Uncertainties

- **Experimental uncertainty**
  - Follows the evaluation by experimenters like ANL.

- **Analytical modeling uncertainty**
  - Assumes it is proportional to the sensitivity against the degree of modeling detail,
  - Absolute value was decided to make the ratio of the chi-square value to the freedom approx. unity.

- **Elimination of abnormal data**
  - Excludes if the deviation of C/E value from unity is three times larger than the total uncertainty value.

<table>
<thead>
<tr>
<th>Core Parameter</th>
<th>Experimental uncertainty</th>
<th>Analytical Modeling uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUPITER, FCA, etc.</td>
<td>0.04%</td>
<td>0.17%</td>
</tr>
<tr>
<td>Los Alamos</td>
<td>0.1~0.18%</td>
<td>0.15%</td>
</tr>
<tr>
<td>F28/F49 Ratio</td>
<td>2.5%</td>
<td>1.1%</td>
</tr>
<tr>
<td>F25/F49, C28/F49 Ratio</td>
<td>2.2%</td>
<td>0.55%</td>
</tr>
<tr>
<td>F49 Distribution</td>
<td>1.0%</td>
<td>0.6~1.2%</td>
</tr>
<tr>
<td>Control Rod Worth</td>
<td>1.2%</td>
<td>1.3%</td>
</tr>
<tr>
<td>Sodium Void Reactivity</td>
<td>2%</td>
<td>5.5~8.8%</td>
</tr>
<tr>
<td>Doppler Reactivity</td>
<td>2.0~3.0%</td>
<td>5.0~6.6%</td>
</tr>
</tbody>
</table>
Change of Nuclear Data
- Pu-239 Fission -

- In the simultaneous evaluation region, the error values are small.
- On the other hand, the errors are large in the resonance region.
- Change of the fission cross-section by adjustment follows such energy dependency.
The C/E values of criticality after adjusted are within ±0.3% Δk, except several small cores.

The good performance is not only for Pu-fuel cores, but enriched-U fuel cores.
The C/E values of reaction rate distribution after adjusted are sufficiently smaller than ±1.5% in the core fuel region.

There is room for improvement for the blanket region.
It seems Re-investigation is needed for the accuracy of sample Doppler reactivity measurements.
The effect of adjustment is small for JUPITER and FCA experiment, and the C/E values are within app. ±10%.

The discrepancy of C/E values from 1.0 may be caused by something, besides nuclear data.
A 600 MWe-class FBR Core

Core structure of a 600 MWe-class FBR
Nuclear Design Accuracy of a 600 MWe-class FBR

*1σ value (Non-diagonal terms show correlation factors.)*

<table>
<thead>
<tr>
<th>Nuclear parameter</th>
<th>Criticality (End of equilibrium cycle)</th>
<th>Breeding ratio (C28/F49 reaction rate ratio)</th>
<th>Power distribution (Outer core region)</th>
<th>Doppler reactivity (Whole core region)</th>
<th>Na void Reactivity (Whole core region)</th>
<th>Burnup reactivity loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>0.81 (0.78)%</td>
<td>-0.54</td>
<td>0.49</td>
<td>-0.54</td>
<td>-0.02</td>
<td>0.24</td>
</tr>
<tr>
<td>(Symmetry matrix)</td>
<td></td>
<td>-1.5 (1.2) %</td>
<td>1.4 (1.1) %</td>
<td>4.0 (3.4) %</td>
<td>6.1 (3.7) %</td>
<td>5.6 (5.4) %</td>
</tr>
<tr>
<td>Contribution from nuclear data covariances.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Design Accuracy Improvement of a 600 MWe-class FBR

( *1σ value )

<table>
<thead>
<tr>
<th>Nuclear parameter</th>
<th>Design method</th>
<th>No use of integral information</th>
<th>E/C-bias method</th>
<th>Cross-section adjustment method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criticality (End of equilibrium cycle)</td>
<td></td>
<td>0.81</td>
<td>0.41</td>
<td>0.23</td>
</tr>
<tr>
<td>Breeding ratio (C28/F49 reaction rate ratio)</td>
<td></td>
<td>1.5</td>
<td>2.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Power distribution (Outer core region)</td>
<td></td>
<td>1.4</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Doppler reactivity (Whole core region)</td>
<td></td>
<td>4.0</td>
<td>4.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Na void Reactivity (Whole core region)</td>
<td></td>
<td>6.1</td>
<td>6.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Burnup reactivity loss</td>
<td></td>
<td>5.6</td>
<td>7.5</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Concluding Remarks

- JAEA has performed the nuclear data adjustment study for 20 years, continuously. As a result, a unified cross-section set, **ADJ2000**, was developed, the features of which are, JENDL-3.2 base, adjustment of self-shielding factors, application of the latest cross-section covariance, experiments of wide-variety cores, adoption of burnup characteristics and Doppler reactivity.

- ADJ2000 can predict **wide-variety cores** with high accuracy, from large to small size cores, and from critical experiments to power reactor, for **various core parameters**, being used in the future FBR development project.

The next adjusted set, **ADJ2010**, is quite soon expected with JENDL-4 and associated **covariance data**.