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Original
ARC reactor – Neutron irradiation analysis / Segantin, S.; Testoni, R.; Zucchetti, M.. - In: FUSION ENGINEERING AND DESIGN. - ISSN 0920-3796. - 159:(2020), p. 111792. [10.1016/j.fusengdes.2020.111792]

Availability:
This version is available at: 11583/2836606 since: 2020-07-01T18:04:43Z

Publisher:
Elsevier Ltd

Published
DOI:10.1016/j.fusengdes.2020.111792

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12 October 2024

ARC reactor - neutron irradiation analysis

Abstract

Neutron irradiation is one of the most concerning issues to design plasma facing components and reactor inner structures in fusion devices, especially for high power density ones, like ARC reactor. This study addresses the main aspects of neutron irradiation on solid materials of ARC reactor. In particular it deeply analizes the effect of neutron induced activation proposing low activation structures, like vanadium alloys and different optimization methods like isotopic tailoring, detritiation and impurity control. Furthermore, irradiation damage issues and their dependence on the energy spectrum are highlighted. It resulted that V-Cr-Ti alloys dramatically reduce the radioactive inventory of ARC with respect to its baseline configuration, which proposes the application of Inconel 718. Such alloy is also optimizable through the tailoring of titanium isotopes and is virtually capable of hitting recycle limits in a couple of decades. Lastly, it shows a relatively growth of gas during irradiation. However, it is highlighted how experiments on neutron damage featuring fission neutrons risk to be able to tell very little about the behavior of the same materials under fusion neutrons, as damaging mechanisms seem to be different.

1. Introduction

Deuterium-tritium (DT) reaction is considered the next step for nuclear fusion machines worldwide. It will be most likely the first nuclear fusion reaction giving energy for the electrical grids. However, one of the main problems that researchers and engineers have to face with DT fusion is that its plasma is a high-density source of fast neutrons. Neutrons cause in fact two main issues. They induce radioactivity on surrounding materials and heavily damage the structure[1][2][3][4][5]. Furthermore, fusion neutron energy is indeed on average one order of magnitude higher than fission neutron one [1][3]. Interaction with matter, especially damage, is expected to be different from fission neutrons effect.

Affordable Robust Compact (ARC) reactor [6][7][8] is a small-modular tokamak proposed by MIT scientists as high-magnetic field tokamak for a pilot plant. It features a high energy density and, it therefore has to deal with the mentioned neutronics-related issues in particular, seeing as how fluxes are expected to be on average higher than other less compact tokamaks [9][10]. A 3-D rendering of the ARC reactor and its main components is displayed in Figure 1.

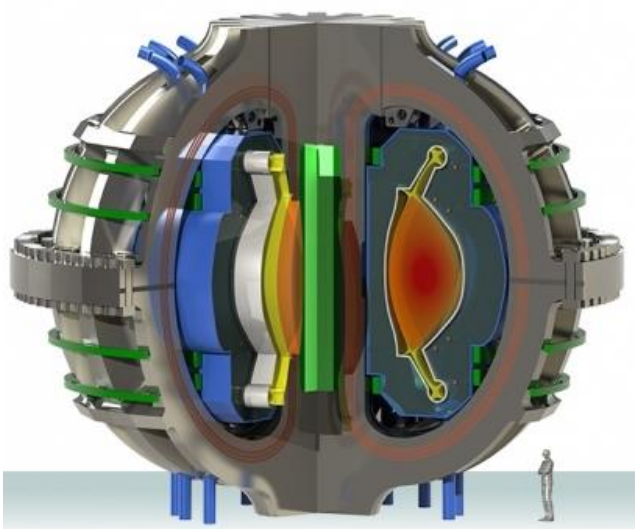


Figure 1: ARC reactor 3-D rendering.

This study focuses on two aspects of neutron interaction with solid materials in ARC-like conditions. First, it evaluates the neutron induced activation. Albeit it is not a crucial aspect for the functioning of the reactor, it is nonetheless an issue of main concern, especially for ARC, which is expected to replace its inner components every two years [6]. Material activation is an aspect that is expected to affect the reactor economics, in terms of decommissioning and radioactive waste management. Moreover, it could affect the public acceptance of this energy source, as activated materials could be associated with the long-lived waste problem of fission. The other aspect related to neutron irradiation of solid material is the damage. This work points out and analyzes the difficulties and limits related to get reliable experimental data that simulate a fusion neutron source, since most common irradiation facilities rely on TRIGA fission reactors having spectra way different from fusion ones.

2. Neutron Induced Activation

This study focuses in particular on ARC vacuum vessel as it is the component that is expected to experience the highest fluxes and to be replaced more frequently, according to preliminary evaluations [6][7][8]. This section will analyze three different configurations proposed for the vessel. The baseline configuration is described in [8] and foresees 1 mm of tungsten, 1 cm of Inconel, 2 cm of flowing FLiBe, 1 cm of beryllium and 3 cm of Inconel 718 (it is here referred as CONF1). Inconel 718 has been proposed in first instance because of its good mechanical properties and chemical resistance at very high temperature [11][12]. The second configuration is proposed in [14][15] and foresees the replacement of Inconel 718 with a V-Cr-Ti alloy as low activation material, it is here referred as CONF2 and implements V-4Cr-4Ti as vanadium alloy as it is also the reference composition for many fusion programs [16][17][18]. The last configuration considered for the vessel activated inventory (CONF3) contemplates the removal of the beryllium layer and optimizes the vanadium alloy by means of isotopic tailoring. The layer of solid beryllium was necessary for multiplying neutrons and achieve a sufficient tritium breeding ratio. Nonetheless, it has been demonstrated that with vanadium structure the tritium breeding ratio reaches satisfactory values even without additional neutron multipliers [14].

Isotopic tailoring, which was applied in CONF 3, is not the only optimization technique for reducing the neutron activation incidence. There are several other strategies, that may also be combined (i.e. detritiation, impurity control and gas removal). Such approach will be also proposed, simulated and discussed in section 2.3. Compositions of simulated materials can be found in [19][20].

In order to evaluate the inventories and the damage this study takes advantage of the FISPACT-II inventory code [13] and simulates ARC hardest conditions, that is 2 full power years with a neutron flux of about 7-8e+14 n/cm2/s. Spectra and fluxes are taken from OpenMC models [14][21][22].

