The Impact of ENDF/B-VIII.0 and FENDL-3.1d on Fusion Neutronics Calculations

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Workshop for Applied Nuclear Data Activities
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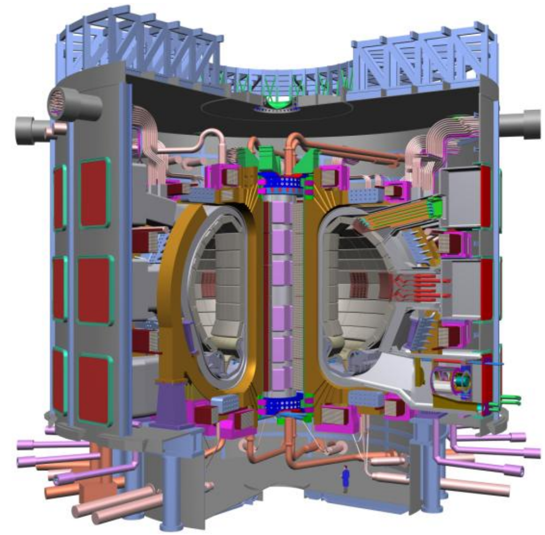
Outline

1) Introduction
2) Nuclear data libraries examined
3) Benchmark/Systems analyzed:
   - ITER-1D
   - ITER-3D
   - FNSF-3D
4) Results
5) Conclusion/Future Work

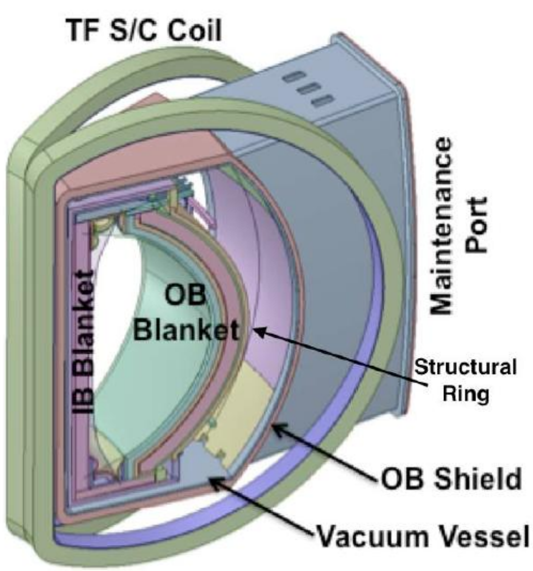
- Details of this work was presented at IAEA:
  - https://www-nds.iaea.org/index-meeting-crp/CM-FENDL-2018/

Introduction

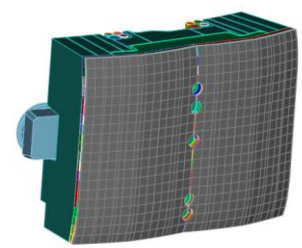
• In the design of fusion reactors, radiation transport calculations are needed to determine radiation levels at various locations in and around the machine
• Both deterministic (Discrete Ordinates) and stochastic (Monte Carlo) methods are used
• These transport codes need to have accurate cross section libraries



ITER



FNSF



ITER Blanket (shield) Module

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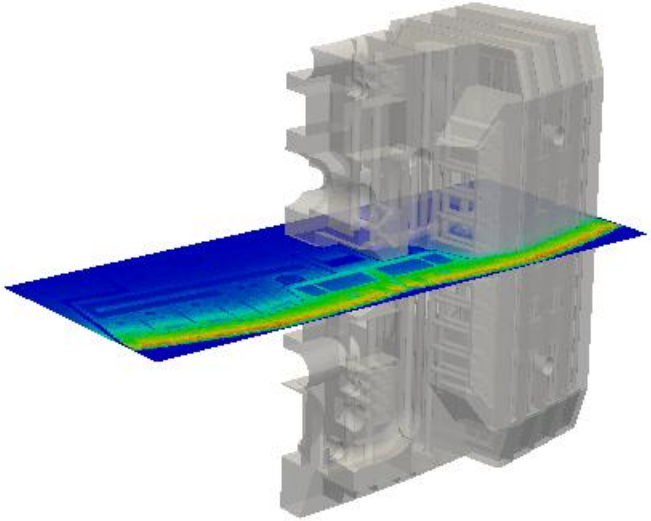
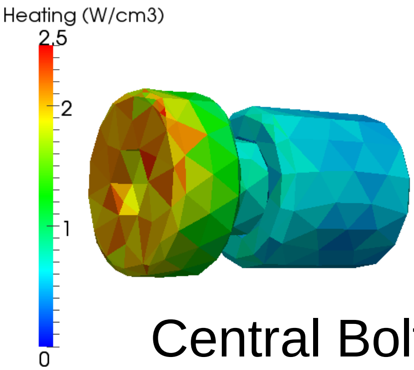
Important Fusion Neutronics Responses

- Neutron flux/fluence (**neutron**)
  - structure, magnets
- Radiation damage/dpa (**neutron**)
  - structural material, magnet degradation
- Helium production (**neutron**)
  - reweldability
- Tritium production (**neutron**)
  - breeding, environmental
- Radiation dose (**neutron+photon**)
  - insulators, electronics, personnel
- Total nuclear heating (**neutron+photon**)
  - coolant system design, thermal stress, etc for structure, magnets
- Activation dose (**photon**)
  - maintenance robotics, personnel

