The impact of FENDL-3.2 on ITER and FNSF fusion reactor computational benchmarks

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Outline

1) Introduction
2) Nuclear data libraries examined
3) Benchmark/Systems Analyzed:
   • ITER-1D computational benchmark
   • FNSF-1D computational benchmark
4) Future Work
Current D-T Fusion Experiments/Reactors

\[
D + T \rightarrow \text{He-4 (3.5 MeV)} + n \ (14.1 \text{ MeV})
\]

JET (UK)
- 1983-present
- \(R_{\text{major}} = 3\) m
- \(V_{\text{plasma}} = 100\) m\(^3\)
- pulse \(
\sim 1\) sec
- \(16\) MW\(_{\text{fusion}}\)

ITER (France)
- under construction
- \(R_{\text{major}} = 6\) m
- \(V_{\text{plasma}} = 840\) m\(^3\)
- pulse \(
\sim 400-600\) sec
- \(500\) MW\(_{\text{fusion}}\)

Soon, maybe? private start-ups (not all D-T or Tokamak based)
- Helion, Common Wealth Fusion, General Fusion, TAE Technologies
- Several others
Important Fusion Neutronics Responses

- **Neutron flux/fluence**
  - structure, magnets
- **Total nuclear heating (neutron+photon)**
  - coolant system design, thermal stress, etc. for structure, magnets
- **Tritium production (neutron)**
  - breeding fuel, environmental concerns
- **Radiation damage/dpa (neutron)**
  - structural material, magnet degradation
- **Helium production (neutron)**
  - re-weldability
- **Radiation dose (neutron+photon)**
  - insulators, electronics, personnel
- **Activation**
  - shutdown dose-maintenance robotics, personnel
  - decay heat-safety (LOCA, LOFA)
  - radioactive waste disposal, recycling
The Fusion Evaluated Nuclear Data Library (FENDL) is an international effort coordinated by the IAEA Nuclear Data Section. It assembles a collection of the best nuclear data from national cross section data libraries for fusion applications. ENDF/B (US), JENDL (Japan), JEFF (Europe), TENDL (EU), RUSFOND/BROND (Russia). The process uses fusion specific experimental and calculational benchmarks to evaluate the data. Data available on-line:
Source of FENDL Data

- 65/180 isotopes in FENDL-3 come from ENDF/B-VII.1
  ➢ See Table 1 in INDC(NDS)-0628
- Some key isotopes for this work:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>FENDL-2.1*</th>
<th>FENDL-3.1</th>
<th>FENDL-3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-1</td>
<td>JENDL-3.3</td>
<td>ENDF/B-VII.1</td>
<td>ENDF/B-VII.1</td>
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<td>0-16</td>
<td>ENDF/B-VI.8</td>
<td>ENDF/B-VII.1</td>
<td>INDEN1.0/Murata et al.**</td>
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<td>ENDF/B-VII.1</td>
<td>INDEN?/Nobre et al.**</td>
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<td>Fe-56</td>
<td>JEFF-3</td>
<td>JEFF-3.1.1</td>
<td>INDEN1.0/IAEA consort.**</td>
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<tr>
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<td>JEFF-3</td>
<td>ENDF/B-VII.0</td>
<td>ENDF/B-VII.0</td>
</tr>
<tr>
<td>Cu-63,65</td>
<td>ENDF/B-VI.8</td>
<td>ENDF/B-VII.0</td>
<td>ENDF/B-VII.0</td>
</tr>
</tbody>
</table>

*FENDL-2.1 is the reference library for ITER neutronics
**INDEN https://www.nds.iaea.org/INDEN/
Goal of this work

- Look at the neutronics impact of using the updated neutron libraries in a **realistic model of fusion systems** using MCNP
- Libraries examined:
  - **Neutron:**
    1. FENDL-2.1 (21c)
    2. FENDL-3.1 (31c)-current version 3.1d
    3. Initial INDEN evaluations for O, Cr, Fe*
    4. FENDL-3.2 (32c)-june 24, 2021 version
      - Includes newer INDEN evaluations for O, Cr, Fe
    5. ENDF/B-VII.1 (80c)
    6. ENDF/B-VIII.0 (00c)
  - **Photon:**
    1. mcplib84 (84p)**

* Previous work has shown that mcplib84 produces results similar to the newer MCNP eprdata12 library, the latest MCNP photon library (eprdata14) has not been tested yet

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* Bohm T.D, Sawan M.E. “Neutronics calculations to support the Fusion Evaluated Nuclear Data Library (FENDL)”, Fusion Science and Technology, on-line early access August 2021.
ITER 1-D Cylindrical Calculation Benchmark

- Based on an **early** ITER design
- Developed for the FENDL evaluation process
- Simple but realistic model of ITER with the Inboard and Outboard portions modeled with the plasma in between
- D-T fusion (14.1 MeV neutrons)
- Flux (neutron and photon), heating, dpa, and gas production calculated

*M. Sawan, FENDL Neutronics Benchmark: Specifications for the calculational and shielding benchmark, INDC(NDS)-316, December 1994*
ITER 1-D Cylindrical Benchmark continued