2.1. Proposed limits

Most limits of radioactive waste are related to dose rate values or defined by the inventory of the nuclides and the type and energy of decay. Proposed limit for fusion and, therefore, the goals that the research community seeks for defining low activation machines are based on the radioactivity and dose rate too. Most cited limits are the shallow land burial, the recycling limits and the clearance index, which are described in [15]. The choice and the classification of a low activation material is therefore linked to such limits. Most of the fusion goals refer to satisfying the mentioned limits within 100 years from the plant shut down or component dismissal. This work proposes the limits and the goals that ARC design team seek in order to classify most of its components as low activation. ARC team mainly focuses on recycling limits as they are considered the best achievable and effective option for fusion components.

- Dose rate of 1e-5 Sv/h as reference for recycling in the nuclear industry (here referred as "in-plant recycling"). In the US annual dose limit for workers in the nuclear industry is 20 mSv/y, which equals

to 1e-5 Sv/h, assuming 8 working hours per day and 5 days per week. The limit conservatively assumes a constant contact with the material for the entire working time.

- Dose rate of 1e-6 Sv/h as reference for recycling in other industries (here referred as "out-plant recycling"). 1e-6 Sv/h corresponds to the 1 mSv/y regulatory limit for non-nuclear workers. Again, assuming a contact time limited to normal working hours.
- Dose rate of 1.14e-7 Sv/h as reference to the natural background average dose (1 mSv/y). Assuming a 24/7 contact, this index is the strictest among the contact dose ones. It is not an actual limit, it is here considered for comparison purposes only. For complete recycling regulations there is the clearance index (CI).
- Clearance index (CI) = 1, for clearance and re-use without restrictions.

Table 1 lists the periods of time usually taken by fusion community for accomplishing the limits here considered [23][24][25]. The last column of the table displays the main goals for ARC vacuum vessel after dismissal.

Table 1: Main recycling limits for fusion radioactive waste, with generic goals of the fusion community and ARC team goals in terms of component cooling time before the achievement of the limit.

Limits	Generic goals	ARC goals
In-plant recycling	100 years	10 years
Out-plant recycling	100 years	50 years
Clearance index	100 years	100 yearss

Lastly, it is necessary to acknowledge the reader that there are several other classifications, limits and parameters for irradiated material management (e.g. high/medium/low level waste and relative disposal regulations, shallow land burial limit etc.). Nonetheless, these limits have not been taken into account for the present study as it aims for recycling and even complete clearance rather than dismissal and disposal. Furthermore, if the vessel can accomplish the recycle limits, that are particularly strict, it should fulfill disposal limits as well.

2.2. Vacuum vessel inventories of activated materials

As mentioned, the first analysis focuses on the radioactive inventory of ARC vessel in three different configurations. Figure 2 shows the results in terms of contact dose rate. STR1 and STR2 are the two structural layers of the vessel while FW and Nmult are the tungsten fist wall and beryllium neutron multiplier, respectively. In Fig.1a STR1 and STR2 trends become horizontal at values way above the recycling limits, the order of magnitude is about five time higher. Hence, according to contact dose rate results, it is clear that Inconel could not be considered a low activation material. The management of irradiated Inconel must evaluate other approaches than recycling. A preliminary analysis on its main elements (Ni, Nb, Mo, Al) and their natural isotopes do no leave space for the improvements required to hit the limits. On the other hand, it seems that vanadium alloy does get a dramatic enhancement to vessel activation. Its contact dose rate curves keep decreasing reaching the first limit in little more than 100 years (Fig.1b).

