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

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Abstract. This paper explores the quality of available activation cross section (XS) data for accurate Shutdown Dose Rate (SDDR) prediction in the ITER Port Cell and Port Interspace areas, where different maintenance activities are foreseen. For this purpose the EAF library (2007 and 2010 versions) has been investigated, as it is typically used by the ITER community.

Based on both reports/papers on SDDR in ITER and own calculations, major nuclides contributing to the SDDR coming from the activation of i) relevant materials placed in ITER and ii) candidate materials for the bioshield plug as L2N and barite concretes, are identified. Then, relevant production pathways are obtained.

EAF XS quality for all pathways is checked following the procedure used for validating and testing the successive EAF versions. Also, possible improvements from using the TENDL-2015 library are assessed by comparing EAF and TENDL XS with available differential experimental data from EXFOR. Results point out that most of the activation XS related to materials currently placed in ITER are reliable, and only a few need improvement. Also, many of the XS related to both L2N and barite concretes need further work for validation.

1. Introduction

Availability of validated cross section (XS) libraries is a key element for the reliability of shutdown dose rate (SDDR) calculations in the ITER Port Cell (PC) and Port Interspace (PI) where the human-access is planned for maintenance activities. These SDDR values are limited to 10 μSv/h 1 day after shutdown in the PC, and 100 μSv/h at 10^6 seconds ($\sim$12 days) for the PI [1,2]. The fulfilment of these target values is an ongoing challenge.

There are several libraries such as EAF (European Activation File), FENDL (Fusion Evaluated Nuclear Data Library) or TENDL (TALYS-based Evaluated Nuclear Data Library) than can be used for activation calculations in fusion applications. Validation activities for these libraries have been carried out and an experimental database is available for this purpose [3,4].

Now, the quality of the XS libraries can be better assessed for its specific use in ITER, since the geometric model and materials in the different areas are at present clearly defined and, thus, the neutron flux and energy spectrum for all the relevant components responsible for the SDDR are known.

Hence, the aim of this work is to provide the status of the main XS reactions involved in the calculation of the SDDR for manual maintenance purposes in the ITER PC and PI. Specifically, EAF-2007, which is typically used and recommended for the ITER SDDR calculation [1,2,5–10] is explored. Furthermore, the effect of possible improvements of EAF-2010 and TENDL-2015 libraries on the SDDR calculation is investigated.

Section 2 describes the methodology procedure used. Section 3 is devoted to compile and systematize previous work carried out in this field [11], where relevant XS pathways for the production of those radionuclides responsible of >4% of the SDDR (produced by the activation of each of the considered materials), were taken into account. Section 4 goes in depth into the XS for the pathways leading to radionuclides contributing 1–4% to the SDDR produced by the activation of each particular material. The aim is to extend this study providing a more complete list of dominant nuclides and pathways. Also, in [11] the sum of the different nuclide contributions to the SDDR produced by the activation of each of the considered materials was, in the worst case 86% and in most of the cases above 90%; now, a sum of 95% is achieved for the worst case and, in most of the cases, above 98%. Finally, Sect. 5 summarizes the main conclusions jointly considering previous [11] and present work, emphasizing the percentage of the SDDR calculated with validated XS, for each of the materials.

2. Methodology

Relevant materials placed in ITER which activation contribute significantly to the SDDR at the PC and PI areas are analyzed: SS316LN-IG, SS304, Eurofer, Inconel718, A660, XM-19, CuCrZr-IG, Cu, W, LiPb and conventional concrete (used in B-lite ITER model) [1]. In addition, other concretes that are being considered to be part of the bioshield plug (L2N and barite) are studied [1].

In a first step, for each material, nuclides contributing more than 1% to a non-negligible SDDR (produced by the activation of each material) are identified. Then, pathways for the production of each radionuclide are

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Table 1. QS description [15,16].

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)

determined, considering a minimum contribution of 1%. All the data regarding dominant radionuclides and pathways are taken from both reports/papers devoted to calculate SDDR at different ITER locations [1,2,5–10], and own calculations carried out to complete the information of those materials partially or not analyzed in the literature. These calculations are performed using the ACAB activation code [12] with the EAF-2007 activation library and the SA2 irradiation scenario [13]. The above-listed materials are subjected to reference neutron spectra from both PC and PI. Such neutron flux spectra and the compositions for the different materials are described in [11].

