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Radiological impact mitigation of waste coming from the European fusion reactor DEMO with DCLL breeding blanket

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In large fusion machines, as the foreseen DEMO, the high energy neutrons produced will cause the transmutation of the interacting materials which will become a source of radioactive waste. Besides the main constituents of a material that could transmute but which presence is essential, the impurities often give rise to significant additional activation compared to the base material. Thus, once identified the nuclides generating the dominant activation products for the DCLL (Dual Coolant Lithium-Lead) concept of Breeding Blanket (BB) for the European DEMO, the objective of the study has been to determine the impurity limits for such materials in order to minimize the radiological impact of the waste produced. This will enable to consider it as Low Level Waste and dispose it in the Spanish near-surface repository of El Cabril. For both the original compositions as well as the revised one with reduced amount of impurities, suggested to mitigate the waste impact, activation calculations have been performed. Hence, total beta-gamma activity, alfa activity, specific activity for different nuclides, decay heat and surface gamma dose rate have been analyzed with reference to the IAEA and SEAFP-2 standards for waste classification and to the specific regulations of El Cabril.

1. Introduction

One of the main presuppositions for the global interest in nuclear fusion is that it should be cleaner and safer comparing to traditional nuclear technology. This implies, among other considerations, that the radioactive waste produced in a fusion power plant is expected to be categorized as Low Level Waste (LLW) after no more than 100 years since the shutdown.

Several works dealing with calculations of various activation responses, such as activity, decay heat (DH) and contact dose rate (CDR), as inputs for the subsequent assessment of radioactive waste in different fusion facilities can be found in literature as well as specific studies on waste management and strategies [1]-[6].

The present paper focuses on analyzing the radiological impact of waste coming from the Dual-Coolant Lithium Lead (DCLL) Breeding Blanket (BB) system, one of the 4 BB concepts under development for the future European DEMOnstration reactor. The aim at the basis of such study is to determine the limits for the impurities content of the structural and functional materials of the DCLL BB to minimize the radiological impact of the radioactive wastes coming from the transmutation produced by the neutrons in a fusion reactor. The reduction of the impurities pursues fulfilling the requirements of LLW and additionally of the disposal in the Spanish near-surface repository El Cabril. Although various papers related to wastes coming from a DCLL BB are available [7][8], this work updates the analysis for the last European DCLL and looks at limitations for impurities.

The procedure followed (model, assumptions, material compositions, irradiation scenario and codes) is described in Section 2.1. Section 2.2 provides the waste management criteria assumed. The results of the activation analyses are detailed in Section 3. Section 4 deals with a preliminary quality assessment of the activation cross sections (XS) used and finally, overall conclusions are summarized in Section 5.

2. Procedure for waste management assessment

2.1 DCLL neutronic model and assumptions

CIEMAT is currently leading the development of the DCLL BB within the EUROfusion Programme [9]. The DCLL concept [10][11] is basically characterized by the use of self-cooled breeding zones with the liquid metal lithium-lead (PbLi) serving as tritium (T) breeder, neutron multiplier and coolant and the ferritic–martensitic steel Eurofer-97 as structural material. The details of the DCLL DEMO design used are described in [11][12]. In figures 1a-c are shown the main constituents of the blanket module and the module's segmentation inside a sector.

Such design has been developed for the DEMO 2014 baseline [13] which plasma parameters (radios, elongation, triangularity, radial shift, source peaking factor) are summarized in [14]. The assumed reactor fusion power is 1572 MW corresponding to $5.581 \cdot 10^{20}$ n/s, with an average neutron wall loading of 1.033 MW/m^2.

The materials compositions for the BB modules structures are taken from the detailed design [11] and summarized in table 1. The analyses have been performed on a heterogeneous DCLL model in which only the thin helium (He) channels have not been realistically described. This simplification has not much relevance due to the fact that the activation of helium is negligible compared to that of the other materials. On contrary, the Back Supporting Structure (BSS) is completely homogenized. The Flow

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Channel Inserts, which design is not still fixed, have not been included.

