ARC reactor materials: activation analysis and optimization

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Nowadays, Fusion Energy is one of the most important sources under study. During the last years, different designs of fusion reactors were considered. At the MIT, an innovative design was created: ARC, the Affordable Robust Compact reactor. It takes advantage of the innovative aspects of recent progress in fusion technology, such as high temperature superconductors, that permit to decrease the dimensions of the machine, reaching at the same time high magnetic fields. Our main goal is the low-activation analysis of possible structural materials for the vacuum vessel, which is designed as a single-piece placed between the first-wall and the tank that contains the breeding blanket. Due to its position, the vacuum vessel is subject to high neutron flux, which can activate it and cause the reduction of the component lifetime and decommissioning problems. The activation analysis was done also for the liquid breeder FLiBe, compared with Lithium-Lead. Codes used for the low-activation analysis were MCNP and FISPACT-II. The first one is based on a neutronics model and for each component a certain neutron flux is evaluated. For FISPACT-II, the main input is the composition of the analyzed material, the neutron flux and the irradiation time. Results from FISPACT-II are the time behavior of specific activity, contact dose rate. To assess suitable structural materials for the vacuum vessel, low-activation properties were considered. Vanadium alloys turn out to be one of the best alternatives to the present material, Inconel-718. Finally, isotopic tailoring and elemental substitution methods were applied. Here, the composition of each alloy is analyzed and critical isotopes or elements are eliminated or reduced. After the modifications, new simulations are done, and those leading to significant improvements in the final results are highlighted.

Keywords: ARC, activation analysis, vacuum vessel, FISPACT-II, V-15Cr-5Ti, FLiBe

1. Introduction

In the energy framework, fusion energy is a fundamental source. A worldwide-shared project is under construction: ITER [1]. In the meantime, an innovative fusion reactor design is under investigation at MIT [2]: ARC, the Affordable Robust Compact reactor. The ARC machine needs careful evaluations of its materials, seeing as how it has a high power density and thus a fairly intense average neutron flux and heat loads on the inner core. In fact, ARC is supposed to generate 525 MW of fusion power on a machine that is a fraction the size of other fusion reactor of similar power (e.g. ITER [1]). The choice of materials for a tokamak is one of the most complex aspects in the reactor design. A nuclear fusion core has to deal with structural, thermal, chemical, magnetic and nuclear issues.

The use of innovative and advanced materials is one of the distinctive characteristics of the ARC design [3][4][5][6][7][8]. While the choice of superconductive materials and magnet components is determined as indicated in [2], some optimization process is conceivable for the vessel and blanket materials.

The main goal of this study is the analysis of possible structural materials for the vacuum vessel, which is designed as a single-piece placed between the first-wall and the tank that holds the breeding blanket. Due to its position, the vessel is subject to high neutron flux, which can cause the reduction of the component lifetime [5] and decommissioning problems [7]. Therefore, neutron-induced radioactivity is one of the critical parameters that has to be taken into account. The activation analysis was done for the liquid breeder FLiBe too, compared with Lithium-Lead for reference: the role of impurities, in both cases, will be put into evidence.

The codes used for the low-activation assessment were MCNP and FISPACT-II. The first one, once set up the neutronic model of the reactor, is able to evaluate the neutron flux in each component [9]. This model has been validated and compared with the reference neutronic model for the ARC machine [8] and it turned out to be consistent with it. For FISPACT-II, the main input is the composition of the analyzed material, the neutron flux and energy spectrum and the irradiation time [10]. Results of main interest for the purpose of this work are the time behavior of specific activity and contact dose rate. To choose the best structural material for the vacuum vessel, both mechanical and low-activation properties [7][11][12][13][14][15][16][17][18][19] have to be considered.

2. Description of the model

2.1 Brief description of ARC

The main components that characterize the design of ARC are shown in Fig. 1 and here listed:

The Vacuum Vessel (VV) is a single-piece and double-walled component with the shape of a torus. It is placed between the first-wall and the tank with the breeding blanket and it has a channel between the two structural walls for the flowing of the liquid coolant. Its original structural material is Inconel-718, which is a Ni-based alloy, with high strength and corrosion resistance at high temperature. Nickel makes the vacuum vessel prone to nuclear activation [7], which is a problem, especially for the final disposal of the component. Beryllium layer is present as neutron multiplier to obtain tritium production self-sufficiency [2][8].

