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Reliability of activation cross sections for prediction of shutdown dose rate in the ITER port cell and port interspace

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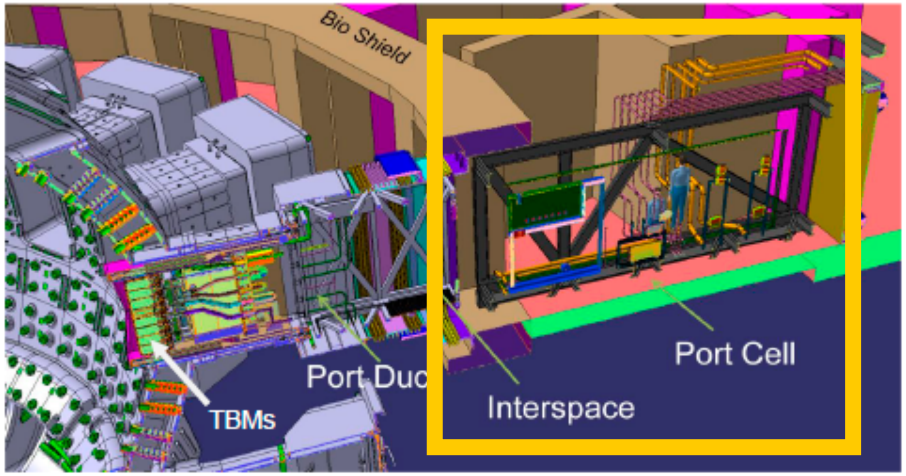
Motivation and goal

- The feasibility to carry out **manual maintenance activities** in **ITER** requires that certain **SDDR limits** are met in different areas.
  - 10 µSv/h 1 day after shutdown in the Port Cell (PC).
  - 100 µSv/h at 10^6 seconds (~12 days) for the Port Interspace (PI).

- The fulfilment of these target values is an ongoing challenge.



Motivation and goal

- Can we **trust** SDDR predictions? An accurate SDDR calculation is conditioned, among other considerations, by the **quality** of the **activation cross sections**.

- **GOAL:** Assess the status of the relevant activation cross sections involved in the SDDR calculation in ITER PC & PI areas.
  - Library? → EAF-2007 (Typically used & recommended for ITER) + evaluation of EAF-2010 & TENDL (2013, 2014 & 2015 versions) posible improvements/updates.

Methodology

1. Relevant materials selection
2. List of dominant radionuclides
3. Identification of relevant pathways
4. EAF (2007 & 2010) cross sections quality evaluation
5. EAF vs. TENDL 2013, 2014 & 2015

Methodology: materials selection

- Materials placed in ITER which activation contribute **significantly** to the SDDR at the PC and PI:
  - SS316LN-IG, SS304, Eurofer, Inconel718, A660, XM-19, CuCrZr-IG, Cu, W, LiPb, and conventional concrete (used in B-lite ITER model*).
- Other concretes that are being considered to be part of the bioshield plug:
  - L2N concrete.
  - Barite concrete.

* Activation of the current C-lite concrete does not lead to any significant difference.

