New evaluations of photon production for JEFF3
Importance of the gamma transport in power reactors

From Lüthi’s thesis (EPFL 1999)

Neutron and gamma heating (total normalized to unity at core center) along the mid-plane of the MASURCA ZONA2B configuration. The relative contribution of gamma heating to the total heating is also indicated.

Photon heating predominant in fast reactor's vessels
Importance of the gamma transport in power reactors

Photon heating predominant in water reactor’s vessel
Needed tools for gamma heating calculations

Coupled neutron and photon transport code:
- APOLLO2, (deterministic)
- TRIPOLI4, MCNPX (Monte Carlo)

Neutron transport library:
- JEFF3.1.1, ENDF/B-VII, JENDL4.0

Neutron induced photon production library:
- JEFF3.1.1, ENDF/B-VII, JENDL4.0

Photon transport library:
- EPDL91, EPDL97

Gamma production spectrum and multiplicities
Need improvements
Needed improvements for JEFF3.1.1

Energy inconsistencies in JEFF3.1.1 in the gamma production spectrum from neutron capture

\[ ^{56}\text{Fe} \]

![Graph showing energy inconsistencies in JEFF3.1.1](image-url)
Needed improvements for JEFF3.1.1

No photon production for all neutron interaction

Gd, Cd, Ag, In, …

Inconsistent total gamma energy emitted after a radiative neutron capture

$^{54}\text{Fe},^{56}\text{Fe},^{57}\text{Fe},^{58}\text{Fe}$

No primary gamma emitted after a radiative neutron capture

$^{54}\text{Fe},^{57}\text{Fe},^{58}\text{Fe}, \text{Hf}$

Need to generate new gamma production evaluations
Processing new gamma production spectra

$Q(\text{ENSDF}) = \sum \sigma_i E_i \left( \frac{l_i}{E_i} \right)$
$Q(\text{Adopted}) = \sum \sigma_i E_i \frac{\sigma_i}{\sigma_0}$

- No continuum needed
- Fe isotopes
- Ag, In, Cd isotopes
- Hf isotopes
- Continuum needed

EGAF:
- An online library containing gamma production measurements induced by neutron capture
- Validated by the IAEA
- Measurements performed at the Budapest facility
- Measurements performed with a thermal neutron beam
- No continuum measurements

Continuum needed
Processing new gamma production spectra

Highlighting of the continuum and discrete gamma production spectrum induced by neutron capture on gadolinium

Fig. 1. Experimental γ-ray spectrum of Gd₂O₃.

Measurements performed by Groshev et al. in the 50’s
Processing new gamma production spectra

TALYS : A modelling nuclear reaction code
-A common development between CEA/DAM and NRG (Holland)
-A deterministic solver of the compound nucleus equation
-5 strength function models and 4 level density models
-Account for well-known discrete levels
-Coupling with the TEFAL code to produce new evaluations at the ENDF format
Composite Gilbert-Cameron model

\[
\rho_{T}^{\text{tot}}(E_x) = \frac{dN(E_x)}{dE_x} = \frac{1}{T} \exp\left(\frac{E_x - E_0}{T}\right) \quad \rho_{F}^{\text{tot}}(E_x) = \frac{1}{\sqrt{2\pi} \sigma} \frac{\sqrt{\pi}}{12} \frac{\exp\left[2\sqrt{aU}\right]}{a^{1/4}U^{5/4}}
\]

Generalized Lorentzian model

\[
f_{E1}(E_\gamma, T) = K_{E1} \left[ \frac{E_\gamma \tilde{\Gamma}_{E1}(E_\gamma)}{(E_\gamma^2 - E_{E1}^2)^2 + E_\gamma^2 \tilde{\Gamma}_{E1}(E_\gamma)^2} + \frac{0.7 \Gamma_{E1} 4\pi^2 T^2}{E_{E1}^3} \right] \sigma_{E1} \Gamma_{E1}
\]

Advised models by Kopecky-Uhl
Processing gamma production spectra

$1 \mu eV < E_n < 1 keV$

~ 90% of the radiative capture rate in a PWR

Discrete part processed with EGAF measurements

If needed, continuum part processed with TALYS ($E_{cont} = S_n - E_{EGAF}$)

