DE LA RECHERCHE À L'INDUSTRIE

Review of (n,cp) evaluations, data, and (possible) needs

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Review of (n,cp) data

① (n,cp) data in evaluated libraries

② (n,cp) data for activation

③ (n,cp) data in the HPRL

④ (n,cp) data for gas production

⑤ Conclusions

Review of (n,cp) data

Evaluations

- Main General Purpose files (ENDF, JEFF, JENDL) initially developed for fission reactors… with (partial) extension for fusion (up to 15 MeV) and later on for ADS (up to 200 MeV)

- Many Special Purpose files developed for other applications, e.g., FENDL for fusion, IRDFF for dosimetry, EAF for activation, JENDL/HE up to 3 GeV, etc…

  See for example JENDL Special Purpose files at https://wwwndc.jaea.go.jp/jendl/jendl.html

- Since ~2007, TENDL aims at providing a true General Purpose file with the initial motto *"First completeness, then quality"* (TENDL is now competing with other main libraries… depending on the application…)

Review of (n,cp) data

Characteristics of (n,cp) cross sections
(wrt usual low-energy scattering/capture/fission xs)

- Many channels above a few MeV
- No data with challenging target accuracy, such as U-235 fission
- Relatively easy to model, plenty of data available thanks to TALYS

Nevertheless…
… model uncertainties are large,

- ~50% for (n,p) on average
- ~100% for (n,α) on average

cf. Table I in [NDS 155 (2019) 1]

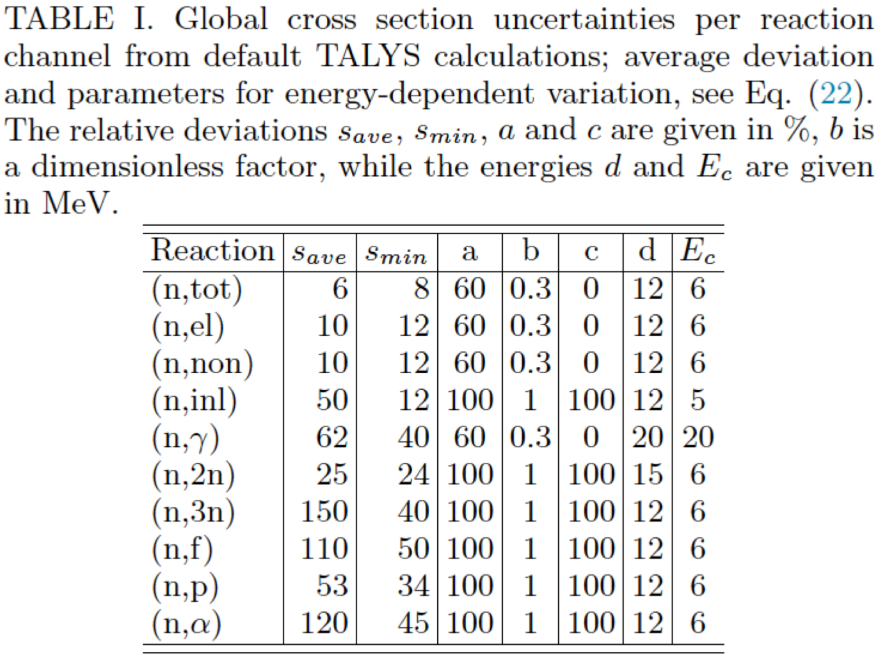
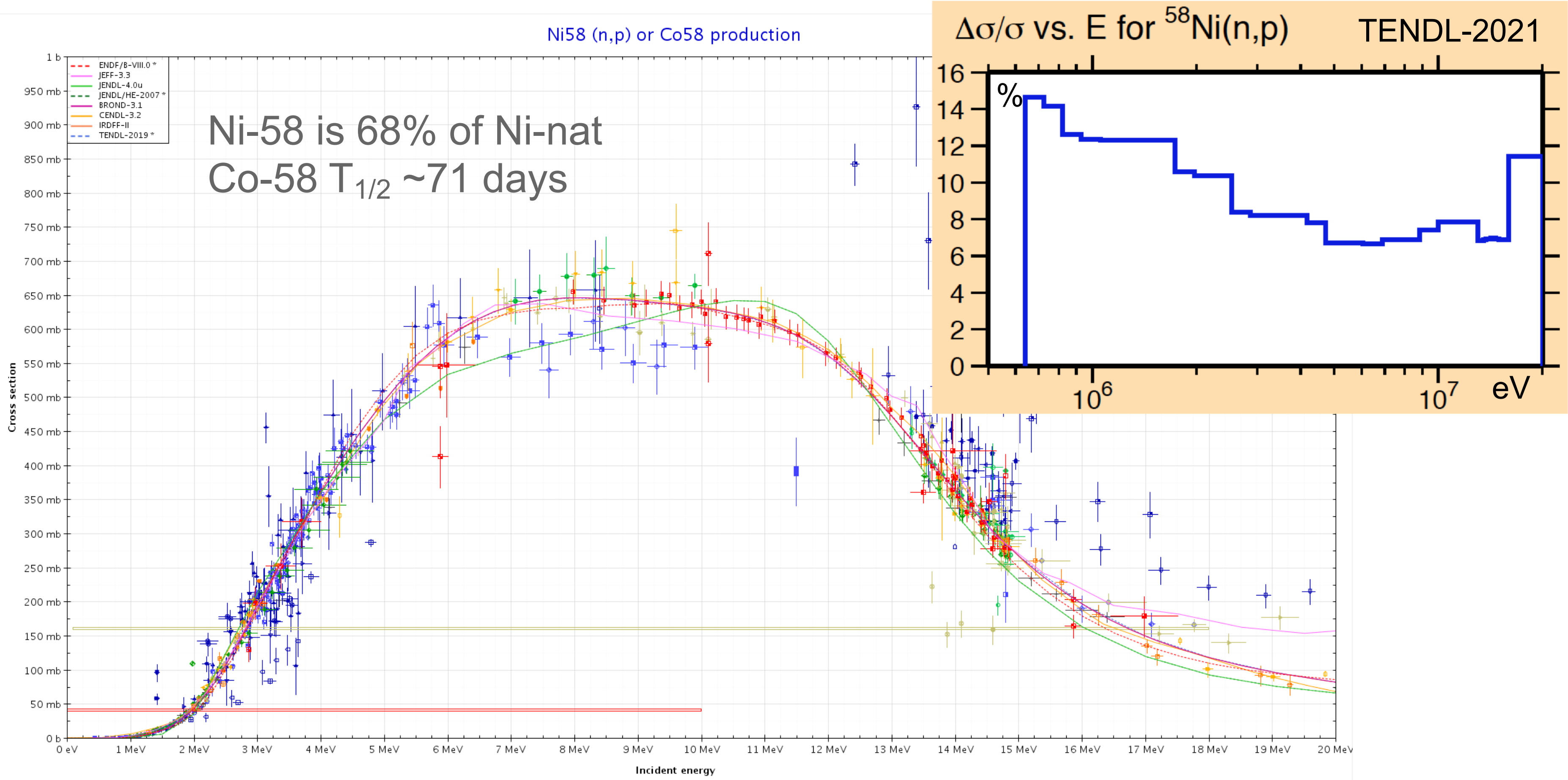


