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Radiological characterization of ceramic materials considered for the HT-DCLL DEMO reactor

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The recent evolution of the Breeding Blanket (BB) Dual Coolant Lithium-Lead (DCLL) concept for the European DEMO from a low temperature (LT) multi-module segment (MMS) approach, limited by the thermal range tolerated by EUROFER, to an advanced high temperature (HT) single-module segment (SMS) architecture, is allowed by the consideration of ceramics and composite materials as main structural material rather than just as thin Flow Channel Inserts (FCI). The amount of the ceramic as main structure instead than as a FCI in the whole reactor could be of several tonnes generating concern regarding the radiological behaviour of such component and the consequent generated waste. For that, a preparatory assessment considering ideal "pure" ceramics has been performed towards a preliminary selection of the structural material, among others, under the criteria of maintenance operations and waste management. To complement such study additional analyses have been carried out considering not only the intendent element but also dopant and impurities which often give rise to significant additional activation. For both the theoretical compositions as well as the industrial ones, with a certain amount of impurities, activation calculations have been performed using the ACAB inventory code. Hence, total beta-gamma activity, specific activity for different nuclides, decay heat and surface gamma dose rate have been analysed with reference to the IAEA and SEAFP-2 standards for waste and handling classifications and to the specific regulations of the near-surface repository El Cabril (Córdoba, Spain). According to El Cabril regulation, pure SiC and TiC would be the best of the options considered since they would be accepted in Level 1 LILW (under detritiation for SiC). This may not be true for industrial compositions with impurities (Level 2), nor according to other standards. Pure zirconia is also a promising option, so further work is ongoing for zirconia and doped zirconia materials.

Keywords: Activation, Waste Management, Ceramics, DCLL BB

1. Introduction

The present paper focuses on the radiological classification and selection of ceramic structure considered for the last Dual-Coolant Lithium Lead (DCLL) Breeding Blanket (BB) for the future European DEMOnstration reactor, based on minimizing the radiological impact of the radioactive wastes coming from the transmutation produced by the neutrons in a fusion reactor.

The DCLL concept is 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.

CIEMAT has acquired large experience in DCLL BB design under different programmes [1][2] and is currently leading its development within EUROfusion [3][4].

During the period 2014-2018 the development of a standard Low Temperature (LT) Multi Module Segment (MMS) DCLL BB approach with the ferritic–martensitic steel Eurofer-97 as structural material was pursued among the Work Package Breeding Blanket (WPBB) [4][5]. This allowed to work within the same generic context than the other 3 BB concepts under development for the European DEMO (HCPB, WCLL and HCLL), although the potentialities of the PbLi self-cooler were limited by the creep-fatigue of the Eurofer, working at a maximum temperature of 550º.

Recently (from 2019 to date), the transition of the DCLL BB development to the Work Package Enabling Research and Prospective Research and Development (WP ENR-PRD) has been produced. This followed the selection of the HCPB and WCLL BB concepts as the most mature and technically sound ones to be used as "driver" blankets for DEMO and the identification of the DCLL BB as an "advanced" blanket potentially more attractive for future fusion power plants [6]. This transition promoted to move to a novel High Temperature (HT) DCLL BB considering a ceramic structure which allows higher fluid temperatures (700-800º) and higher thermal conversion efficiency. For that, it was advisable going to a Single Module Segment (SMS) approach, trying to diminish the liquid metal velocity thanks to a unique route along the poloidal direction [7].

Since the mass of ceramic used as structural material could be several tonnes for the whole reactor, its radiological behaviour and the consequent generated waste would raise concern.

Although various papers related to wastes coming from a DCLL are available [8][9][10], this work updates the analysis for the last European DCLL DEMO and looks at limitations of impurities for the 'advanced' ceramic HT-SMS DCLL BB concept. A preparatory assessment has been done for ideal "pure" ceramics in order to perform a preliminary selection of the structural material also, among others, under the criteria of maintenance operations and waste management. Complementing such study, additional

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analyses have been carried out for the most promising options considering not only the intendent element but also dopant and impurities either naturally occurring or purposely, accidentally, or inevitably added during the production process, which often give rise to significant additional activation compared to the base material.

The aim at the basis of such study is to determine the limits for the impurities content of the ceramic material to minimize the radiological impact of the radioactive wastes. The reduction of the impurities in the structural material pursues fulfilling the requirements of Low Level Waste (LLW) after no more than 100 years since the shutdown and additionally its disposal in the Spanish near-surface repository El Cabril. This possibility would be a crucial achievement for the viability, acceptability and competitively of fusion technology.

The procedure followed (model, irradiation scenario, codes and criteria assumed) are given in Section 2. The preliminary selection and classification of the ceramic material under the waste management point of view is detailed in Section 3 dealing also with the radwaste classification for industrial ceramics compositions determining impurity control requirements. Finally, overall conclusions are summarized in Section 4.

2. Procedure for activation assessments

The activation analyses here described have been performed using the neutron spectra calculated over the most irradiated positions of a previous DCLL DEMO model [4][5] in order to be comparable with the results obtained for the traditional materials (Eurofer, W, PbLi and alumina) considered for the components of the standard LT-MMS DCLL [10][11]. The highest spectra were found in the positions closest to the plasma and at equatorial inboard (IB) and outboard (OB) level. The same intensity ($5.32\cdot10^{14}$ $n\cdot cm^{-2}\cdot s^{-1}$) considered for the activation of the PbLi and the alumina Flow Channel Inserts (FCIs) of the LT MMS DCLL has been considered here for the ceramic structure in order to obtain a comprehensive comparison.

