UK Atomic Energy Authority

Decay-heat validation of simulations with fusion neutrons
(+ nuclear heating importance)

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Contents

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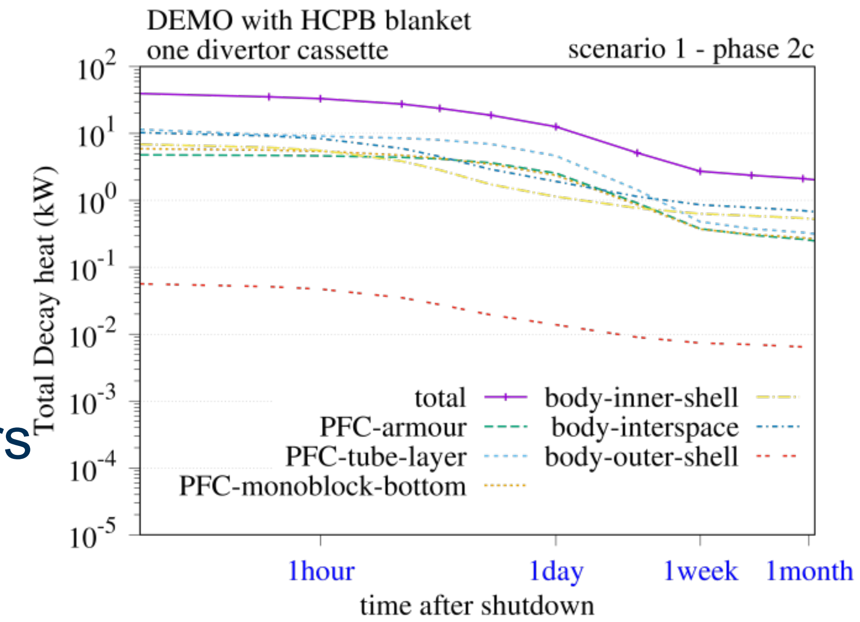
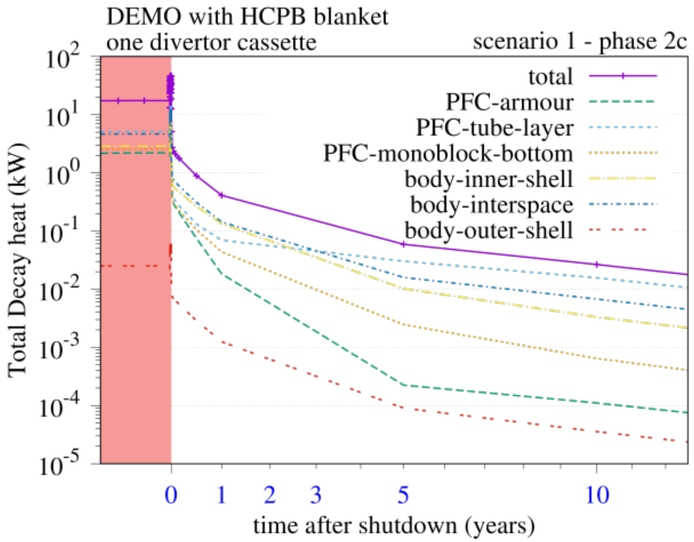
- Why decay heat predictions are important for fusion engineering
- FNS Decay heat benchmark to test codes and libraries
- Nuclear heating evaluations; contribution of photons

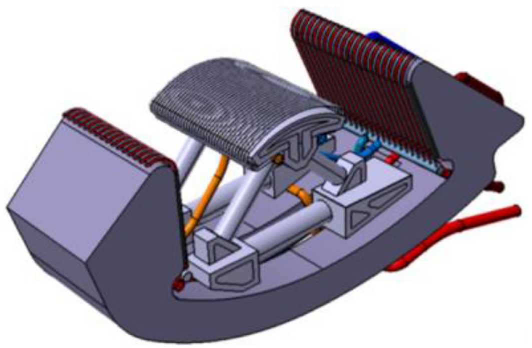
Decay heat

Motivation for high accuracy in decay heat predictions

- Fusion is moving towards engineering delivery of prototype and near-commercial reactors
- Cooling requirements, both during and after operation, are critical engineering parameters
- Large uncertainty is not acceptable when designing cooling plants and will jeopardize net energy gain
- A single divertor cassette on DEMO may have cooling requirements of 10s of kW at shutdown
    - One of 54 in this design
    - Mixture of steels, W, copper-alloys