➢ Need accurate neutron **and** photon libraries



ITER Shield Block



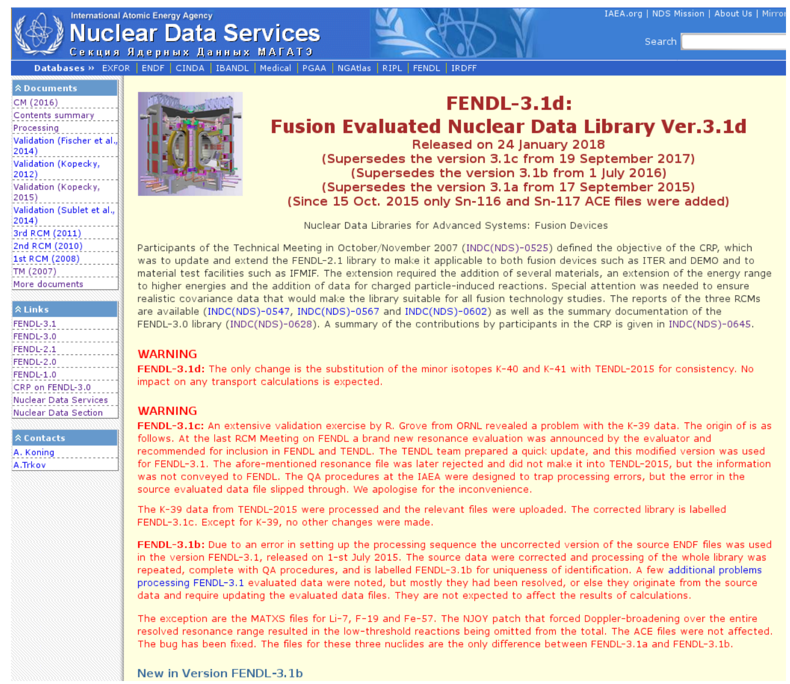
Central Bolt

Goal of this work

- Want to look at the impact of using the updated neutron libraries in calculations of a realistic model of fusion systems *(not just in a small scale isolated laboratory experiment)*
- Libraries examined:
  - *Neutron:*
    1. FENDL-2.1 (21c)
    2. FENDL-3.1 (31b, 31d)-current version 3.1d
    3. ENDF/B-VII.1 (80c)
    4. ENDF/B-VIII.0 (00c)
  - *Photon:*
    1. mcplib84 (84p)

FENDL

- The Fusion Evaluated Nuclear Data Library (FENDL) is an international effort coordinated by the IAEA Nuclear Data Section
- Assembles a collection of the best nuclear data from national cross section data libraries for fusion applications
  - ENDF/B (US), JENDL (Japan), JEFF (Europe), BROND (Russia)
- Process uses fusion specific experimental (e.g. SINBAD) and calculational benchmarks to evaluate the data
- https:/www-nds.iaea.org/fendl21/
- https://www-nds.iaea.org/fendl3/



ENDF/B-VIII.0 Data

- Major new release of the ENDF/B neutron library
- ACE formatted data for MCNP distributed by LANL
    - https://nucleardata.lanl.gov
- Some key isotope updates for neutron sub-library (see Appendix A in reference* for comprehensive list):
    - H-1,2, Li-6, B-10, O-16, Fe-54,56,57,58, Ni-58-62,64, Cu-63,65, W-182-186, U-235,238, Pu-239

**D.A. Brown et al., "ENDF/B-VIII.0: The 8th major release of the nuclear reaction data library with CIELO-project cross sections, new standards, and thermal scattering data", Nuclear Data Sheets, vol 148, p. 1-142, 2018*

Photon Data Libraries in FENDL/MCNP

- Significant efforts performed evaluating neutron data for FENDL
  - FENDL provides ACE formatted neutron data libraries for use with MCNP
- Less effort examining photon cross section data in the FENDL evaluation process
  - No MCNP (ACE formatted) photon libraries provided with FENDL

➢ *But photon heating contributes 90% of the nuclear heating for important fusion materials (e.g. stainless steel, Cu, tungsten)*

MCNP Photon Data:

- Standard library: mcplib04/84 (note: mcplib84 corrects bug in mcplib04)
- New library: eprdata12 (for MCNP6.1) and eprdata14 (for MCNP6.2)
  - includes low energy < 1keV data

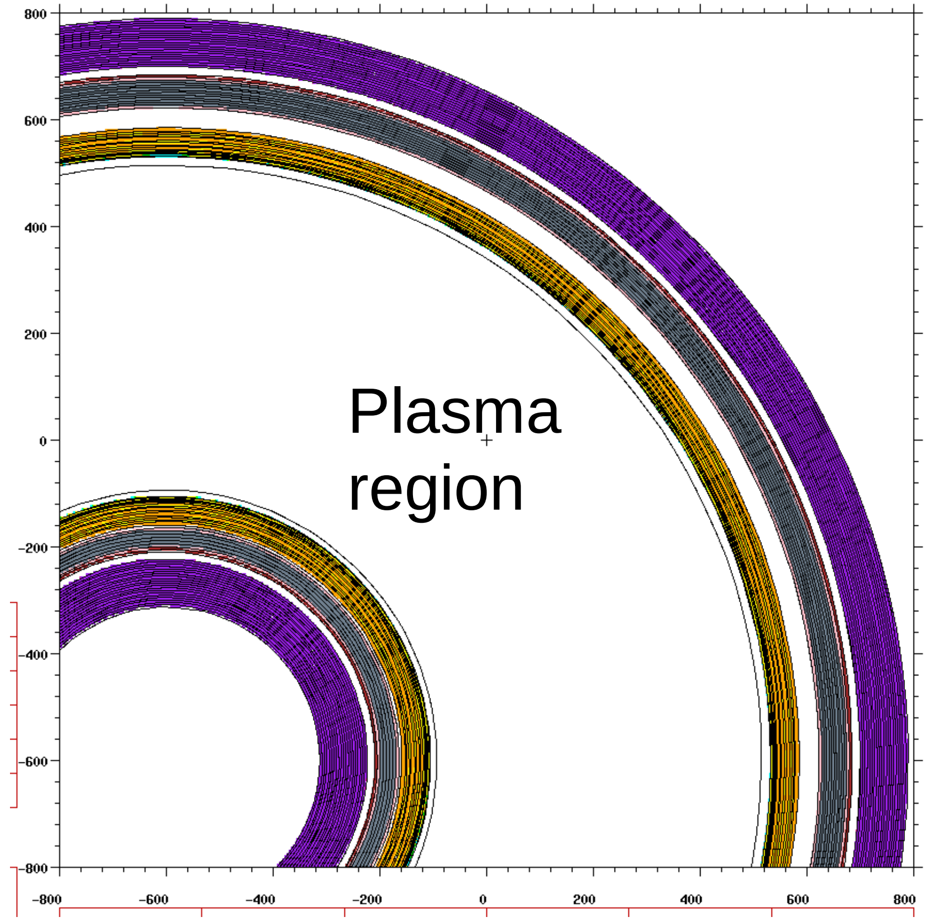
➢ Previous work* has shown that mcplib84 produces results similar to the new eprdata12 library

➢ eprdata14 has not been tested yet

**Bohm T.D, Sawan M.E. "The impact of updated cross section libraries on ITER neutronics calculations", Fusion Science and Technology, Vol 68 p. 331-335, 2015.*