The First-Wall (FW) is made with W and it is placed in the inner part of the VV: it faces the plasma's chamber. The VV is subject to high thermo-mechanical loads and neutron fluxes, which cause a faster deterioration of the material. VV and FW could be subject to plasma disruptions, so in order to avoid problems to the entire structure of the reactor it is designed as an independent component, that can be replaced without damages to other permanent modules [2][8]. **The Divertor** is an integrated component of the vessel and it is a solution for avoiding plasma-wall interactions phenomena.

The Blanket is important for its breeding function and in ARC a molten salt was chosen, satisfying both the breeding and cooling functions for the reactor. An innovative aspect of ARC's design is the presence of a liquid immersion blanket [2][8], where the percentage of solid materials is reduced and the tank is a sort of pool full of FLiBe that surrounds the entire vacuum vessel (Fig.2). Tritium breeding ratio (TBR) must be greater than one, to sustain the entire tritium reaction cycle, in particular for ARC a TBR 1.08 [8] was considered in its design. **The Cooling system** is designed with flow channels in the double-walled vacuum vessel.

The Superconductor magnets are extremely important for the stability and confinement of the plasma. For ARC the selected material is Rare Earth Barium Copper Oxide (REBCO), a high temperature superconductor that can work at temperature up to 80 K [4], which is higher than the one for Nb3Sn used for ITER (i.e. 4 K) [1].

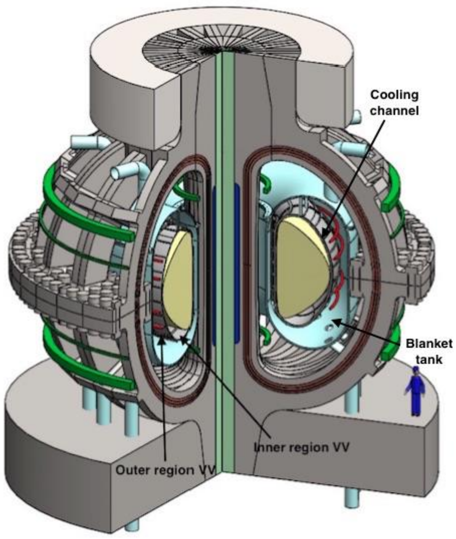


Figure 1: ARC's regions used for the activation analysis [2].

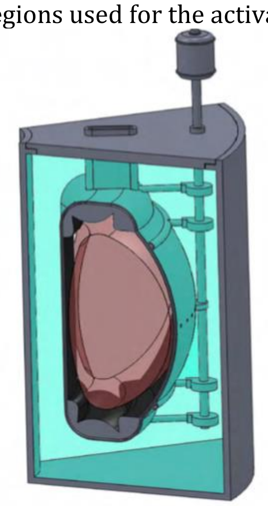


Figure 2: Schematic structure of the liquid immersion blanket [2].

2.2 Long-term classification criteria

Neutron-induced radioactivity in D-T fusion structural materials can be only avoided through the selection of specific alloys that permit to reduce it. Before starting the description of the activation analysis, let's see the considered low-activation criteria that were taken into consideration for this study: Clearance, Recycling or Shallow Land Burial as Low–Level Waste (LLW) [11][12][13][14][15][16][17][18][19]. For **Recycling** within the nuclear industry [7], the reference value is 10 μSv/h (HOR – Hands-On Recycling). For Recycling outside the nuclear industry, the limit is 0.1 μSv/h. Both limits should be reached in some tens of years of cooling [11]. The **Clearance Index (CI)** permits to verify if a material contains radioactive species above natural level and, for a non-homogeneous alloy, it is evaluated with the following formula [11][13]:

$$CI = \sum_{i=1}^{\#\ isotopes} \frac{A_i}{L_i} \qquad (1)$$

A_i and L_i are the specific activity [Bq/kg] and the clearance limit for the i-th isotope contained in the material. CI < 1 by 100 years of storage is the limit to classify the material "cleared", i.e., non-radioactive material. **Shallow Land Burial (SLB)** is the criterion used for possible waste final disposal, according to the US regulations and its fusion extensions [11].

