First feedback with the AMMON integral experiment for the JHR calculations

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1. Context

2. Description of the AMMON experiment

3. Analysis of the AMMON experiment:
   - Reduction of the a priori uncertainty due to ND on JHR calculated reactivity
   - Elements of integral validation for Hf and Be ND

4. Conclusion/ Outlook
**A NEW MTR UNDER CONSTRUCTION: JHR**

**In reflector**
- \( \Phi \geq 5.5 \times 10^{14} \text{ n/cm}^2\cdot\text{s} \)
- 20 fixed positions
- 6 displacement systems

**In core**
- \( \Phi \geq 5.5 \times 10^{14} \text{ n/cm}^2\cdot\text{s} > 1 \text{ MeV} \)
- \( \Phi \geq 10^{15} \text{ n/cm}^2\cdot\text{s} > 0.1 \text{ MeV} \)

**Fast neutron flux**
- About 20 experiments at the same time

**Thermal neutron flux**
- \( 70 \text{ MWth / 100 MWth} \)
- Cycle between 25 and 30 days
- 6-7 days between cycles

**Displacement system:**
- Adjustment of power
- Power transient studies
SOME JHR SPECIFICITIES

- LWR with a spectrum harder than a « standard » PWR/BWR
- Fuel: $U_3Si_2$ –Al with e$\%$ $^{235}U \geq 20\%$
- A high power density
- Presence of specific isotopes: $^{27}Al$ (fuel matrix, cladding, rack, structure,…)
  $^9Be$ (reflector)
  Hf (control rods)

Example: A priori ND uncertainty propagation on reactivity (BOL) in pcm

<table>
<thead>
<tr>
<th></th>
<th>JHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}U$</td>
<td>342</td>
</tr>
<tr>
<td>$^{238}U$</td>
<td>122</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>194</td>
</tr>
<tr>
<td>$^{27}Al$</td>
<td>402</td>
</tr>
<tr>
<td>$^9Be$</td>
<td>59</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>637</td>
</tr>
</tbody>
</table>
NEEDS OF INTEGRAL VALIDATION

The accuracy of $^{27}$Al, $^9$Be, Hf ND has a direct impact on the accuracy of the calculations of JHR safety and performance parameters (n and $\gamma$):

- Few feedback on $^{27}$Al ND => important for reactivity calculation

- Few feedback on $^9$Be ND => important for the calculation of the plate power close to the reflector, radial macroscopic flux shape in the core, neutron flux levels and $\gamma$ heating in the reflector

- Existing feedback on Hf ND for rod efficiency calculation (French experimental programs in EOLE and AZUR) => extension of the validation field for JHR (harder neutron spectrum)
  - Few feedback on Hf ND for $\gamma$ heating calculation
Aims of the AMMON experiment:

> Determination of the global calculation bias and uncertainty associated with the JHR calculation formalism on neutron / photon parameters such as reactivity, reactivity worth, power distributions, kinetics parameters, spectrum indexes, gamma-ray dose …

> Feedback on nuclear data for the JEFF-3.1.1 library: aluminum, beryllium, hafnium for neutron and gamma interactions
• **JHR**: daisy flower shaped pattern

• **Configurations**:
  - Reference core: 7 JHR assemblies
  - Ejected follower
  - Hf rod: totally or half inserted
  - Beryllium block
  - Voided assembly
  - Water cell

• **AMMON-EOLE**:
  - **Experimental zone**: aluminum rack hosting $U_3Si_2-Al$ e=27% fuel assemblies
  - **Driver zone**: 500 to 900 UOx e=3.7% fuel pins

Hexagonal lattice pitch optimized in order to get the same neutron spectrum in EZ/DZ
3D reference continuous-energy calculations with the Monte Carlo TRIPOLI4 code and the JEFF3.1.1 nuclear data library (processed at room temperature)

Modelling of the 3D-exact geometry with TRIPOLI4

Simulation of several billions of neutron histories to reach a satisfactory statistical uncertainty
Core criticality adjusted with the insertion of an automatic pilot rod