Secondly, the quality of each of the XS is analyzed following the EAF procedure for validating and testing the successive versions since 2001. A validated XS means that both integral and differential available experiments are consistent with the EAF data. Reference [14], and specially the updated revision [15], are used to assess the status of the identified XS since they are focused on the EAF-2007 XS quality. They provide a Quality Score (QS) from 0–6 for a large number of reactions, indicating how much the EAF data are backed up by experimental data (Table 1). Moreover, possible improvements/updates from the EAF-2007 in the EAF-2010 and the recent TENDL-2015 libraries are assessed by comparing EAF and TENDL XS with available differential experimental data from EXFOR database using the JANIS display software.

3. Results for radionuclides contributing above 4% to the SDDR

Table 2 summarizes the main results achieved in [11]. A total number of 14 radionuclides were found as relevant for the SDDR analysis in the PC: ^{24}Na, ^{42}K, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{64}Cu, ^{131}Ba, ^{133}Ba, ^{182}Ta, ^{187}W, and ^{203}Pb; while for the PI, only 9 are important: ^{42}K, ^{51}Cr, ^{54}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{182}Ta, ^{187}W, and ^{203}Pb. Note that ^{42}K, ^{131}Ba, and ^{133}Ba only need to be considered in case barite concrete is finally used in ITER.

26 one-step production pathways were encountered. 20 of these XS reactions are differential and integral validated so that no further work is needed for them. Nevertheless, future work for validation is required for 6 XS: ^{59}Co(n,2n)^{58}Co, ^{63}Cu(n,g)^{64}Cu, ^{50}Cr(n,g)^{51}Cr, ^{130}Ba(n,g)^{131}Ba, ^{132}Ba(n,g)^{133}Ba, and ^{134}Ba(n,2n)^{133}Ba. The last 3 are only relevant for the barite concrete [11].

Table 2. Summary of relevant radionuclides and pathways involved in the determination of SDDR at ITER PC and PI.

Nuclide	Responsible material	Main Pathways
^{24}Na	LiPb, conventional and L2N concretes	^{23}Na(n,g)^{24}Na* ^{24}Mg(n,p)^{24}Na* ^{27}Al(n,a)^{24}Na*
^{42}K	Barite concrete	^{41}K(n,g)^{42}K*
^{51}Cr	SS316LN-IG	^{50}Cr(n,g)^{51}Cr ^{52}Cr(n,2n)^{51}Cr* ^{54}Fe(n,a)^{51}Cr*
^{54}Mn	Conventional and L2N concretes, Eurofer, SS316LN-IG, SS316L, SS304L, XM-19, Inconel 718, CuCrZr-IG, LiPb	^{55}Mn(n,2n)^{54}Mn* ^{54}Fe(n,p)^{54}Mn*
^{56}Mn	SS316LN-IG	^{55}Mn(n,g)^{56}Mn*
^{59}Fe	Conventional and barite concretes, Eurofer, SS316LN-IG, SS304L, Inconel 718, CuCrZr-IG	^{58}Fe(n,g)^{59}Fe* ^{59}Co(n,p)^{59}Fe* ^{62}Ni(n,a)^{59}Fe*
^{58}Co	SS316LN-IG, SS316L, CuCrZr-IG, Inconel 718, XM-19, A660, LiPb	^{59}Co(n,2n)^{58}Co ^{58}Ni(n,p)^{58}Co*
^{60}Co	L2N concrete, Eurofer, SS316LN-IG, SS304/316L, Cu, CuCrZr, Inconel 718, XM-19, A660, LiPb	^{59}Co(n,g)^{60}Co* ^{60}Ni(n,p)^{60}Co* ^{63}Cu(n,a)^{60}Co*
^{64}Cu	Cu	^{63}Cu(n,g)^{64}Cu
^{131}Ba	Barite concrete	^{130}Ba(n,g)^{131}Ba
^{133}Ba	Barite concrete	^{132}Ba(n,g)^{133}Ba ^{134}Ba(n,2n)^{133}Ba
^{182}Ta	Eurofer, SS304L/316L, SS316LN-IG, CuCrZr, Inconel 718, XM-19, A660, W	^{181}Ta(n,g)^{182}Ta* ^{182}W(n,p)^{182}Ta*
^{187}W	Eurofer, W, LiPb	^{186}W(n,g)^{187}W*
^{203}Pb	LiPb	^{204}Pb(n,2n)^{203}Pb*

* means validated XS.