TABLE I. Global cross section uncertainties per reaction channel from default TALYS calculations; average deviation and parameters for energy-dependent variation, see Eq. (22). The relative deviations s_{ave}, s_{min}, a and c are given in %, b is a dimensionless factor, while the energies d and E_c are given in MeV.

Reaction	s_{ave}	s_{min}	a	b	c	d	E_c
(n,tot)	6	8	60	0.3	0	12	6
(n,el)	10	12	60	0.3	0	12	6
(n,non)	10	12	60	0.3	0	12	6
(n,inl)	50	12	100	1	100	12	5
(n,γ)	62	40	60	0.3	0	20	20
(n,2n)	25	24	100	1	100	15	6
(n,3n)	150	40	100	1	100	12	6
(n,f)	110	50	100	1	100	12	6
(n,p)	53	34	100	1	100	12	6
(n,α)	120	45	100	1	100	12	6

Review of (n,cp) data

Example of well-known activation (and gas production) xs

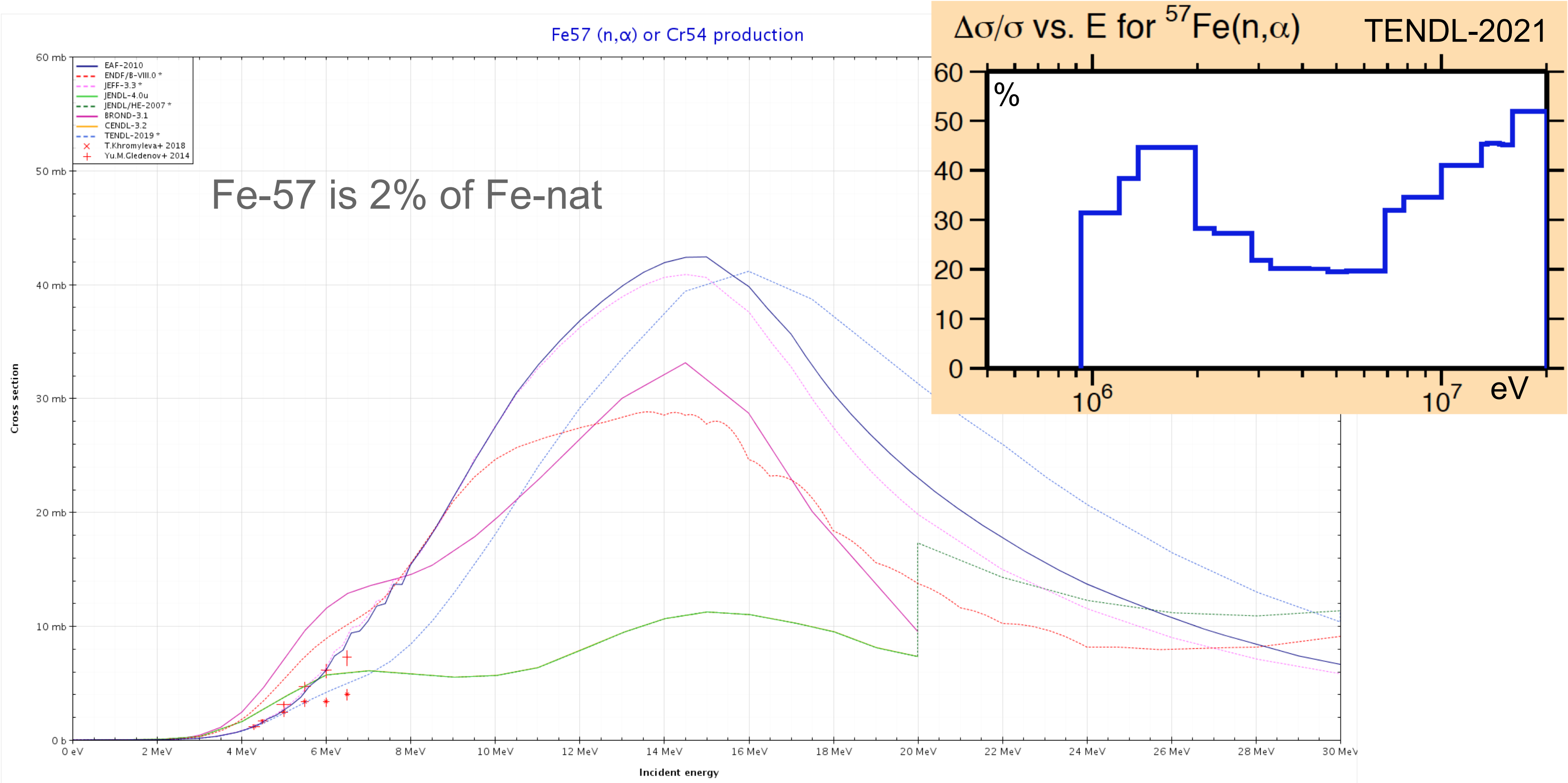


Ni-58 is 68% of Ni-nat

Co-58 $T_{1/2}$ ~71 days

Review of (n,cp) data

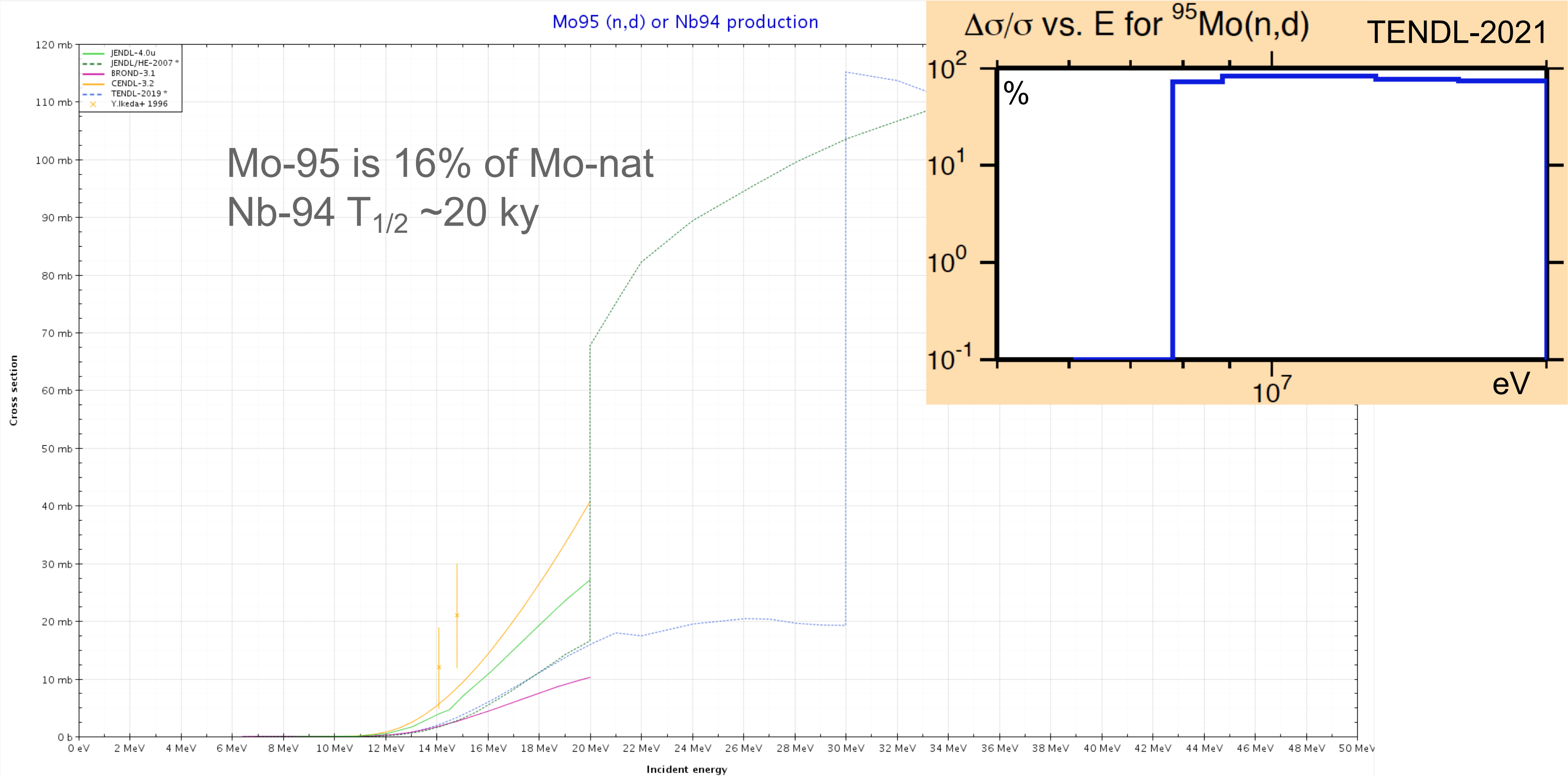
Example of not so well-known gas production xs