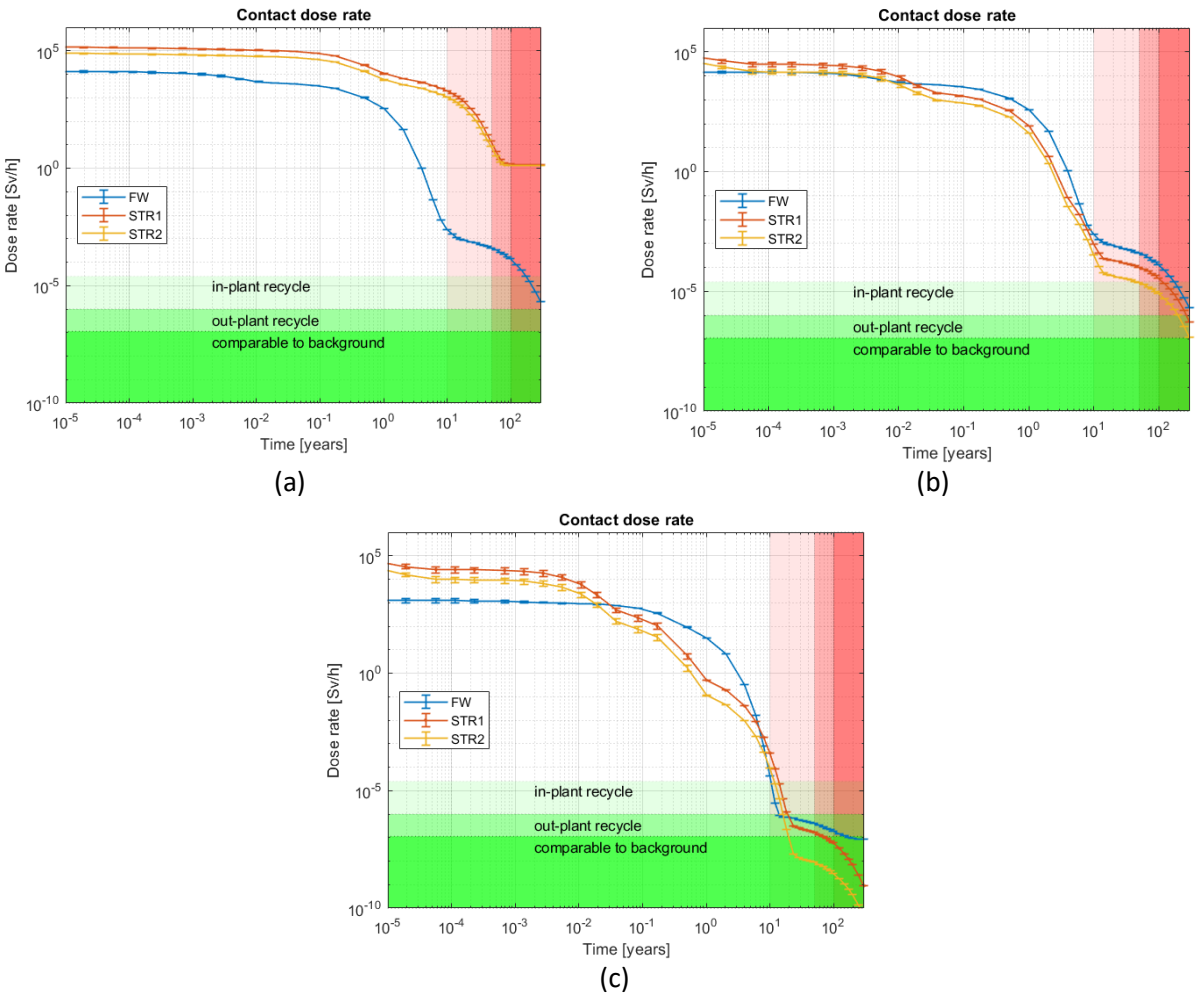


Figure 2: Contact dose rate vs cooling time of ARC vacuum vessel. Inconel structure (a), V-4Cr-4Ti structure (b), tailored V-4Cr-4Ti structure (c).

V-4Cr-4Ti main cause of long-lived nuclides is related to titanium, as vanadium and chromium do not generate radionuclides with particularly high half-life under neutron irradiation. An analysis of titanium and tungsten natural isotopes showed that there is room for improvement. Indeed, it seems that Ti-50 and W-184 could additionally decrease the cooling time of the component in order to reach the recycling limits. Figure 2 (c) depicts the effect of such isotopic tailoring under the assumption of perfect condition: a total tailoring of Ti-50 for the V-4Cr-4Ti structure and W-184 for the first wall. For what concerns the clearance index, it turned out that V-Cr-Ti with a perfect tailoring of Ti-50 could virtually achieve clearability in few decades, in ideal conditions. However, the generation of tritium and especially the unavoidably present impurities, mainly N, O, C, cause V-Cr-Ti clearance index to raise above the limit for a longer period of time.

2.3. Sensitivity and optimization techniques

In the previous section a perfect tailoring, namely enriching an element with an isotope of choice, has been assumed. However, it is not said that it is viable. Both for technological issues related to perfectly separating isotopes and for economic reasons. It is in fact well known from fission industry that enriching uranium dramatically grows its price. Hence, it is not clear whether the different type of disposal for the vessel would pay-off the titanium tailoring, provided that it is a component that gets replaced every two years. For this reason, a sensitivity analysis over titanium enrichment fraction has been carried out and summarized in Figure 3. The enrichment fraction goes from 0.05, which roughly the natural fraction of Ti-50 in titanium up to 1.

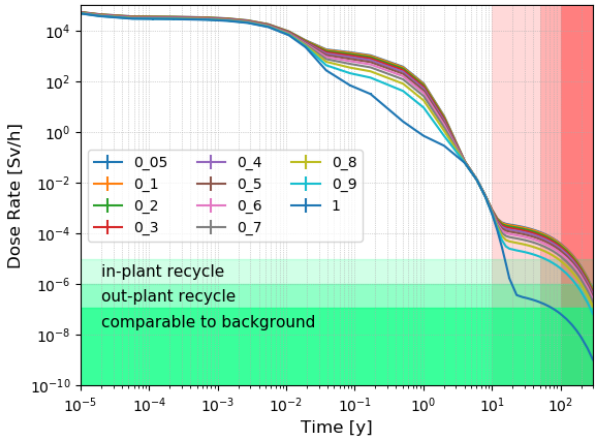


Figure 3: Dose rate vs cooling time of ARC vacuum vessel for different fractions of Ti-50 enrichment.

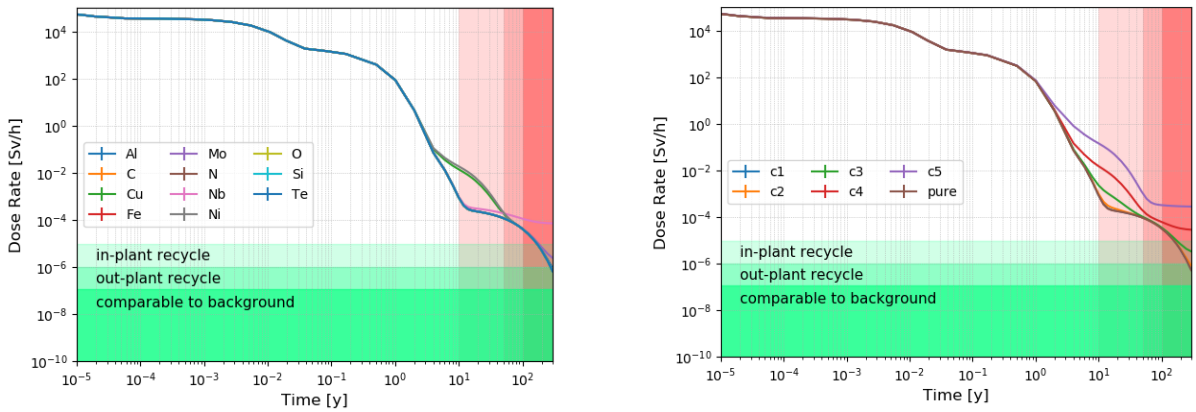
In Figure 3, it is possible to divide the plot in four vertical regions. The first one goes from 1e-5 to around 1e-2 years. In this first region the dose rate is mainly caused by V-51, Ti-51, Sc48. They have a high activity but low half-life. The second region goes from 1e-2 to 3 years and it is dominated by V-49 coming from vanadium and Sc-46 coming from the lighter isotopes of titanium. The effect of tailoring is here observable as the curve with 100% of Ti-50 in titanium shows is affected only by the effect of V-49 while there is almost no Sc-46. Nevertheless, V-49 and especially Sc-46 have still a relatively short half-life (330 and 84 days, respectively). As Sc-48 decays faster than V-49, the third region is entirely dominated by the latter. Such region goes from 3 to 10 years. The last region starts at 10 years of cooling time and goes up to the right end of the plot. V-49 has decayed and most of the contact dose rate is given by K-42, daughter of Ar-42, which comes from neutron interaction with lighter titanium isotopes. Once again, K-42 is dramatically reduced by applying only the heavier Ti-50. This is a mechanism that can be experienced in fusion spectra, where neutron energy is fast enough to tear atoms apart, favoring reactions like (n, 2n), (n, p), (n, D) and (n, α) over absorption. Neutrons of such energy are able to transmute Ti-46 down to Ar-42 that has a half-life of 33 years[26][27]. Its daughter, K-42 has a high energy β- decay (3.5 MeV) and a very short half-life, but it is always recovered from decaying Ar-42. Because of the mentioned issues related to lighter titanium isotopes, the isotopic tailoring on titanium effectively works only for extremely high enrichment fractions, very close to unit.