2.3 Main material composition

One of the most important inputs for the FISPACT-II model is the material inventory composition. In fact, even the presence of extremely low percentage of unwanted elements, namely impurities, can heavily affect a material's induced radioactivity, as it will be shown in the results. More specifically, if the neutron fluence is high enough, either because of high flux or long irradiation time, a high number of impurities becomes likely to interact with neutrons and get activated. In the low activation alloys case, activated impurities can become preponderant in the long term activity of the component. Hence the chosen alloys have been evaluated in either pure and with impurities cases.

The vessel structure and the liquid blanket are the main concerning components in ARC for this study. For the vessel alloys analysed are Inconel 718, V-15Cr-5Ti and the Eurofer97.

The Inconel 718 composition is reported in Table 1 ([20]). It has been chosen as main vessel structure because of its resilience in high temperature environments. However, it is well known to be an high activation alloy because of the high content of nickel.

V-15Cr-5Ti is mainly composed by vanadium, chromium and titanium and is actually known for its low activation properties, as it will be seen in the result section. Therefore, being its alloying elements low activation, it is likely that main impurities could play an important role on the analysis outcome, even though impurities are supposed to have a chemical concentration 4 to 6 order of magnitudes lower than main alloy elements [21]. Vanadium weight compositions for both pure and with impurities cases are listed in Table 2. Among the displayed impurities, nitrogen is the most likely concerning as it causes the generation of the long lived radioisotope C-14 through the (n, γ) reaction. The downside of vanadium alloys is that further R&D is required. More specifically, technological production and doping against chemically aggressive environment need a further development [22].

Eurofer97 is the third considered alloy for the activation analysis. It is an iron – chromium – tungsten – manganese alloy [23] that has been developed specifically for nuclear application, as it has either good thermo-mechanical properties and low activation properties. Nonetheless, as vanadium alloys Eurofer's activation is highly subjected to its impurities, Table 3 displays the weight percentage composition of such material.

Table 1 Inconel-718 chemical composition by wt% [20].

Element composition	Al	C	Co	Cr	Cu	Fe	Mo	Ti	Nb	Ni
Inconel-718	0.52	0.021	0.11	19.06	0.02	18.15	3.04	0.93	5.08	53.0

Table 2 V-15Cr-5Ti chemical composition by wt% for both pure and with impurities cases [21].

	V	Cr	Ti	N	O	C	Si	Fe
V-15Cr-5Ti pure	80.5	14.5	5	-	-	-	-	-
V-15Cr-5Ti w/ impurities	80.39	14.5	5.0	0.0096	0.033	0.012	0.04	0.02

Table 3: Eurofer97 chemical composition by wt% for both pure and with impurities cases [23].

	Cr	C	W	V	Ta	B	N	O	S	Fe	Mn	P
Eurofer97 pure	9.0	0.11	1.5	0.2	0.07	0.001	0.03	0.01	0.005	88.664	0.4	0.005

Eurofer97 w/ impurities	9.0	0.11	1.5	0.2	0.07	0.001	0.03	0.01	0.005	88.558	0.4	0.005
	Si	Ni	Mo	Ti	Cu	Nb	Al	Co	As	Sn	Zr	Sb
Eurofer97 pure	-	-	-	0.01	-	-	-	-	-	-	-	-
Eurofer97 w/ impurities	0.05	0.005	0.005	0.01	0.005	0.001	0.01	0.005	0.005	0.005	0.005	0.005

An analogous impurities study have been made for the liquid blanket proposed materials. FLiBe, which actually is 2LiF –BeF_2, has chromium, iron, nickel, copper, molybdenum and tungsten as most likely impurities [24]. In Table 4, FLiBE weight compositions for both pure and with impurities cases are listed. While, PbLi (83Pb-17Li) has been modeled with very low percentages of bismuth, cadmium, silver, nickel, tin, iron and zinc [25] (Table 5).