$E_n > 1 keV$

All the spectrum processed with TALYS

Spectrum placed in MF6MT102 in the ENDF format

16 nuclei: $^{54}Fe$, $^{56}Fe$, $^{57}Fe$, $^{58}Fe$, $^{107}Ag$, $^{109}Ag$, $^{113}In$, $^{115}In$, $^{113}Cd$, $^{155}Gd$, $^{174}Hf$, $^{177}Hf$, $^{178}Hf$, $^{179}Hf$, $^{180}Hf$
Comparison between JEFF and the new evaluations

$^{54}$Fe

APOLLO94_GAMMA mesh

High energy gamma production spectrum not described in JEFF3.1.1
Comparison between JEFF and the new evaluations

Better description of the gamma peaks

$^{56}\text{Fe}$

APOLLO94_GAMMA mesh
Comparison between JEFF and the new evaluations

**177Hf APOLLO94_GAMMA mesh**

I MeV peaks not accounted for in JEFF3.1.1

High energy primary gamma peak
Comparison between JEFF and the new evaluations

$^{180}\text{Hf}$

APOLLO94_GAMMA mesh

Better precision of low energy photons

No primary gamma peak in JEFF3.1.1
Effects of the new evaluations

Gamma source created by neutron capture at the center of the sphere

Created photons transported

Local energy deposition (gamma heating)

Calculation of the gamma heating in each shells with TRIPOLI4
Comparison between JEFF3.1.1 and the new evaluations
Test of the new evaluations

$^{54}\text{Fe}$ $d=8.3 \times 10^{-2}$ nuclei.cm$^{-1}$.barn$^{-1}$

<table>
<thead>
<tr>
<th>Total deposited energy</th>
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</thead>
<tbody>
<tr>
<td>JEFF3.1.1</td>
</tr>
<tr>
<td>3.08 MeV</td>
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</table>
Test of the new evaluations

$^{56}\text{Fe}$ $d=8.3 \times 10^{-2}$ nuclei.cm$^{-1}$.barn$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>Total deposited energy</th>
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</thead>
<tbody>
<tr>
<td>JEFF3.1.1</td>
<td>New evaluation</td>
</tr>
<tr>
<td>6.43 MeV</td>
<td>6.22 MeV</td>
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</tbody>
</table>

Deposited energy [MeV.cm$^{-3}$]

Distance [cm]
Test of the new evaluations

Stainless steel

\( d = 8.3 \times 10^{-2} \text{nuclei.cm}^{-1}.\text{barn}^{-1} \)

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<tbody>
<tr>
<td>JEFF3.1.1</td>
</tr>
<tr>
<td>6.72 MeV</td>
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</table>
The PERLE experiment

- A stainless steel reflector
- 9 measurements points of the gamma heating

With JEFF3.1.1, underestimation of the gamma heating in the reflector

-7.5 ± 6 % (1σ)
The PERLE experiment

<table>
<thead>
<tr>
<th>Distance from the core center [cm]</th>
<th>Differences with JEFF3.1.1 C2/C1-1 [%]</th>
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<tbody>
<tr>
<td>20.9</td>
<td>0.9</td>
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<tr>
<td>23.76</td>
<td>1.3</td>
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<tr>
<td>26.4</td>
<td>1.5</td>
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<tr>
<td>29.01</td>
<td>1.5</td>
</tr>
<tr>
<td>31.66</td>
<td>2.3</td>
</tr>
<tr>
<td>34.2</td>
<td>2.3</td>
</tr>
<tr>
<td>36.8</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

The new evaluations allow to decrease the gamma heating calculation bias
Conclusion and perspectives

Before in JEFF3.1.1:

- Bad accuracy of the gamma production spectra
- Energy inconsistencies

Now:

- 14 new evaluations proposed for JEFF3.2
- Accounting for the latest EGAF measurements
- Improvement of the gamma heating calculation in a stainless steel reflector

Future:

- Calculation of the gamma heating in Hafnium with the new evaluations