Transport calculations have been performed using Monte Carlo code MCNP5 [12] and JEFF3.1.1 XS data library [13]. The activation responses have been then determined by the use of the ACAB inventory code [14] and the nuclear data library EAF2007 [15].

The irradiation scenario assumed for the activation calculations is based on the operation scheme specified for the 1st DEMO phase [16]: 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).

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. Hence, a set of standard decay times from 1 to 1000 years has been considered, including also 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.

2.1 Applicable regulation

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 [17] which proposes a Decay Heat (DH) of 2 kW/m^3 as the limit between Low and Intermediate Level Waste and High Level Waste (LILW and HLW).

On the other hand, activated material from the Power Plant Conceptual Study (PPCS) fusion reactor models [18][19] were categorized according to the SEAFP-2 [20] [21] classification system based on both the DH and the Contact Dose Rate (CDR) assessment. According to that, the wastes are sorted as 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 [22] and IAEA 96 [23]. 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 [17], CRM corresponds to Medium Level Waste (MLW) while SRM does to LLW. A summary of the adopted criteria for DH and CDR is given in Table 1.

Table 1. Categories adopted in SEAFP-2 [20][21] and IAEA classification [23] of radioactive waste

Activated material classifications		CDR (mSv/h)	DH (W/m^3)
SEAFP-2 classification at 50 years after shutdown	HLW= PDW (not recyclable)	> 20	> 10
	MLW=CRM (recyclable with complex RH procedures)	2-20	1-10
	LLW= SRM (recyclable with simple RH procedures, HOR for D < 10 µSv/h)	< 2	< 1
IAEA classification	HLW		> 200
	LILW		< 200

HLW: High Level Waste; PDW: Permanent Disposal Waste; MLW: Medium Level Waste; CRM: Complex Recycle Material; LLW: Low Level Waste; SRM: Simple Recycle Material; HOR: Hands On Recycling; LILW: Low and Intermediate Level Waste; CDR: Contact Dose Rate; DH: Decay Heat; RH: Remote Handling

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 (3.70E+04 Bq/g for the total β-γ) is defined as El Cabril Level 1 (L1). Waste above those values but below other limits is categorized as Level 2 (L2) material [24]. A summary of the adopted criteria for the specific activity (ACT) is given in Table 2.

Table 2. El Cabril activation limits for specific nuclides for being accepted in Level 1 or Level 2 of the LILW level zone [24]

Limit of specific activity (ACT) for Storage Unit of Level 1	
Isotope	(Bq/g)
H-3	7.40E+03
Na-22	2.00E+04
Mn-54	3.70E+04
Fe-55	3.70E+04
Co-60	3.70E+03
Zn-65	1.00E+04
Sr-90	3.70E+03
Ru-106	9.00E+03
Ag-110m	2.00E+04
Sn-119m	3.70E+04
Sb-125	3.70E+04
Cs-134	3.70E+03
Cs-137	3.70E+03
Ce-144	9.00E+03
Pm-147	3.70E+04
Eu-152	3.00E+04
Eu-154	2.00E+04
Tl-204	3.70E+04
Pb-210	3.70E+01
Ac-227	1.00E+01
C-14	3.70E+03
Ni-59	3.70E+03
Ni-63	3.70E+03
Zr-93	2.60E+03
Mo-93	3.70E+02
Nb-94	1.20E+02
Tc-99	1.00E+03
Pd-107	3.70E+03
I-129	4.60E+01
Cs-135	1.00E+04
Sm-151	3.70E+03
Total Activity beta-gamma	**3.70E+04**

Limit of specific activity (ACT) for Storage Unit of Level 2	
Isotope	(Bq/g)
H-3	1.00E+6
C-14	2.00E+5
Ni-59	6.30E+4
Ni-63	1.20E+7
Co-60	5.00E+7
Sr-90	9.10E+4
Nb-94	1.20E+2
Tc-99	1.00E+3
I-129	4.60E+1
Cs-137	3.30E+5

3. Ceramic waste assessments for the advanced HT SMS DCLL BB

3.1 Advanced HT SMS DCLL BB features and rationale

The recent evolution of the European DEMO DCLL BB concept to an advanced high temperature HT SMS architecture [7][25], implied the consideration of a ceramic structure to give shape to large continuous channels throughout the whole SMS, in which the metal-liquid PbLi circulates, isolated from the external steel box by a low pressure inert gas (Figure 1).

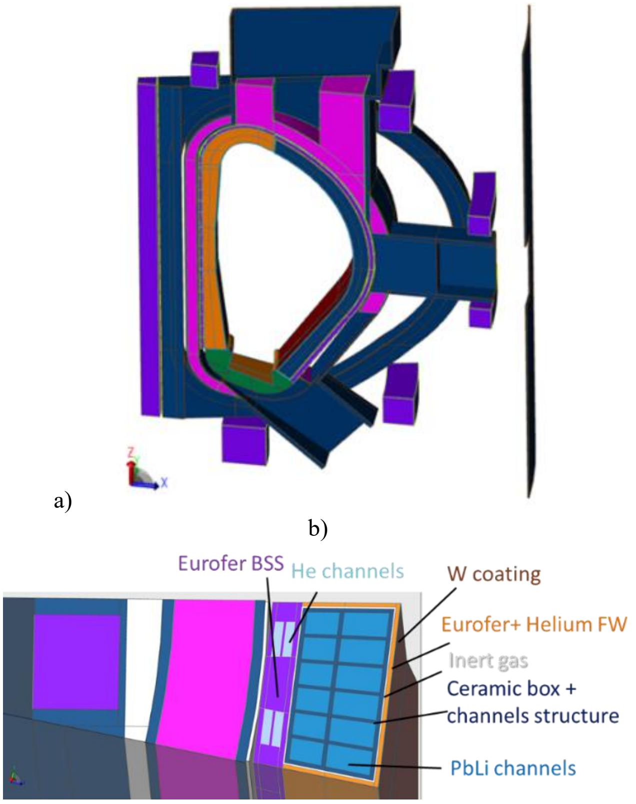


Figure. 1. HT SMS DCLL BB neutronic model: a) SMS architecture, b) internal detailed structure

