Status of Fusion Neutronics Predictive Capabilities

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VLT Research Highlight Presentation
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Nuclear Data Development for Fusion

- Represent US fusion neutronics community in the Cross Section Evaluation Working Group (CSEWG)
- Make sure that nuclear data needs for US fusion neutronics community are addressed satisfactorily
- Support development of updated FENDL-3 through participation in the IAEA sponsored Coordinated Research Project (CRP) and performing benchmark calculation for library validation and identification issues from the user’s perspective
FENDL-2.1 Background

- Revision to FENDL-2.0 (1995/96)
- Compiled November 2003, INDC(NDS)-451
- 71 elements/isotopes
- Reference data library for nuclear analysis of ITER and other fusion systems

Data Source for FENDL-2.1

<table>
<thead>
<tr>
<th>No.</th>
<th>Library</th>
<th>NMAT</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ENDF/B-VI.8 (E6)</td>
<td>40</td>
<td>$^2$H, $^3$H, $^4$He, $^6$Li, $^7$Li, $^{10}$Be, $^{10}$B, $^{11}$B, $^{16}$O, $^{17}$F, $^{28-30}$Si, $^{31}$P, S, $^{35}$Cl, K, $^{50,52-54}$Cr, $^{54,57,58}$Fe, $^{59}$Co, $^{61,62,64}$Ni, $^{65,66}$Cu, $^{197}$Au, $^{206-208}$Pb, $^{209}$Bi, $^{182-184,188}$W</td>
</tr>
<tr>
<td>2</td>
<td>JENDL-3.3 (J33)</td>
<td>18</td>
<td>$^1$H, $^3$He, $^{25}$Na, $^{46-53}$Ti, $^{55}$Mn, $^{92,94}$Mo, $^{181}$Ta, V</td>
</tr>
<tr>
<td>3</td>
<td>JENDL-3.2 (J32)</td>
<td>3</td>
<td>Mg, Ca, Ga</td>
</tr>
<tr>
<td>4</td>
<td>JENDL-FF (JFF)</td>
<td>4</td>
<td>$^{12}$C, $^{15}$N, Zr, $^{95}$Nb</td>
</tr>
<tr>
<td>5</td>
<td>JEFF-3 (EFF) JEFF3</td>
<td>4</td>
<td>$^{27}$Al, $^{56}$Fe, $^{58}$Ni, $^{60}$Ni</td>
</tr>
<tr>
<td>6</td>
<td>BROND-2.1 (BR2)</td>
<td>2</td>
<td>$^{15}$N, Sn</td>
</tr>
</tbody>
</table>

- Majority (40) of materials in FENDL-2.1 taken from ENDF/B-VI.8
- Investigated effect of recently released ENDF/B-VII.0 (December 2006) on results for ITER calculational benchmark and four FNG ITER relevant integral experiments
Calculational and Experimental Benchmarks

Tungsten

Neutron source

DENSIMET-176
DENSIMET-180
(95% W)

Streaming

Bulk shielding

HCPB breeder

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An effort was initiated by the IAEA in 2008 to update the FENDL library with the objective of improving the status of nuclear databases for fusion devices including IFMIF.

The library (FENDL-3) represent a substantial extension of FENDL-2.1 library toward higher energies, with inclusion of incident charged particles and the evaluation of related uncertainties (covariance data).

FENDL-3 will be released at the end of the 3 years of the Coordinated Research Project (CRP) activities.
During the 2\textsuperscript{nd} RCM held in March 2010, a decision was made to nearly double the number of materials in the library and the source of evaluation for each material was agreed on.

\textit{Materials added to the library} were based on input obtained from the fusion neutronics community for ITER and IFMIF. These are 23 elements with their constituent isotopes:

\textit{Re, Zn, Ag, Ba, Y, Cd, Ce, Ar, Er, Sb, Rh, Sc, Br, Ge, I, Lu, La, Cs, Pt, Hf, Gd, U, Th}

\textit{Only 3 actinide isotopes} will be added as they are needed for neutron measurement by fission chambers (U-235, U-238) or exist in the ITER concrete (Th-232)

Total number of isotopes in library increased to 166

Evaluations to be utilized for these materials were selected

M.E. Sawan, “Summary Report from 2\textsuperscript{nd} RCM on Nuclear Data Libraries for Advanced Systems – Fusion Devices (FENDL-3),” INDC (NDS)-567, IAEA (June 2010)
Neutronics Codes

• **Deterministic**
  – PARTISN, DOORS, DENOVO, ATTLA

• **Monte Carlo**
  – MCNP, TRIPOLI
  – CAD-based
    • Translators: MCAM, McCAD
    • Direct coupling: DAGMC
**Generic Diagnostic Upper Port Plug Neutronics**