Fe-57 is 2% of Fe-nat

Review of (n,cp) data

Example of unknown activation xs



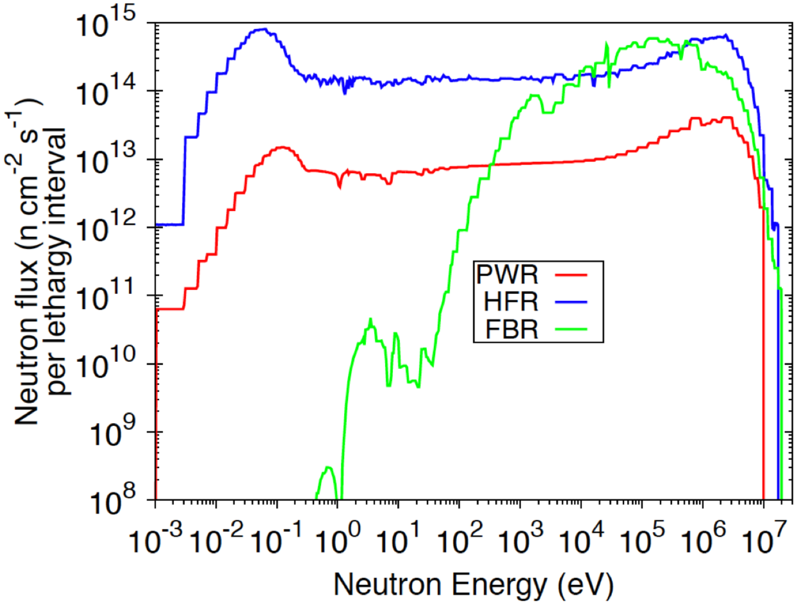
Mo-95 is 16% of Mo-nat

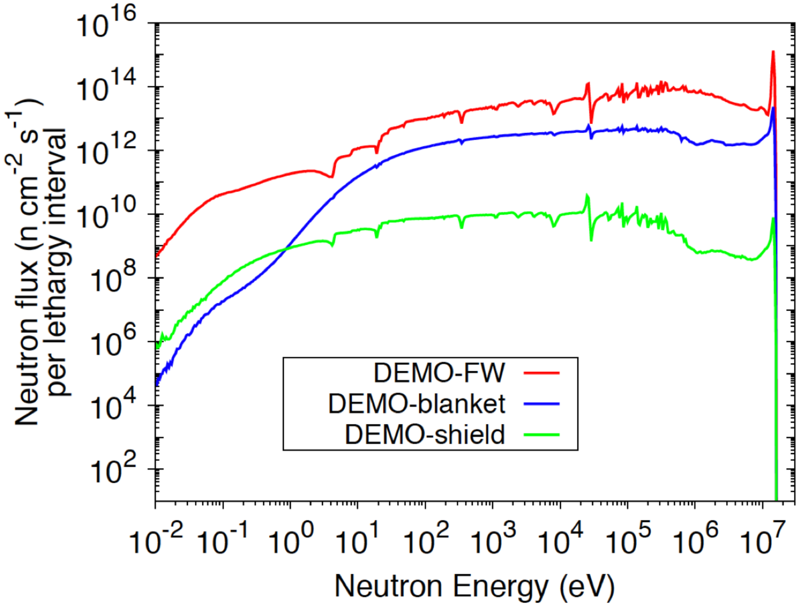
Nb-94 $T_{1/2}$ ~20 ky

Review of (n,cp) data

Applications

- Fast fission breeder reactors (FBR) up to ~10 MeV
- Fusion reactors (DEMO) up to 15 MeV (+ IFMIF/DONES up to 60 MeV)
- FBR and DEMO have similar neutron flux in the keV-MeV range
- They essentially share the same structural materials





(n,cp) data for activation

Activation

- Some general information
  - A wide range of materials need to be considered, including impurities
  - Low xs matter as the neutron fluence can be extremely large
  - From the application viewpoint the focus is on the production xs of the residual, whatever the reaction, (n,np) or (n,d) for example
  - (n,t) reaction is the exception as it is important for tritium production

- The European Activation System (EASY) is widely used, it includes
  - an inventory code (FISPACT)
  - and various libraries (EAF, TENDL…)

- The European Activation File (EAF) was the reference until recently (EAF-2010 is the last version, efforts are now directed towards TENDL)

(n,cp) data for activation

Importance diagrams reveals the main production routes of the major activation products for any irradiated element [Forrest, Fusion Engineering and Design 43 (1998) 209]