Table 4: FLiBe chemical composition by wt% for both pure and with impurities cases [24].

	F	Li	Be	Fe	Cr	W	Ni	Mo	Cu	Na	Mg	Al	K	Ca
FLiBe pure	76.79	14.12	9.09	-	-	-	-	-	-	-	-	-	-	-
FLiBe w/ impurities	76.79	14.1	9.0	0.0004	0.0003	-	0.0001	-	-	0.089	0.018	0.0033	-	-

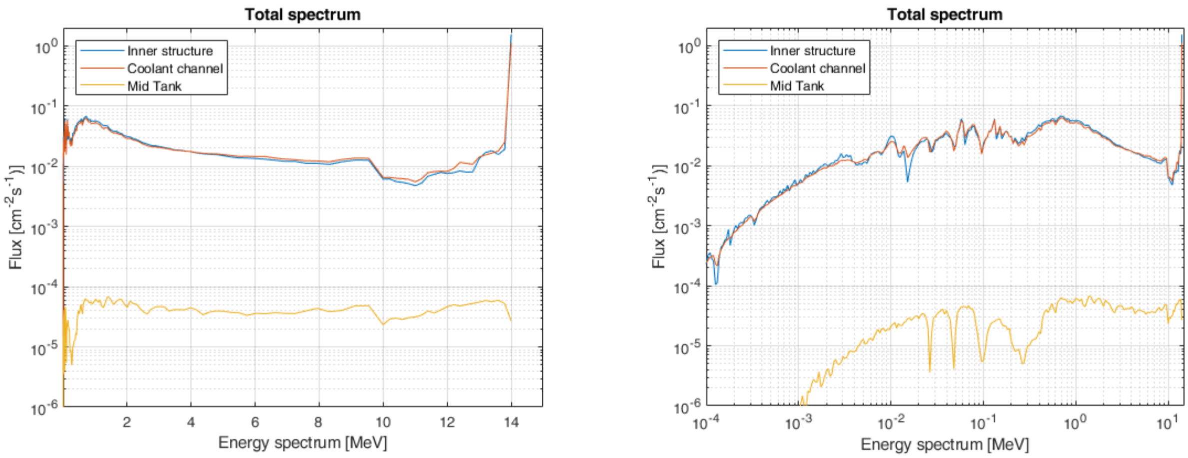
Table 5: PbLi chemical composition by wt% for both pure and with impurities cases [25].

	Pb	Li	Bi	Cd	Ag	Ni	Sn	Fe	Zn
PbLi pure	99.31	0.69	-	-	-	-	-	-	-
PbLi w/ impurities	99.2925	0.7	0.0043	0.0005	0.0005	0.0002	0.0005	0.001	0.001

3. Results of the neutronic model

The MCNP code [9] permits to evaluate the neutron flux, defined as [n/cm^2 s] in different regions of the reactor. ENDFB-VII has been used for the analysis while for the spectrum output the CCFE-709 energy group has been imposed in order to be applied as input for the FISPACT-II analysis [7][10]. Taking advantage of the ARC core's simplicity, made of a few layers of vacuum vessel and then an homogeneous bulk FLiBe tank [2][8], a cylindrical model that implements the same type of layers have been developed. The model has been subsequently validated on the basis of fluxes, energy deposition and TBR against the main ARC's neutronics model [8][26]. For the purpose of this study a cell tally measuring the scalar flux on the vessel and the FLiBe regions have been applied. 5e+7 random walks have been generated, for the computational time of 8 h/CPU and a maximum relative error on the fluxes of 0.001.

An example of the results is available in Figure 3, where neutron spectrum, normalized on one n/s source, at the inner region of the vessel structure is shown, compared with the same parameter for the FliBe blanket between the two vessel's walls and at the radial midpoint of the bulk blanket tank. It can be verified that the fast energy component is still predominant in the vessel structure, while scattered neutrons with lower energy are more relevant in the FLiBe region.