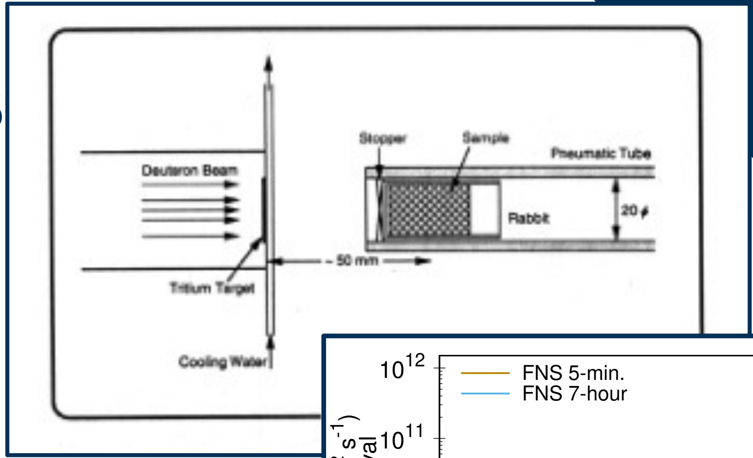


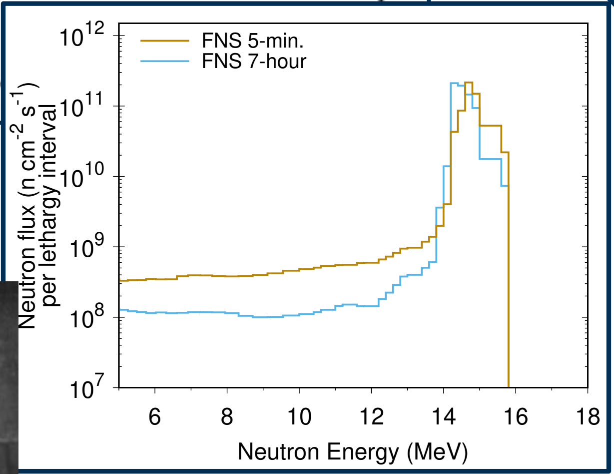


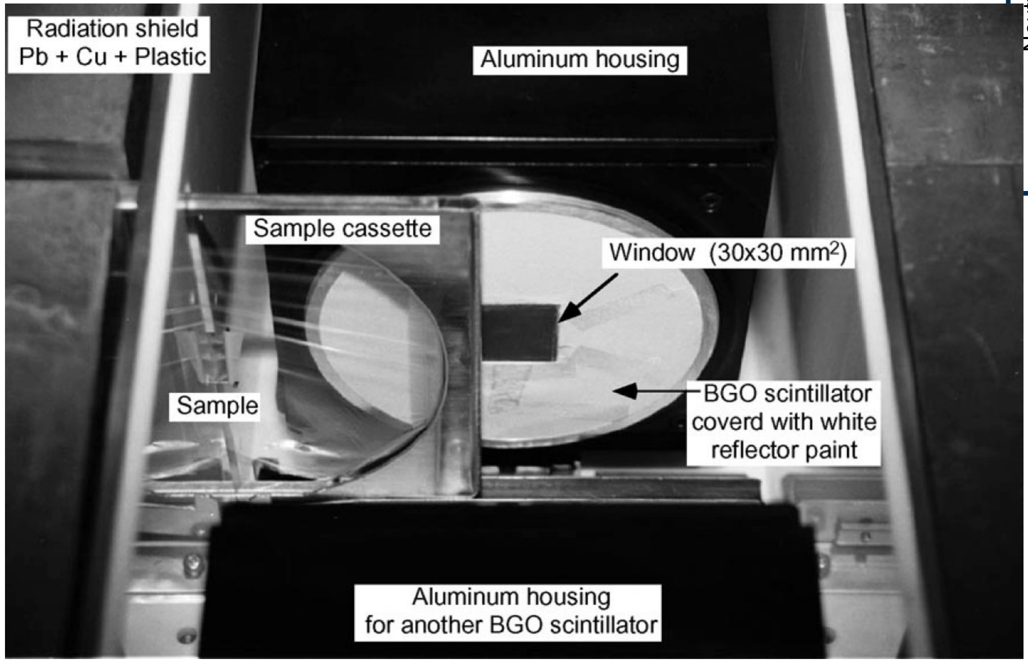


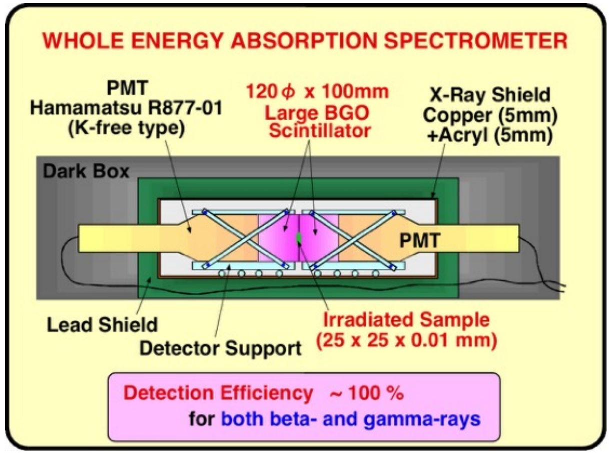
FNS decay-heat experiments

- JAEA experiments in 1996-2000 aimed at providing fusion-relevant decay-power data for important materials
- 2 mA deuteron beam onto a tritium target producing 14 MeV-peaked neutron fluxes of ~10^{10} n/cm^2/s
- Decay heat measured after 5-minute or 7-hour irradiations using Whole Energy Absorption Spectrometer (WEAS)









Z	Material	Form	Z	Material	Form
9	Fluorine	CF_2	46	Palladium	Metallic Foil
11	Sodium	Na_2CO_3	47	Silver	Metallic Foil
12	Magnesium	MgO	48	Cadmium	Metallic Foil
13	Aluminium	Metallic Foil	49	Indium	Metallic Foil
14	Silicon	Metallic Powder	50	Tin	SnO_2
15	Phosphorus	P_3N_5	51	Antimony	Metallic Powder
16	Sulphur	Powder	52	Tellurium	TeO_2
17	Chlorine	$C_2H_2Cl_2$	53	Iodine	IC_6H_4OH
19	Potassium	K_2CO_3	55	Caesium	Cs_2O_3
20	Calcium	CaO	56	Barium	$BaCO_3$
21	Scandium	Sc_2O_3	57	Lanthanum	La_2O_3
22	Titanium	Metallic Foil	58	Cerium	CeO_2
23	Vanadium	Metallic Foil	59	Praseodymium	Pr_6O_{11}
24	Chromium	Metallic Powder	60	Neodymium	Nd_2O_3
25	Manganese	Metallic Powder	62	Samarium	Sm_2O_3
26	Iron	Metallic Foil	63	Europium	Eu_2O_3
Alloy	SS304	Metallic Foil	64	Gadolinium	Gd_2O_3
Alloy	SS316	Metallic Foil	65	Terbium	Tb_4O_7
27	Cobalt	Metallic Foil	66	Dysprosium	Dy_2O_3
Alloy	Inconel-600	Metallic Foil	67	Holmium	Ho_2O_3
28	Nickel	Metallic Foil	68	Erbium	Er_2O_3
Alloy	Nickel-chrome	Metallic Foil	69	Thulium	Tm_2O_3
29	Copper	Metallic Foil	70	Ytterbium	Yb_2O_3
30	Zinc	Metallic Foil	71	Lutetium	Lu_2O_3
31	Gallium	Ga_2O_3	72	Hafnium	Metallic Powder
32	Germanium	GeO_2	73	Tantalum	Metallic Foil
33	Arsenic	As_2O_3	74	Tungsten	Metallic Foil
34	Selenium	Metallic Powder	75	Rhenium	Metallic Powder
35	Bromine	BrC_6H_4COOH	76	Osmium	Metallic Powder
37	Rubidium	Rb_2CO_3	77	Iridium	Metallic Powder
38	Strontium	$SrCO_3$	78	Platinum	Metallic Foil
39	Yttrium	Y_2O_3	79	Gold	Metallic Foil
40	Zirconium	Metallic Foil	80	Mercury	HgO
41	Niobium	Metallic Foil	81	Thallium	Tl_2O
42	Molybdenum	Metallic Foil	82	Lead	Metallic Foil
44	Ruthenium	Metallic Powder	83	Bismuth	Metallic Powder
45	Rhodium	Metallic Powder			

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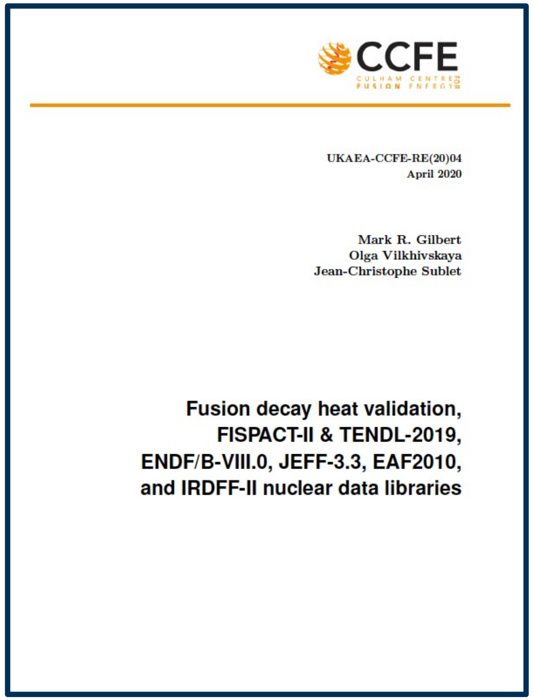
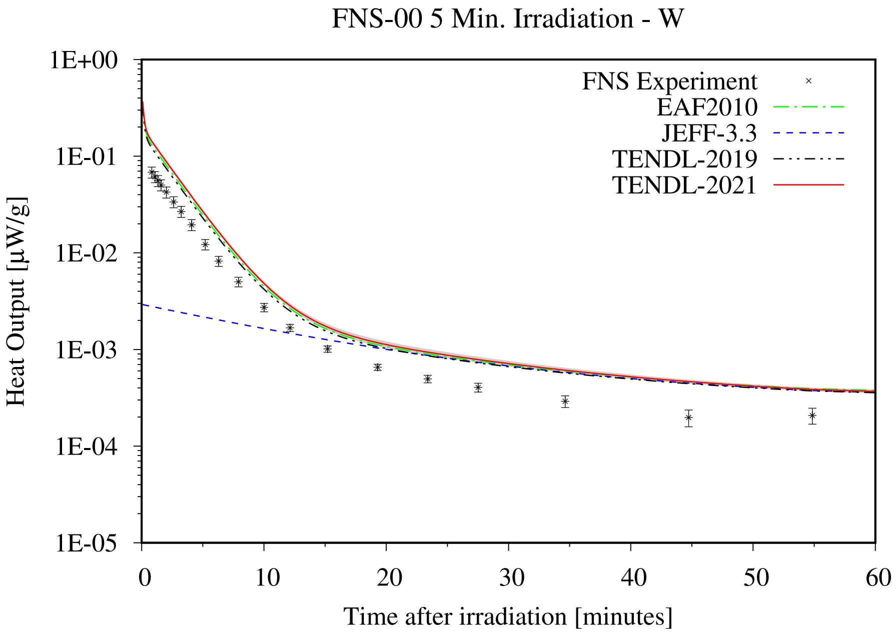
- Measurements for 73 different materials
- Crafted into a simulation benchmark to test decay-heat predictions with inventory codes (FISPACT-II) and different nuclear data libraries