Methodology: relevant nuclides & pathways

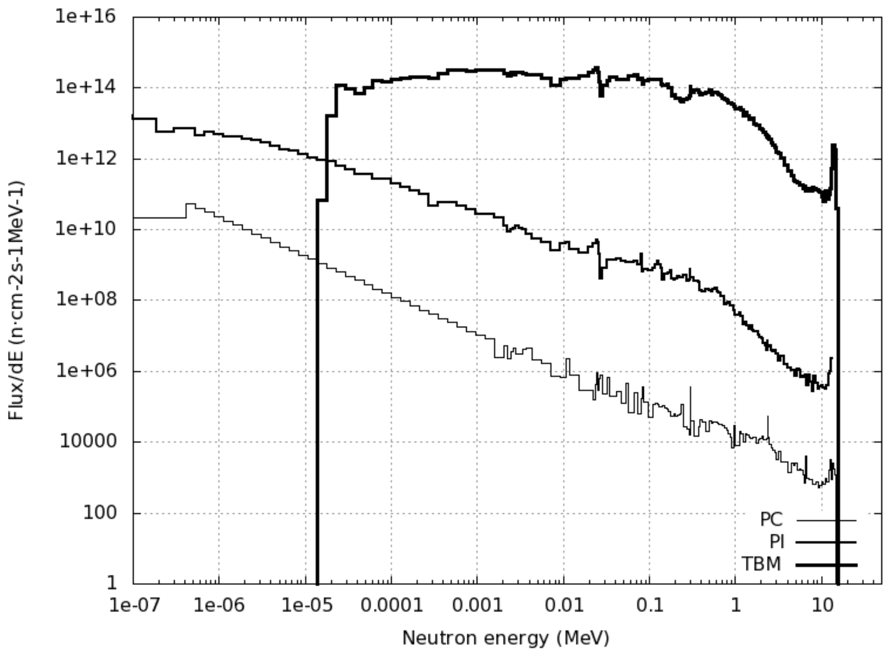
- Radionuclides and pathways identification according to the following criteria:
  - Radionuclides contributing >1% to a non-negligible CDR produced by the activation of each material.
  - Pathways contributing >1% to the production of each major radionuclide.

- Information from
  - Papers & reports dedicated to SDDR in ITER
  - Own calculations, specially to identify pathways & for corroborating nuclides from reports

Methodology: own calculations

- Using ACAB, EAF-2007 & SA2 irradiation scenario
- The neutron spectra used were computed with MCNP5:

- For the **LiPb**, spectrum used is that from the **TBM** with a total neutron flux of **$1.04 \cdot 10^{14}$ n/cm$^2 \cdot$s**.
- Remaining materials → results for **1 day** cooling were obtained using spectrum from **PC** (in the last 5 cm of the bioshield plug frame) with a total neutron flux of **$1.65 \cdot 10^{6}$ n/cm$^2 \cdot$s** while results for **12 days** cooling were obtained using spectrum from **PI** (in the closure plate of the port plug) with a total neutron flux: **$6.06 \cdot 10^{8}$ n/cm$^2 \cdot$s**).



Neutron flux per energy interval used for activation calculations

- Calculation of the Contact Dose Rate (CDR) at 1 & 12 days.

Methodology: EAF cross section quality evaluation

- Using EAF specific reports dedicated to validating (against integral & differential data) & testing the successive versions since 2001 → Quality Score (QS) indicates how much the EAF data are backed up by experiments Also, QS in () indicates score for total cross section & * means updated QS.

QS	Description
0	No experimental data exists
1	Limited differential data which disagrees with the library (weak disagreement)
2	Limited differential data which agrees with the library (weak agreement)
3	Differential data which disagrees with the library (strong disagreement)
4	Differential data which agrees with the library (strong agreement)
5	Both differential and integral data exist or only integral data exist and these are not in agreement with the library
6	Both differential and integral data exist and they are in agreement with the library

Validation

Methodology: EAF vs. TENDL

- TENDL library (2013, 2014 & 2015 versions) & EAF (2007 & 2010 versions) are plotted joined to the available differential experimental data from **EXFOR** (Experimental Nuclear Reaction Data Library) database, using the **JANIS** (Java-based Nuclear Data Information System) display software.
- Goals:
  - Find possible improvements in the TENDL library.
  - Check if there are many or few experiments for each reaction cross section and if they are in agreement with the libraries.

Results: radionuclides

- **27 dominant radionuclides** for the ITER SDDR prediction:
  - **19** related to the ITER **PC**: ^{24}Na, ^{42}K, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{57}Ni, ^{64}Cu, ^{106m}Ag, ^{110m}Ag, ^{124}Sb, ^{131}Ba, ^{133}Ba, ^{135m}Ba, ^{182}Ta, ^{187}W & ^{203}Pb.
  - **20** concerning the **PI**: ^{42}K, ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{65}Zn, ^{92m}Nb, ^{106m}Ag, ^{110m}Ag, ^{124}Sb, ^{125}Sb, ^{134}Cs, ^{152}Eu, ^{154}Eu, ^{160}Tb, ^{182}Ta, ^{181}W, ^{187}W & ^{203}Pb.
- ^{134}Cs, ^{152}Eu, ^{154}Eu & ^{160}Tb have to be taken into account only in the case that L2N concrete is used in ITER while ^{42}K, ^{131}Ba, ^{133}Ba & ^{135m}Ba and only if the barite concrete is used.