In second instance, from preliminary analysis and previous works [15] it was clear that impurities play a major role in the induced activation field. V-Cr-Ti main impurities are N, C and O. Despite they are less effective on contact dose rate than other alloys impurities (e.g. nickel in iron-based alloys), they still increase the radioactive inventory. Moreover, V-Cr-Ti have other minor impurities whose effect is still non-negligible (e.g. Al, Cu, Mo, Ni, Nb etc.) [20][28][29][30]. Figure 4 shows the effect on contact dose rate of every single impurity (a) and the effect of all the impurities put together at different concentrations (b), starting from the concentration values usually present in literature [20][28][29][30]. Table 2 summarizes the concentration applied for the second graph. Concentration set c4 has the same order of magnitude of main concentration findable in literature [28][30], c3 has similar order of magnitude of high-purity vanadium [31], the sensitivity analysis has been conducted changing order of magnitude of concentration, as a linear sensitivity did not show visible effects and impurities show a very broad range of concentrations depending on the raw material and the production process.

Table 2: V-Cr-Ti impurities and concentration applied to the dose rate sensitivity analysis.

Impurity	Pure (wppm)	c1 (wppm)	c2 (wppm)	c3 (wppm)	c4 (wppm)	c5 (wppm)
C	0	0.05	0.5	5	50	500
N	0	0.1	1	10	100	1000
O	0	0.2	2	20	200	2000

Al	0	0.1	1	10	100	1000
Si	0	0.3	3	30	300	3000
Fe	0	0.1	1	10	100	1000
Ni	0	0.01	0.1	10	100	1000
Cu	0	0.005	0.05	0.5	5	50
Nb	0	0.001	0.01	0.1	1	10
Mo	0	0.025	0.25	2.5	25	250
Te	0	0.05	0.5	5	50	500



(a) (b)

Figure 4: Dose rate vs cooling time of V-4cr-4Ti after irradiation in ARC-like conditions. Effect of impurities simulated one by one (a), effect of all impurities with different concentrations (b).

Nb, Mo, Te, Cu and Ni are the most threatening impurities, even though they are present in minimum quantities they affect the dose rate behavior over time. Main long-lived nuclides generated by impurities are C-14, Al-26, Nb-94 and Mo-93, they all have a half-life on the order of thousands of years. Activation of impurities also raises clearance index above unit, in the case of V-Cr-Ti systems. From Figure 4 (b) it is possible to notice that the impurity concentration set C4, which is the one reported in literature is still too high for reaching the recycling limits in a satisfactory period of time. In this instance, concentrations lower by one or two orders of magnitude (c3 and c2) could be considered sufficient. In this sense, researchers are providing technological solutions for producing V-Cr-Ti ingots with lower impurity concentrations [31].

As previously mentioned, impurities, generation of tritium and gases like Ar-42 heavily affect the radioactivity of irradiated V-Cr-Ti systems. In this framework, optimization methods like isotopic tailoring of Ti-50 showed an enhancement of the dose rate since it dramatically reduced the generation of Ar-42 and its daughter K-42. Nevertheless, in order to be effective, the tailoring of Ti-50 should be nearly perfect. Another proposal that should be considered is the application of detritiation and degasification techniques. Detritiation is needed anyway as the structure would absorb way more tritium than that simulated in FISPACT-II because of the transport from the liquid blanket, gas removal needs instead to be demonstrated, as it is here just proposed. Effect of tritium is not seen in contact dose rate, as it has a low-energy β- decay, which would be stopped by the first layers of skin. It does however strongly affect the material activity and clearance index. Figure 5 shows the effect of the gases (including tritium and K-42, as daughter of Ar-42 noble gas) on V-4Cr-4Ti specific activity (a), contact dose rate (b) and clearance index (c). Such plots assume a low concentration of impurities and no isotopic tailoring.