Comparing these EAF XS to be improved with the TENDL library, some differences are appreciated; however, it is not clear which one is better to be used since there is a lack of experimental data in the energy range in which they differ from each other. For the validated XS reactions, most of them are the same in the TENDL-2015 library and only a few present some changes: ^{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.

4. Results for radionuclides contributing 1–4% to the SDDR

Table 3 compiles the 22 radionuclides contributing 1–4% to the SDDR, along with their 26 production pathways. Some of the considered materials do not appear therein since no nuclides contributing in this range are found.

15 out of 22 radionuclides are related to the PC: ^{24}Na, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{57}Ni, ^{64}Cu, ^{106m}Ag, ^{110m}Ag, ^{124}Sb, ^{135m}Ba, ^{182}Ta, and ^{187}W; while other 15 are to the PI: ^{51}Cr, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{92m}Nb, ^{106m}Ag, ^{110m}Ag, ^{124}Sb, ^{125}Sb, ^{134}Cs, ^{152}Eu, ^{154}Eu, ^{160}Tb, ^{182}Ta, and ^{181}W.

Table 3. Nuclides contributing 1–4% to SDDR and pathways.

Responsible material	Nuclide	Cooling time (days)	Pathways and contribution (%)
SS316LN-IG	^{51}Cr	12[a]	^{50}Cr(n,g) (75.7) ^{52}Cr(n,2n) (22.1) ^{54}Fe(n,a) (2.2)
	^{59}Fe	12[a]	^{58}Fe(n,g) (98.1) ^{62}Ni(n,a) (1.5)
	^{58}Co	1[a]	^{58}Ni(n,p) (99.8)
	^{57}Ni	1[c]	^{58}Ni(n,2n) (100)
	^{64}Cu	1[a]	^{63}Cu(n,g) (100)
	^{182}Ta	1[a]	^{181}Ta(n,g) (99.9)
SS304L	^{51}Cr	1[a]	^{50}Cr(n,g) (99.9)
	^{56}Mn	1[a]	^{55}Mn(n,g) (99.9)
	^{59}Fe	1[a]	^{58}Fe(n,g) (100)
		12[a]	^{58}Fe(n,g) (97.2) ^{59}Co(n,p) (1.7) ^{62}Ni(n,a) (1.1)
	^{64}Cu	1[a]	^{63}Cu(n,a) (100)
LiPb	^{60}Co	1[a]	^{59}Co(n,g) (78.1) ^{60}Ni(n,p) (21.8)
	^{65}Zn	12[a,c]	^{64}Zn(n,g) (72.5) ^{66}Zn(n,2n) (27.5)
	^{92m}Nb	12[a]	^{93}Nb(n,2n) (84.3) ^{92}Mo(n,p) (14.9)
	^{106m}Ag	1[c]	^{107}Ag(n,2n) (100)
		12[a,c]	^{107}Ag(n,2n) (100)
	^{110m}Ag	1[c]	^{109}Ag(n,g) (99.9)
		12[a,c]	^{109}Ag(n,g) (99.9)
	^{125}Sb	12[c]	^{124}Sn(n,g)^{125}Sn(B$^-$) (100)
	^{187}W	1[a]	^{186}W(n,g) (100)
Cu	^{110m}Ag	12[a]	^{109}Ag(n,g) (100)
W	^{182}Ta	12[a]	^{182}W(n,p) (98.3) ^{183}W(n,D) (1.2)
	^{181}W	12[a]	^{180}W(n,g) (50.6) ^{182}W(n,2n) (49.4)
Eurofer	^{51}Cr	1[c]	^{50}Cr(n,g) (99.9)
		12[c]	^{50}Cr(n,g) (73.2) ^{52}Cr(n,2n) (21.3) ^{54}Fe(n,a) (5.5)
	^{60}Co	1[c]	^{59}Co(n,g) (100)
		12[c]	^{59}Co(n,g) (100)
	^{124}Sb	1[c]	^{123}Sb(n,g) (100)
		12[c]	^{123}Sb(n,g) (100)
Barite concrete	^{24}Na	1[a,b,d]	^{24}Mg(n,p) (33.6) ^{27}Al(n,a) (66.3)
	^{54}Mn	1[a]	^{54}Fe(n,p) (100)
	^{135m}Ba	1[a,d]	^{134}Ba(n,g) (58.6) ^{135}Ba(n,n′) (32.5) ^{136}Ba(n,2n) (8.9)
L2N	^{59}Fe	12[a,d]	^{58}Fe(n,g) (98.8) ^{59}Co(n,p) (1.2)
	^{134}Cs	12[a,d]	^{133}Cs(n,g) (100)
	^{152}Eu	12[a,d]	^{151}Eu(n,g) (100)
	^{154}Eu	12[a,d]	^{153}Eu(n,g) (100)
	^{160}Tb	12[a,d]	^{159}Tb(n,g) (100)
	^{182}Ta	12[a,d]	^{181}Ta(n,g) (100)

Superscript in column #3 refers to the source of information: [a] own calculations using ACAB, [b] Ref. [1], [c] Ref. [5], [d] Ref. [9].