Results: Example of nuclides & pathways for SS316LN-IG

Major radionuclide	Half-life	Cooling time (days)	Relevant pathways & contribution (%)
^{51}Cr	27.7 d	1	^{50}Cr(n,g) (99.9)
		12	^{50}Cr(n,g) (75.7) ^{52}Cr(n,2n) (22.1) ^{54}Fe(n,a) (2.2)
^{54}Mn	312.1 d	12	^{54}Fe(n,p) (67.5) ^{55}Mn(n,2n) (32.5)
^{56}Mn	2.6 h	1	^{55}Mn(n,g) (99.9)
^{59}Fe	44.5 d	1	^{58}Fe(n,g) (100)
		12	^{58}Fe(n,g) (98.1) ^{62}Ni(n,a) (1.5)
^{58}Co	70.9 d	1	^{58}Ni(n,p) (99.8)
		12	^{58}Ni(n,p) (99.6)
^{60}Co	5.3 y	1	^{59}Co(n,g) (99.8)
		12	^{59}Co(n,g) (93.6) ^{60}Ni(n,p) (6.3)
^{64}Cu	12.7 h	1	^{63}Cu(n,g) (100)
^{182}Ta	114.7 d	1	^{181}Ta(n,g) (99.9)
		12	^{181}Ta(n,g) (99.9)

Results: Pathways (45)

- $^{23}Na(n,g)^{24}Na$
- $^{24}Mg(n,p)^{24}Na$
- $^{27}Al(n,a)^{24}Na$
- $^{41}K(n,g)^{42}K$
- $^{50}Cr(n,g)^{51}Cr$
- $^{52}Cr(n,2n)^{51}Cr$
- $^{54}Fe(n,a)^{51}Cr$
- $^{55}Mn(n,2n)^{54}Mn$
- $^{54}Fe(n,p)^{54}Mn$
- $^{55}Mn(n,g)^{56}Mn$
- $^{58}Fe(n,g)^{59}Fe$
- $^{59}Co(n,p)^{59}Fe$
- $^{62}Ni(n,a)^{59}Fe$
- $^{59}Co(n,2n)^{58}Co$
- $^{58}Ni(n,p)^{58}Co$
- $^{59}Co(n,g)^{60}Co$
- $^{60}Ni(n,p)^{60}Co$
- $^{63}Cu(n,a)^{60}Co$
- $^{58}Ni(n,2n)^{57}Ni$
- $^{64}Zn(n,g)^{65}Zn$
- $^{66}Zn(n,2n)^{65}Zn$
- $^{181}Ta(n,g)^{182}Ta$
- $^{182}W(n,p)^{182}Ta$
- $^{183}W(n,D)^{182}Ta$
- $^{107}Ag(n,2n)^{106m}Ag$
- $^{109}Ag(n,g)^{110m}Ag$
- $^{204}Pb(n,2n)^{203}Pb$
- $^{180}W(n,g)^{181}W$
- $^{182}W(n,2n)\ ^{181}W$
- $^{186}W(n,g)^{187}W$
- $^{63}Cu(n,g)^{64}Cu$
- $^{133}Cs(n,g)^{134}Cs$
- $^{151}Eu(n,g)^{152}Eu$
- $^{153}Eu(n,g)^{154}Eu$
- $^{159}Tb(n,g)^{160}Tb$
- $^{123}Sb(n,g)^{124}Sb$
- $^{124}Sn(n,g)^{125}Sn(B-)^{125}Sb$
- $^{130}Ba(n,g)^{131}Ba$
- $^{132}Ba(n,g)^{133}Ba$
- $^{134}Ba(n,2n)^{133}Ba$
- $^{134}Ba(n,g)^{135m}Ba$
- $^{135}Ba(n,n')^{135m}Ba$
- $^{136}Ba(n,2n)\ ^{135m}Ba$
- $^{93}Nb(n,2n)^{92m}Nb$
- $^{92}Mo(n,p)\ ^{92m}Nb$

