CARMEN: an experimental configuration in the MINERVE critical facility for the qualification of neutron cross sections in epithermal spectrum

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   - Estimation of experimental signals
   - Optimization of the design
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Introduction

To gain experimental data to under-moderated reactors, the following different studies were made:

Qualification of neutronic parameters 
(ERASME program in the EOLE facility (1985))

Determination of capture rates (heavy nuclides, fission products) 
(ICARE irradiations in the MELUSINE facility (1986-1988))

Measurement of the global capture of fission products 
(oscillation of spent fuels) 
(MORGANE program in the MINERVE facility (1986))

Complementary results were foreseen:

Improvement of cross sections for heavy nuclides and new neutron absorbers 
(OSMOSE and OCEAN programs in the MINERVE facility)

A new configuration has been designed:
CARMEN (Core with An epitheteRMal nEutron moderatioN)
The MINERVE facility

Devoted to neutronics studies using the reactivity oscillator method

- Pool: 100 m$^3$ of water
- Zero power (< 100 W)
- Thermal flux: $10^7$ n.cm$^{-2}$.s$^{-1}$.W$^{-1}$

- Driver zone on mobile grids

- Central cavity for experimental lattices
The MINERVE facility

Neutronics spectra in the experimental zone:

- Over moderated
- PWR UOX
- PWR MOX
- Epithermal (MORGANE & CARMEN)
- Fast

![Graph showing neutron flux spectra](image-url)
Oscillation technique of measurement

\[ \frac{\delta \phi}{\delta t} \neq 0 \]

MINERVE experimental core

Measurement sample
Aluminium "low train" sample

\[ \delta S (\text{pilot unit}) = f (\delta \rho \text{ (pcm)}) \]

Accuracy: about 3% for absolute reactivity worth (including the uncertainties on the material balance and on the calibration step)

Reactivity effects of less than 2 cents can be measured

1 measurement = 5 cycles of 120 s
1 sample = 5 measurements
The OSMOSE and OCEAN programs (2005 - 2012)

To improve the knowledge on the absorption cross sections of:

**OSMOSE : OSCillation in Minerve of isOtopes in "Eupraxic" Spectra**

<table>
<thead>
<tr>
<th>Actinides:</th>
<th>Th-232</th>
<th>U-233</th>
<th>Np-237</th>
<th>Pu-238</th>
<th>Am-241</th>
<th>Cm-244</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U-234</td>
<td>URE</td>
<td></td>
<td>Pu-239</td>
<td>Am-243</td>
<td>Cm-245</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pu-240</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pu-241</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pu-242</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

L = 10.35 cm

**OCEAN : Oscillation in Core of SamplEs of Neutron Absorbers**

<table>
<thead>
<tr>
<th>Absorbers:</th>
<th>Eu-151</th>
<th>Gd-155</th>
<th>Dy-160</th>
<th>Er-166</th>
<th>Hf-177</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eu-153</td>
<td>Gd-157</td>
<td>Dy-161</td>
<td>Er-167</td>
<td>Hf-178</td>
<td></td>
</tr>
<tr>
<td>Eu nat</td>
<td>Gd nat</td>
<td>Dy-162</td>
<td>Er-168</td>
<td>Hf-179</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dy-163</td>
<td>Er-170</td>
<td>Hf-180</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dy-164</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ø = 1.06 cm

Since 2006

- PWR UOX type spectrum *(R1-UO2)*
- PWR MOX type spectrum *(R1-MOX)*

Measure in different neutron spectra for having a better decomposition in energy domains for the qualification of nuclear data

- 2012 Epithermal (High Conversion LWR) type spectrum *(CARMEN)*
- To be integrated into the library JEFF3.1.1
Characteristics of the CARMEN configuration

Main parameters required for the design:

- Epithermal spectrum with a moderation ratio \( V_m/V_f = 0.9 \)
- A high content in plutonium (representative of under-moderated concepts)
- Pins already available in the facility (7% in Pu and 3.7% in U-235)
- Several safety criteria to be respected (importance of the experimental zone compared to the driver zone)

Oscillation in a dry environment (to improve the reproducibility of the measurement)
Estimation of experimental signals

Experimental signals in R1-MOX lower than in R1-UO2

<table>
<thead>
<tr>
<th></th>
<th>R1-UO2 configuration</th>
<th>R1-MOX configuration</th>
<th>CARMEN configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta S_{H^3-H_1}$ (pilot unit)</td>
<td>410 400 ± 1 000</td>
<td>119 600 ± 1 000</td>
<td>expected signal ~ 50 000 ± 1 000</td>
</tr>
<tr>
<td>Relative uncertainties</td>
<td>0.24%</td>
<td>0.84%</td>
<td>~ 2%</td>
</tr>
</tbody>
</table>