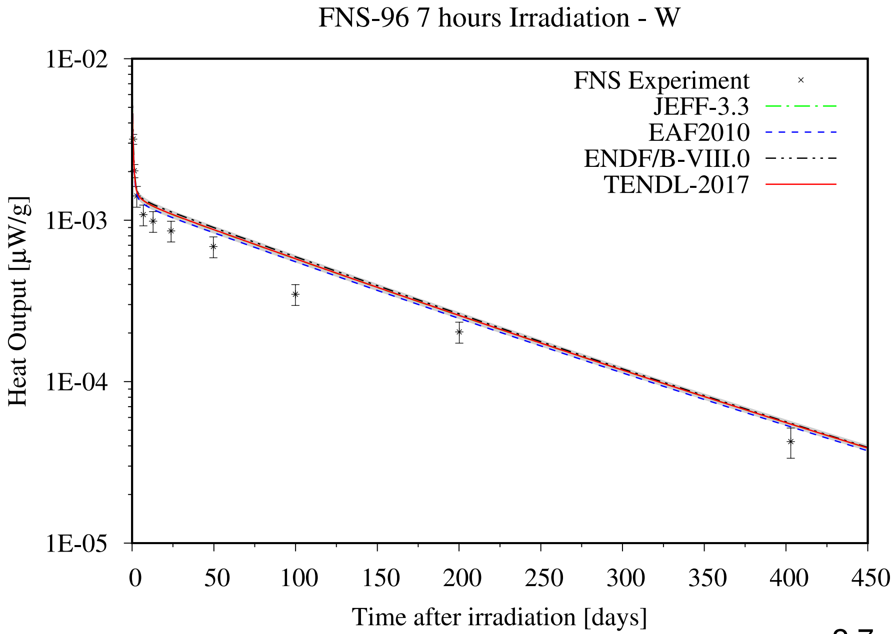


- Latest version:
- Mostly tests cross sections (not decay data)
- Data and benchmark guidance available on CoNDERC website https://nds.iaea.org/conderc/

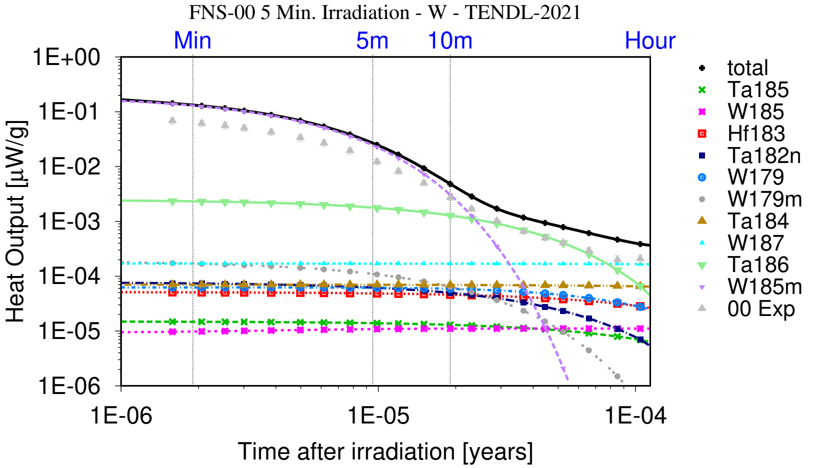
Gilbert, Sublet, Nucl. Fusion **59** (2019) 086045