In the previous LT MMS DCLL BB concept, the adopted FCIs consisted of electrically insulating (ceramic) tubes floating inside the liquid (PbLi) which allowed minimizing magnetohydrodynamic (MHD) effects [11]. Differently from the FCI concept, the ceramic structure of the HT-SMS design eliminates completely the contact between the liquid metal and the Eurofer structure. This implies that the limit in the operational temperature imposed by creep in Reduced-Activation Ferritic-Martensitic (RAFM) steels can be surpassed by the use of the ceramic. Furthermore, the PbLi and the magnetic field are decoupled by the use of an electrically resistive ceramic material reducing the electromagnetic loads acting on the fluid and resulting in lower pressure drops.

However, this line entails relevant challenges linked to the behaviour of brittle materials and obliges to develop ceramic-metallic pipe connections. Furthermore, there are not too many ceramics that combine good mechanical and electrical properties with a desirable low-activation behaviour. For that and considering the huge amount of the ceramic as main structure instead than as a thin FCI, a preliminary selection and radiological characterization of different materials for the DCLL structure has been carried out.

3.2 Ceramic selection under maintenance operations and waste management point of view

A preparatory assessment has been done for ideal "pure" ceramics in order to perform a preliminary selection of the structural material. 17 tentative ceramics have been preliminarily elected according to their generic thermo-physic properties as well as their general mechanic behaviour. For them, the main radiological magnitudes decay heat (DH) per unit volume, contact dose rate (CDR) and specific activity (ACT) have been studied to characterize them in terms of kind of maintenance operations and waste management. The contact dose rate is a magnitude established by international convention for comparative purposes. It is the dose rate that would be experienced at the surface of a semi-infinite slab of a certain material. Therefore, it does not take into account the volume/mass of the element/material used.

The chemical species considered and their formulas are: Al_2O_3, SiC, ZrO_2, Si_3N_4, TiC, ZrC, TiZrC, TiB_2, $TiZrB_2$, $MgAl_2O_4$, AlON, SiAlON, AlN, B_4C, Al_4+2xSi_2-2xO_{10}-x (x~0.4) (mullite), SiO_2 (fused Silica) and MACOR (MACOR is made up of fluorphlogopite mica in a borosilicate glass matrix. Its composition is roughly: 46% silica (SiO_2), 17% magnesium oxide (MgO), 16% aluminium oxide (Al_2O_3), 10% potassium oxide (K_2O), 7% boron trioxide (B_2O_3), 4% fluorine (F)).

From this extensive list, the main constituents have been extracted and assessed individually (Table 3), to observe which one should be avoided/ is not recommended/ or is a viable solution under the activation point of view. These are: B, C, N, O, Mg, Al, Si, Ti, and Zr. To this list, for comparison with previous analysed BB components, the following elements/compounds have been added: Pb, as main radio-activatable component of PbLi, and Fe, Cr, Mn, V, as important EUROFER components.

Apart from C and Si individually, SiC on the whole has been also analysed as typical structural component in the fusion facilities conceptual design and as the most promising ceramic material under neutronic/activation potentials. Vanadium (in addition to being a EUROFER element) is also another typical structural component analysed in past concepts for fusion reactors. Moreover, Ag and Nb are given for comparison as known undesired elements.

The results of the Decay Heat (in W/cm^3), Contact Dose Rate (in Sv/h) and Specific Activity (in Bq/g), are shown in Figures 2a, b and c, respectively, giving values along all the cooling times, and in comparison with the limits established following the IAEA/SEAFP-2 standards and the specific regulation of El Cabril. A summary of the results at 100 years for the Specific Activity and at 50 years for Decay Heat and Contact Dose Rate is given in Table 3.

Table 3. Colour classification of the elements of the 17 ceramics according to different activation parameters and in comparison with applied limits

