Evaluation on Calculation Accuracy of the Sodium Void Reactivity for Low Void Effect Fast Reactor Cores with Experimental Analyses

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1. Introduction

• Considerable positive reactivity insertion by sodium voiding due to unlike event of an unprotected transient in fast reactors →Important issue on reduction of sodium void reactivity in terms of safety enhancement

• Low or Negative sodium (Na) void effect core concepts in recent fast reactor core designs

• Compilation of FBR core design database based on the latest Japanese core analysis system
2. Low Na Void Effect Core Concepts

Adoption of **Na plenum, Heterogeneous arrangement** and/or **Core height difference** to achieve negative or low sodium void effect

3. Low Na Void Effect Experiments (1/4)
- Experimental Facilities -

ZPPR (Critical facility, US)  BFS-2 (Critical facility, Russia)  FCA (Critical facility, Japan)

3. Low Na Void Effect Experiments (2/4)
- Core Geometries for Experiments -

ZPPR-9 (Homogeneous)

ZPPR-13A
(Radially-heterogeneous)

ZPPR-17A
(Axially-heterogeneous)

BFS-66-1
(With Na plenum)

FCA XVII-1
(With Na plenum)

Na voided region
Radial blanket region
Axially-Internal blanket region
3. Low Na Void Effect Experiments (3/4)
- Analysis Results with Japanese System -

Fig. Analysis Results with Japanese latest core analysis system
(Detailed deterministic method with JENDL-4.0)

Larger discrepancies in ZPPR-13A and BFS-66-1 than those in others
(However, disadvantage in conventional Monte Carlo method for small reactivity)
3. Low Na Void Effect Experiments (4/4)

- Uncertainty Evaluation Results -

- Consistency between larger calculation uncertainties and larger experiment-calculation discrepancies in ZPPR-13A and BFS-66-1
- Requirement of much finer treatment for these cores

Fig. Uncertainty evaluation results with Japanese system
4. Utilization of Core Design Database (1/5)
- Facilities and Cores for Experiments -


2-component (Non-leakage / Leakage) bias-factor method utilizing ZEBRA, MASURCA and Joyo in addition to ZPPR, BFS and FCA for an improvement of Na void reactivity calculation accuracy

4. Utilization of Core Design Database (2/5)
- Estimation of 2-component Bias-factors -

Table 1  **Core region void without Na plenum** from ZPPR and ZEBRA

<table>
<thead>
<tr>
<th>Core</th>
<th>Non-leakage</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZPPR-9</td>
<td>0.88</td>
<td>0.80</td>
</tr>
<tr>
<td>ZPPR-10A</td>
<td>0.86</td>
<td>0.71</td>
</tr>
<tr>
<td>ZPPR-10B</td>
<td>0.85</td>
<td>0.73</td>
</tr>
<tr>
<td>ZPPR-13A</td>
<td>0.90</td>
<td>0.95</td>
</tr>
<tr>
<td>ZPPR-17A</td>
<td>0.87</td>
<td>0.89</td>
</tr>
<tr>
<td>ZEBRA</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>ZPPR Homo</td>
<td>0.86</td>
<td>0.73</td>
</tr>
<tr>
<td>ZPPR Hetero and ZEBRA</td>
<td>0.89</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 2  **Core region void without Na plenum** from BFS and MASURCA

<table>
<thead>
<tr>
<th>Core</th>
<th>Non-leakage</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFS-2</td>
<td>0.96</td>
<td>1.04</td>
</tr>
<tr>
<td>BFS-1</td>
<td>0.98</td>
<td>1.13</td>
</tr>
<tr>
<td>MASURCA</td>
<td>0.97</td>
<td>1.13</td>
</tr>
<tr>
<td>BFS-1 and MASURCA</td>
<td>0.97</td>
<td>1.13</td>
</tr>
</tbody>
</table>

Table 3  **Blanket region void** from ZPPR and ZEBRA

<table>
<thead>
<tr>
<th>Core</th>
<th>Non-leakage</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket all</td>
<td>1.12</td>
<td>1.02</td>
</tr>
</tbody>
</table>

Table 4  **Core or Na plenum region void with Na plenum** from BFS and FCA

<table>
<thead>
<tr>
<th>Core</th>
<th>Non-leakage</th>
<th>Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFS-2 core</td>
<td>0.83</td>
<td>0.81</td>
</tr>
<tr>
<td>BFS-2 all</td>
<td>0.87</td>
<td>0.89</td>
</tr>
<tr>
<td>All (Reference)</td>
<td>0.87</td>
<td>0.89</td>
</tr>
<tr>
<td>All (Secondary)</td>
<td>0.85</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Prudent estimation or grouping of 2-component bias-factors considering **Core arrangement** (Homogeneous/Heterogeneous), **Core size** (Middle/Small), **Voided region** (Core/Blanket/Na plenum) and **Cell structure** (Plate, Pellet, Pin)
4. Utilization of Core Design Database (3/5)  
- Results with Bias-factor method (C-E) -