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

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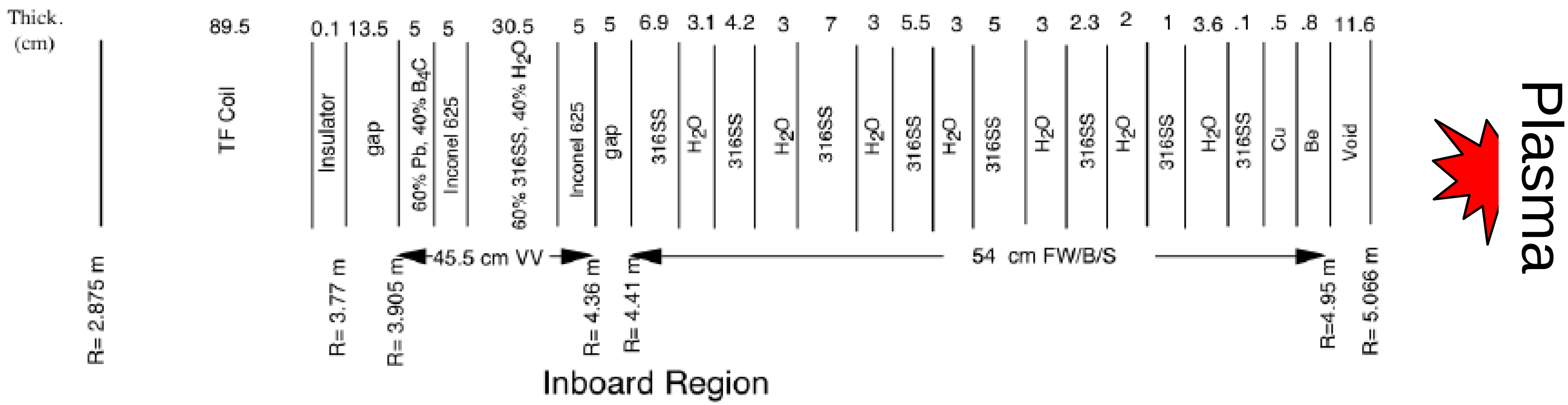
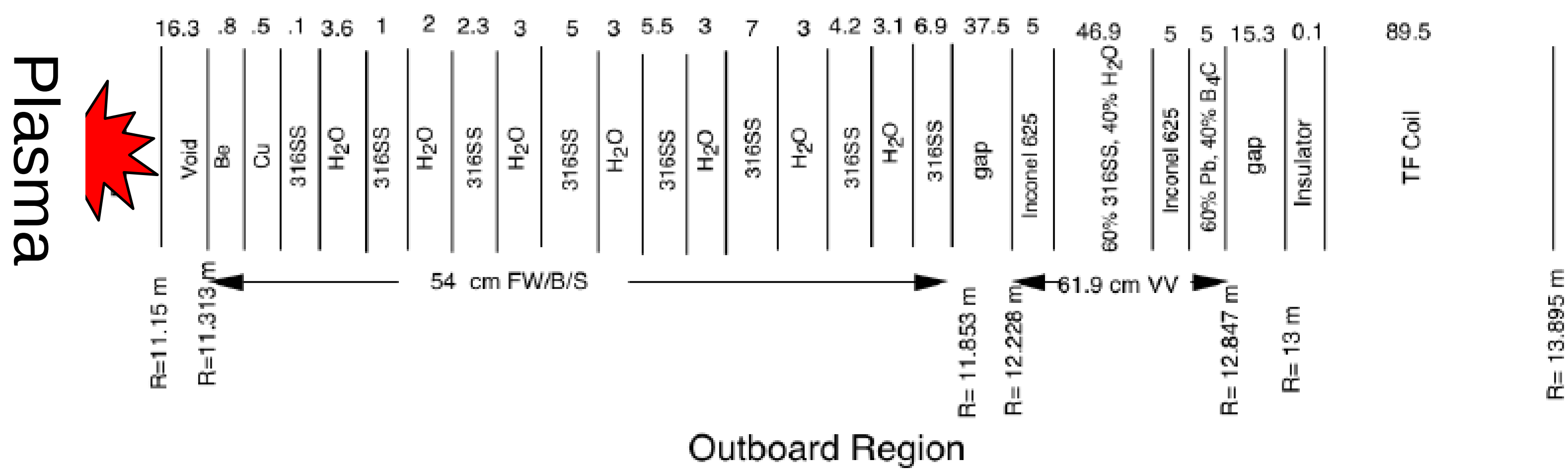
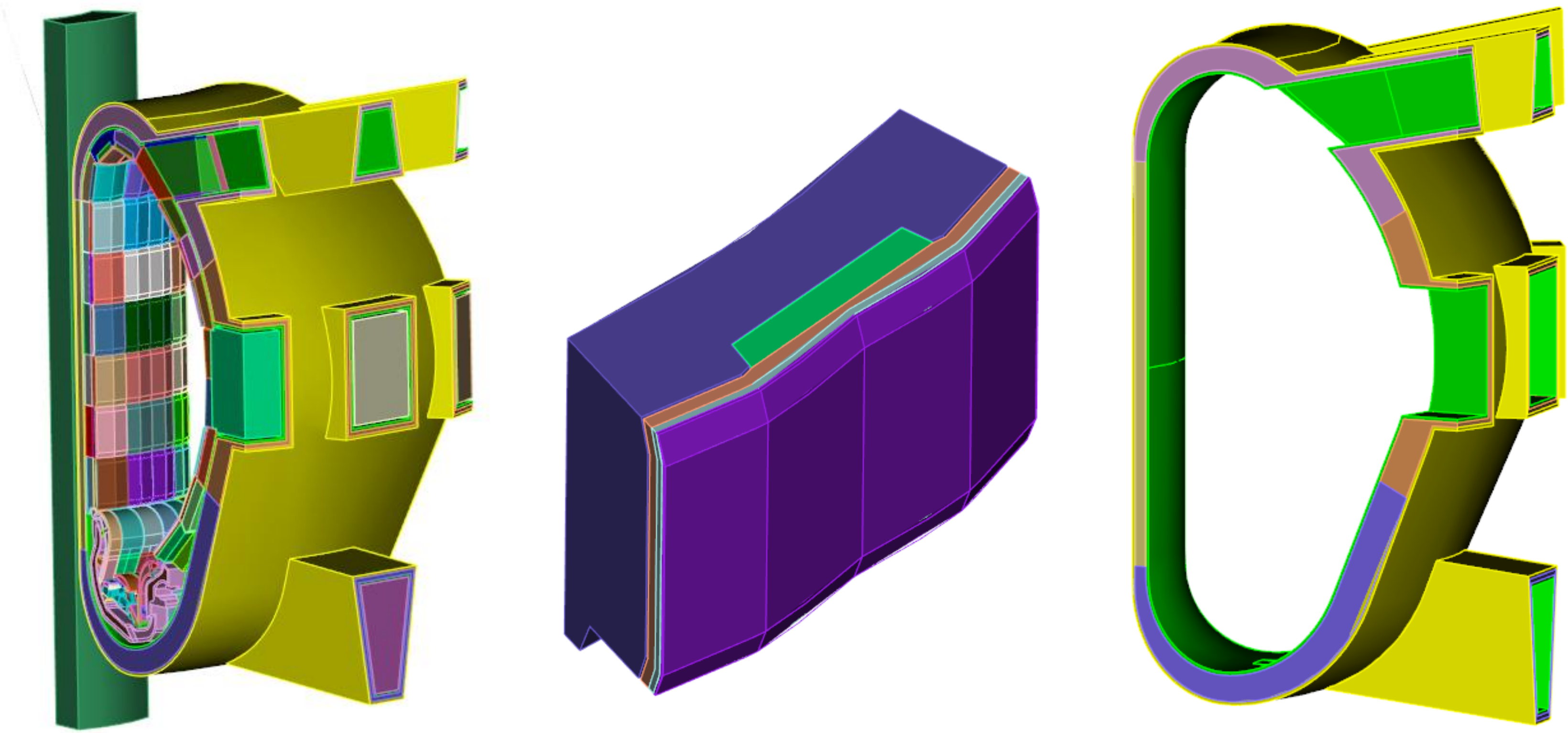
ITER 1-D Cylindrical Benchmark continued