isotope/ mat. / LIMIT		ACT (Bq/g) at 100 y	CDR (Sv/h) at 50 y		DH (W/cm^3) at 50 y	
(1)	**(2)**				**H/LILW**	**2.00E-03**
Nb	Nb	1.93E+08	Ag	3.63E+01	Ag	2.99E-04
N		1.07E+08	Nb	8.05E+00	Nb	1.11E-04
Ag		1.05E+08	**H/M**	2.00E-02	**CRM**	**1.00E-05**
B		3.35E+07	Al	9.52E-03	B	1.19E-06
Al		3.29E+05	Al_2O_3	4.97E-03	N	1.13E-06
Al_2O_3		2.08E+05	**M/L**	2.00E-03	**SRM**	**1.00E-06**
Zr		1.15E+05	Zr	4.30E-04	Zr	9.04E-08
ZrO_2		1.04E+05	SiC_1	3.77E-04	ZrO2	5.93E-08
O		7.28E+04	ZrO_2	1.59E-04	Al	3.03E-08
Mn		5.84E+04	SiC_2	3.63E-05	Al2O3	2.46E-08
TiC_3		4.93E+04	Fe	2.43E-05	TiC_3	7.74E-09
El Cabril L1/2		**3.70E+04**	Pb	9.14E-06	Mn	6.56E-09
SiC_1	SiC_1	3.49E+04	TiC_3	7.54E-06	SiC_1	1.69E-09
C	C	3.12E+04	Ti	6.55E-06	C	8.96E-10
Mg		2.08E+04	TiC	4.95E-06	O	8.45E-10
SiC_2	SiC_2	1.24E+04	B	2.29E-06	Fe	8.18E-10
UK LLW		**1.20E+04**	Si	5.25E-07	SiC_2	5.63E-10
SiC	SiC	1.13E+04	SiC	3.71E-07	Mg	5.45E-10
TiC	TiC	6.61E+03	Mg	1.36E-07	TiC	5.05E-10
Fe	Fe	3.79E+03	C	1.41E-08	SiC	4.78E-10
V	V	2.85E+03	Mn	7.08E-09	Pb	4.10E-10
Si	Si	2.82E+03	N	1.82E-09	V	2.64E-10
Pb	Pb	2.22E+03	O	8.21E-11	Ti	1.29E-10
Cr	Cr	7.43E+02	V	6.27E-11	Si	1.00E-10
Ti	Ti	4.42E+02	Cr	9.40E-13	Cr	8.09E-11

The classification (1) changes to (2) when the specific ACT limits for each isotope are also verified.

According to the results, and considering especially the values reached at 50 and 100 years for the single elements, a colour classification (Table 4) of the above mentioned ceramics has been created with reference to the international standards and in comparison with the Eurofer classification [10][11] of the composition [26] considered for the traditional structure of the LT DCLL.

Table 4. Colour classification of the 17 ceramics according to different activation parameters and in comparison with Eurofer [10] [26]

Activation Parameter	**Al_2O_3**	**$MgAl_2O_4$**	**ZrO_2**	**AlON**	**SiAlON**	**SiO_2**
DH						
CDR						
ACT						
	B_4C	**TiC**	**ZrC**	**SiC**	**TiZrC**	**Mullite***
DH						
CDR						
ACT						
	AlN	**Si_3N_4**	**TiB_2**	**$TiZrB_2$**	**MACOR****	*EUROFER*
DH						
CDR						
ACT						

*Mullite: Al_4+2xSi_2-2xO_{10}-x (x~0.4) **MACOR is fluorphlogopite mica in a borosilicate glass matrix. Composition roughly: 46% silica (SiO_2), 17% magnesium oxide (MgO), 16% aluminium oxide (Al_2O_3), 10% potassium oxide (K_2O), 7% boron trioxide (B_2O_3), 4% fluorine (F)

The adopted colour classification means:
for DH: green = SRM (LLW), yellow = CRM (MLW), red = PDW (HLW);
for CDR: green = LLW, yellow = MLW, red = HLW;
for ACT: green = VLLW or L1 LILW El Cabril, yellow = L1 LILW El Cabril under specific limits verification, orange = L2 LILW El Cabril under specific limits

verification, red = deep geological repository. In Table 3 the classification (1) changes to (2) when the specific activity limits for each isotope are also verified.

According to the Decay Heat results shown in Figure 2a and Table 3 no one of the selected ceramic elements would be High Level Waste, since all remain below the Low and Intermediate Level Waste (LILW) limit. Most of them would accomplish the limit of 1 W/m^3 of Simple Recycle Materials with the exception of B and N which would be Complex Recycle Materials until 50 years. For this reason, the ceramics with B and N have been rated in yellow in the classification by colours. The rest are classified as green.

Regarding the results of CDR in Figure 2b and Table 3 it is possible to observe that again no one is categorized as High Level, and most of the ceramic elements would fulfil the limit of Low Level Waste, 2 mSv/h, already after 20 years, with the exception of Al. In fact, Al (and thus, Al_2O_3) would be categorized as Medium Level Waste, being the values higher than 2 mSv/h but lower than 20 mSv/h. For this reason, all the Al-based ceramics have been categorized as yellow in Table 4 and the rest in green.

Lastly, considering the results of Specific Activity of Figure 2c and Table 3 and taking into account the classification of El Cabril, it results that:

B, N, Al, Al_2O_3, O, and Zr would reach higher total β-γ activities than El Cabril Level 1 (3.7E+04 Bq/g) and could enter in El Cabril Level 2 (column 1 of Table 3) if the specific activation of some isotopes would be confirmed to be under specific limits;