The analyzed materials are those considered to be the main sources of radioactive waste: the Eurofer structure, the Tungsten (W) coating (used as plasma facing component covering the First Wall, FW) and the PbLi breeder. Beside the main constituents that could transmute but which presence is essential, the impurities either naturally occurring or purposely, accidentally, or inevitably added during the production process, often give rise to significant additional activation compared to the base material. The compositions for Eurofer, W and PbLi, with its initial impurity content, are given in [15], [16], and [17], respectively. The PbLi breeder material (with 90% enrichment in ^{6}Li) has been considered motionless notwithstanding it actually flows through the breeding regions with a velocity of about 2 cm/s. However, the assumption of a motionless PbLi is conservative.

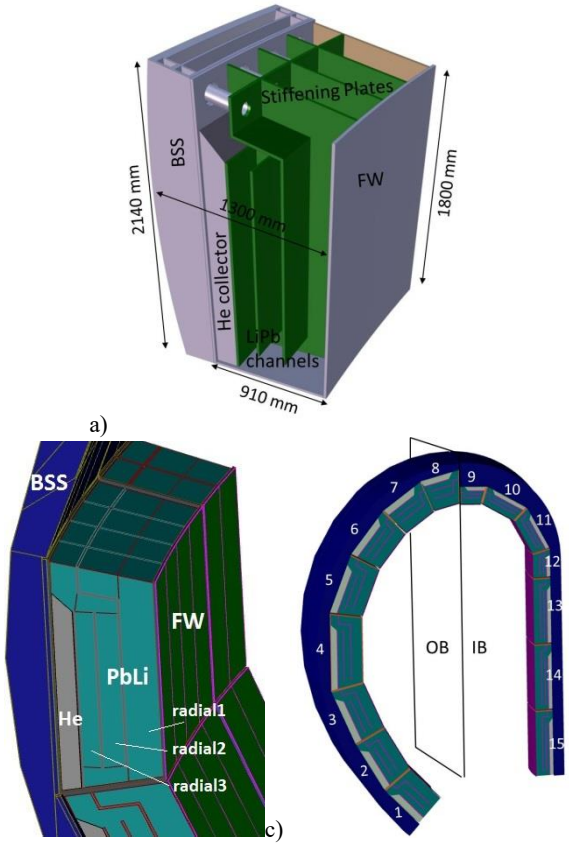

Figure 1. a) DCLL DEMO detailed outboard equatorial module b) neutronic model of the module; c) complete DCLL segment.

Table 1. Compositions of the DCLL blankets components.

Vol. (%)	*Eurofer*	*PbLi*	*W*	*He*
Armour			100	
First Wall, Caps, BackPlate	85.54			14.46
Stiffening plates	91.33			8.67
Breeder channels		100		
Helium collectors	53			47
BSS	51.29	44.36		4.35

Neutron spectra have been calculated at different radial and poloidal positions (figure 1a-b) within the structures of the two most exposed (equatorial) outboard (OB) and inboard (IB) blanket modules for the different materials. The highest spectra are found in the positions closest to the plasma and the corresponding intensities assumed for the activation calculation of the 3 materials are: $7.70 \cdot 10^{14}$ n·cm^{-2}·s^{-1} at the FW of OB#4, $7.59 \cdot 10^{14}$ n·cm^{-2}·s^{-1} in the W of IB#13 and $5.32 \cdot 10^{14}$ n·cm^{-2}·s^{-1} for the radial zone 1 of PbLi (see figure 1b) of OB#4 (modules' number is displayed in figure 1c). Transport calculations have been performed using Monte Carlo code MCNP5 [18] and JEFF3.1.1 XS data library [19]. The activation responses have been then determined by the use of the ACAB inventory code [20] and the nuclear data library EAF2007 [21].

The irradiation scenario assumed for the activation calculations is based on the operation scheme specified for the 1st DEMO phase [22]: continuous operation over 5.2 years (CY) minus 10 days at 30% of the nominal fusion power followed by 10 days pulsed operation with 48 pulses of 4 hours at full power and 1 hour dwell time in between, reaching a total of 1.57 full power years (FPY). A set of standard decay times from 1 second to 1000 years has been considered, including: 50 years, in the effort to reduce the radiological impact of wastes as soon as possible (ASAP) on the road to not be a burden for future generations; and 300 years because some of the El Cabril requirements are defined at that period.