Results: EAF cross section quality evaluation example

Reaction	Product	Half-life	EAF-2007 QS	EAF-2007 Total cross section QS	EAF-2010 QS
Cr50(n,g)	Cr51	27.7 d	4	4	4
Ba130(n,g)	Ba131g	11.5 d	2	Not included	2
	Ba131m	14.6 min	2		2
Mg24(n,p)	Na24g	15.0 h	0	(5)*	0
	Na24m	20.2 ms	0		0
Co59(n,2n)	Co58g	70.9 d	2	(5)	2
	Co58m	9.1 h	5		6
Co59(n,g)	Co60g	1925.3 d	0	(6)	0
	Co60m	10.47 min	5		5
Ta181(n,g)	Ta182g	114.7 d	6	(6)	6
	Ta182m	283 ms	2		2
	Ta182n	15.8 min	5		6
Pb204(n,2n)	Pb203g	51.9 h	2	(6)	2
	Pb203m	6.2 s	5		5
	Pb203n	480 ms	2		2
Ni62(n,a)	Fe59	44.5 d	5	6*	6
Mn55(n,2n)	Mn54	312.1 d	6	6	6
Mn55(n,g)	Mn56	2.6 h	6	6	6
Fe58(n,g)	Fe59	44.5 d	6	6	6

Results: EAF cross section quality evaluation (I)

- Most of metastable isotopes decay by isomeric transition to ground state at least in 99.8%. If the half-lives of the involved metastable states are also very small compared to the cooling times of interest (1 and/or 12 days) → Consider the total reaction cross section.
- Split reactions should be taken into account separately in these cases:
  - $^{59}Co(n,2n)^{58}Co$
  - $^{58}Ni(n,p)^{58}Co$
  - $^{151}Eu(n,g)^{152}Eu$
  - $^{132}Ba(n,g)^{133}Ba$
  - $^{24}Sn(n,g)^{125}Sn(B-)^{125}Sb$

Results: EAF cross section quality evaluation (II)

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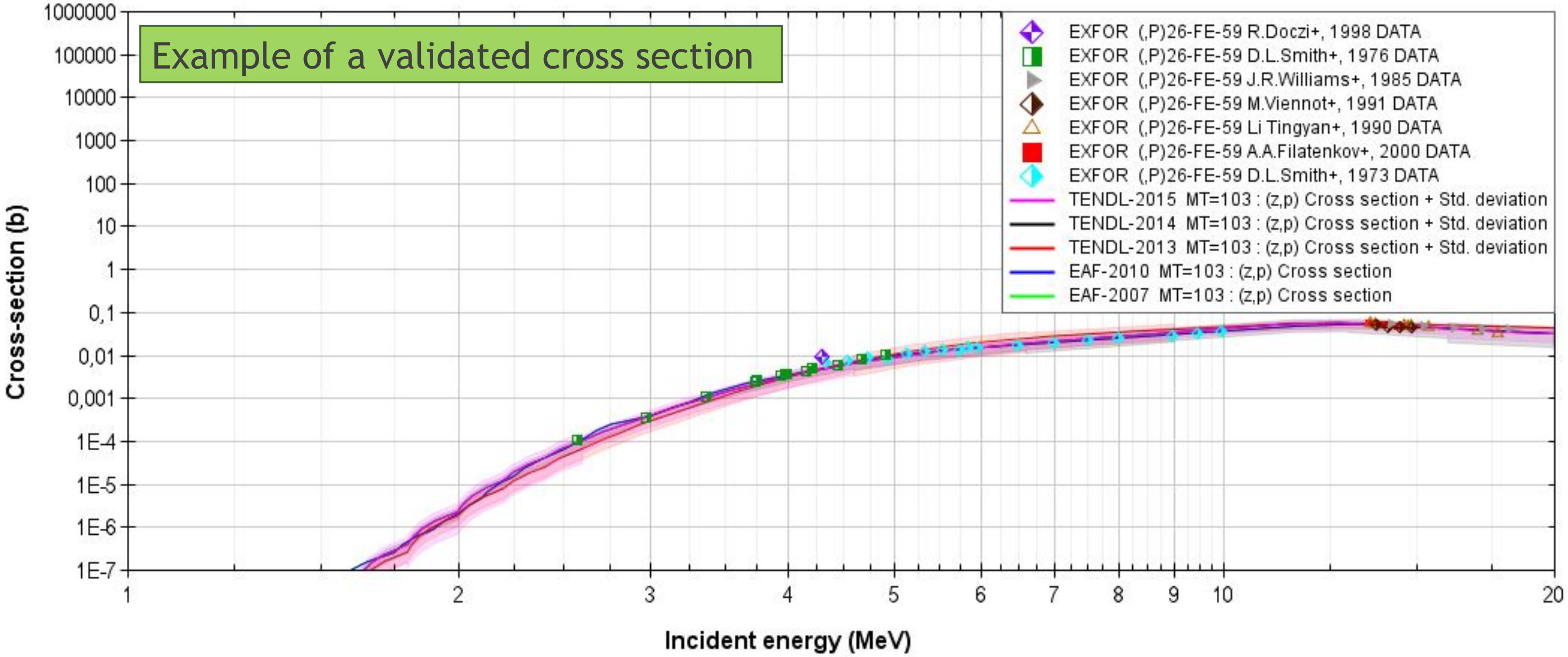
- **25** cross sections with **QS=6** → **Validated**. Most of the cross sections pathways for the production of radionuclides contributing most to the SDDR belong to this group.
- **1** cross section ($^{63}Cu(n,g)^{64}Cu$) with **QS=5** → Both differential and integral data exist or only integral data exist and these are not in agreement with the library. In this case: **Satisfactory agreement with differential and unsatisfactory agreement with integral data.**
- **1** split cross section ($^{59}Co(n,2n)^{58g}Co$) with **QS=2** →**Limited differential data** which agrees with the library (**weak agreement**)
- **18** cross sections **without QS** for the total reaction.