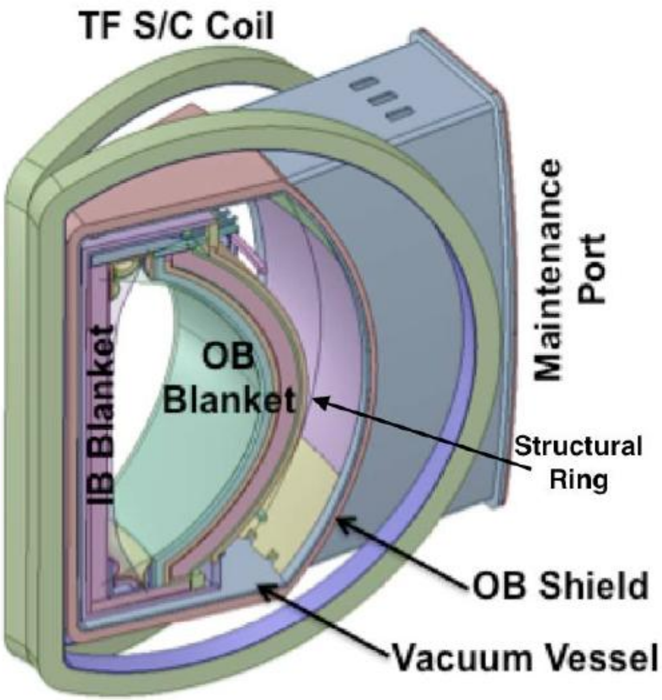
3-D ITER CAD Model

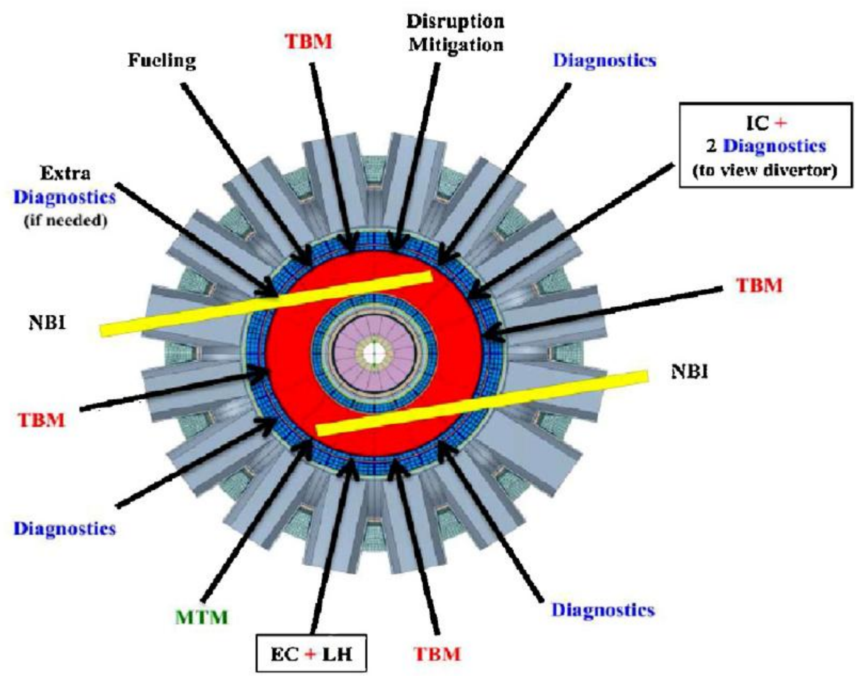
- Based on UW BL-Lite model with added IB Toroidal Field Coil (TFC) volume
- All BMs homogenized and consist of 5 volumes (Be layer, Cu layer, SS finger layer, Beam layer, SB)
- VV consists of 3 homogenized parts (inner shell, body, outer shell)
- Model has 723 volumes, 12067 surfaces, 29467 curves



3-D FNSF

- U.S. Fusion Nuclear Science Facility (FNSF)
  - Step on the path to commercial fusion power plant
  - Next step is a DEMO