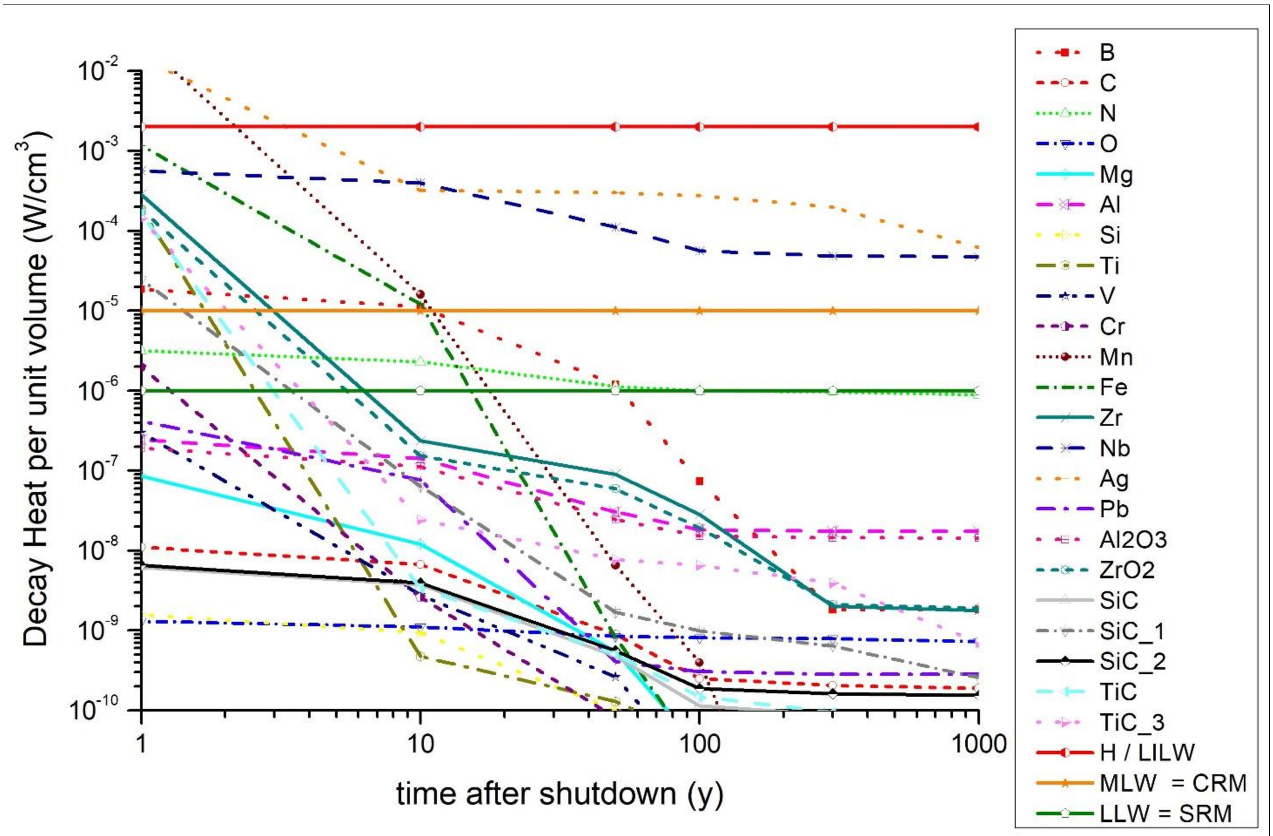
C, SiC, Si, Ti and Mg have lower activity than 3.7E+04 Bq/g after 100 years entering in El Cabril Level 1 column 1 of Table 3) if the specific activation of some isotopes would be confirmed to be under specific limits. This will be examined in Section 3.3 and the updated classification would be the corresponding to column (2) of Table 3.

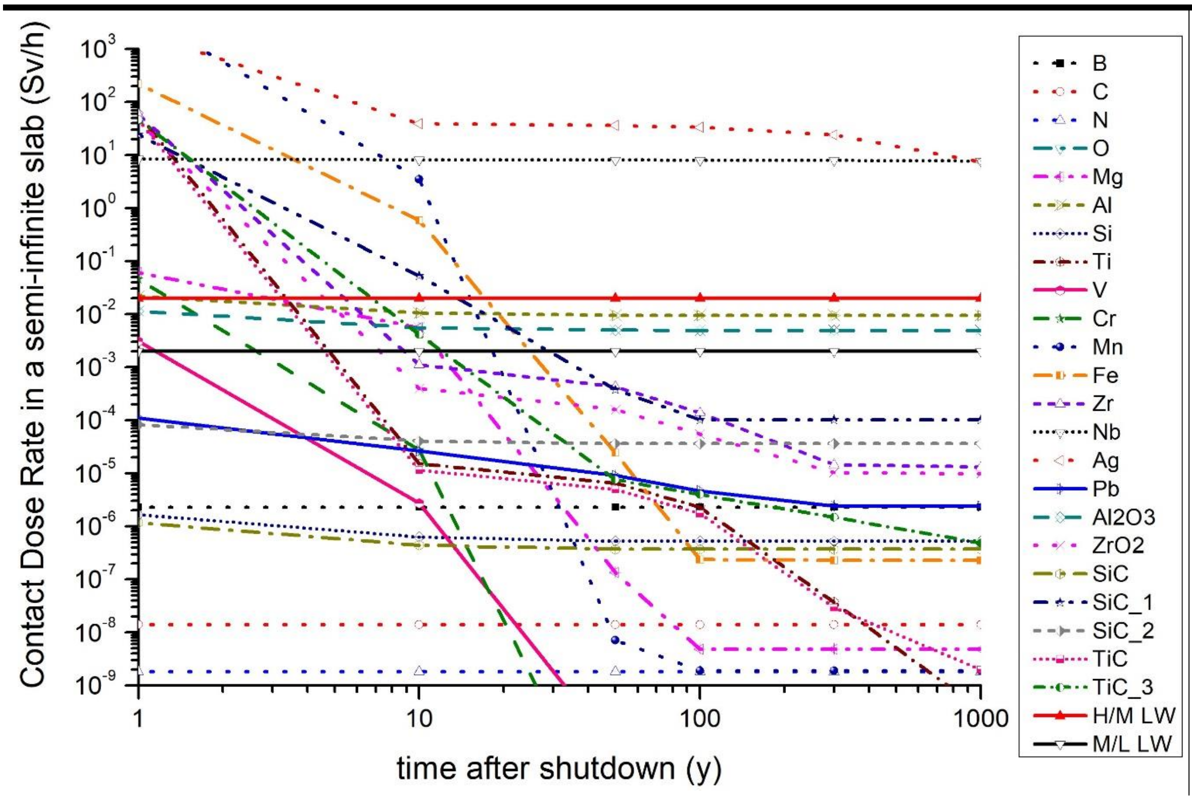
For this reason, the ceramics containing the first elements would follow in orange, the second in yellow. There is not a “green ceramic” in this sense, since it has to be confirmed by the specific activation of some isotopes.