Table 4. QS for new radionuclides contributing 1–4% to SDDR: i) split reactions for EAF-2007 [14] and EAF-2010 [16] and ii) total reaction for EAF-2007 [15].

Reaction	Product	Half-life	QS [14]	QS [15]	QS [16]
^{58}Ni(n,2n)[a]	^{57}Ni	35.6 h	6	6	6
^{64}Zn(n,g)[b]	^{65}Zn	243.8 d	4	–	4
^{66}Zn(n,2n)[b]	^{65}Zn	243.8 d	4	–	4
^{93}Nb(n,2n)[b]	^{92m}Nb	10.2 d	6	6	6
^{92}Mo(n,p)[b]	^{92m}Nb	10.2 d	6	6	6
^{107}Ag(n,2n)[a,b]	^{106m}Ag	8.3 d	4	–	4
^{109}Ag(n,g)[a,b]	^{110m}Ag	249.8 d	4	–	4
^{123}Sb(n,g)[a,b]	^{124g}Sb	60.2 d	4	–	4
	^{124m}Sb	93 s	2		2
	^{124n}Sb	20.2 min	2		2
^{124}Sn(n,g)^{125}Sn(B$^-$)[b]	^{125g}Sn	9.6 d	2	–	2
	^{125m}Sn	9.5 min	4		4
^{133}Cs(n,g)[b]	^{134g}Cs	2.1 y	4	–	4
	^{134m}Cs*	2.9 h	3		3
^{134}Ba(n,g)[a]	^{135m}Ba	22.7 h	4	–	4
^{135}Ba(n,n')[a]	^{135m}Ba	22.7 h	2	–	2
^{136}Ba(n,2n)[a]	^{135m}Ba	22.7 h	6	6	6
^{151}Eu(n,g)[b]	^{152g}Eu	13.5 y	2	–	2
	^{152m}Eu	9.3 h	5		5
	^{152n}Eu*	96 min	2		2
^{153}Eu(n,g)[b]	^{154g}Eu	8.6 y	4	–	4
	^{154m}Eu	46.3 min	0		0
^{159}Tb(n,g)[b]	^{160}Tb	72.3 d	4	–	4
^{183}W(n,D)[b]	^{182g}Ta	114.7 d	0	–	0
	^{182m}Ta*	283 ms	0		0
	^{182n}Ta*	15.8 min	0		0
^{180}W(n,g)[b]	^{181}W	121.2 d	4	–	4
^{182}W(n,2n)[b]	^{181}W	121.2 d	6	6	6

Superscript refers to the cooling time (days): [a] 1, [b] 12; – means reaction not included in [15]; * means 100% decay by isomeric transition.

Worth mentioning that 10 of the 22 nuclides (^{24}Na, ^{51}Cr, ^{54}Mn, ^{56}Mn, ^{59}Fe, ^{58}Co, ^{60}Co, ^{64}Cu, ^{187}W, and ^{182}Ta) had already came into sight in [11] and consequently exhibited in Table 2. These radionuclides appear in different materials now but however, no new pathways come out for their production. Therefore, of 17 (out of 26) coincident pathways between Tables 2 and 3, only ^{63}Cu(n,g)^{64}Cu and ^{50}Cr(n,g)^{51}Cr XS require further effort for validation and verification, as it was drawn in [11].

On the other hand, most of the new nuclides come from the L2N and barite concrete (e.g.^{135m}Ba, $^{152/154}$Eu) or from impurities (e.g. ^{124}Sb).

Table 4 provides QS, both for the total reactions [15] and for the split ones [14,16], corresponding to the new pathways which did not appear in [11]. No QS changes, for any of the XS, between the EAF-2007 and 2010.