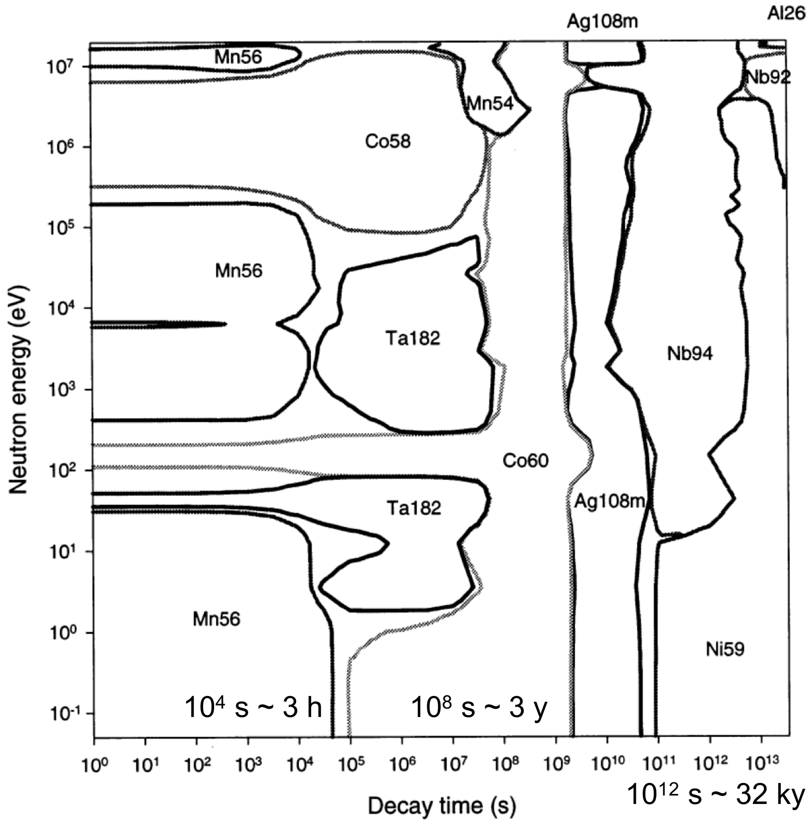


Fig. 9. γ Dose importance diagram for SS316 in a flux of 1×10^{12} n cm^{-2} s^{-1} and an irradiation time of 1 year.

Example of an importance diagram for stainless steel SS316 irradiated for 1 year in a flux of 10^{12} n/cm^2/s

Production of Co-58 ($T_{1/2}$ ~71 days)

- Ni-58(n,p)Co-58 (major pathway)
- Co-59(n,2n)Co-58 (minor pathway)

Production of Nb-94 ($T_{1/2}$ ~20 ky)

- Mo-95(n,d)Nb-94 (major pathway)*
- Mo-94(n,p)Nb-94 (major pathway)*

*depending on the neutron energy

(n,cp) data for activation

- Activation xs are measured using… the activation technique! But stable residuals appear in multistep production routes!

  Example for the production of Na-22 ($T_{1/2}$ ~3y) from silicium,

  $^{28}\mathbf{Si}(n,n\alpha) \rightarrow {}^{24}\mathbf{Mg}(n,np) \rightarrow {}^{23}\mathbf{Na}(n,2n) \rightarrow {}^{22}\mathrm{Na}$ (stable isotopes are in bold)

- EAF-2003 contains more than 12 000 cross sections up to 20 MeV, but only 1340 reactions are required to describe the production of all dominant activation products [Gilbert and Forrest, UKAEA FUS 509, 2004]

- R. Forrest reviewed the priority needs for EAF in Fusion Engineering and Design 81 (2006) 2143

- This review highlights 61 high-priority (n,cp) reaction cross sections on stable targets (on a total of more than 400 priority needs) – most of them difficult/impossible to measure using the activation technique

(n,cp) data for activation

- Top-priority (n,cp) xs measurements (rows 1-15) requested in Table 2,3,4 of Fusion Engineering and Design 81 (2006) 2143

Nuclide	Abund.	Reaction	Residual	Half-life	Intensity	Comment
Ne-20	90%	(n,d)	F-19	stable	N/A	No data, difficult to measure
Ne-20	90%	(n,p)	F-20	11 s	Iγ ~100%	No data, judged measurable
Ne-22	9.2%	(n,α)	O-19	27 s	Iγ ~96%	No data, judged measurable
Ne-22	9.2%	(n,d)	F-21	4 s	Iγ ~99%	No data, judged measurable
Mg-24	79%	(n,d)	Na-23	stable	N/A	No data, difficult to measure
S-34	4.2%	(n,d)	P-33	25 d	?	No data, judged measurable
S-34	4.2%	(n,α)	Si-31	2.6 h	Iγ ~0%	Discrepant data
Cl-37	24%	(n,p)	S-37	5 m	Iγ ~94%	Discrepant data
Ca-40	97%	(n,2p)	Ar-39	269 y	?	No data, difficult to measure
Ti-46	8.2%	(n,α)	Ca-43	stable	N/A	No data, difficult to measure
Ti-47	7.4%	(n,α)	Ca-44	stable	N/A	No data, difficult to measure
Ti-47	7.4%	(n,t)	Sc-45	stable	N/A	No data, difficult to measure
Ni58	68%	(n,t)	Co-56	77 d	Iγ ~100%	Discrepant data
Zn-64	49%	(n,d)	Cu-63	stable	N/A	No data, difficult to measure
Zn-67	4.1%	(n,p)	Cu-67	62 h	Iγ ~49%	Discrepant data

(n,cp) data for activation

- Top-priority (n,cp) xs measurements (rows 16-30) requested in Table 2,3,4 of Fusion Engineering and Design 81 (2006) 2143