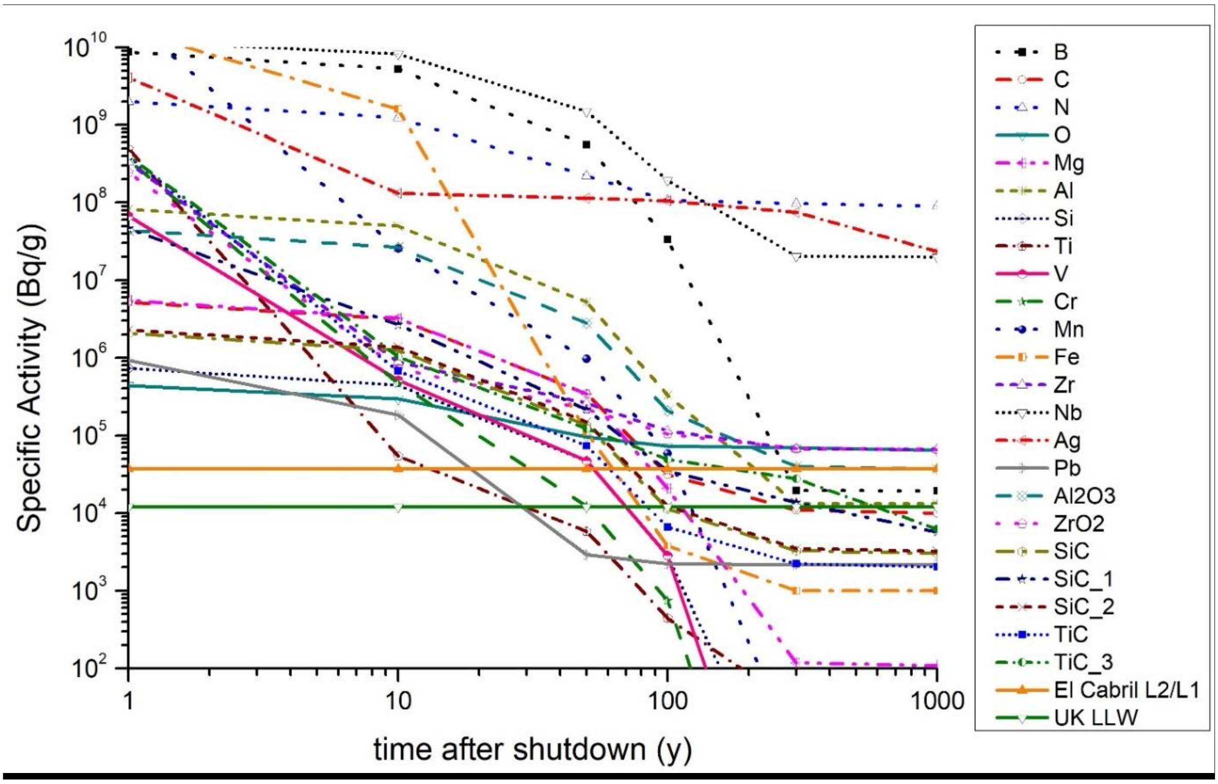
As a result of the categorization provided for each one of the three analysed responses, it can be observed in Table 4 that the pure alumina (Al_2O_3) considered for thin FCI, is not the preferred option for structural ceramic due to high CDR (yellow) which made that this cannot be considered as LLW. Some ceramics oxides (ZrO_2 and SiO_2) and carbides (ZrC and TiZrC) shows a similar radiological classification than Eurofer (LLW according to DH and CDR (green) and El Cabril L2 (orange) according to specific activity results) although their mechanical behaviour is not well known. For future assessments, zirconia (ZrO_2) and Yttria-Stabilized Zirconia (YSZ) will be kept as an option since they show good resistivity. Nonetheless, further corroborations on industrial compositions has to be done to determine if the impurities, dopants and additives could modify drastically its waste classification.

According to the table, pure SiC and TiC are the most favourable ones since they would be accepted in Level 1 LILW (yellow) if the specific limits for certain nuclides is also confirmed to be under the limits and, furthermore, are categorized as LLW under DH and CDR (green) SEAFP-2 criteria.

Having more expectative by the use of SiC, and also considering past studies for fusion reactor designs, such material has been selected as the first option for the development of a HT SMS DCLL BB design and for exploring its viability according to its neutronic behaviour among others [25][7]. In fact, SiC and SiCf/SiC composites (SiC fibres embedded in a SiC matrix) have been widely studied and used in nuclear industry [27][28][29] and are among the most promising low-activation structural materials options in the R&D DEMO programs [30]. They have been already considered for blanket structural material due to their potential to increase the thermal efficiency in “advanced concepts” as the self-cooled LiPb BB concept [18][31].