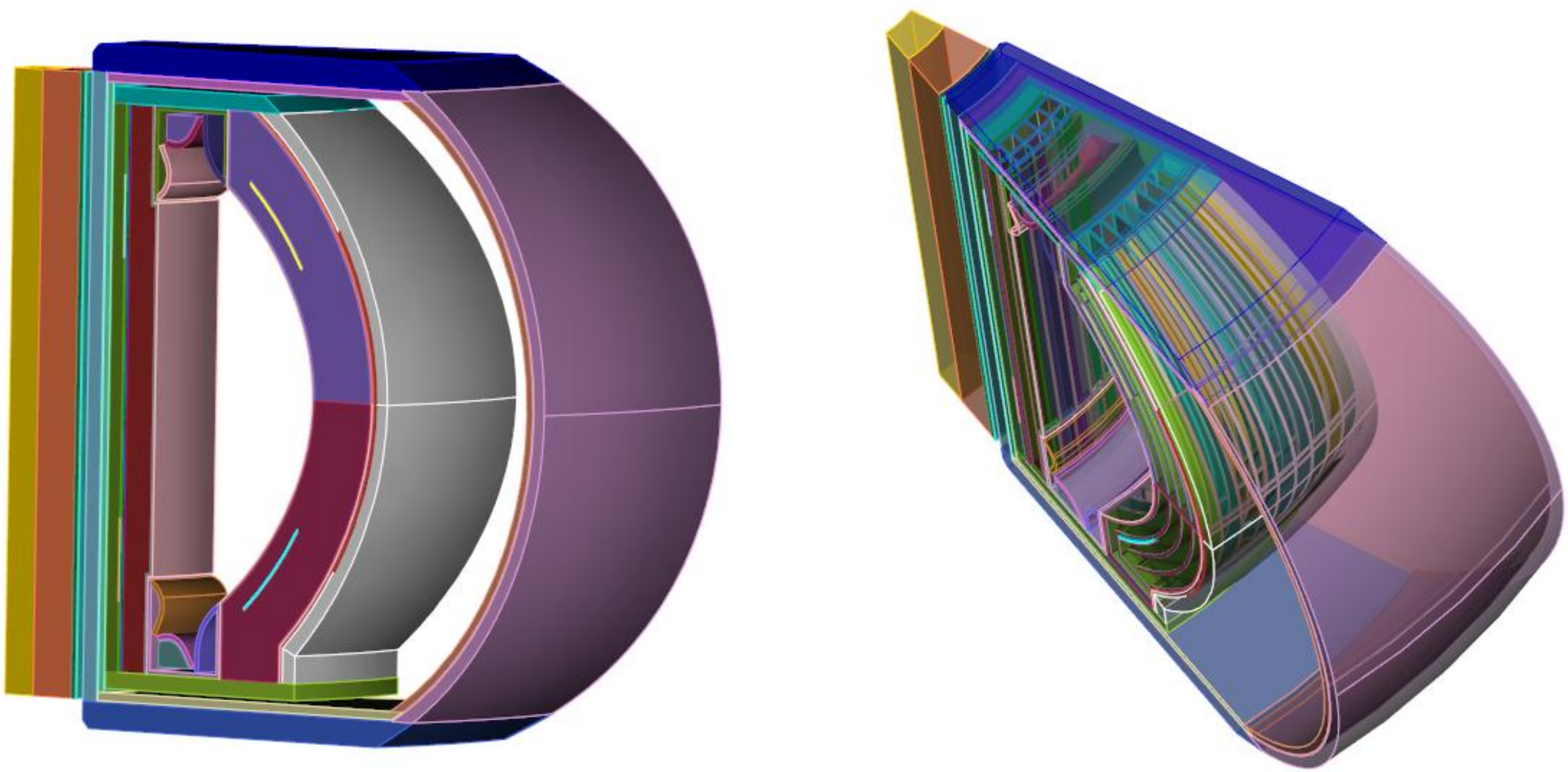




Special Issue: FESS-FNSF Study, Fusion Engineering and Design, Vol 135 Part B, p. 235-426, October 2018.

3-D FNSF Model

- A single sector (22.5 deg) model of FNSF for DAG-MCNP
  - No ports, 2 cm straight gaps between sectors
  - 518 MW fusion power, 3 region plasma source model
  - PbLi breeding region detailed, other components partially homogenized



A. Davis et al. "Neutronics aspects of the FESS-FNSF", *Fusion Engineering and Design*, 2017.

Results/Conclusions

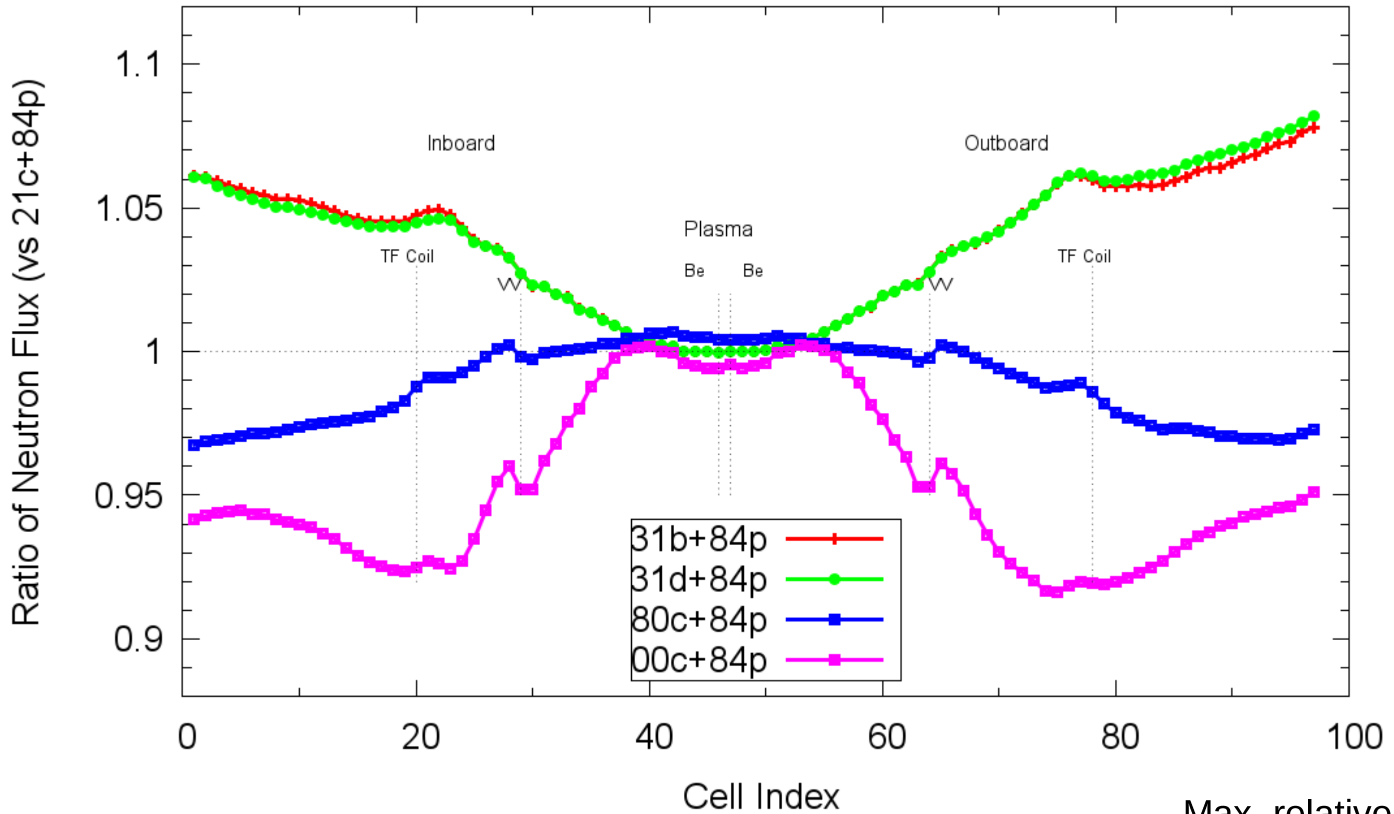
- The maximum differences observed in this study:
  1. Neutron flux 12%
  2. Photon flux 22%
  3. Dpa 9%
  4. He production 18%
  5. Tritium production in structural material 200%
  6. Tritium breeding in PbLi breeding material (FNSF) 1.7%
  7. Total nuclear heating 14%
- Caveat: not all radiation quantities were determined in all models at all component locations
- These impact levels provide reactor designers with an estimate of potential uncertainty in the calculations used in reactor design