Nuclide	Abund.	Reaction	Residual	Half-life	Intensity	Comment
Ga-71	40%	(n,t)	Zn-69	stable	N/A	No data, judged measurable
As-75	100%	(n,t)	Ge-73	stable	N/A	No data, difficult to measure
Br-79	51%	(n,t)	Se-77	stable	N/A	No data, difficult to measure
Kr-78	0.3%	(n,α)	Se-75	120 d	Iγ ~59%	No data, judged measurable
Kr-82	12%	(n,α)	Se-79	295 ky	?	No data, difficult to measure
Rb-85	72%	(n,t)	Kr-83	stable	N/A	No data, difficult to measure
Sr-84	0.6%	(n,α)	Kr-81	229 ky	Iγ ~0%	No data, difficult to measure
Sr-88	83%	(n,d)	Rb-87	stable	N/A	No data, difficult to measure
Zr-90	51%	(n,p)	Y-90g	2.7 d	Iγ ~0%	Discrepant data
Zr-91	11%	(n,α)	Sr-88	stable	N/A	No data, difficult to measure
Zr-91	11%	(n,t)	Y-89	stable	N/A	No data, difficult to measure
Mo-92	15%	(n,d)	Nb-91	680 y	Iγ ~0%	Discrepant data
Mo-94	9.2%	(n,p)	Nb-94	20 ky	Iγ ~100%	Discrepant data
Mo-95	16%	(n,d)	Nb-94	20 ky	Iγ ~100%	No data, difficult to measure
Ru-96	5.5%	(n,α)	Mo-93	4 ky	?	No data, difficult to measure

(n,cp) data for activation

- Top-priority (n,cp) xs measurements (rows 31-45) requested in Table 2,3,4 of Fusion Engineering and Design 81 (2006) 2143

Nuclide	Abund.	Reaction	Residual	Half-life	Intensity	Comment
Cd-110	12%	(n,α)	Pd-107	6.5 My	?	No data, difficult to measure
In-113	4.3%	(n,p)	Cd-113m	14 y	Iγ ~0%	No data, difficult to measure
Sn-116	14%	(n,α)	Cd-113m	14 y	Iγ ~0%	No data, difficult to measure
Sb-121	57%	(n,p)	Sn-121m	44 y	Iγ ~2%	No data, difficult to measure
Te-124	4.7%	(n,α)	Sn-121m	44 y	Iγ ~2%	No data, difficult to measure
Te-126	19%	(n,d)	Sb-125	2.8 y	Iγ ~30%	No data, difficult to measure
I-127	100%	(n,t)	Te-125	stable	N/A	No data, difficult to measure
Xe-129	26%	(n,p)	I-129	16 My	Iγ ~8%	No data, difficult to measure
Xe-132	27%	(n,α)	Te-129	70 m	Iγ ~16%	No data, judged measurable
La-138	0.1%	(n,α)	Cs-135	2.3 My	?	No data, difficult to measure
La-139	99.9%	(n,h)	Cs-137	30 y	Iγ ~85%	No data, difficult to measure
Ce-136	0.2%	(n,α)	Ba-133	10 y	Iγ ~62%	No data, difficult to measure
Ce-140	88%	(n,t)	La-138	stable	N/A	No data, difficult to measure
Eu-151	48%	(n,p)	Sm-151	90 y	Iγ ~0%	No data, difficult to measure
Gd-155	15%	(n,p)	Eu-155	4.7 y	Iγ ~31%	No data, difficult to measure

(n,cp) data for activation

- Top-priority (n,cp) xs measurements (rows 45-61) requested in Table 2,3,4 of Fusion Engineering and Design 81 (2006) 2143

Nuclide	Abund.	Reaction	Residual	Half-life	Intensity	Comment
Er-166	33%	(n,p)	Ho-166m	1.2 ky	Iγ ~73%	No data, difficult to measure
Er-167	23%	(n,t)	Ho-165	stable	N/A	No data, difficult to measure
Tm-169	100%	(n,t)	Er-167	stable	N/A	No data, difficult to measure
Yb-171	14%	(n,p)	Tm-171	1.9 y	Iγ ~0%	No data, difficult to measure
Yb-171	14%	(n,t)	Tm-169	stable	N/A	No data, difficult to measure
Lu-175	97%	(n,t)	Yb-173	stable	N/A	No data, difficult to measure
Hf-176	5.3%	(n,p)	Lu-176	stable	N/A	No data, difficult to measure
W-184	31%	(n,h)	Hf-182	8.9 My	Iγ ~80%	No data, difficult to measure
Re-187	63%	(n,t)	W-185	75 d	Iγ ~0%	No data, judged measurable
Os-186	1.6%	(n,p)	Re-186m	200 ky	Iγ ~18%	No data, difficult to measure
Pt-195	34%	(n,d)	Ir-194m	171 d	Iγ ~8%	No data, judged measurable
Pt-196	25%	(n,h)	Os-194	6 y	Iγ ~5%	No data, difficult to measure
Au-197	100%	(n,t)	Pt-195	stable	N/A	No data, difficult to measure
Hg-196	0.1%	(n,α)	Pt-193	50 y	?	No data, difficult to measure
Pb-204	1.4%	(n,p)	Tl-204	3.8 y	?	No data, difficult to measure
Pb-208	52%	(n,t)	Tl-206	4 m	Iγ ~0%	No data, judged measurable