Decay Heat per unit volume (W/cm3)
time after shutdown (y)
B
C
N
O
Mg
Al
Si
Ti
V
Cr
Mn
Fe
Zr
Nb
Ag
Pb
Al2O3
ZrO2
SiC
SiC_1
SiC_2
TiC
TiC_3
H / LILW
MLW = CRM
LLW = SRM
a)


Contact Dose Rate in a semi-infinite slab (Sv/h)
time after shutdown (y)
B
C
N
O
Mg
Al
Si
Ti
V
Cr
Mn
Fe
Zr
Nb
Ag
Pb
Al2O3
ZrO2
SiC
SiC_1
SiC_2
TiC
TiC_3
H/M LW
M/L LW
b)



c)

Figure. 2. Decay heat (a), contact dose rate (b) and specific activity (c) for main elements and ceramic compositions in comparison with international standards and limits

3.3 Radwaste classification for selected pure and industrial ceramic compositions

For the most promising ceramics, the carbides SiC and TiC, 3 industrial compositions (Table 5) have been analysed: SiC_1 is a porous SiC (at 50% porosity) fabricated by gel-casting technique at the CEIT Basque Research and Technology Alliance (BRTA); SiC_2 is a Si_SiC material fabricated by extrusion at Ceramic Powders S.L. and TiC_3 is a TiC fabricated by Neyco Vacuum & Materials.

Regarding the total specific activity (Table 3, Figure 2c and, in detailed view, in Figure 3), according to El Cabril limits (Table 2) the industrial composition TiC_3 overpasses the total limit of Level 1 (being 4.93E+04 Bq/g at 100 y) and it should be managed in Level 2 if it is confirmed by further analyses of specific limits for certain nuclides. SiC_1 and SiC_2 could be still managed in L1 if it is confirmed by the specific isotopes limits. The other responses (decay heat and contact dose rate, Figure 2a-b) although higher for the industrial compositions than for the theoretical ones does not alter the classification of TiC and SiC as LLW.

By the way, if the UK regulation for LLW classification would be applied (($\beta+\gamma$) activity < 1.2E+04 Bq/g) [32] only the pure compositions for TiC and SiC would be classified as LLW. This implies that different criteria may change the effectiveness of a waste mitigation strategy and some effort at European level should be done to establish common repositories procedures (fusion oriented) and settle common criteria to follow in the analyses.

Table 5. Industrial compositions with impurities for SiC and TiC

SiC_1	**wt %**	**SiC_2**	**wt %**
C	29.243	C	27.630
O	1.7000	O	0.6200
Al	1.1000	Al	0.3900
Si	67.000	Si	71.360
S	0.0065	density	3 g/cm^3
Cl	0.0060	**TiC_3**	**wt %**
Ca	0.0230	C	20.0587
Ti	0.0120	Na	0.00358
V	0.0090	Al	0.003
Fe	0.0450	Si	0.001
Ni	0.0220	K	0.00236
Cu	0.0024	Ca	0.00872
Y	0.8300	Ti	79.90403
Zr	0.0013	Fe	0.01859
density	1.75 g/cm^3	density	4.29 g/cm^3

Regarding the specific limits for certain nuclides established in the El Cabril regulation, it can be observed (Table 6) that although the total activity for SiC compositions stays under the limit for L1, this is not true for H3, C14 and Ni63 specific limits.

To dispose pure SiC and SiC_2 in L1 a detritiation process is required, otherwise they should be disposed in L2. For TiC pure composition, it is confirmed that could be disposed in L1, while industrial composition TiC_3 overpasses the total (due to Ar39 production) and should be disposed in L2.

Table 6. Ceramic classifications following El Cabril limits [24] for Specific Activity (total and per nuclide)

material	element	Bq/g at 100 y	limit L1	limit L2
SiC_pure	*H3*	7.97E+03	7.40E+03	1.00E+06
	C14	3.31E+03	3.70E+03	2.00E+05
	NA22	5.47E-12	2.00E+04	
	TOTAL	**1.13E+04**	3.70E+04	
SiC_1	*H3*	1.13E+04	7.40E+03	1.00E+06
	C14	4.45E+03	3.70E+03	2.00E+05
	NA22	9.01E-10	2.00E+04	
	MN54	6.43E-30	3.70E+04	
	FE55	9.81E-05	3.70E+04	
	CO60	5.80E-01	3.70E+03	5.00E+07
	NI59	2.54E+02	3.70E+03	6.30E+04
	NI63	6.53E+03	3.70E+03	1.20E+07
	SR90	1.29E+00	3.70E+03	9.10E+04
	ZR93	4.35E-01	2.60E+03	
	NB94	4.23E-04	1.20E+02	1.20E+02
	MO93	5.62E-06	3.70E+02	
	TC99	9.40E-08	1.00E+03	1.00E+03
	RU106	8.06E-58	9.00E+03	
	PD107	2.31E-34	3.70E+03	
	TOTAL	**3.49E+04**	**3.70E+04**	
SiC_2	*H3*	8.79E+03	7.40E+03	1.00E+06
	C14	3.50E+03	3.70E+03	2.00E+05
	NA22	3.23E-10	2.00E+04	
	TOTAL	**1.24E+04**	**3.70E+04**	
TiC_pure	H3	4.29E+03	7.40E+03	1.00E+06
	C14	2.22E+03	3.70E+03	2.00E+05
	TOTAL	**6.61E+03**	**3.70E+04**	
TiC_3	H3	4.33E+03	7.40E+03	1.00E+06
	C14	2.22E+03	3.70E+03	2.00E+05
	NA22	2.89E-07	2.00E+04	
	MN54	2.65E-30	3.70E+04	
	FE55	3.72E-05	3.70E+04	
	CO60	2.60E-06	3.70E+03	5.00E+07
	NI59	2.14E-09	3.70E+03	6.30E+04
	NI63	2.21E-14	3.70E+03	1.20E+07
	TOTAL	**4.93E+04**	**3.70E+04**	
Al_2O_3_pure	*H3*	1.68E+05	7.40E+03	1.00E+06
	C14	3.36E+04	3.70E+03	2.00E+05
	NA22	4.31E-08	2.00E+04	
	TOTAL	**2.08E+05**	**3.70E+04**	
ZrO_2_pure	H3	2.41E+03	7.40E+03	1.00E+06
	C14	1.85E+04	3.70E+03	2.00E+05
	SR90	1.70E+04	3.70E+03	9.10E+04
	ZR93	2.48E+04	2.60E+03	
	NB94	2.41E+01	1.20E+02	1.20E+02
	TC99	5.35E-03	1.00E+03	1.00E+03
	TOTAL	**1.04E+05**	**3.70E+04**	