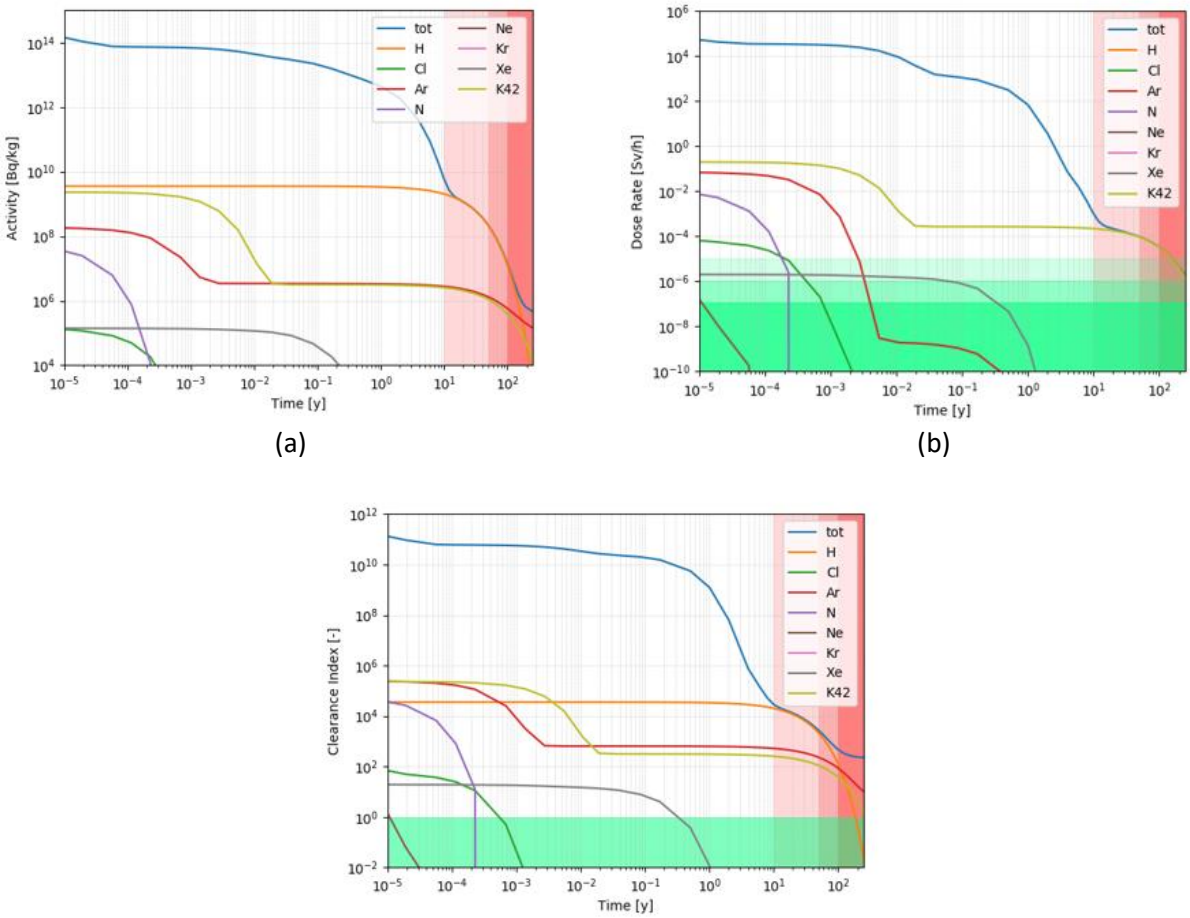
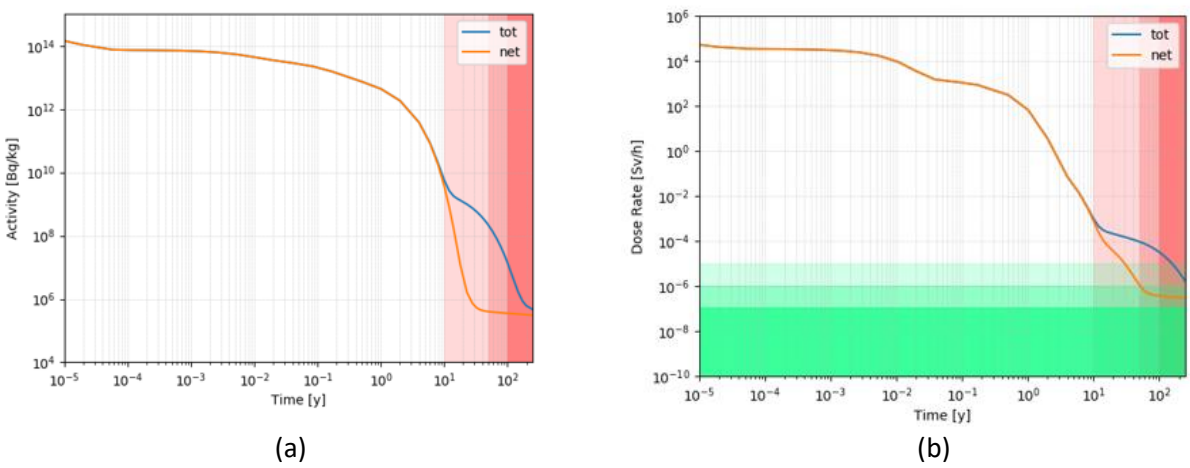
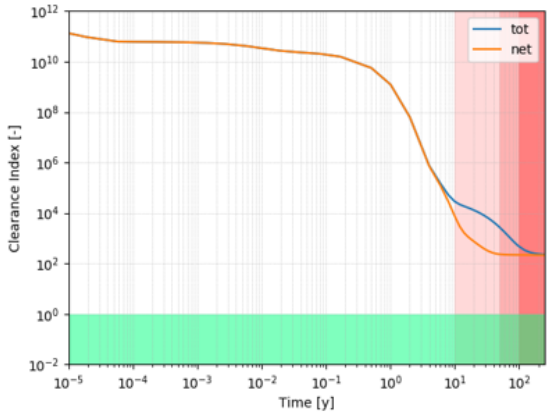


Figure 5: Specific activity (a), contact dose rate (b) and clearance index (c) vs cooling time of V-4Cr-4Ti in ARC-like conditions. Highlighted the component given by main gases and K-42 as daughter of Ar-42 noble gas.

From Figure 5 it is possible to notice that in the period 10-50 years it is tritium (referred as H in the figure) that causes most of the activity and clearance index. In second instance and, especially, in the case of contact dose rate, potassium-42 is the main cause of values higher than the limits. In the case of V-Cr-Ti systems would be therefore very effective to apply a detritiation and gas removal at the early stages of vessel dismissal. Figure 6 displays the effect of removing tritium and other radioactive gases, together with their daughters, generated during the irradiation phase. It is assumed a perfect removal.