Future Work

- Examine some individual nuclide cross sections directly
- Examine a more detailed ITER-3D model with less homogenization
- Examine more radiation quantities and locations in FNSF and ITER 3D models
- Examine the impact for activation calculations

More Details: ITER 1-D Results

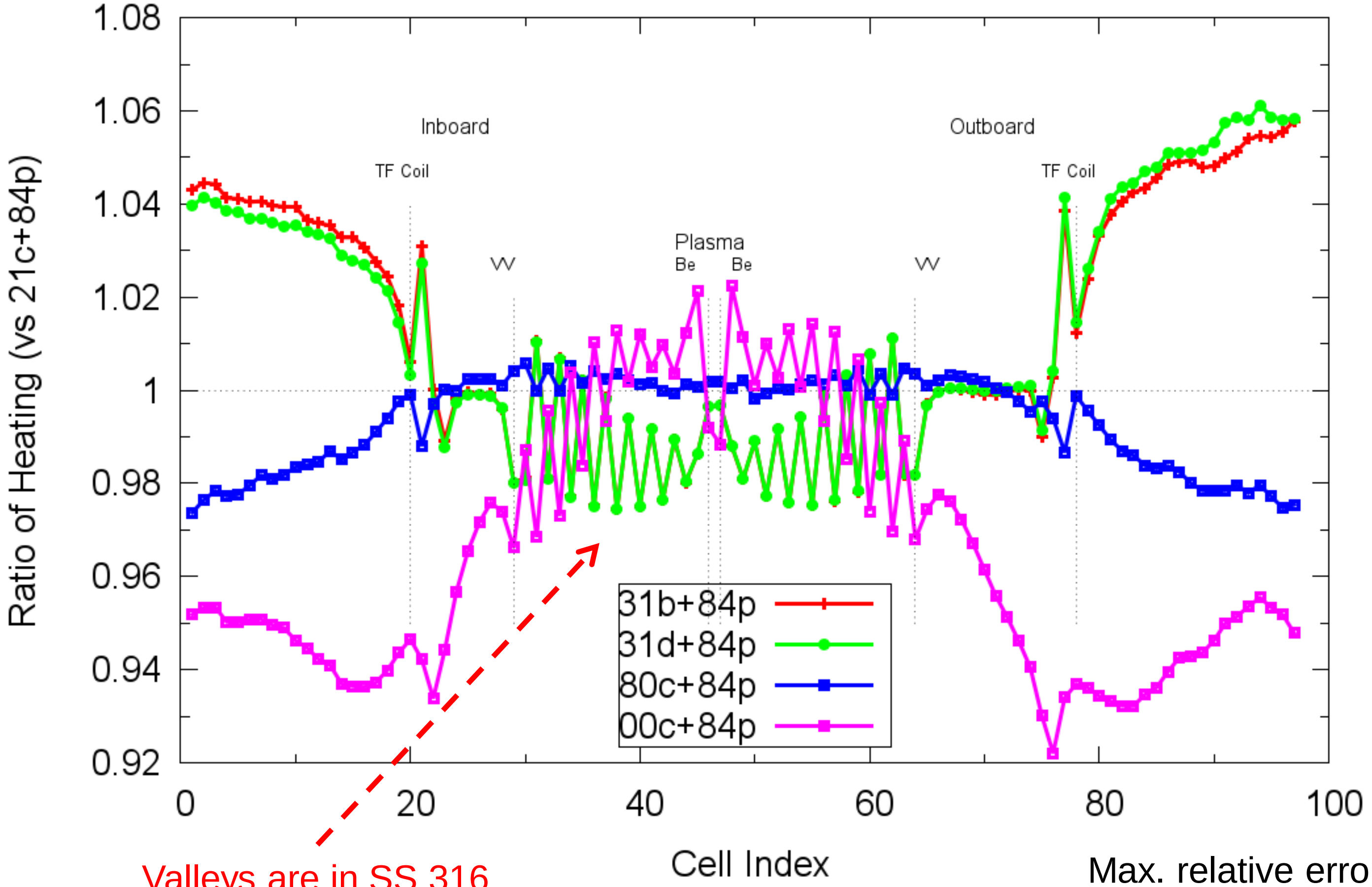
Results: Neutron Flux



Max. relative error <0.26%

- With updated FENDL-3.1 neutron library see neutron fluxes up to 8% higher than FENDL-2.1 (21c) at deep depths in TF coil
- With ENDF/B-VII.1 (80c) see neutron fluxes up to 3% lower
- With ENDF/B-VIII.0 (00c) see neutron fluxes up to 8% lower
- In FENDL-3.1, Fe-56 and Cu data come from JEFF-3.1.1 and ENDF/B-VII.0

Results: Total nuclear heating



Valleys are in SS 316

Max. relative error <0.27%

- With updated FENDL-3.1 neutron library (31b, 31d) see total heating up to 6% higher than FENDL-2.1 (21c) at deep depths in TF coil
- With ENDF/B-VII.1 (80c) see total heating up to 3% lower
- With ENDF/B-VIII.0 (00c) see total heating up to 8% lower

Results: dpa

	21c+84p	31d+84p	%diff.	80c+84p	%diff.	00c+84p	%diff.
IB							
FW Cu (Cu)	9.16416E+00	9.13508E+00	-0.32	9.18390E+00	0.22	9.05766E+00	-1.16
FW SS (Fe)	7.78771E+00	7.78231E+00	-0.07	8.22207E+00	5.58	7.79910E+00	0.15
VV Inc. (Ni)	1.01076E-02	1.04139E-02	3.03	1.01171E-02	0.09	9.30322E-03	-7.96
VV SS (Fe)	3.35716E-03	3.44928E-03	2.74	3.46625E-03	3.25	3.23331E-03	-3.69
Mag. (Cu)	3.88072E-05	4.05628E-05	4.52	3.84160E-05	-1.01	3.53317E-05	-8.96
OB							
FW Cu (Cu)	1.37635E+01	1.37251E+01	-0.28	1.37831E+01	0.14	1.36202E+01	-1.04
FW SS (Fe)	1.18140E+01	1.18102E+01	-0.03	1.24828E+01	5.66	1.18256E+01	0.10
VV Inc. (Ni)	1.38127E-02	1.42370E-02	3.07	1.38188E-02	0.04	1.27151E-02	-7.95
VV SS (Fe)	5.02005E-03	5.16161E-03	2.82	5.18489E-03	3.28	4.84738E-03	-3.44
Mag. (Cu)	5.61928E-06	5.97332E-06	6.30	5.55328E-06	-1.17	5.09857E-06	-9.27