For a comprehensive comparison, pure alumina and zirconia has been also examined. They should be disposed in the El Cabril LILW L2. Regarding alumina, considered in the past for thin FCI, industrial composition with impurities have been not analysed since the most critical response, the CDR (Figure 2b) is dominated by the indented element Al26 (being ~5 mSv/h at 50 y and practically constant up to the end of the cooling times) [11]. For that, the alumina would be considered as a Complex Recycle Material (CRM) and a Medium Level Waste. As the impurities found in some industrial compositions (Mg, C) seems to be less problematic than the main constituent (Al), no further studies have been performed to identify possible increase in the activation caused by impurities.

Otherwise, regarding zirconia, further work is ongoing to determine the behaviour of industrial compositions with impurities since pure zirconia is a promising option from the structural, electrical and activation levels. Doped zirconia materials as Yttria-Stabilized Zirconia (YSZ) or calcia-, magnesia-, ceria- or hafnia-stabilized zirconias, will be also considered.

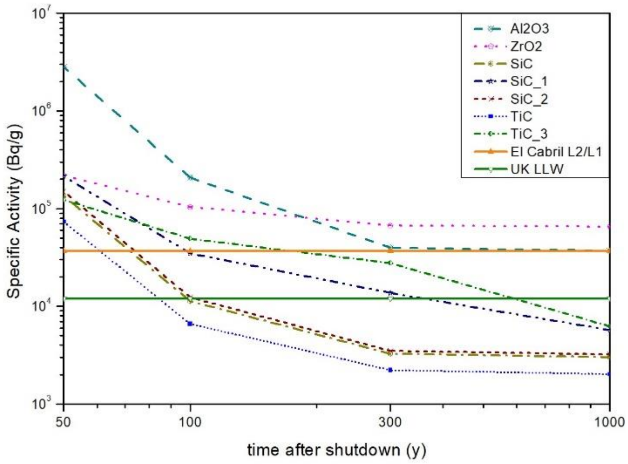


Figure. 3. Specific Activity for SiC and TiC pure and industrial compositions in comparison with the Spanish near-surface repository El Cabril and UK LLW classification rules. Zirconia and alumina results are also displayed for comparison.

4. Conclusions

Activation analyses have been performed to support an improved novel High Temperature Single Module Segment (HT SMS) design of a DCLL breeding blanket concept for the pulsed European DEMO reactor. For such design in depth analyses of the radwaste generated from the structural/functional material have been performed pursuing the mitigation of its radiological impact. The aim is that such waste could be categorized as Low Level Waste (LLW) since 100 years from shutdown and also disposed in the Spanish near-surface repository of El Cabril, being a crucial achievement for the viability, acceptability and competitively of fusion technology.

A selection of the ceramic material, which partially substitutes the Eurofer structure considered in the previous 'traditional' LT MMS DCLL in order to go to higher temperature and heat conversion efficiencies, has been performed. The 17 preliminary selected theoretical (pure) ceramics compositions have been classified in terms of kind of maintenance operations and waste management.

Due to the high CDR, alumina (Al_2O_3) considered for thin FCI in the LT MMS DCLL BB, is not the preferred option for a huge amount of structural ceramic inside the HT MMS DCLL BB since it would be not categorized as LLW. Pure zirconia (ZrO_2) shows a similar radiological categorization than Eurofer (LLW and L2 under impurity control) so further studies on industrial compositions will be considered in the future.

According to El Cabril regulation, pure SiC and TiC would be the best options since they would be accepted in Level 1 LILW (under detritiation for SiC), but this could be not true for industrial compositions with impurities (L2), nor according to other standards. If the UK regulation for LLW classification would be applied only the pure compositions for TiC and SiC would be classified as LLW.

Similarly, it has been observed in the past that, for Eurofer, Nb reduction is required under Spanish/French repositories regulations [10] while decarburization is required according to UK ones [32]. Hence, it become urgent to establish common repositories protocols. An effort at European level should be done to establish fusion oriented repositories set-ups and to settle common criteria to follow in the analyses until a site for the European DEMO reactor has been established. Different criteria may change the effectiveness of a waste mitigation strategy.

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