Inboard Region

Outboard Region
Results: Neutron Flux ITER

- ENDF/B-VIII.0+CrInitial,FeInitial closer to FENDL-2.1 but see structure at VV, TF Coil
  - main difference due to Ni and Cu XS respectively
- FENDL-3.1+CrInitial,FeInitial quite close to FENDL-2.1 but structure at VV (Ni)
  ➢ FENDL-3.2 even closer to FENDL-2.1

Max. relative error <0.26%
Results: Total Nuclear Heating ITER

- FENDL-3.2 see peak at H2O regions and TF coil insulator (low Z)
  - neutron heating up to 4X>photon heating in water regions

Max. relative error <0.27%
Neutron Heating Numbers in Water

• Neutron fluxes similar in water regions
• Neutron heating numbers in water are similar except at very low and very high energies (8-15 MeV)
• Using FENDL-2.1 for transport and heating tallies with variety of XS libs indicates that different heating numbers are the cause for the FENDL-3.2 heating differences in water
1-D FNSF Cylindrical Computational Benchmark

- Need to test XS libraries on fusion designs other than ITER (different structural materials, coolants)
- Created 1-D model of Fusion Energy Systems Studies Fusion Nuclear Science Facility (FESS-FNSF)
- Breeding Zone: He cooled steel structure (90 w/o Fe, 7.5w/o Cr, 2w/o W, 0.2w/o V), PbLi breeder

- 85 radial zones
- Includes SiC flow channel inserts in breeding zone
- Includes face plates and filler for SR, VV, Ltshield
- Includes IB, OB magnet and cryostat
- MCNP materials created with PyNE

Results: Neutron Flux FNSF

- All libs show higher flux than FENDL-2.1 (except FENDL-3.2 at OB CC, WP)
- FENDL-3.1d shows highest flux (also seen in ITER benchmark)
- ENDF/B-VIII.0 & FENDL-3.2 quite close up to depth of IB LTshield and OB VV
- FENDL-3.2 vs FENDL-3.1d flux values 6% lower at IB CC, 15% lower at OB CC
Results: Total Nuclear Heating FNSF

- Heating in tungsten at FW is lower for FENDL-3.2 and 3.1d compared to FENDL-2.1
- All libs show higher heating than FENDL-2.1 beyond the Breeder except FENDL-3.2 at OB WP (not seen in the ITER benchmark)
- All newer libs show some significant differences esp. at deep locations (LT, CC, WP)
- FENDL-3.2 peaks are in BZ channel walls, BW, OB SR back plate (MF82H)
Results-Tritium Breeding Ratio FNSF

- FNSF uses PbLi for breeding:
  - 84.3 atomic% Pb
  - 15.7 atomic% Li (enriched to 90% Li-6)
- Recall 1-D model includes He cooled flow channels for the PbLi with thin SiC inserts

<table>
<thead>
<tr>
<th>Library</th>
<th>IB TBR</th>
<th>Ratio</th>
<th>OB TBR</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>FENDL-2.1</td>
<td>0.4016</td>
<td>1</td>
<td>0.9992</td>
<td>1</td>
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<tr>
<td>ENDF/B-VIII.0</td>
<td>0.4076</td>
<td>1.015</td>
<td>1.0168</td>
<td>1.017</td>
</tr>
<tr>
<td>FENDL-3.1d</td>
<td>0.4070</td>
<td>1.013</td>
<td>1.0173</td>
<td>1.018</td>
</tr>
<tr>
<td>FENDL-3.2</td>
<td>0.4065</td>
<td>1.012</td>
<td>1.0154</td>
<td>1.016</td>
</tr>
</tbody>
</table>

Max. relative error <0.01%

- TBR ~1.2-1.8% higher than that calculated with FENDL-2.1
- Newer libraries are quite close to each other
Future Work

- Plot dpa, He production, T production results (for both benchmark models)
  - already calculated but not plotted and studied in detail
- Dig into differences of heating in FNSF model
- Add more resolution for heating tallies
Results: Photon Flux FNSF

- Valleys are PbLi
- Peaks are BZ channel walls, BZ SiC channel liners

Max. relative error <0.1% except CC, WP 1-2%
Results: Photon Heating FNSF

- Valleys are in PbLi
- FENDL-3.2 peaks are in BZ channel walls, BW, OB SR back plate (MF82H)

Max. relative error <0.1% except CC, WP 1-2%
UW Neutronics Capabilities (3-D)

- DAGMC (detailed 3-D CAD based Monte Carlo transport)
  - Transports directly in the CAD model (not a translator)
  - Handles complex surfaces without simplification
  - Couples to MCNP, Geant4, FLUKA, SHIFT, OpenMC
  - Provides a common domain for coupling to other analysis
  - [http://fti.neep.wisc.edu/ncoe/](http://fti.neep.wisc.edu/ncoe/)
  - [http://github.com/svalinn](http://github.com/svalinn)

- 3-D CAD model based analysis:

ITER BM08

Nuclear heating mapped to ANSYS mesh for thermal analysis