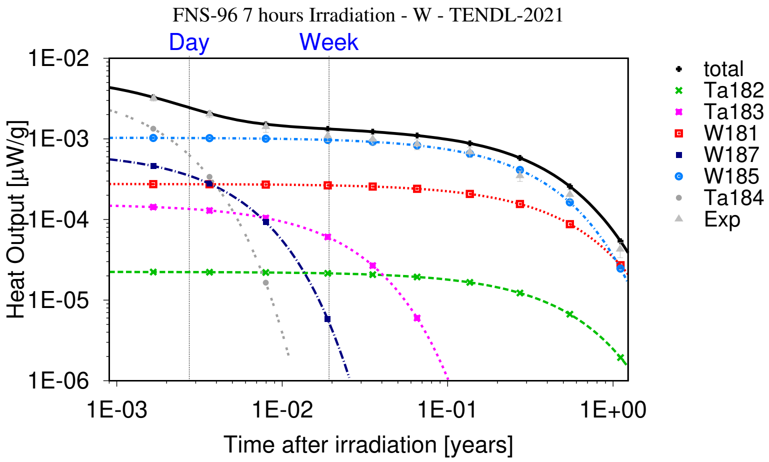
Typical benchmark output: W

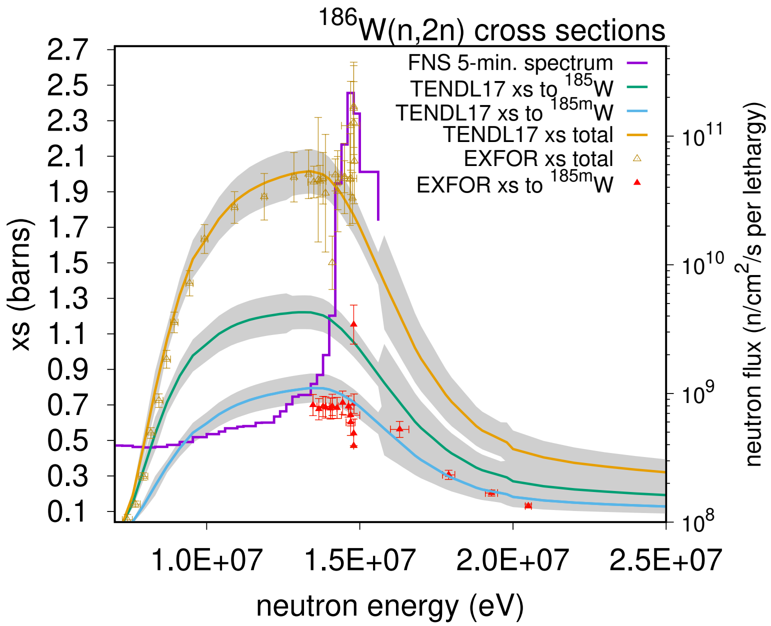




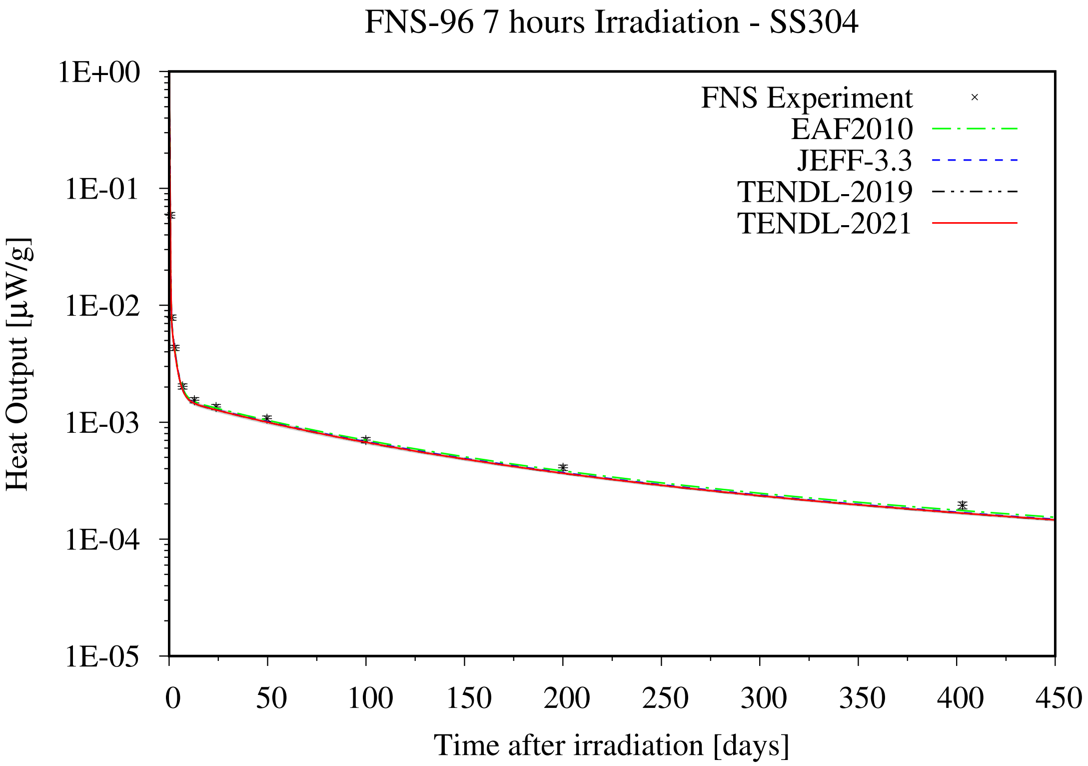
- Simulations overpredict relative to experiments after both 5-min and 7-hour irradiation
- Potential unresolved issue with ^{186}W(n,2n)