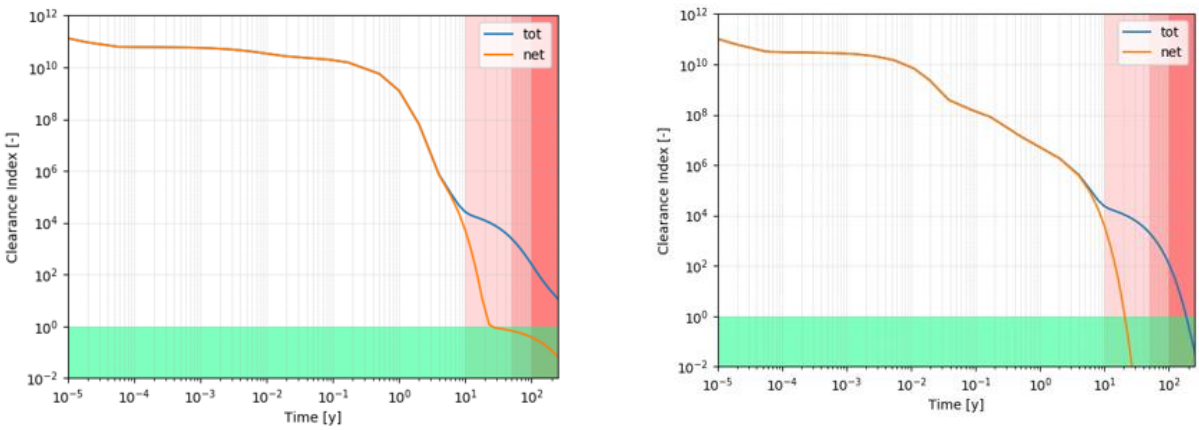




(c)

Figure 6: Specific activity (a), contact dose rate (b) and clearance index (c) vs cooling time of V-4Cr-4Ti in ARC-like conditions. Total curves after irradiation (tot) and effect of removing tritium gases and relative daughters (net).

Despite the presence of impurities, the recycling limits are achieved in very few decades (20-30 years). Specific activity instead stabilizes to its minimum values earlier, after about a decade of cooling time. Clearance index is still too high for reaching the limit. This is mainly due to the presence of impurities. However, V-Cr-Ti systems, unlike most of other alloys, are virtually able to achieve clearability. Figure 7 assumes pure V-Cr-Ti systems and shows how removing tritium and gases is effective on clearability. Material is virtually clearable after a decade of cooling time.



(a) (b)

Figure 7: Clearance index vs cooling time of V-4cr-4Ti. Total curve after irradiation (tot) and effect of removing tritium, gases and relative daughters (net). No tailoring of Ti-50 (a) and perfect Ti-50 tailoring (b).

Gas removal and titanium-50 tailoring have similar effects. A perfect tailoring of Ti-50 would prevent the formation of noble gas Ar-42 and, therefore, its high-energy decaying daughter K-42. Assuming gas removal is possible, it would remove the noble gas Ar-42 having similar effect of titanium tailoring. Neglecting the effect of impurities and tritium, in both cases, a V-Cr-Ti system irradiated in ARC conditions would be clearable after two decades of cooling time. As titanium tailoring and gas removal have similar effect it would be possible to apply just one technique or a mix of both, which would relax the necessity of perfect tailoring or perfect gas removal. In any case, if gas and tritium removal is to be applied, tritium could be recovered for reactor refueling, while gas could even be released in the atmosphere. In fact, ARC's vacuum vessel structure will be on the order of 10^4 kg and will be replaced every 2 years. This causes a total gas activity of 10^12 Bq/y and 2x10^13 Bq/y of tritium. Both values are below or comparable to other nuclear power plant's releases [32].

3. Irradiation Damage

Damage is the other main issue related to neutron irradiation on structural materials. In this work, a preliminary analysis will point out main effects of damage: displacements per atoms (dpa) and light gas generation (i.e. hydrogen and helium atoms). Both the mechanisms cause distortion and damage to the material lattice dramatically increasing the probability of initiate a crack and embrittle the component. For such evaluations, this study takes advantage of FISPACT-II program. Table 3 lists the main damage data for Inconel718 and V-4Cr-4Ti for the inner layer of the vessel, namely the structural material closest to plasma.

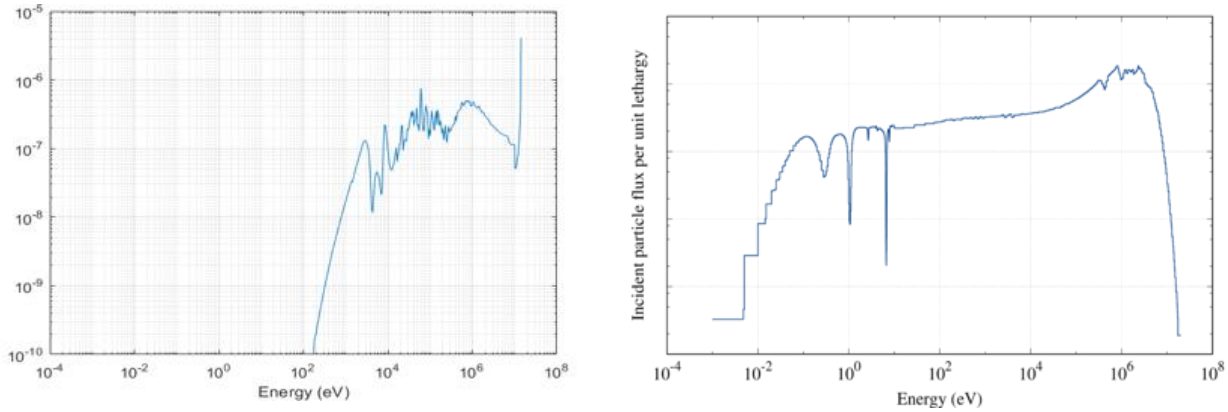
Table 3: Damage rate and gas production rate results for Inconel 718 and V-Cr-Ti in ARC-like irradiation conditions.

	Damage rate (dpa/y)	H (appm/y)	He (appm/y)
Inconel-718	22	3000	400
V-4Cr-4Ti	23	500	65

While the damage rate is roughly similar for the two alloys, the gas production rate is visibly lower for vanadium. Irradiation experiments suggest that Inconel could have a dpa limit of very few tens before incurring into embrittlement and failure [33], while V-Cr-Ti systems demonstrated to have a superior irradiation resistance, up to 40-60 dpa [34][35]. For what concerns the gas generation, light nuclei could travel across the lattice, especially at high temperature. Gases could merge in microbubbles that can initiate a crack in a shorter time than expected from usual material lifetime, especially if it is present a thermal load that raises the partial pressure of the microbubbles. Materials with higher gas generation rate are expected to be more sensitive to radiation damage than materials with a lower gas production, especially if the gas generation is orders of magnitude higher.