(a) (b)

Figure 3: Neutron flux normalized on the neutron source and spread over the spectrum for three different core region: the inner vessel structure right behind the first wall (blue line), the cooling channel between the two walls (orange line) and the middle of the tank (yellow line). Plotted in both semilog (a) and loglog (b) scale.

Final results for the average neutron flux are 7.54E+014 [neutrons/cm^2 s] for the inner region of vacuum vessel, which is close to the plasma, and 5.02E+014 [neutrons/cm^2 s] for the region near the tank that contains the breeding blanket. In addition, FISPACT requires the irradiation time. For structural integrity reasons, the component is foreseen to be replaced every 2 years [2][5]. As worst case scenario for activation viewpoint, in FISPACT's models a continuous irradiation time of 2 full power years has been set.

4. Results of the activation model

FISPACT-II is an activation code that calculates the specific activity [Bq/kg], contact dose rate [Sv/h], and decay heat [kW/kg] of a material under a certain neutron flux by means of specific cross-section libraries, like the TENDL2017 library, that has been used for this work. The main input data for FISPACT-II are the material composition (including impurities), the neutron flux and the irradiation time [10]. For the latter one, the expected lifetime of the vacuum vessel was considered of 2 years [2], then in order to have a realistic situation a pulsed mode time was used. ARC is supposed to be characterised by long pulses, which could last at least 6 months and the final goal of the design is the achievement of the steady state mode.

Inconel-718 could be the best choice as a structural material for its good thermal-mechanical properties at high temperature [2][8], which is the main reason of its choice as original structural material for ARC. Through the activation analysis it is possible to conclude that it does not respect the low-activation criteria explained before, due to the high presence Nickel, Molybdenum and Niobium, which are high activation elements. In particular (see Figure 4, which is the result of the contact dose evaluations for the candidate materials) a long-term contact dose rate above 1 Sv/h shows the need for a substitution of Inconel-718. Such a high dose rate would imply the need for remote maintenance and operation procedures for ARC, even after long cooling times, in contrast with the ARC approach of fast and relatively easy maintenance and substitution of components. Figure 5 shows the same results in terms of specific activity.

In order to evaluate some alternative solutions, the modification of Inconel-718 composition was considered first. However, it results that Inconel-718 main alloying elements, such as Ni, cannot be neither substituted nor isotopically tailored. Therefore, some alternative candidate materials have to be considered.

The Reduced-Activation Ferritic-Martensitic RAFM steel Eurofer97 was considered, being this alloy the reference material for DEMO [1]. In the ideal case of pure Eurofer, its results are similar to V-alloys ones (discussed below), reaching the reacycling limits within about a century of cooling time. However, the unavoidable presence of impurities cause such material to stabilize its contact dose rate at more than one order of magnitude higher than the hands-on recycling limit. This is mainly caused by Nb, Co and Mn radioactive isotopes. After these results, isotopic tailoring was applied to Eurofer's main alloying elements (i.e. Fe, Cr, W) by assuming the application of the lower-activation isotopes for each of the elements. Relevant improvements were found only in the case of the composition without impurities, which reached both the recycling limits, but the clearance limit turned out to be unreachable. However, if the reference level of impurities that is set up for Eurofer-97 for DEMO [1], this material – irradiated in ARC – cannot fulfil the recycling limit due to high long-term dose. Even if a quite important improvement in the long term dose, compared with Inconel-718, is achieved (more than 1000 times lower), in the end Eurofer-97 does not seem an ideal candidate to substitute Inconel-718 as ARC vessel material.

V-15Cr-5Ti is often quoted to be a low-activation alloy, to the presence of main alloying elements with intrinsic low-activation characteristics [14].

Some concern might come from Ti activation, since the activation analysis of this element shows potential problems due to the build-up of Al-26 [14].