Max. relative error <0.15%

- different neutron flux and spectrum at FWSS, VV, magnet
- dpa values higher for FENDL-3.1d than FENDL-2.1 (up to 6%)
- dpa values lower for ENDF/B-VIII.0 than FENDL-2.1 (up to 9%)

Results: He production

	21c+84p	31d+84p	%diff.	80c+84p	%diff.	00c+84p	%diff.
IB							
FW Be	4.09900E+03	4.10054E+03	0.04	4.12365E+03	0.60	4.13189E+03	0.80
FW CuBeNi	2.10289E+02	2.11118E+02	0.39	2.12205E+02	0.91	2.18079E+02	3.70
FW SS316	1.77311E+02	1.84824E+02	4.24	1.88600E+02	6.37	1.88231E+02	6.16
VV Inconel	6.76921E-02	7.98512E-02	17.96	7.68869E-02	13.58	7.23245E-02	6.84
VV SS316	7.62989E-02	8.24448E-02	8.06	7.97493E-02	4.52	7.72624E-02	1.26
Mag. (Cu)	3.80472E-04	3.99561E-04	5.02	3.79698E-04	-0.20	3.76025E-04	-1.17
OB							
FW Be	5.98127E+03	5.98548E+03	0.07	6.01139E+03	0.50	6.03494E+03	0.90
FW CuBeNi	3.23240E+02	3.24753E+02	0.47	3.26056E+02	0.87	3.35372E+02	3.75
FW SS316	2.45343E+02	2.56163E+02	4.41	2.62737E+02	7.09	2.62457E+02	6.98
VV Inconel	9.04495E-02	1.06714E-01	17.98	1.02669E-01	13.51	9.67467E-02	6.96
VV SS316	1.07582E-01	1.16260E-01	8.07	1.12537E-01	4.61	1.09184E-01	1.49
Mag. (Cu)	5.56782E-05	5.95003E-05	6.86	5.53346E-05	-0.62	5.48316E-05	-1.52

Max. relative error <0.19%

- different neutron flux and spectrum at FWSS, VV, magnet
- He production values higher for FENDL-3.1d than FENDL-2.1 (up to 18%)
- He production values higher for ENDF/B-VIII.0 than FENDL-2.1 (up to 7%) except magnet (lower)

Results: Tritium production

	21c+84p	31d+84p	%diff.	80c+84p	%diff.	00c+84p	%diff.
IB							
FW Be	6.10392E+01	6.10364E+01	0.00	6.11245E+01	0.14	6.07546E+01	-0.47
FW CuBeNi	1.56402E+00	1.56365E+00	-0.02	1.56666E+00	0.17	1.85655E+00	18.70
FW SS316	1.19527E-01	1.19131E-01	-0.33	2.22290E-01	85.97	2.27089E-01	89.99
VV Inconel	2.92231E-06	6.92835E-06	137.08	6.86316E-06	134.85	8.74980E-06	199.41
VV SS316	2.47763E-05	2.53431E-05	2.29	4.19001E-05	69.11	4.34842E-05	75.51
Mag. (Cu)	1.34326E-06	1.42165E-06	5.84	1.30178E-06	-3.09	1.54948E-06	15.35
OB							
FW Be	8.96548E+01	8.96784E+01	0.03	8.97799E+01	0.14	8.92987E+01	-0.40
FW CuBeNi	2.44711E+00	2.44778E+00	0.03	2.45166E+00	0.19	2.90682E+00	18.79
FW SS316	1.86724E-01	1.86233E-01	-0.26	3.49079E-01	86.95	3.56251E-01	90.79
VV Inconel	3.78742E-06	9.02442E-06	138.27	8.95916E-06	136.55	1.14236E-05	201.62
VV SS316	3.57871E-05	3.66194E-05	2.33	6.04256E-05	68.85	6.29001E-05	75.76
Mag. (Cu)	1.82708E-07	1.97197E-07	7.93	1.76016E-07	-3.66	2.11448E-07	15.73

Max. relative error <0.27%

- T production substantially different in SS 316 for 31d versus 80c, 00c
- T production substantially different in magnet for 00c versus 80c
- FENDL-3.1d and ENDF/B-VII.1,VIII.0 (80c,00c) still missing rxn mt=205 for tungsten isotopes

More Details: ITER 3-D Results

Results- total nuclear heating IB TFC

Library	Tally IB TFC (W/cm^3)	Ratio
21c+84p	3.72074E-05	1
31d+84p	3.73618E-05	1.00
80c+84p	3.62283E-05	0.97
00c+84p	3.44389E-05	0.93

Max. relative error <0.66%

- With updated FENDL-3.1 library, see total heating about the same as FENDL-2.1 (21c) at IB TFC
- With ENDF/B-VII.1 (80c) see total heating 3% lower
- With ENDF/B-VIII.0 (00c) see total heating 7% lower