Measurement of core reactivity with the divergence technique when the pilot rod is withdrawn

<table>
<thead>
<tr>
<th>Residual reactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AMMON/REF</strong></td>
</tr>
<tr>
<td>Measurement</td>
</tr>
<tr>
<td>TRIPOLI4</td>
</tr>
<tr>
<td>C-E</td>
</tr>
</tbody>
</table>

(C-E) value very satisfactory

Direct propagation of a priori nuclear data uncertainty on reactivity -> 670 pcm (1σ) uncertainty (360 pcm only comes from $^{27}$Al nuclear data)
## Impact of nuclear data libraries on AMMON/REF residual reactivity calculation

<table>
<thead>
<tr>
<th></th>
<th>JEFF3.1.1</th>
<th>JEF2.2</th>
<th>ENDF-B/VII.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIPOLI4</td>
<td>+560 pcm ± 3</td>
<td>+1015 pcm ± 3</td>
<td>+652 pcm ± 3</td>
</tr>
</tbody>
</table>

- Significant improvement (270 pcm) due to the new $^{27}$Al evaluation in JEFF3
- 100 pcm overestimation when using ENDF/B-VII.0
Objective: transposition of the bias and uncertainty from AMMON to JHR

A. The representativity study concerning the reactivity parameter

Dot product of sensitivity vectors $S$ of the Reactor (R) and the Experiment (E) weighted by the nuclear data covariance matrix $M$

$$r_{(R,E)} = \frac{S_R^t M S_E}{\sqrt{(S_R^t M S_R)(S_E^t M S_E)}}$$

Indication of the relevancy of the Experiment to the Reactor case (for the considered neutron parameter):

For the JHR and AMMON/REF cores:

$$r_{(JHR,AMMON/REF)} = 0.95$$

Very good representativity ($r>0.9$) => the bias and uncertainties can be transposed
B. The Calculation Bias and posterior uncertainty due to nuclear data for JHR

Neutronic weight of the experiment concerning the Reactor: (ratio between the experimental uncertainties and the ND uncertainties)

\[ w = \frac{1}{1 + \sigma_E^2 / \left(S_E^T MS_E\right)} \]

Bias on the Reactor calculated reactivity as a function of the bias on the Experiment calculated reactivity:

\[ \left(\frac{\text{Exp} - \text{Cal}}{\text{Cal}}\right)_\text{Reactor} = a_E^R \left(\frac{\text{Exp} - \text{Cal}}{\text{Cal}}\right)_\text{Experiment} \]

With the transfer coefficient:

\[ a_E^R = \frac{r_{R,E}}{1 + \sigma_E^2 / \left(S_E^T MS_E\right)} \sqrt{\frac{S_R^T MS_R}{S_E^T MS_E}} = w \cdot r_{R,E} \cdot \frac{I_R}{I_E} \]

From a AMMON/REF\textsubscript{ND} bias = +376 pcm (1\(\sigma\)), a JHR bias\textsubscript{ND} = +250 pcm (1\(\sigma\)) is expected

Reduction of the uncertainties due to Nuclear Data (depending of the representativity and the weight):

\[ \alpha^2 = \frac{I_R^*}{I_R^2} = 1 - \frac{r_{R,E}^2}{1 + \sigma_E^2 / \left(S_E^T MS_E\right)} = 1 - w \cdot r_{R,E}^2 = 0.24 \]

From a 597pcm (1\(\sigma\)) prior uncertainty, the reduction gives 328 pcm (1\(\sigma\)) posterior uncertainty on the JHR reactivity
Synthesis of the transposition for the reactivity parameter

\[(C-E)_{\text{AMMON/REF}} = +376 \text{ pcm} \pm 340\]

and

A priori uncertainty on \(\rho_{\text{JHR}}=+597 \text{ pcm}\)

\[(C-E)_{\text{JHR-BOL}} = +250 \text{ pcm} \pm 328\]
* Importance to have realistic covariance matrices associated with the ND library used for the calculation.