Comparison TENDL vs. EAF (I)

- Regarding **cross sections without QS**, some slight differences among the EAF & TENDL libraries are detected as well as a lack of differential experimental data, especially in the high-energy region for some (n,g) reactions (usually from 3 MeV onwards) → it is not clear which one is better to be used.
- For the **EAF validated reactions**, TENDL has performed further work on some of them since some changes are detected in the cross section for ^{54}Fe(n,a)^{51}Cr, ^{55}Mn(n,2n)^{54}Mn, ^{58}Ni(n,p)^{58}Co, ^{181}Ta(n,g)^{182}Ta, and ^{41}K(n,g)^{42}K reactions.

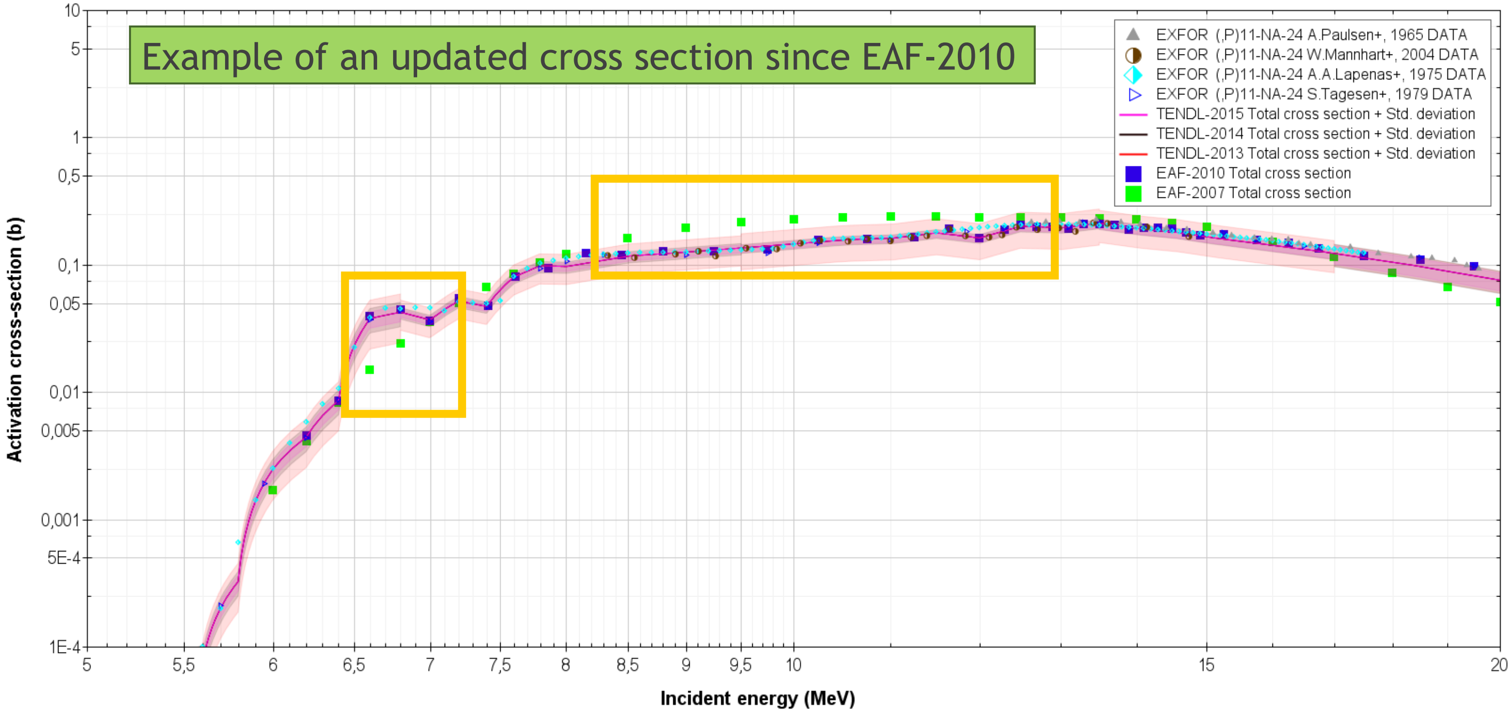
Comparison TENDL vs. EAF(II)

- Cross section for **$^{59}Co(n,p)^{59}Fe$ reaction** → QS=6. EAF-2007 & 2010, and TENDL-2014 & 2015 are coincident.



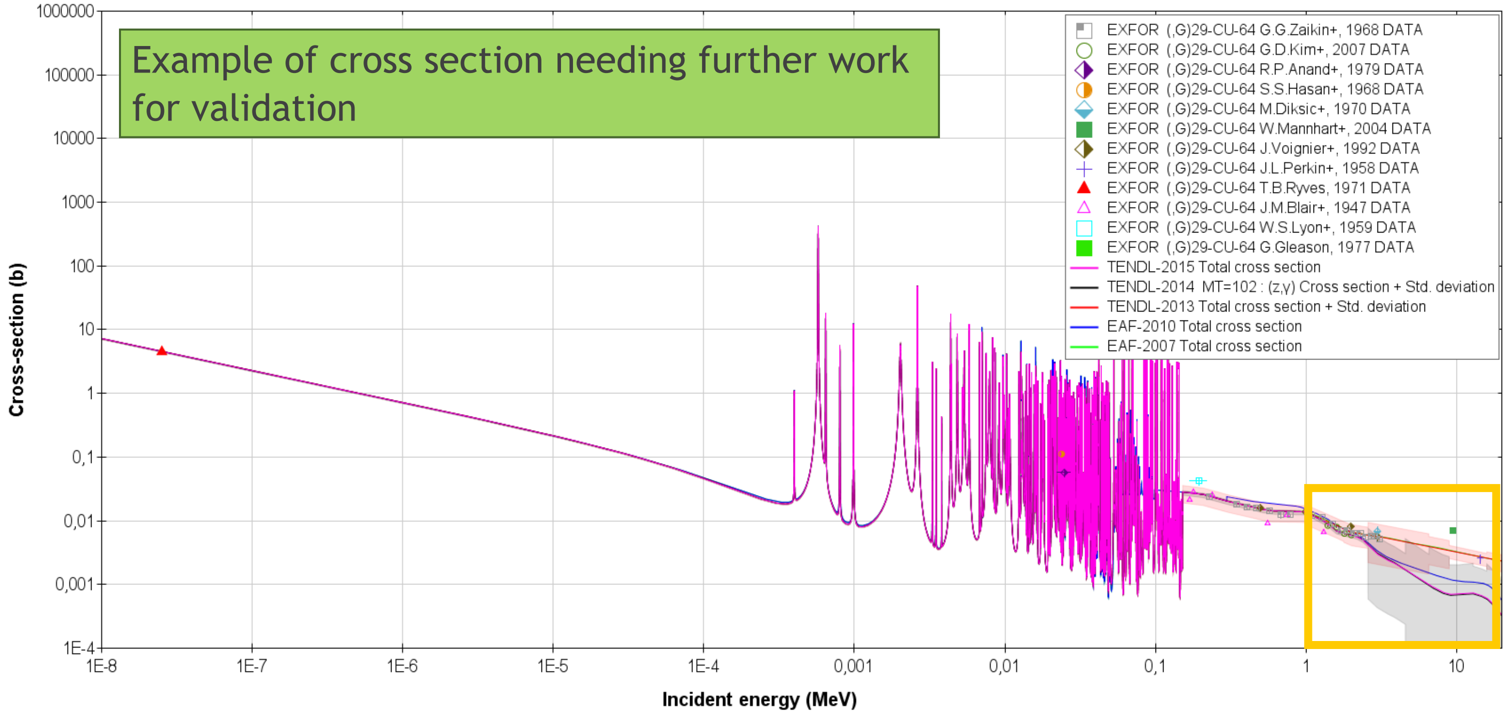
Comparison TENDL vs. EAF(III)