To optimize relative uncertainties for CARMEN lattice, experimental signals have to be as high as possible

Whatever the experimental lattice:

$$\Delta S = \alpha^{\text{calib}} \Delta \rho$$
Estimation of experimental signals

\( \alpha_{\text{calib}}^{\text{CARMEN}} \) can be estimated by a combination of:

- 3D Monte-Carlo calculations (MCNP5 code)
- 2D deterministic calculation (APOLLO2.8 code)
- results of previous measurement (R1-UO2)

Checking of this method with the well known R1-MOX lattice

<table>
<thead>
<tr>
<th>( \alpha_{\text{calib}}^{\text{R1-MOX}} ) (pilot unit)</th>
<th>Estimation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>815 ± 98</td>
<td>790 ± 15</td>
<td></td>
</tr>
</tbody>
</table>

Good agreement
### Optimization of the design

<table>
<thead>
<tr>
<th>Lattice number</th>
<th>Calibration factor $\alpha_{\text{calib}}^{\text{CARMEN}}$</th>
<th>$\Delta S_{\text{CARMEN}}$ (pilot unit)</th>
<th>$\Delta S_{R1-MOX}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>835 ± 89</td>
<td>114 178 ± 12 170</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1063 ± 90</td>
<td>145 355 ± 12 307</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1475 ± 103</td>
<td>201 692 ± 14 084</td>
<td></td>
</tr>
</tbody>
</table>

**Hexagonal lattice of 12.8 mm**

- **Lattice 1**: Homogeneous 816 MOX 7% fuel pins
  - Overclad 11 mm of $\Theta$ ext

- **Lattice 2**: Heterogeneous 330 MOX 7% fuel pins
  - 486 UO2 (3.7% U-235) fuel pins (buffer zone)
  - Overclad $\Theta$ ext=11 mm

- **Lattice 3**: UO2 drilled overclad $\Theta$ ext=10.2 mm

*IGORR September 19-23 2010 Knoxville, TN USA*
Optimization of the design

- Small increase of the flux level (lattice 3)

Third lattice will provide better results
Mechanical design

- 2 dedicated grid in an aluminum cask (versatility)
- Thick grid to drive the pins under 2 m of water
- Biological protection
- Dedicated device for extracting samples from the top of the pool
Conclusion and perspectives

- Neutronic conception achieved
- Mechanical building in progress
- Reduction of experimental uncertainties
- New calibration samples
- Oscillations in CARMEN lattice should start in 2012

⇒ Improvements of nuclear data used for the JEFF3 library
Conclusion and perspectives

- Measurements under Cadmium shield to complete the decomposition in energy domains for the qualification of nuclear data
- MOX fuel pins can be replaced by Graphite or Beryllium cylinders

Neutron spectra in the experimental device

- R2-UO2-2
- CARMEN
- Graphite + 1mm Cd
- Beryllium + 1mm Cd
- Water + 1mm Cd
Estimation of experimental signals

A reactivity effect introduced by a sample is exactly compensated by an automatic pilot rod, made of overlapping cadmium sectors:

\[
\Delta \rho = \frac{\Delta N_{\text{Cd}}}{I_f} \int \sigma_{\text{Cd}}(E)\Phi(E)\Phi^*(E)dE \Rightarrow \Delta S = \frac{1}{c} \int \sigma_{\text{Cd}}(E)\Phi(E)\Phi^*(E)dE \Delta \rho
\]

Eq. 1

As the proportionality factor \( c \) depends only of the acquisition system, Eq 1 is rewritten for each core configuration:

\[
\Delta S_C = \frac{\int \sigma_{\text{Cd}}(E)\Phi(E)\Phi^*(E)dE}{\int \sigma_{\text{Cd}}(E)\Phi(E)\Phi^*(E)dE} \frac{\Delta \rho_C}{\Delta \rho_R} \Delta S_R
\]

Eq. 2

The integrals can be simplified:

the capture cross section of cadmium is essentially thermal,

and by assuming the same spectral variations for both the adjoin and direct neutron fluxes:

\[
\Delta S_C = \frac{\Phi_{\text{th}}^2}{\Phi_{\text{th}}^2} \frac{\Delta \rho_C}{\Delta \rho_R} \Delta S_R
\]

Eq. 3

The experimental signals in each configurations can be related to the reactivity effects calculated from 2D deterministic calculations though the same calibration process:

\[
\Delta S = \alpha^{\text{calib}} \Delta \rho^{A2} \Rightarrow \alpha^{\text{calib}}_C = \frac{\Delta \rho_C}{\Delta \rho_R} \frac{\Phi_{\text{th}}^2}{\Phi_{\text{th}}^2} \frac{\Delta \rho^{A2}_C}{\Delta \rho^{A2}_R} \alpha^{\text{calib}}_R
\]