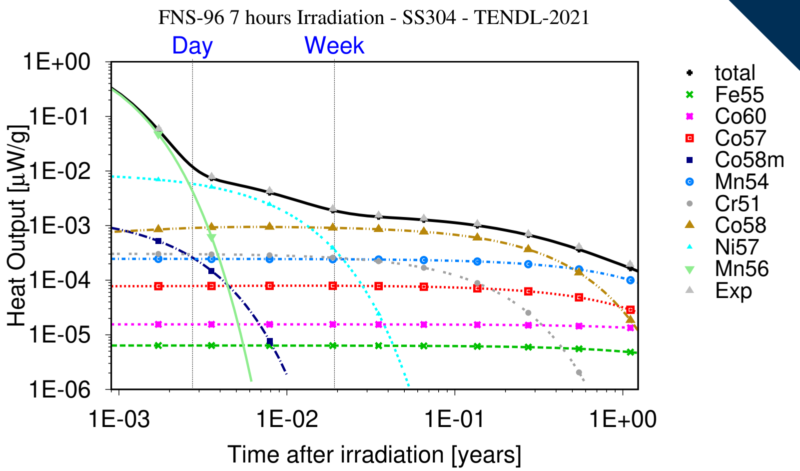




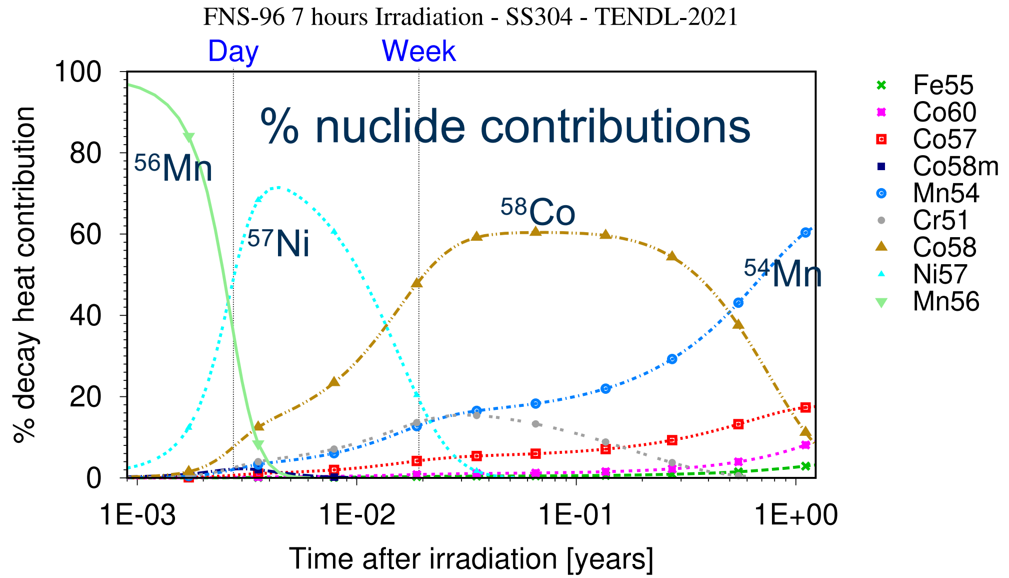


Good performance: SS304



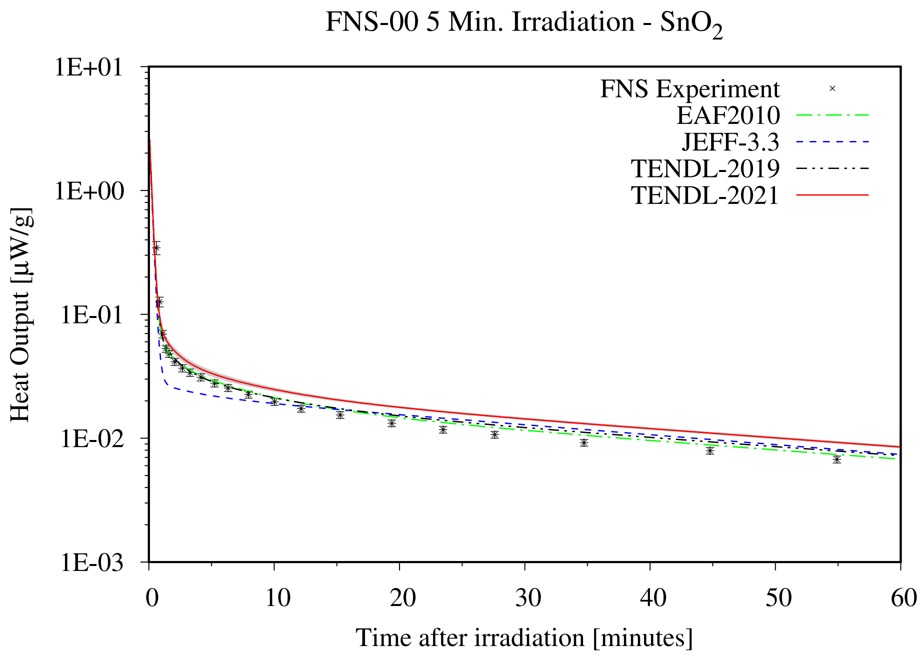


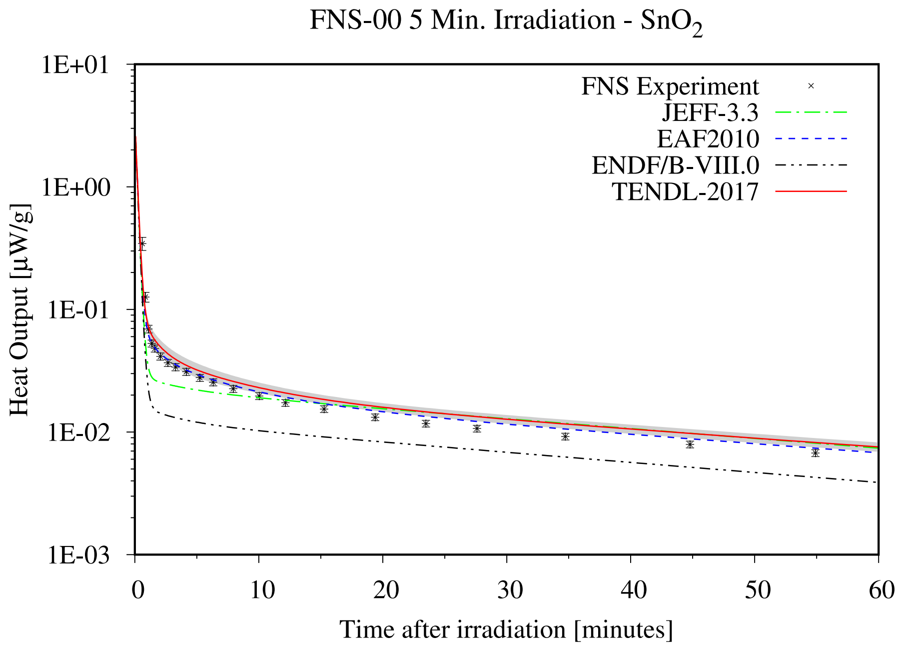
- Benchmark provides excellent validation of decay heat predictions for many materials, even complex alloys
- Sometimes requiring close match of several reaction channels over several orders of decay times



Product	$T_{1/2}$	Pathways	Path %
Mn56	2.58h	Fe56(n,p)Mn56	99.8
Ni57	1.50d	Ni58(n,2n)Ni57	100.0
Co58	70.87d	Ni58(n,p)Co58	80.0
		Ni58(n,p)Co58m(IT)Co58	20.0
Mn54	312.16d	Fe54(n,p)Mn54	53.1
		Mn55(n,2n)Mn54	46.8

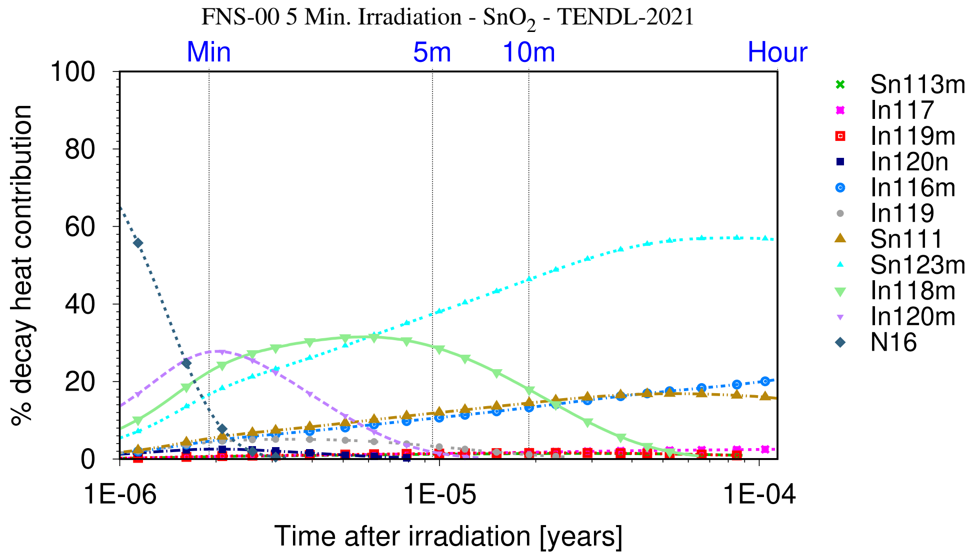
Metastable importance: tin



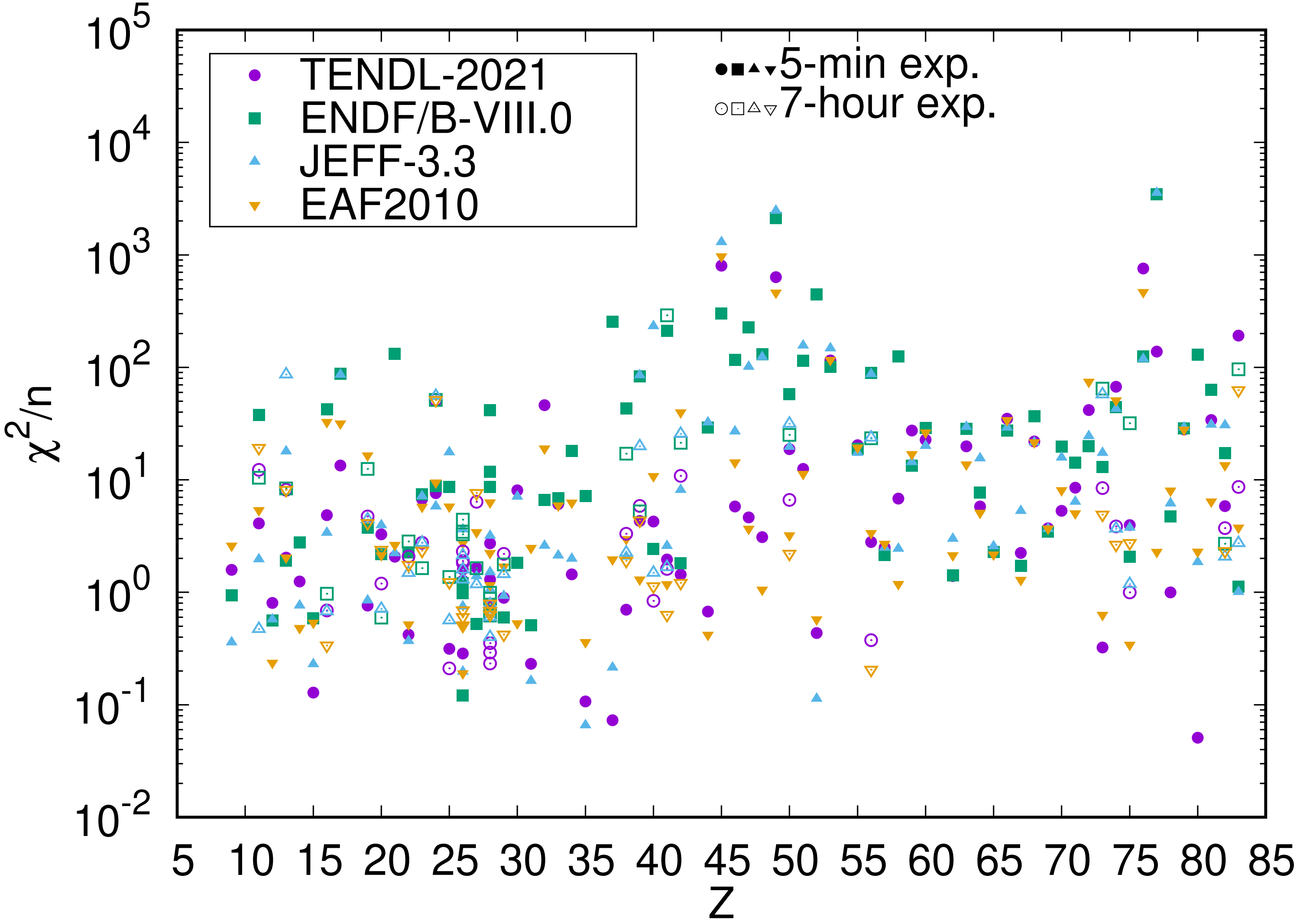


Measurements were taken soon after exposure, allowing validation of the production of short-lived metastables in some materials,
and even ^{16}N ($T_{1/2}$=7s)