- Applied bias-factors: ZPPR homogeneous for ZPPR-9, ZPPR heterogeneous for ZPPR-13A and 17A, with Na plenum for BFS-66-1 and FCA XVII-1
- Agreement within 2 cents after application of the bias-factor method

Fig. C-E value results of 2-component bias-factor method for representative cores
Fig. C/E-1 value results of 2-component bias-factor method for representative cores

Agreement within 10% after application of the bias-factor method except for the small reactivity cases with larger experimental uncertainty
4. Utilization of Core Design Database (5/5)
- Prediction for Designed Low Void Effect Core -

Results of Na void reactivity prediction for low void effect core (Including original results by EDF and CEA)

<table>
<thead>
<tr>
<th>Method</th>
<th>Core</th>
<th>Plenum</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>[EDF and CEA]</td>
<td>[4.33]</td>
<td>[-5.26]</td>
<td>[-0.93]</td>
</tr>
<tr>
<td>No correction</td>
<td>3.73</td>
<td>-4.96</td>
<td>-1.23</td>
</tr>
<tr>
<td>Corrected</td>
<td>3.22</td>
<td>-4.44</td>
<td>-1.22</td>
</tr>
<tr>
<td>(Reference)</td>
<td>(-14%)</td>
<td>(-11%)</td>
<td>(-1%)</td>
</tr>
<tr>
<td>Corrected</td>
<td>3.26</td>
<td>-3.93</td>
<td>-0.67</td>
</tr>
<tr>
<td>(Secondary)</td>
<td>(-13%)</td>
<td>(-21%)</td>
<td>(-46%)</td>
</tr>
</tbody>
</table>

Unit: $F$

- Difference of 0.5$ through 1.0$ in region-wise reactivity components due to the bias-factor method
- Possibility of considerable impact to transient analysis

5. Conclusion

• Larger calculation uncertainty of sodium void reactivity in low or negative void effect core concepts and requirement of much finer treatment for these cores in comparison with conventional homogeneous core concepts

• Some or considerable impact to transient analysis by reflecting information of the FBR core design database

• Importance of extension on sodium void reactivity experimental data and their reflection to enhance the reliability of safety analysis
Complements
A. Sodium Voiding Pattern in ZPPR-9
(Homogeneous core)

A. Sodium Voiding Pattern in ZPPR-13A (Radially-heterogeneous core)

A. Sodium Voiding Pattern in ZPPR-17A
(Axially-heterogeneous core)

Inner core void steps: IC-1 → IC-2 → IB-1 → AB-1 (Cumulative)
Outer core void steps: OC-1 → OC-2 → OC-3 → AB-2 (Cumulative)

A. Sodium Voiding Pattern in BFS-66-1
(Core with Na plenum)

A. Sodium Voiding Pattern in FCA XVII-1 (Core with Na plenum)

A. Result of the Cross Section Adjustment

- C/E shift in ZPPR-9 and 13A by the adjustment of the number of delayed neutron per fission.
- No alteration in BFS-66-1 and Na void pattern dependence due to large calculation modeling uncertainty (See next slide)

A. Calculation Uncertainty

- Larger calculation modeling uncertainty with the deterministic method particularly in BFS-66-1
- Necessity of the Monte Carlo calculations with enough small statistical uncertainty for V&V of Na void reactivity analysis

Fig. Uncertainty evaluation results with Japanese latest core calculation system
A. Calculation Modeling Uncertainty

- Assumption
  Proportionality to the amount of correction

- Estimation from correction factors
  \[ V_{m,i} = \sum_j \left\{ \alpha \left( f_{i,j} - 1 \right) \right\}^2 \]
  \( f_{i,j} \): Correction factor

- Example of estimation

| Correction            | Factor | |Factor-1| | Variance | Uncertainty |
|-----------------------|--------|-----------------|-----------------|-----------|------------|
| Spatial mesh          | 1.10   | 0.10            | 2.5E-3          | 0.05      |
| Transport theory      | 1.20   | 0.20            | 10.0E-3         | 0.10      |
| Ultra-fine group      | 0.90   | 0.10            | 2.5E-3          | 0.05      |
| Overall               | 1.19   | -               | 15.0E-3         | 0.12      |

- Base calculation conditions: Multi-group, finite difference diffusion theory
- \( \alpha=0.5 \)