However, if we look at the results (Figures 4 and 5), V-Cr-Ti alloy is the material that showed the best results by far, even if the clearance criteria could not be respected: Shallow Land Burial requirement was reached even with the presence of impurities, like Nitrogen, Carbon and Iron [21]. The contact dose rate is characterized by a rapid decrease, and recycling limits are reached after little more than a century of cooling time. On the other hand, Inconel-718 and Eurofer-97 as it can be produced (namely, including impurities) stabilize their contact dose rate well above the recycling limits, getting the curve to a nearly horizontal line.

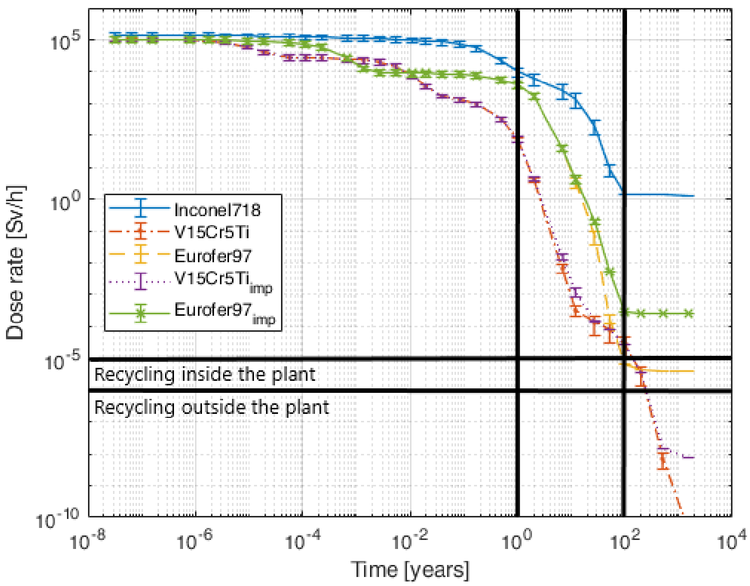


Figure 4: Dose rate: comparison between Inconel-718, V-15Cr-5Ti, and Eurofer97 -in the inner wall of the vacuum vessel, with and without the presence of possible impurities.

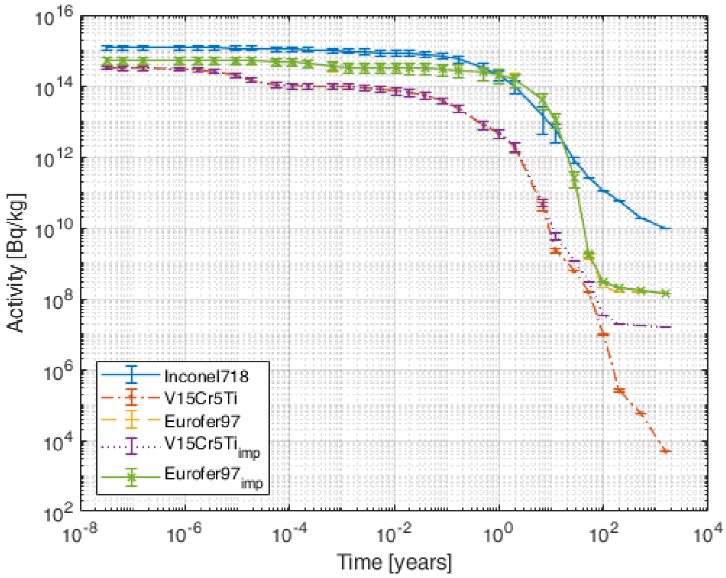


Figure 5: Specific activity: comparison between Inconel-718, V-15Cr-5Ti, and Eurofer97 in the inner wall of the vacuum vessel, with and without the presence of possible impurities.

A similar analysis has been carried out for the coolant flowing in the channels between the vessel's walls. The main choice is FLiBe [2][8]. However, to complete the study also PbLi has been evaluated, as it is the liquid blanket proposed for DEMO [1].

This time, the analysis has been carried out taking into account the realistic exposure of the liquid breeder, which is circulated outside the blanket for tritium extraction and heat exchange with the secondary Brayton cycle [2], before re-entering it.