- Cross section for **$^{24}Mg(n,p)^{24}Na$ reaction** → QS=(5)* in the EAF-2007 report. TENDL-2013, 2014 & 2015 are coincident.



Comparison TENDL vs. EAF (IV)

- Cross section for **$^{63}Cu(n,g)^{64}Cu$** reaction → QS= 5. EAF-2007 & TENDL-2013 are superimposed; TENDL-2014 & 2015 too.



Conclusions (I)

- This work provides a global map of radionuclides & pathways for the calculation of the SDDR at the ITER PC & PI. The sum of the different radionuclide contributions to the CDR produced by each of the materials was, in the worst case 95% & in most of the cases > 98%.
- Using EAF-2007:
  - **27 dominant radionuclides** for the ITER SDDR calculation at PC (19) & PI (20) areas → **45** identified **pathways**.
  - **25** cross sections differential & integral **validated**. Most of the cross sections of this group are the production pathways for radionuclides contributing most to the SDDR.
  - **20** cross sections require further efforts for **validation**:
    - $^{59}Co(n,2n)^{58}Co$, $^{63}Cu(n,g)^{64}Cu$ & $^{50}Cr(n,g)^{51}Cr$ → Higher priority, since they appear for radionuclides contributing most and/or in the activation of more than one material.
    - $^{64}Zn(n,g)^{65}Zn$, $^{66}Zn(n,2n)^{65}Zn$, $^{107}Ag(n,2n)^{106m}Ag$, $^{109}Ag(n,g)^{110m}Ag$, $^{123}Sb(n,g)^{124}Sb$, $^{124}Sn(n,g)^{125}Sn(B-)^{125}Sb$, $^{183}W(n,D)^{182}Ta$ & $^{180}W(n,g)^{181}W$ → Lower priority.
    - 4 more cross sections for the L2N concrete case & 5 for the barite concrete case.

Conclusions (II)

- To date, without any further work & considering radionuclides & pathways with contributions >1%, **the calculated CDR** (produced by the activation of each of the materials) **with EAF validated cross sections** is at least:
  - SS316LN-IG (91%)
  - SS304L (97%)
  - Eurofer (95%)
  - LiPb (85%)
  - W (98%)
  - Conventional concrete from B-lite (98%)
  - L2N concrete (94%)
  - The SDDR prediction for Cu & barite concrete is not trustworthy (very low %)

- The use of any of the analyzed **EAF & TENDL** libraries would lead to **similar results** in the ITER SDDR calculations. However, for the reactions pointed out further work for validation & verification is needed.