2.2 Applicable regulations

In Europe, the classification of waste and the waste management policies are coordinated at national level. Nevertheless, in general, most of the countries follow the IAEA categorization [23] which at present proposes a DH of 2 kW/m^3 as the limit between Low and Intermediate Level Waste and High Level Waste (LILW and HLW), and 4000Bq/g of α-activity to separate LILW-SL and LILW-LL (where SL and LL refer respectively to short lived and long lived, the limit between both being at 30 years half-life). On the other hand, activated material from the Power Plant Conceptual Study (PPCS) fusion reactor models [24] were categorized according to the SEAFP-2 [25] classification system: Non Active Waste (NAW; to be cleared), Simple Recycle Material (SRM; CDR <2 mSv/h), complex recycle material (CRM; CDR 2–20 mSv/h) and permanent disposal waste (PDW, not recyclable; CDR >20 mSv/h). SRM includes material which may be recycled by Hands On Operation (HOR; CDR < 10 μSv/h). The limits on decay heat in CRM and SRM are 10 W/m^3 and 1 W/m^3 respectively. These are in line with the recommendations of ICRP 90 [26] and IAEA 96 [27]. Being more restrictive than the IAEA DH limits and being more complete for considering also CDR limits, the SEAFP-2 criteria are applied in the following assessments. According to [25], CRM corresponds to Medium Level Waste (MLW) while SRM does to LLW.

For the disposal of Very Low Level Waste (VLLW) and LILW, the near-surface facility El Cabril, in Cordoba (Spain), has been operating since 1992. El Cabril is divided into two areas: one for VLLW and another one for LILW. This second zone, at the same time, has two levels. Waste

with: i) total α, ii) total β-γ and iii) specific activities for different nuclides below certain values is defined as El Cabril Level 1 (L1). Waste above those values but below other limits is categorized as Level 2 (L2) material [28].

3. Results

Considering the previously explained conditions, DH, CDR, total α, total β-γ and specific activity for different nuclides have been analysed with reference to the IAEA/SEAFP-2 standards and to the specific regulations of El Cabril.

The total values of DH, CDR and β-γ activity at 50, 100 and 300 years, as well as the corresponding limits, are shown in table 2 for Eurofer, W and PbLi and displayed in figure 2 along all the cooling time. Values in bold are those which exceed the limits. The α activity (not displayed) is several orders of magnitude below the limit for El Cabril in all the cases.

The results of the contribution of each daughter nuclide to each of the responses are shown in tables 3, 4, and 5 for Eurofer, W and PbLi respectively, giving values at 50 and 100 years after shutdown and separating the contributions in more than 1% and 10%. The nuclides which sum more than 90% to the response are highlighted in bold. Unless there are many contributors for each response potentially offering an efficient way of radiological impact mitigation, most of them come from intendent elements (i.e. ^{55}Fe is intrinsic to Eurofer, ^{178}Hf comes from W) and hence they cannot be reduced. In other cases their reduction is not needed since the limit for the global response is not overpassed.

Table 2. Global activation responses

Eurofer	50y	100y	300y	limit
DH (W/cm^3)	4.55E-08	6.73E-09	5.64E-09	*LLW < 1E-06*
CDR (Sv/h)	**7.54E-03**	5.11E-04	4.92E-04	*LLW < 2E-03*
Activity (Bq/g)	**1.19E+06**	**1.38E+05**	**6.65E+04**	*L1 < 3.7E+04*
Tungsten	50y	100y	300y	limit
DH (W/cm^3)	1.83E-07	8.42E-08	3.49E-08	*LLW < 1E-06*
CDR (Sv/h)	**3.95E-03**	1.49E-03	8.60E-04	*LLW < 2E-03*
Activity (Bq/g)	**1.59E+05**	**7.96E+04**	**4.55E+04**	*L1 < 3.7E+04*
PbLi	50y	100y	300y	limit
DH (W/cm^3)	7.32E-07	4.92E-08	3.09E-09	*LLW < 1E-06*
CDR (Sv/h)	6.94E-04	4.37E-04	2.84E-04	*LLW < 2E-03*
Activity (Bq/g)	**8.28E+07**	**5.02E+06**	6.75E+03	*L1 < 3.7E+04*

Table 6 details the pathways of production of critical nuclides specifying the main impurity parents which content must be reduced to fulfil the limits, as explained in the following discussion. Additionally, it gives a Quality Score (QS) value for a reliability assessment of the activity calculations that is explained in Section 5.