In order to evaluate the behavior of structural materials under neutron irradiation, most experimental campaign rely on research fission reactors [36][37][38][39]. Nevertheless, results derived from numerical irradiation analysis simulating fusion reactors often show significant divergences from experimental data. Damage, gas generation and transmutation, often seen as an issue for V-Cr-Ti systems [38], are mechanisms that seem to be extremely different in fusion than in fission. Once fluence is on the same order of magnitude, sensitivity to spectra is identified as the main cause of such issue. The risk is that, if material damaging mechanisms change too much in the two cases (i.e. fission and fusion), experimental data could help very little while predicting the behavior of an irradiated component.

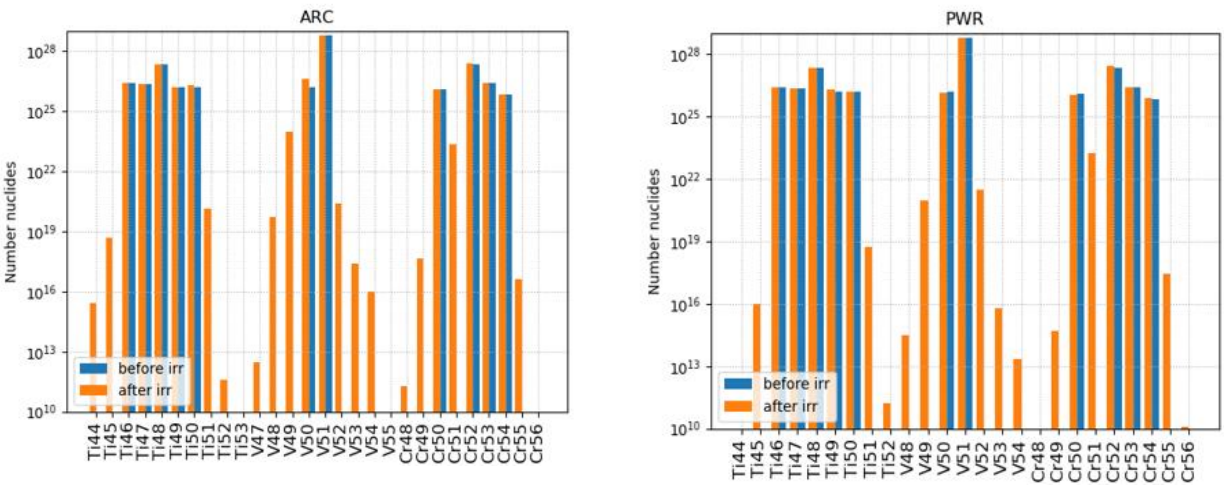
The problem is that experimental facilities can rely only on fission spectra [38][40][41], for irradiating specimens. For the purpose of better explaining the difference in the main damaging mechanisms, it is here proposed a study that shows the sensitivity of irradiated V-4Cr-4Ti to the spectrum. Using similar models previously presented (i.e. same fluence), such alloy has been irradiated in first instance with ARC spectrum and, secondly, with a PWR and a BWR spectra provided by FISPACT website [42]. Here just ARC and PWR spectra results will be presented as BWR did not show any substantial difference with respect the PWR results. Figure 8 displays the ARC and PWR spectra applied.



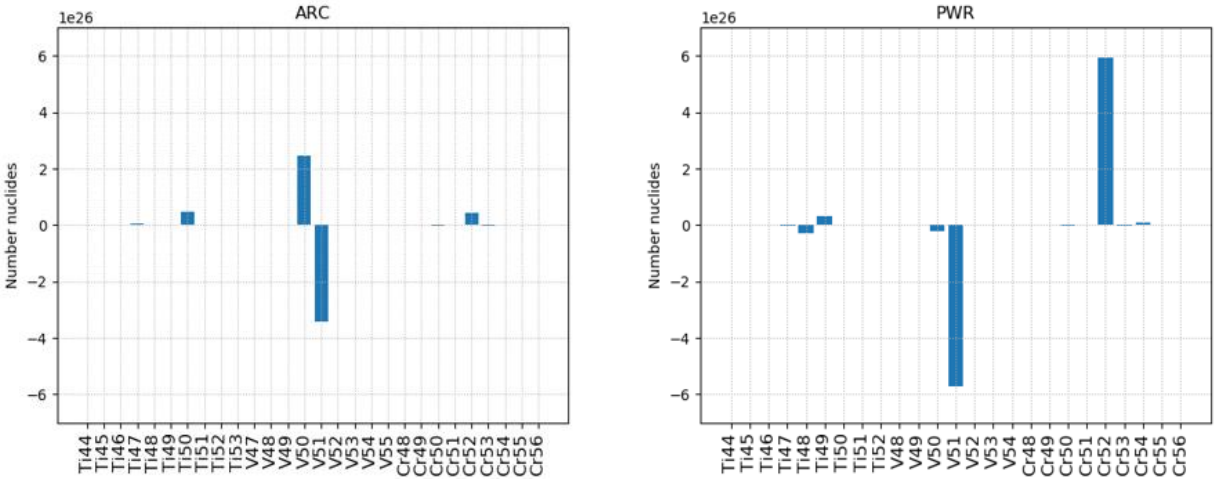
(a) (b)

Figure 8: Neutron energy spectra of ARC reactor on the inner vacuum vessel (a) and PWR reactor [42].

It is clear that ARC spectrum has a huge peak of neutrons that exceed the 10 MeV of energy, while the population in the thermal region is nearly zero. On the contrary, the PWR spectrum has a considerable amount of thermal-epithermal neutrons and its peaks aroung 1 MeV of energy before dropping to zero. The PWR peak energy is one order of magnitude lower than ARC one. Literature identifies the transmutation of vanadium into chromium as the main cause of embrittlement of the alloy [38]. This is most likely the cause that lead fusion scientists to set the low-chromium V-4Cr-4Ti as reference vanadium alloy for fusion applications, although higher Cr contents would have better mechanical and thermal properties [35][43][44]. Figure 9 shows the transmutation effect on the V, Cr and Ti isotopes for the ARC and PWR spectra. Fig. 8(a) and (b) depict the overall transmutation, while Fig.8(c) and (d) display the differential that is the growth or loss of different isotopes, for ARC and PWR spectra, respectively.