(n,cp) data in the HPRL

HPRL

HPRL request for NaK used for cooling materials under irradiation at IFMIF/DONES (https://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=466)

- K-39(n,p)Ar-39 cross section
  - Ar-39 ($T_{1/2}$ ~269 years) is the dominant contribution to the long-lived radioactive inventories in NaK
  - Gas production (Ar)

- K-39(n,np)Ar-38 cross section
  - Gas production (Ar)

- Request for xs measurements at 14 MeV with an accuracy of 10%

(n,cp) data in the HPRL

HPRL request for fast chloride molten salt reactors (https://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=540)

- Cl-35(n,p) cross section
  - Impact on the reactor reactivity (i.e. the neutron multiplication factor)
  - Production of S-35 (which is an issue for corrosion)

- Request for xs measurements
  - in the energy range 100 keV – 5 MeV
  - with an accuracy of 5-8%

(n,cp) data for gas production

Gas production

- Gas production (H and He) from (n,p/d/t) and (n,h/α) reactions in structural materials could be an issue for their mechanical properties
- Main structural material isotopes (with natural abundance > 1%)

Be-9	as plasma-facing material
V-51	in vanadium-based alloy of the first-wall structure
Cr-50,52,53,54	as major component of stainless steel
Fe-54,56,57	as major component of stainless steel
Ni-58,60,62	as major component of stainless steel
Cu-63,65	mixed with Nb-Ti superconducting strands
Zr-90,91,92,94	in the CuCrZr alloy of the blanket
Nb-93	in the Nb-Ti superconducting magnets
Ta-181	in W-Ta alloy
W-182,183,184,186	in the divertor structure
etc…	

(n,cp) data for gas production

(n,p) and (n,α) xs of the main structural material isotopes lacking experimental data (Be-9, V-51, Fe-54, Ni-58,60, Cu-63, Zr-94 are better known)

Nuclide	Abund.	Reaction	Comments (2022) *
Cr-50	4.3%	(n,α) (n,p)	No/little data
Cr-52	83.8%	(n,α)	One data set only
Cr-53	9.5%	(n,α)	One data set only
Cr-54	2.4%	(n,α) (n,p)	Lack of data below 14 MeV
Fe-56	91.7%	(n,α)	Discrepant data
Fe-57	2.1%	(n,α) (n,p)	Lack of (n,α) / Discrepant (n,p)
Ni-60	26%	(n,α)	One data set only
Ni-62	4%	(n,p)	Discrepant data
Cu-65	31%	(n,a)	Discrepant data
Zr-90	51%	(n,α)	No data
Zr-91	11%	(n,α)	No data
Zr-92	17%	(n,α)	Lack of data below 14 MeV

Nuclide	Abund.	Reaction	Comments (2022) *
Nb-93	100%	(n,p)	No data
Ta-181	100%	(n,α) (n,p)	Lack of (n,α) data above 14 MeV
W-182	26%	(n,α) (n,p)	Lack of data / No data for (n,α)
W-183	14%	(n,α) (n,p)	Lack of data / No data for (n,α)
W-186	28%	(n,α) (n,p)	Discrepant (n,p) data

* As of July 2022 after visual checking of EXFOR content in JANIS Book (https://www.oecd-nea.org/janisweb)

Review of (n,cp) data

Conclusions

- The (n,cp) data playground is wide and getting wider with energy
  - No key xs to measure as accurately as possible
  - Many xs are equally relevant for the applications
  - All xs are available from TALYS (with large uncertainties by default)
  - Measurements are needed to reduce uncertainties (down to ~10%)

- Needs (priority should be discussed with users)
  - HPRL includes two requests for (n,cp) data: (n,p) on K-39 and Cl-35
  - R. Forrest has reviewed the priority needs for improving EAF below 20 MeV. That work should be extended to 60 MeV for IFMIF/DONES.
  - Very basic review of gas production in structural material shows a lack of data. This could be further investigated with the user community.

Thank you for your attention!

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