* Origin of the covariance matrices:
  - JEFF3.1.1 / JENDL3.3
  - recommandations of CEA
  - determination of a new $^{27}\text{Al}$ covariance matrix (retroactive marginalization technique in the CONRAD code)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction</th>
<th>AMMON Keff uncertainty</th>
<th>JHR Keff uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>Fission</td>
<td>201</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>336</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>Capture</td>
<td>187</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>Scattering</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>Fission</td>
<td>130</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>$\gamma$</td>
<td>26</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Capture</td>
<td>156</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Scattering</td>
<td>58</td>
<td>42</td>
</tr>
<tr>
<td>$^{27}\text{Al}$</td>
<td>Capture</td>
<td>177</td>
<td>221</td>
</tr>
<tr>
<td></td>
<td>Elastic</td>
<td>150</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>Inelastic</td>
<td>272</td>
<td>224</td>
</tr>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>Capture</td>
<td>50</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Scattering</td>
<td>148</td>
<td>179</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>Capture</td>
<td>82</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Scattering</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>$^{9}\text{Be}$</td>
<td>Scattering</td>
<td>No Be</td>
<td>60</td>
</tr>
<tr>
<td><strong>Total uncertainty (1\sigma)</strong></td>
<td><strong>671 pcm</strong></td>
<td><strong>597 pcm</strong></td>
<td></td>
</tr>
</tbody>
</table>
AMMON Hf AND Be CONFIGURATIONS

A hafnium rod inserted in the central assembly

A beryllium block inserted in the rack central cell
Residual reactivity (analysis of the 3 critical states)

<table>
<thead>
<tr>
<th>AMMON configuration</th>
<th>REF</th>
<th>Hf</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>+184 pcm ±9</td>
<td>+ 212 pcm ±11</td>
<td>+ 155 pcm ±8</td>
</tr>
<tr>
<td>TRIPOLI4</td>
<td>+560 pcm ±3</td>
<td>+ 573 pcm ±2</td>
<td>+ 521 pcm ±2</td>
</tr>
<tr>
<td>C-E</td>
<td>+376 pcm</td>
<td>+ 361pcm</td>
<td>+ 366 pcm</td>
</tr>
</tbody>
</table>

$$\frac{\delta \rho}{\Delta \rho} = \frac{(\rho_{calc}^{Hf/Be} - \rho_{calc}^{REF}) - (\rho_{mes}^{Hf/Be} - \rho_{mes}^{REF})}{\Delta \rho_{mes}}$$

Bias on the reactivity worth

<table>
<thead>
<tr>
<th>AMMON configuration</th>
<th>Hf</th>
<th>Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental worth</td>
<td>-3356 pcm</td>
<td>-2526 pcm</td>
</tr>
<tr>
<td>(C-E)/E</td>
<td>+0.5% ± 1.8%</td>
<td>+0.4% ± 2.0%</td>
</tr>
</tbody>
</table>

- The Bias due to ND (Hf and Be) are within the uncertainty (1σ)
- Preliminary results: to be completed with sensitivity studies…
New measurements in progress in the EOLE facility with the AMMON experimental program => 2 goals: experimental validation of the design and safety calculation formular for JHR + elements of validation for specific ND (Al, Hf, Be)

Transposition of the bias and uncertainty due to ND from AMMON to JHR thanks to the representatity methodology

A priori uncertainty on the calculated JHR reactivity reduced by a 2 factor:
\[(C-E) \text{ JHR BOL} = +250 \text{ pcm } \pm 328 \ (1\sigma)\]

No bias due to JEFF3.1.1 ND on Hf efficiency and Be reactivity worth

First feedback which will be completed in the next months:
- Neutron data: Analysis of spectral indexes with activation foils at the center of the Be block
- Photon data: analysis of gamma heating in Al, Hf and Be
Elastic cross section  Inelastic cross section  Capture cross section