More Details: FNSF 3-D Results

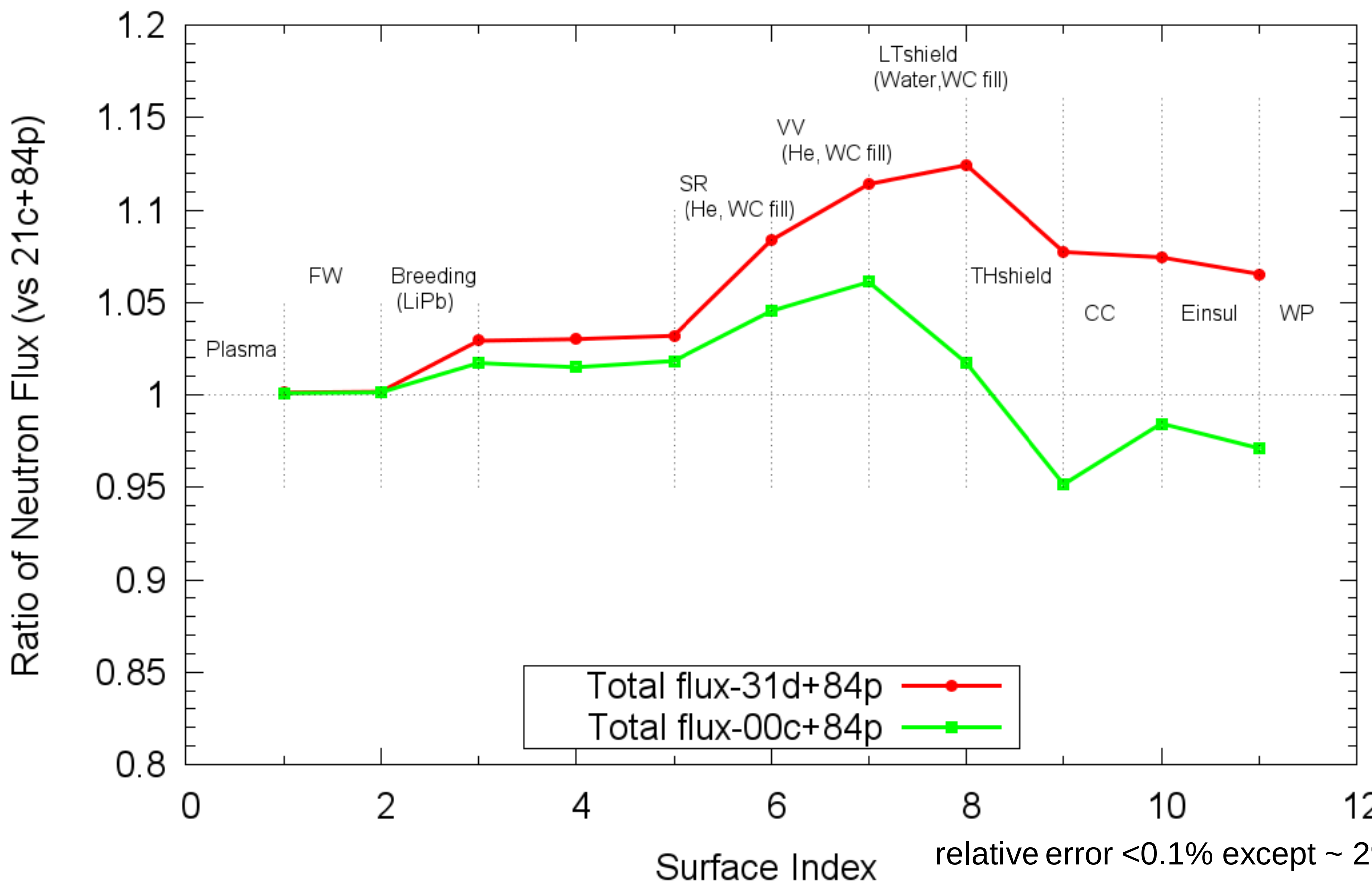
FNSF Results-Fe dpa

Library	IB FW (dpa/sec)	Ratio	IB VV (dpa/sec)	Ratio
21c+84p	4.478E-07	1	2.586E-09	1
31d+84p	4.482E-07	1.00	2.825E-09	1.09
00c+84p	4.522E-07	1.01	2.742E-09	1.06

VV relative error <0.27%

- At the FW, dpa values are similar for all libraries
- At the VV, dpa values are 9% higher with the FENDL-3.1 library compared to FENDL-2.1 (21c)
- At the VV, dpa values are 6% higher with the ENDF/B-VIII.0 library as compared to FENDL-2.1 (21c)

FNSF Results- IB neutron flux



relative error <0.1% except ~ 2% at TH shield-WP

- With updated FENDL-3.1 neutron library see neutron fluxes up to 12% higher than FENDL-2.1 (21c) at the LT shield
- With ENDF/B-VIII.0 (00c) see neutron fluxes up to 6% higher at LT shield but 5% lower at coil case

FNSF Results-total nuclear heating

Library	IB VV (MW)	Ratio	IB Coil Case (MW)	Ratio
21c+84p	1.757E-01	1	7.184E-05	1
31d+84p	1.852E-01	1.05	8.153E-05	1.14
00c+84p	1.842E-01	1.05	7.746E-05	1.08

VV is 3CrFS, WC filler, He cooled
Magnet Coil Case is SS316

VV relative error <0.03%
Coil Case relative error <1.3%

- At the VV, heating values are 5% higher for FENDL-3.1 and ENDF/B-VIII.0 compared to FENDL-2.1
- At the CC, heating values are 14% higher for FENDL-3.1 as compared to FENDL-2.1
- At the CC, heating values are 8% higher for ENDF/B-VIII.0 as compared to FENDL-2.1

FNSF Results-He production

Library	IB FW (dpa/sec)	Ratio	IB VV (dpa/sec)	Ratio
21c+84p	4.665E-06	1	3.050E-09	1
31d+84p	4.693E-06	1.01	3.056E-09	1.02
00c+84p	5.099E-06	1.09	3.418E-09	1.12

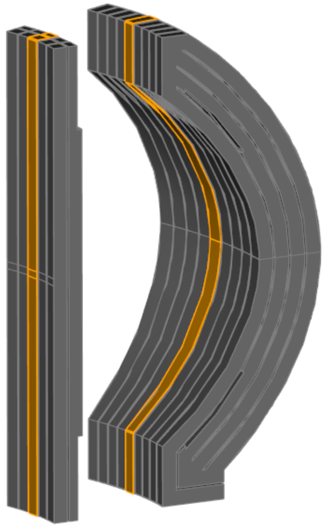
FW is MF82H, VV is 3CrFS

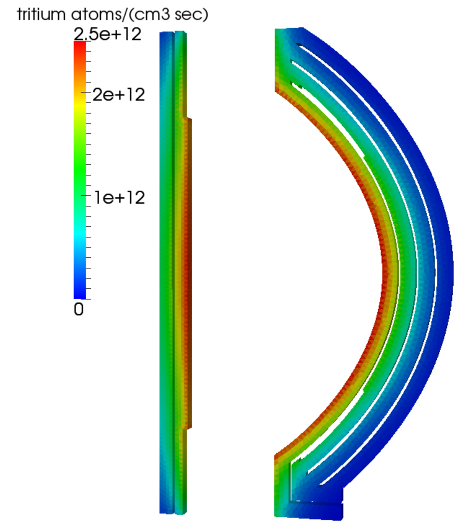
VV relative error <0.27%

- At the FW, He production values are similar for the FENDL libraries but the ENDF/B-VIII.0 library is 9% higher
- At the VV, He production values are similar for the FENDL libraries but the ENDF/B-VIII.0 library is12% higher

Results-Tritium Breeding Ratio

- PbLi Breeding
  - 84.3 atomic% Pb
  - 15.7 atomic% Li (enriched to 90% Li-6)





Library	IB TBR	Ratio	OB TBR	Ratio
21c+84p	0.2961	1	0.8135	1
31d+84p	0.3000	1.013	0.8274	1.017
00c+84p	0.3003	1.014	0.8265	1.016

Max. relative error <0.01%

- With updated FENDL-3.1 library and with ENDF/B-VIII.0 (00c) see tritium breeding about 1.65% higher than FENDL-2.1 (21c)