Section Through Upper Port  
Showing the Visible/IR Camera Labyrinth

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**Generic Upper Port Nuclear Heating**

Total: 316 kW  
First Wall + Diagnostic Shield: 309 kW  
GUPP Structure: 7 kW

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Generic Upper Port Plug  
SolidWorks Analysis Model
Direct Accelerated Geometry Monte Carlo (DAGMC)

Motivations

• **Cheaper**
  – Reduce human effort

• **Better**
  – Avoid human error in conversion
  – Include higher-order surface descriptions in analysis

• **Faster**
  – Reduce human effort – faster design iteration
  – Provide common domain for coupling to other analyses
Detailed High-Resolution, High-Fidelity Calculations with DAG-MCNP in CAD Model of ITER FWS Module 13

Interesting heterogeneity effects revealed
Detailed Calculations with DAG-MCNP for Revised FWS Module Design
Detailed 3-D Neutronics for DCLL TBM

Source Input Table

Mid-plane nuclear heating

Mid-plane T production

Steel damage at section X2

DCLL TBM

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Application to ARIES-CS Compact Stellarator

- Geometry and source complex
- Cannot be modeled by standard MCNP

Examined effect of helical geometry and non-uniform blanket and divertor on NWL Distribution, TBR and nuclear heating.
Fast neutron flux at dielectric optics depends on material choice for the GIMM and total GIMM areal density

AlBeMet GIMM results in highest flux level (factor of ~1.6 higher than with lightweight SiC GIMM)

Significant drop in nuclear environment occurs as one moves from the GIMM to dielectric focusing and turning mirrors
Multi-Physics: Coupling to CFD

• Fine mesh DAG-MCNP5 results
  – 1-3 mm Cartesian mesh overlay
  – Total nuclear heating
• Arbitrary mesh on CAD geometry
  – Tetrahedral
  – Polyhedral (Star-CCM+)
• Automated interpolation using MOAB
Multi-Physics: Coupling to CFD

- 1 of 40 fingers in ITER First Wall concept
- Beryllium plasma facing component
- CuCrZr heat sink into pressurized water
- Steel backing for structural support
- 0.2 MW/m^2 heat flux onto Beryllium
- Inlet: 0.2 kg/s water, 373 K, 3 Mpa
Neutronics+CFD Coupling

Notice “hot spot” at elbow and center due to nuclear heating.
Research Directions

Analysis of Deformed Systems

• Thermal response can lead to structural/geometric changes
• Nuclear analysis on deformed system will help understanding the feedback on performance parameters
• Not applied yet for fusion but used for deformed fission reactors
Research Directions

Advanced Mesh Tallies

• Perform tallies on arbitrary polyhedral mesh
  – Prototype exists for tetrahedral mesh
• Get detailed isotopic compositions after activation/transmutation
• Solve separate activation problem in millions of mesh elements
• Use previous source sampling capability to represent distributed photon source
Research Directions

Hybrid Methods

- Monte Carlo not well-suited to deep penetration problems
- Deterministic methods not well suited to gap streaming problems
- Use deterministic methods to develop importance maps for Monte Carlo problems

- Large size
- Complex geometry
- Massive shielding
ORNL hybrid methods (CADIS, FW-CADIS) suitable for fusion applications

ITER magnet heating

<table>
<thead>
<tr>
<th></th>
<th>Time (day)</th>
<th>Max. uncertainty</th>
<th>Normalized FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog</td>
<td>121.3</td>
<td>5.9%</td>
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<tr>
<td>WWG</td>
<td>11.0</td>
<td>3.6%</td>
<td>30</td>
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<tr>
<td>FW-CADIS</td>
<td>0.8</td>
<td>4.5%</td>
<td>275</td>
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</table>

ITER prompt dose

<table>
<thead>
<tr>
<th></th>
<th>Dose (mrem/hr)</th>
<th>Relative uncertainty</th>
<th>Time (day)</th>
<th>Normalized FOM</th>
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</thead>
<tbody>
<tr>
<td>MC (No CADIS)</td>
<td>0.48</td>
<td>76.7%</td>
<td>610.0</td>
<td>1</td>
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<tr>
<td>MC (CADIS)</td>
<td>0.27</td>
<td>3.8%</td>
<td>8.6</td>
<td>10,566</td>
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<tr>
<td>Denovo</td>
<td>0.18</td>
<td>280 million cell</td>
<td></td>
<td>= 610 processors days</td>
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</tbody>
</table>

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Summary

• An updated comprehensive (ns to 150 MeV, activation, p, d, covariance) fusion evaluated nuclear data library FENDL-3 that is suitable for all fusion systems will be developed, validated, and released by the end of 2011

• Progress made on improving fusion neutronics predictive capabilities for accurate and fast analysis of the large geometrically complex fusion systems

• Many challenging issues remain to allow efficient automated integration with other multi-physics analyses