Product	$T_{1/2}$	Pathways	Path %
In120m	46.21s	Sn120(n,p)In120m	100.0
In118m	4.45m	Sn118(n,p)In118m	88.6
		Sn118(n,p)In118n(IT)In118m	10.4
Sn123m	40.06m	Sn124(n,2n)Sn123m	99.9



Overall performance of libraries

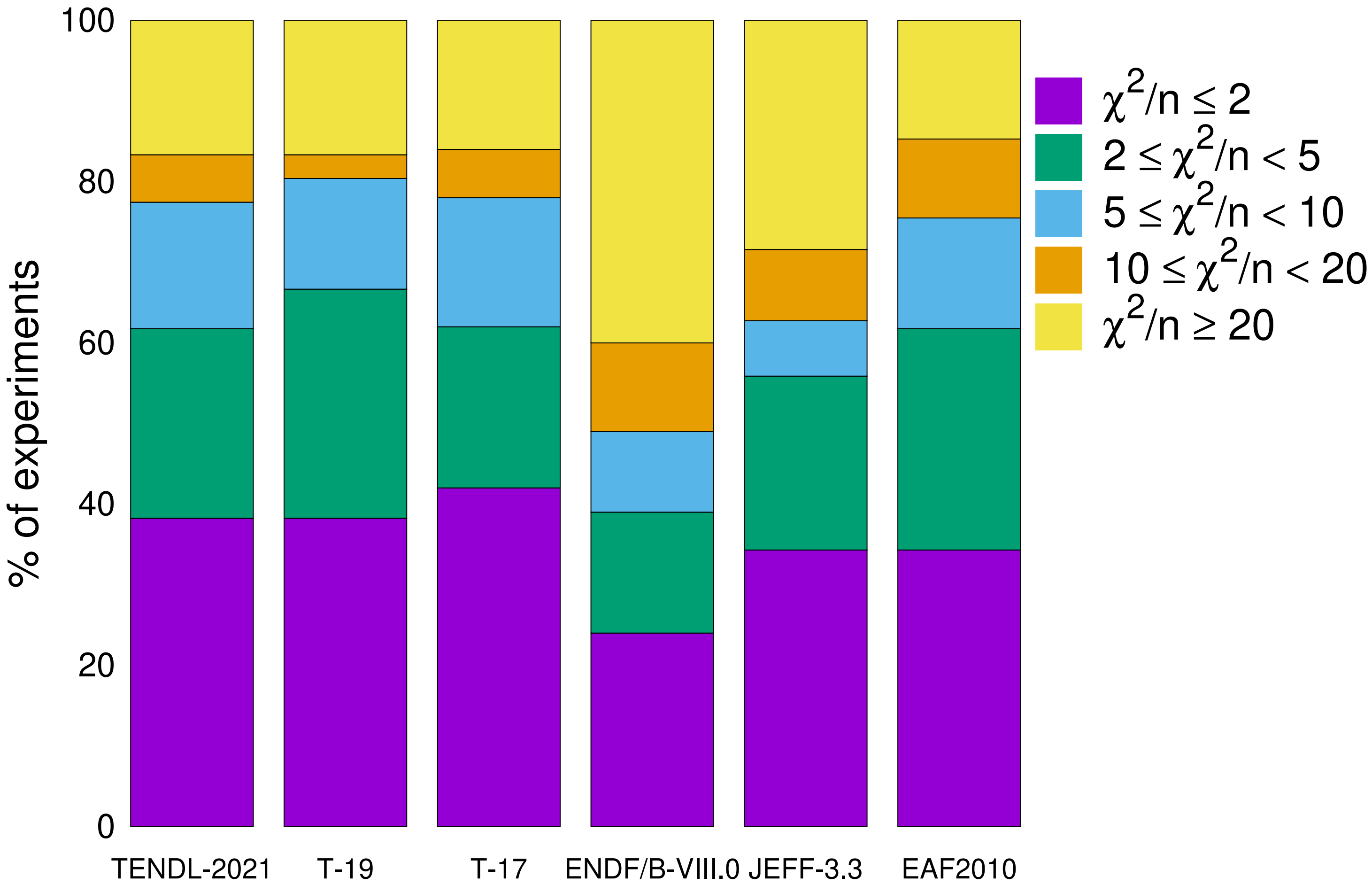


- Deviations from experiment increase with Z
- χ^2 values are reasonably consistent across the materials (high Z materials typically had larger errors in the experiments)

$$\chi^2 = \left(\frac{D_{sim} - D_{exp}}{\Delta D_{exp}}\right)^2$$

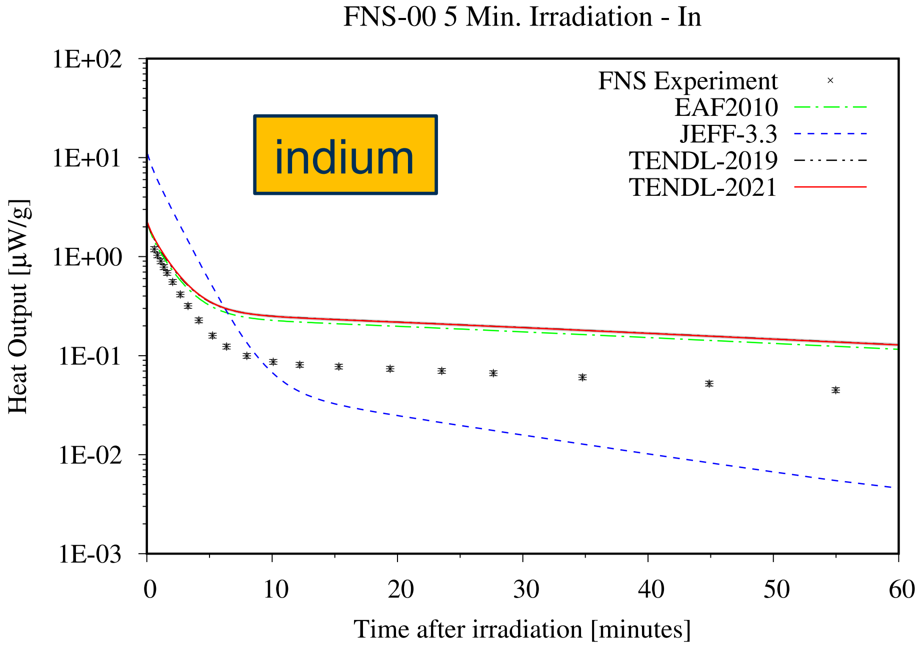
n – number of measurements in experiment