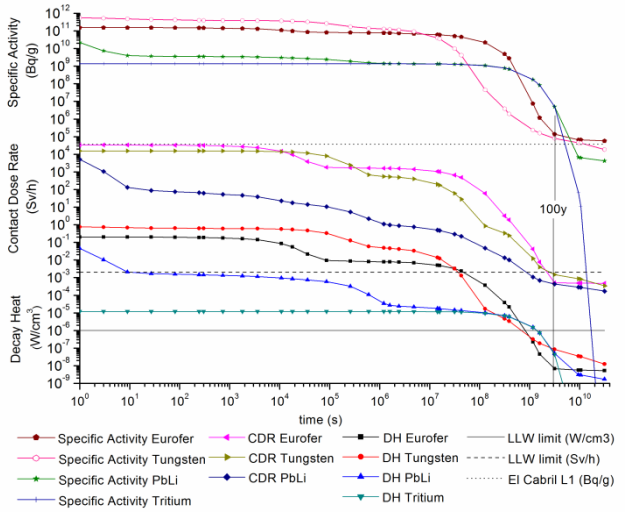

Figure 2. Global activation responses for Eurofer, W and PbLi.

According to table 2 and figure 2, one of the most crucial parameter turns out to be the activity. In fact, while the DH limit of LLW is already fulfilled at 50 years for Eurofer, W and PbLi, and the CDR limit of LLW is respected from 100 years for Eurofer and W and already at 50 years for PbLi, the limit of El Cabril L1 on the total activity is not observed even after 300 years for Eurofer and W, and only after 300 years for PbLi. To achieve the CDR limit for LLW instead of Intermediate Level Waste (ILW) from 50 years, a reduction of the Co content is needed from the main contributor to CDR. In both Eurofer and W, ^{60}Co is coming mostly from ^{59}Co (table 6). Thus, with a reduction from the initial 50 ppm to 6.8 ppm on the Eurofer composition and from 10 to 5.1 ppm on the W one, the LLW limit for CDR would be fulfilled.

Regarding El Cabril, it seems very difficult to dispose the waste coming from Eurofer in L1 as can be observed from data of table 2. Nonetheless, the storage in L2 could be affordable only if a reduction of the Nb impurity content from the initial 50 ppm to 4.4 ppm is carried out in order to reduce the specific activity on ^{94}Nb from $1.36\cdot10^3$ to the limit of $1.2\cdot10^2$ Bq/g (table 7).

In the case of W, to be stored in L1 after 100 years the Mo content should be reduced from 100 to 16.6 ppm to diminish the specific activity of ^{93}Mo from $2.22\cdot10^3$ to its specific limit for L1 ($3.7\cdot10^2$ Bq/g). Most important, the total activity should decrease almost to one half (from $7.96\cdot10^4$ to $3.7\cdot10^4$ limit, table 2) implying that the activity coming from ^{39}Ar and ^{91}Nb (which sum about 60% of the total) should be almost zeroed. This could be done by eliminating completely ^{39}K and ^{92}Mo which, according to the pathways analysis (table 6), are the precursors of the two daughter nuclides. Being a very strict option it limits the alternatives to the disposal of W in L2. Nevertheless, this could only be done if the Nb content is decreased from 10 to 3.5 ppm, so that the specific activity of ^{94}Nb is reduced from $3.4\cdot10^2$ Bq/g to the limit (table 7).

Concerning the peculiarities of PbLi, being difficult to reach the limit for storage in El Cabril L1, the option of L2 would be possible but only with a Nb reduction from 10 to 5.8 ppm in order to lower the ^{94}Nb specific activity from

$2.06 \cdot 10^2$ to $1.2 \cdot 10^2$ Bq/g (table 7). As the responses have taken into account of all the T produced inside the breeder, a minimum extraction requirement can be given in view of a feasible disposal in L2. According to the specific activity of T ($5 \cdot 10^6$ Bq/g at 100 years, table 7), a reduction factor of 5 should be applied to reduce it to the limit, meaning that at least 80% of T extraction should be achieved by the T extraction system (TES) of the DEMO reactor.