It is confirmed that the initial choice of FLiBe for ARC was a good one. Figure 6 shows that the contact dose rate of the molten salt, even with the presence of impurities, reaches both recycling limits in less than 1 year after the end of the operation of the reactor. The behavior of Li-Pb is acceptable too, however with higher neutron-induced radioactivity levels. Even though the cost of FLiBe is higher than Lithium-Lead, it permits – due to its lower density - to reduce the weight of solid materials in the breeding tank, reducing the final cost for the design. While evaluations on the breeding performance will have to be considered, as far as activation is concerned we do not see any reason to substitute FLiBe with another liquid breeding material.

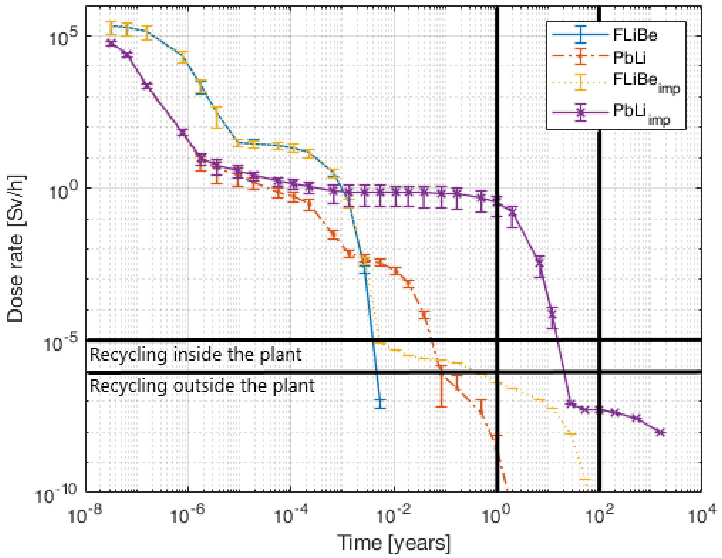


Figure 6: Dose rate: comparison between FLiBe and PbLi in the cooling channel, with and without the presence of possible impurities.

4. Conclusions

The main goal of this study has been a coupled neutronics and activation analysis of possible alternative structural materials for the vacuum vessel. The same investigation has been carried out for the liquid breeder materials in the blanket. ARC reactor is a design of a fusion power reactor: the vacuum vessel will be substituted after about two full-power years, so it needs a material that can support high thermal loads and at the same time it must permit hands-on operation, or at least a simplified remote maintenance equipment. Although the vessel will not be a plant lifelong component, there is the need of particular precision for its fabrication. For instance, according to the results of this work, the material is required to be as pure as possible, since impurities concentration could have a major effect on resulting activity and, therefore, the decision of following management strategies, especially in the low activation alloys.

The results obtained by Inconel-718 as-it-is, as well as through elemental substitution and isotopic tailoring of its main alloying elements (Ni, Fe, Mo, Ti), are not enough to define it as an adequate material as far as its activation is concerned. The presence of nickel element in any of its isotopes is responsible for the increase of long-lived radionuclides by several orders of magnitude, with respect other ferritic or vanadium alloys.

The best alternative for the vacuum vessel is a Vanadium-based alloy: the V-15Cr-5Ti composition has been considered for the activation analysis. Its mechanical properties are enough for the ARC vessel [7], and it is a low activation material [11], since dose rate decays to low enough values such as to permit hands-on operation within a relatively short decay time, and the material recycling outside the nuclear industry within a feasible intermediate storage.

As far as the liquid blanket material is concerned, the initial choice of FLiBe for ARC turned out to be an adequate one even from the neutron-induced radioactivity viewpoint, permitting to fulfill the goal of recycling of the precious molten-salt material.

To summarize, with a correct choice of its structural materials, ARC can become, besides a cheaper, safer and efficient tokamak alternative project, also a low-activation and reduced radioactive inventory reactor, with the perspective of a low environmental impact.

In future works structural soundness of V-alloys for ARC will be evaluated. In addition, irradiation damage will be assessed for all the alloys in order to identify the most suitable in nuclear environments. Further studies will comprehend a more detailed analysis of impurities, including minor impurities, provided by specific material samples for case studies.

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