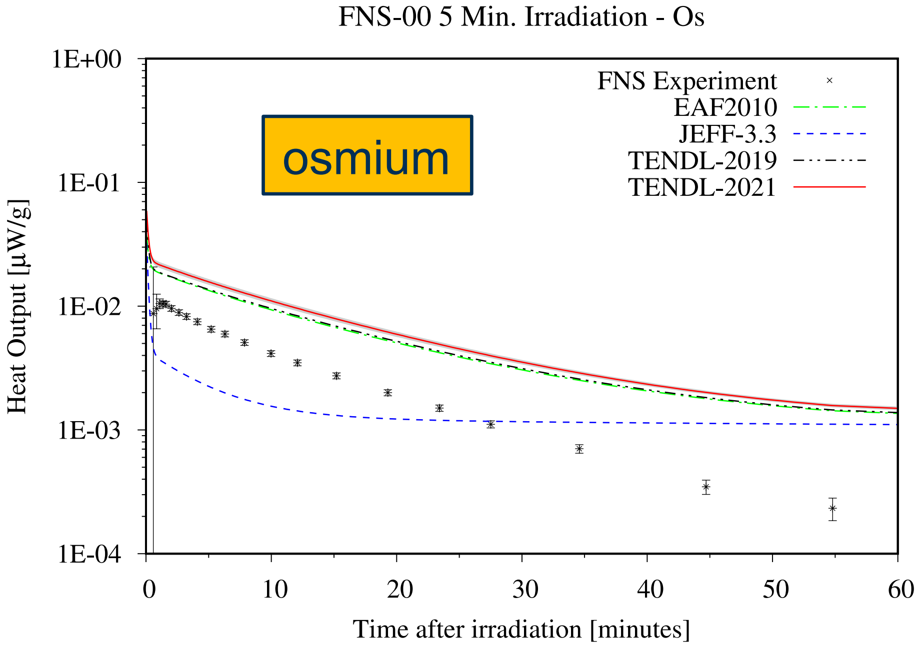
Library comparison

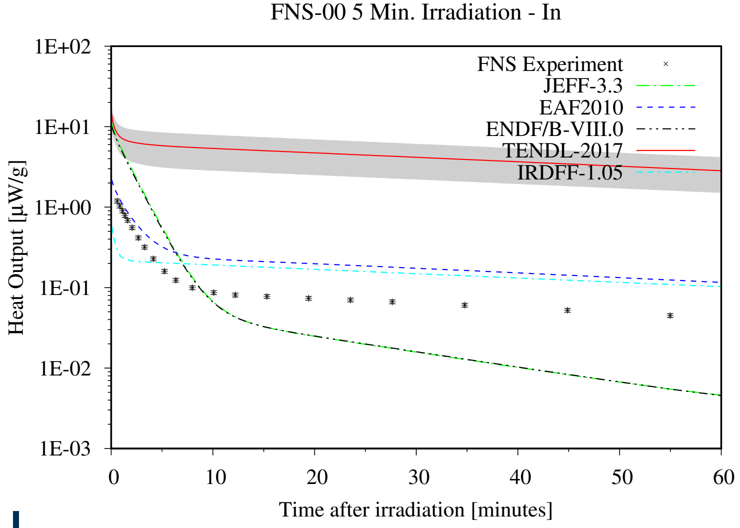


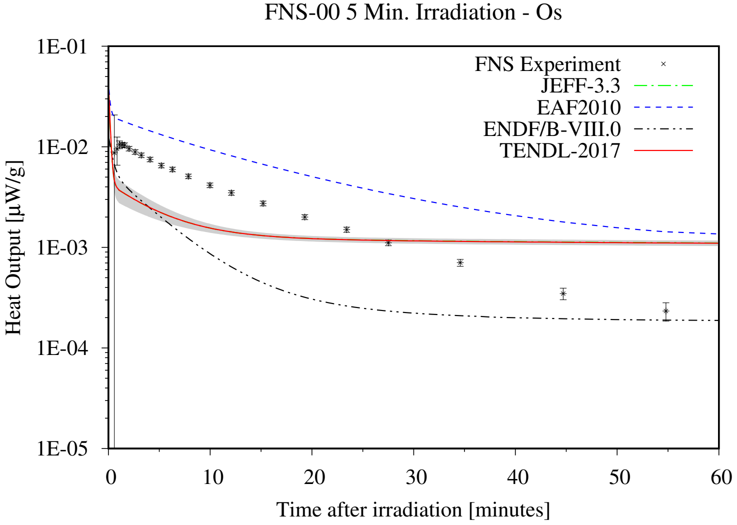
- Measuring performance based on χ^2 shows TENDL libraries do about as well as fusion-tailored EAF2010
- No improvements recently; is this the limit of agreement for this benchmark?....

Still room for improvement?