Considering that most of the metastable isotopes decay 100% by isomeric transition (except in the ^{124m}Sb case, 75%) and the half-lives of the involved metastable states are very small compared to the cooling times of interest (1 and/or 12 days), it would only be necessary to consider the total XS. However, ^{125m}Sn and^{152m}Eu do not decay to the ground, and only the split XS reaction for the ground state (and to the second metastable in the ^{152}Eu case)

should be studied; additionally the decay process for these radionuclides does not emit photons.

Table 4 shows that 5 XS are validated (QS=6), corresponding to ^{58}Ni(n,2n), ^{93}Nb(n,2n), ^{92}Mo(n,p), ^{136}Ba(n,2n), and ^{182}W(n,2n) pathways, while no QS is provided in [15] for 14 XS. When plotting these 14 XS from EAF-2007 and 2010 joint to the available experimental differential data and TENDL-2015, some slight differences among the libraries are detected as well as a lack of experimental data, especially in the high-energy region for some (n,g) reactions (usually from 3 MeV onwards). However, considering the low contribution of these pathways to the SDDR, the clarification work needed is less important than that for the ^{59}Co(n,2n)^{58}Co, ^{63}Cu(n,g)^{64}Cu and ^{50}Cr(n,g)^{51}Cr XS reactions. Regarding to the 5 validated XS, no significant differences between EAF and TENDL are found.

5. Conclusions

This paper extends a previous study related to the XS quality of the EAF-2007 activation library for its specific use in the ITER SDDR prediction at PC and PI. In that work, the analysis was done for those radionuclides contributing more that 4% to the SDDR. Now, it is expanded to contributions in the range of 1–4%. Also, possible effects in the updating in both EAF-2010 and TENDL-2015 compared to EAF-2007 are investigated.

Using EAF-2007 and considering both works, a total number of 27 radionuclides are found as relevant.

- For the ITER PC (19): ^{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, and ^{203}Pb.
- For the ITER PI (20): ^{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, and ^{203}Pb.

It is necessary to highlight that ^{134}Cs, ^{152}Eu, ^{154}Eu, and ^{160}Tb have to be taken into account only in the case that L2N concrete is used in ITER. The same applies for ^{42}K, ^{131}Ba, ^{133}Ba, and ^{135m}Ba and the barite concrete.

A total number of 45 pathways appear for the production of all the 27 dominant radionuclides:

- 25 XS reactions are differential and integral validated. Hence, no further work is needed for them. To this category belong those reactions leading to radionuclides contributing most to the SDDR.
- 20 XS reactions are not validated since a lack of integral experimental data, and also of differential data in some cases, is detected. Also, slight discrepancies among the EAF (2007 and 2010) and TENDL-2015 are found for some XS, but it is not clear which one fits better with the available differential experiments, or the differences are found in the energy range without experiments. This fact makes difficult any conclusion about the best evaluated XS library to be used for the SDDR estimation in ITER, indicating that further work to determine their reliability degree is needed, priorized as follows:
  - Efforts on improvement should be prioritized on ^{59}Co(n,2n)^{58}Co, ^{63}Cu(n,g)^{64}Cu, and ^{50}Cr(n,g)^{51}Cr XS reactions as these production pathways appear for radionuclides contributing most to the SDDR and/or in the activation of more than one material.
  - 8 more XS require further work (less priority): ^{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, and ^{180}W(n,g)^{181}W.
  - If L2N and barite concretes are used in ITER some other XS reactions require effort, especially for the validation at low energies:
    - For the L2N concrete case: ^{133}Cs(n,g)^{134}Cs, ^{151}Eu(n,g)^{152}Eu,^{153}Eu(n,g)^{154}Eu and ^{159}Tb (n,g)^{160}Tb.
    - For the barite concrete case: ^{130}Ba(n,g)^{131}Ba, ^{132}Ba(n,g)^{133}Ba, ^{134}Ba(n,2n)^{133}Ba, ^{134}Ba(n,g)^{135m}Ba, and ^{135}Ba(n,n')^{135m}Ba.

To date, without any further work and considering radionuclides and pathways with contributions >1%, the calculated CDR (Contact Dose Rate 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%), and L2N concrete (94%). On the contrary, the SDDR prediction for Cu and barite concrete is not trustworthy.

Finally, the use of any of the analyzed EAF and TENDL libraries would lead to similar results in the SDDR calculation in ITER. However, for the reactions pointed out further work for the XS validation is needed.

The views and opinions expressed herein do not necessarily reflect those of F4E.

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