The impurities detected in the analysis (Nb, Mo, Co) are commonly identified as undesired [5][29] and Nb minimization has been demonstrated to be one of the most effective ways to reduce the activation at long times.

Table 3. Contribution of activation products of Eurofer to the activation responses at 50 and 100 years since the shutdown.

Decay Heat		50y			100y
>10%	**Co60**	**65.4%**	>10%	**C14**	**44.6%**
	H3	**10.9%**		**Nb94**	**37.9%**
>1%	Nb93m	7.1%	>1%	Nb93m	5.8%
	C14	6.6%		H3	4.5%
	Nb94	5.6%		Ni63	3.5%
	Fe55	2.6%			
Contact Dose Rate		50y			100y
>10%	**Co60**	**92.4%**	>10%	**Nb94**	**96.1%**
>1%	Nb94	6.5%	>1%	Co60	1.9%
				Hf178m	1.0%
Activity		50y			100y
>10%	**H3**	**67.6%**	>10%	**C14**	**40.7%**
	Fe55	**16.4%**		**H3**	**35.3%**
>1%	Nb93m	8.1%	>1%	Ni63	9.2%
	C14	4.7%		Nb93m	8.5%
	Ni63	1.5%		Nb91	2.3%
				Mn52m	2.3%

Table 4. Contribution of activation products of Tungsten to the activation responses at 50 and 100 years since the shutdown.

Decay Heat		50 y			100 y
>10%	**Hf178s**	**29.8%**	>10%	**Ar39**	**28.0%**
	Hf178m	**26.3%**		**Ag108m**	**23.6%**
	Ar39	**14.6%**		**Hf178s**	**21.2%**
	Ag108m	**11.8%**		**Hf178m**	**18.7%**
	Co60	**11.1%**	>1%	Re186	2.4%
>1%	Nb93m	1.2%		Nb94	2.2%
	Re186	1.1%			
	Cd113m	1.0%			
	Nb94	1.0%			
Contact Dose Rate		50 y			100 y
>10%	**Co60**	**42.1%**	>10%	**Ag108m**	**69.3%**
	Ag108m	**28.5%**		**Hf178m**	**22.8%**
	Hf178m	**26.3%**	>1%	Nb94	7.2%
>1%	Nb94	2.7%			
Activity		50y			100y
>10%	**Ar39**	**25.0%**	>10%	**Ar39**	**43.9%**
	H3	**19.5%**		**Nb91**	**18.1%**
	Nb93m	**14.5%**		Hf178m	5.6%
>1%	Nb91	9.5%		Hf178s	5.6%
	Hf178m	8.6%		Nb93m	5.6%
	Hf178s	8.6%		Ag108m	4.9%
	Ni63	3.0%	>1%	Ni63	4.2%
	Ag108m	2.7%		Mo93	2.8%
	Cd113m	2.1%		H3	2.4%
	Co60	1.6%		Re186	2.3%
	Mo93	1.4%		Re186m	2.3%
	Re186	1.2%		C14	1.0%
	Re186m	1.2%			

Table 5. Contribution of activation products of PbLi to the activation responses at 50 and 100 years since the shutdown.

Decay Heat		50y			100y
>10%	**H3**	**98.7%**	>10%	**H3**	**88.6%**
			>1%	Ag108m	4.9%
				Bi207	1.6%
				Sn121	1.4%
				Nb94	1.1%
Contact Dose Rate		50y			100y
>10%	**Bi207**	**38.2%**	>10%	**Ag108m**	**51.6%**
	Ag108m	**35.3%**		**Bi207**	**20.4%**
>1%	Co60	8.9%		**Bi208**	**14.0%**
	Bi208	8.8%		**Nb94**	**13.7%**
	Nb94	8.6%			
Activity		50y			100y
>10%	**H3**	**100%**	>10%	**H3**	**99.6%**

Table 6. Relevant XS pathways, contribution to radionuclide, and QS for the total reaction (when provided in [30]).