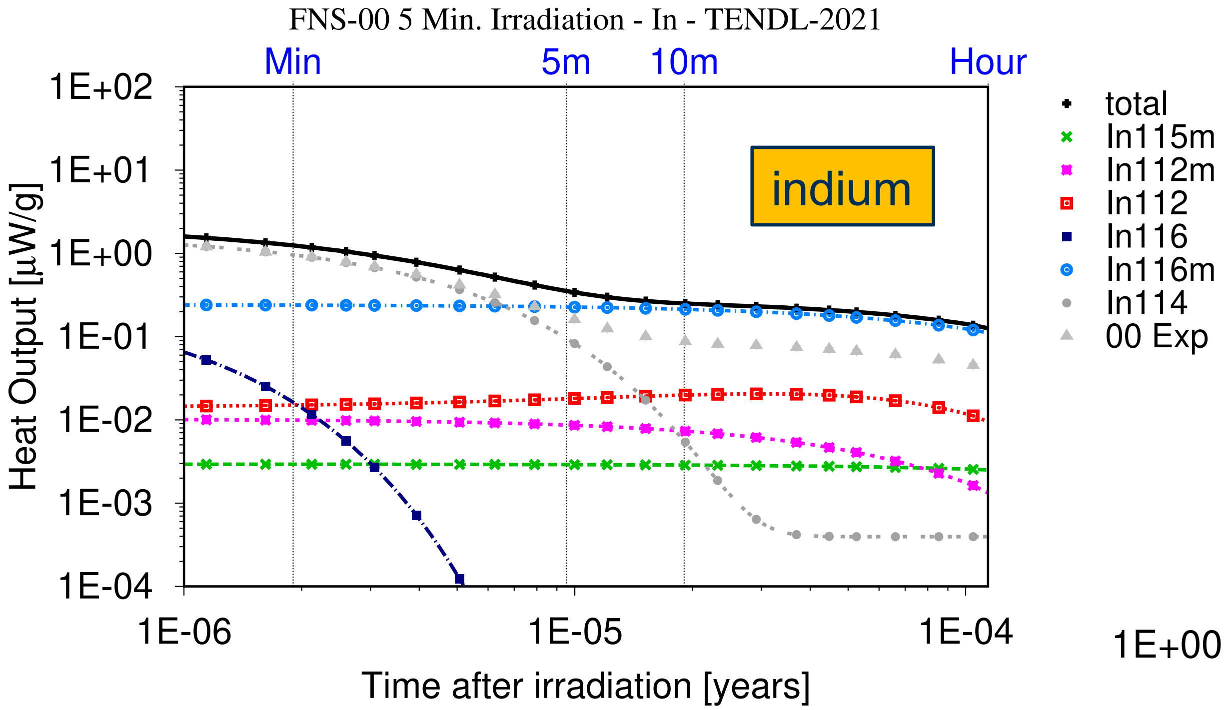




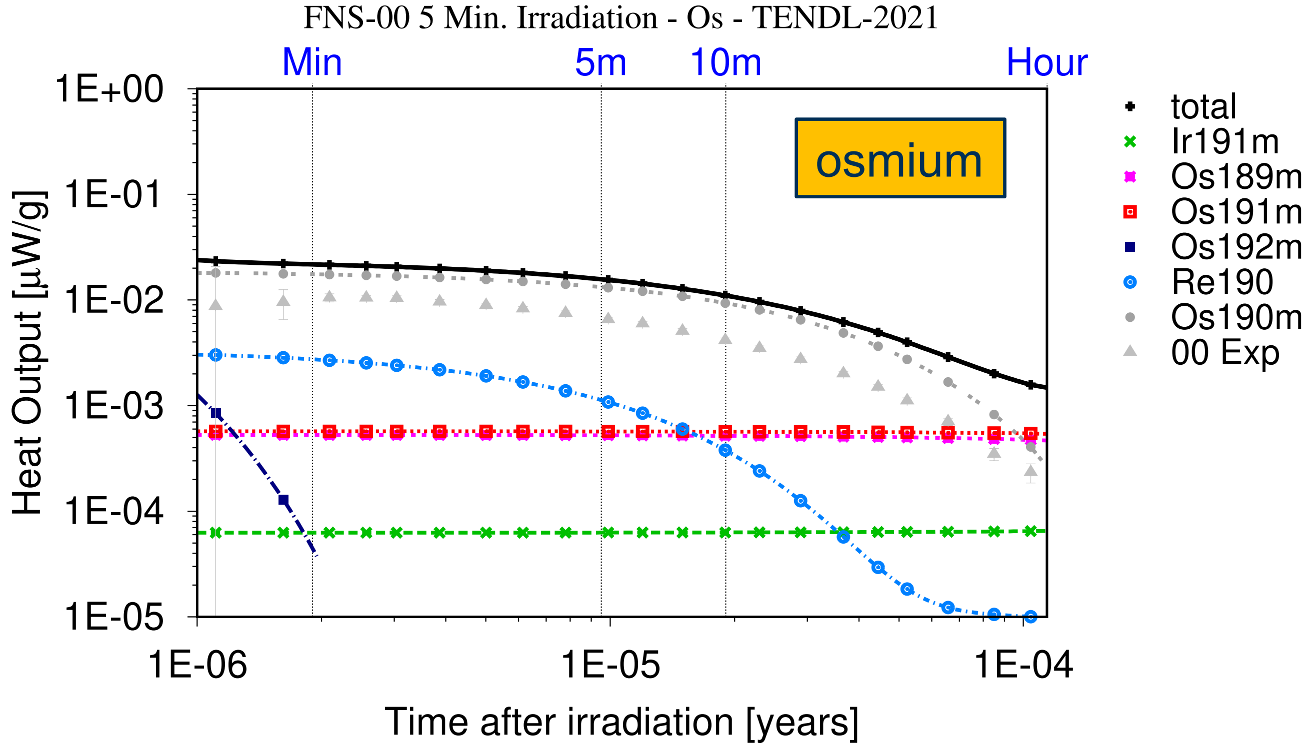




- Fundamental disagreement in decay profiles still exist for these two materials with all libraries



- Too much $^{115}In(n,\gamma)^{116m}In$?
- Experimental limitation (improperly characterized thermal fluxes)?



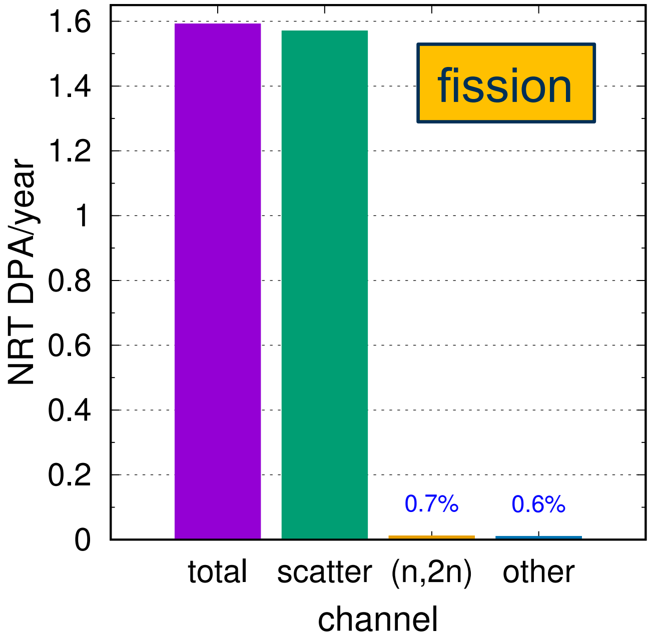
- Too much $^{190}Os(n,n')^{190m}Os$?
- Incorrect production pathway?

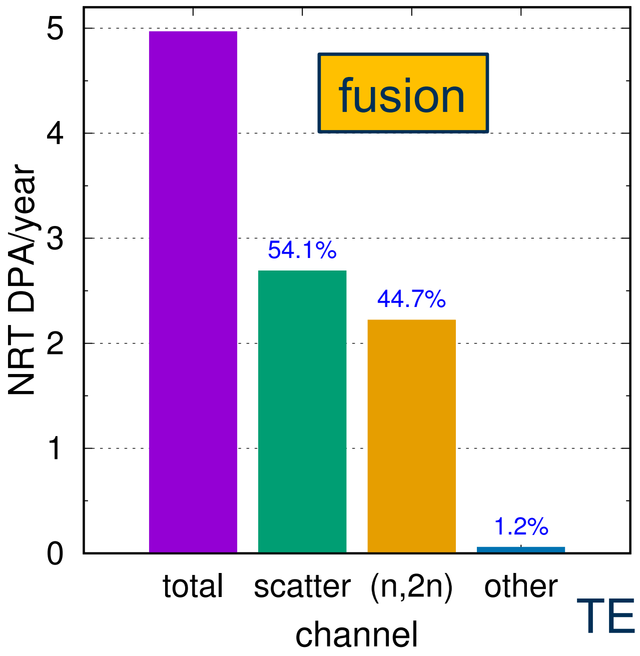
Nuclear heating

Importance of nuclear heating predictions for fusion material testing

- Qualifying performance of materials being considered for future fusion reactors relies on a combination of ion irradiation and campaigns in fission test reactors
- It is important to understand the damage evolution and the origin of that damage
- Comparison between techniques and relevance of fission experiments for fusion needs accurate prediction of nuclear damage dose
- E.g., dpa in W
- Damage created by (n,2n) reactions predicted to be important in fusion, but almost absent in fission

Gilbert, Sublet, J. Nucl. Mater. **504** (2018) 101





TENDL-2017

Nuclear heating fusion vs fission

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W/g DEMO	Fusion total (mt 301)	Fusion photon (442)	Fusion nonelastic (303)	Fusion Elastic (302)
W	2.731	2.650 (97%)	2.727	4.279e-3
Fe	1.683	1.191 (71%)	1.646	3.666e-2
Be	3.645	2.885e-3 (0%)	2.078	1.567

W/g HFR	Fission total	Fission photon	Fission nonelastic	Fission Elastic
W	10.479	10.358 (99%)	10.476	3.794e-3
Fe	1.997	1.626 (81%)	1.954	4.277e-2
Be	2.146	8.369e-7 (0%)	4.451e-1	1.701

- Damage-dose prediction based on dpa does not (?) include energy from photons, which in materials like W is most of the energy deposited in materials (local deposition assumption in NJOY-HEATR)
- Could explain anecdotal evidence of self-annealed materials under neutron exposure (compared to ion irradiation) – photons may provide enough energy to anneal damage – ongoing work
- Accurate nuclear heating predictions would then become critical for predicting material performance

Summary

- Decay heat predictions are important for design engineering of fusion power plants (~ few 100s of W cooling required per kW of decay heat)
- Benchmarking of decay heat predictions against experiments under fusion conditions demonstrate good performance across a range of materials
    - Improvements have slowed recently – possible limit of benchmark, but some materials still show clear discrepancies
- Further experiments, particularly on primary fusion materials, including new alloys (steels), are needed
- Nuclear heating calculations could be critical to understand the observed damage in neutron-irradiated materials and thus to predict performance evolution