Material	Response	Pathway and contribution (%)	QS
Eurofer	CDR	Co59(n,g)Co60 (96.9)	(6)
		Ni60(n,p)Co60 (2.5)	(6)
	Activity	Nb93(n,g)Nb94 (99.5)	-
W	CDR	Co59(n,g)Co60 (96.0)	(6)
		Ni60(n,p)Co60 (1.6)	(6)
	Activity	K39(n,p)Ar39 (96.3)	-
		Nb93(n,g)Nb94 (93.7)	-
		Mo92(n,np)Nb91 (76.0)	-
		Mo92(n,g)Mo93 (64.1)	-
		Mo94(n,2n)Mo93 (35.9)	-
PbLi	Activity	Nb93(n,g)Nb94 (98.9)	-

Table 7. Specific activity limits for T and Nb94 considered in the recommendations for storage unit Level 2 of El Cabril.

Bq/g @100y	Eurofer	W	PbLi	*El Cabril L2*
H3	4.87E+04	1.87E+03	**5.00E+06**	*< 1E+06*
Nb94	**1.36E+03**	**3.40E+02**	**2.06E+02**	*< 1.2E+02*

Table 8. Volume and mass of Eurofer, W and PbLi in the reactor.

Component	Eurofer (m^3)	W (m^3)	PbLi (m^3)
FW	16.65	2.02	
Back Plate + Caps	61.73		
BB	136.86		559.71
BSS	231.09		199.87
total (m^3)	446.33	2.02	759.58
mass (tons)	3512.66	38.97	7241.65
% of the reactor weight (41600 tons)	8.4%	0.093%	17.4%

Applying conservatively the results of the most exposed areas to the rest of zones inside the modules and to the rest of modules inside the reactor it could be managed the total amount of waste given in table 8 in the same category. A specific assessment for the BSS Eurofer and PbLi could demonstrate reduced waste category pushing towards their separate waste management.

4. Preliminary assessment on XS quality

With regard to the reliability of the results, a preliminary assessment about the quality of the XS reactions leading to the critical radionuclides coming from impurities has been also performed. For this purpose, the procedure for validating and testing the successive EAF versions described in [30] has been followed, as previously applied for ITER reactor [31]. As a result, table 6 collects, besides the pathways, the QS for the total XS taken from [30]. The

QS is a value from 0 to 6 indicating the degree to which the EAF data are backed up by experiment. Validation requires that both integral and differential data are consistent with the EAF data, indicated with a QS=6. QS for total XS are displayed because all the metastable isotopes decay by isomeric transition to the ground state (99.6% at least), and the half-lives of the metastable states are negligible compared to the cooling times of interest (> 50 years). As shown, only two XS reactions are validated: $^{59}Co(n,g)^{60}Co$ and $^{60}Ni(n,p)^{60}Co$. For the remaining, no QS is provided but a comparison between the EAF2007 and differential experimental data from EXFOR [32] shows that in most of the cases there are enough differential data, especially for $^{93}Nb(n,g)^{94}Nb$ XS, and they agree with the EAF2007 data. For $^{39}K(n,g)^{39}Ar$ XS, limited differential experiments have been found, with weak agreement. For ensuring validation, additional differential experiments - in this case - and integral experiments - for the un-validated XS of table 6 - would be useful.

5. Conclusions

Activation analyses have been performed pursuing the mitigation of the radiological impact of the waste coming from structural and functional materials of the DCLL BB system of the European DEMO reactor, for being considered as LLW and also disposed in the Spanish near-surface repository of El Cabril. According to the results, a reduction on Nb content from 50 to 4.4 ppm, from 10 to 3.5 ppm and from 10 to 5.8 ppm is required respectively for the Eurofer, W and PbLi impurity compositions in order to dispose respectively 3513, 7242 and 39 tons of such materials as LLW in El Cabril Level 2 after 100 years since the DEMO reactor shutdown. Additionally, a minimum T extraction of 80% should be also provided by TES. Ongoing work will determine if such impurity control is viable from the industrial and manufacturing point of view. Preliminary information have confirmed such possibility but at high industrial costs [33]. Analysis on the quality of the involved EAF2007 XS for those reactions with impurities as parents, which are all found as one-step, concludes that for the production of ^{60}Co the XS reactions are validated, while for the others additional efforts are required to ensure their reliability.

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