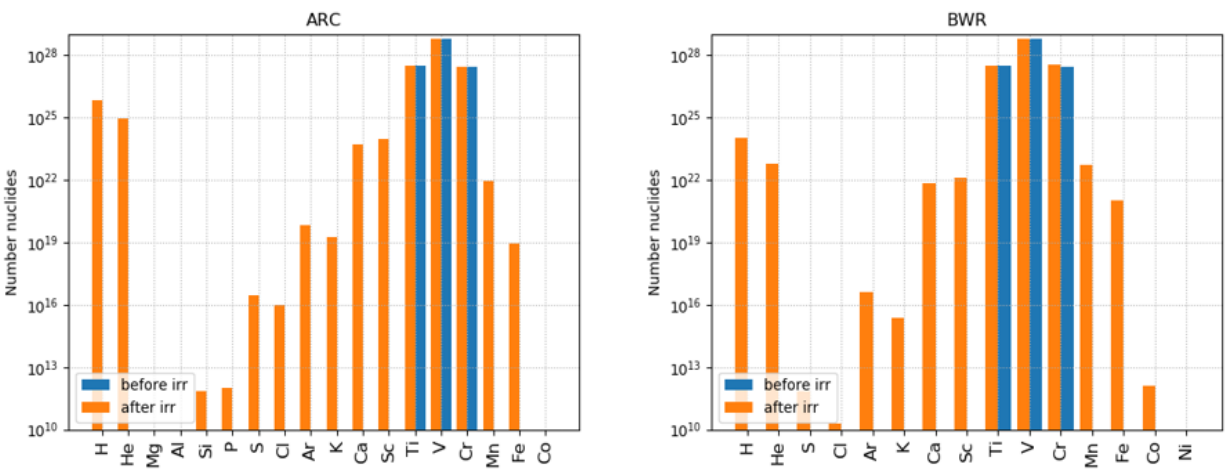
(a) (b)



(c) (d)

Figure 9: Transmutation results of V, Cr and Ti isotopes in V-4Cr-4Ti model, for ARC spectrum (a) and PWR spectrum (b). Differential results of ARC spectrum (c) and PWR spectrum (d).

There is a substantial difference in transmutation with the two spectra. ARC has a hugely fast spectrum and its neutrons tend to tear atoms apart, favoring formation of lighter elements. Indeed Figure 9 (c) shows that V-51 has decreased in favor of mainly V-50 and a few Ti and Cr atoms. On the other hand, slower spectra, such as the PWR one, prefer the absorption mechanism. Figure 9 (d) shows than V-51 hugely decreased in favor of Cr-52 growth. There is also a slight decrease of lighter elements (i.e. Ti-48) in favor of heavier ones that is not recorded in ARC spectrum. Similar effect can be seen in Figure 10 where the transmutation into other elements for both the spectra is depicted. It is clear that ARC spectrum causes transmutation into lighter elements and, especially, into light gases like hydrogen and helium. On the other hand, the fission spectrum grows more heavier elements, up to cobalt and nickel. Analysis on radioactivity also suggest that fission spectrum causes much less induced activity on V-Cr-Ti as titanium atoms are less likely to be teared apart down to the Ar-42 – K-42 decay series.



(a) (b)

Figure 10: Transmutation results of V-4Cr-4Ti in other elements. Irradiation with ARC spectrum (a) and irradiation with PWR spectrum (b).

Lastly, Table 4 lists the other main data regarding damage, like gas growth and dpa rate.

Table 4: damage rate and light gases growth of V-4Cr-4Ti in ARC fluence with ARC and PWR spectra.

	dpa/y	H (appm/y)	He (appm/y)
ARC	23	500	65

PWR	14.7	8	0.4

While the damage rate is almost doubled in ARC with respect the PWR, the growth of light gases changes by two orders of magnitude, defining the fission spectra as less harmful.

The numerical analysis shown that the material damaging mechanisms are significantly sensitive to the energy spectrum applied. Because of the difference in transmutation direction, in the dpa rate and the order of magnitude of gas growth, it is likely that damage mechanisms seen in experimental data could not predict and simulate the actual damaging mechanisms in a fusion reactor. This difference in the operating conditions highlights the necessity of ad-hoc experiments for fusion (e.g. IFMIF and ITER-BA projects [45][46][47]) or the development of other technical strategies in the modeling phase.

4. Conclusion

Deuterium – tritium fueled tokamaks will have a high neutron load on the first wall and its structure. Such neutron flux will cause neutron induced activation of material and damage on solid structures. Since ARC reactor will be a compact fusion machine it is expected to experience higher neutron loads than other low-field tokamaks. It was therefore necessary to evaluate the radioactive inventory of irradiated structures and investigate the damaging effect of neutrons. Results shown that a structure made of Inconel-718 causes a high inventory of radioactive materials. Nickel is the main cause of such high radioactivity. Its main products have a long-half life and the dose rate stabilizes at about five orders of magnitude more than any recycling limit. Inconel 718 is therefore not able to reach the limit here described nor in the time goals set by ARC team nor in the time usually taken by fusion community. On the contrary V-Cr-Ti systems get close to recycling limits in about a century. This is enough to evaluate the possibility of optimization methods. Techniques analysed are the isotopic tailoring, detritiation and the here proposed gas removal. Detritiation and tailoring would be enough to potentially achieve the total clearability of V-Cr-Ti within two decades of cooling time, well below the ARC team time goals. However, impurities play a major role causing the clearance index to increase by at least two orders of magnitude. Hence, in normal conditions, clearance index is not likely to get achieved in 100 years of cooling time. In any case, even in presence of impurities, optimization techniques could help reaching the recycling limits in about 30 or 40 years. In this instance, the in-plant recycling limit is not expected to actually be reached before 10 years, but it can be reached largely before the century of cooling time. On the other hand, the off-plant recycling limit seems to be feasible in 50 years of cooling time. Alongside with impurities, the main problem of activation in V-Cr-Ti systems in the case of fast neutrons is the generation of Ar-42 and its daughter K-42. Ar-42 has a low-energy decay and high half-life. Hence, it keeps decaying into K-42 for decades. K-42, on the other hand has a short half-life and a high energy β- decay, which is harmful for biologic bodies even without ingestion or inhalation. Ar-42 generates by fast neutrons that tear apart the lighter isotopes of titanium. Isotopic tailoring of Ti-50 and/or gas removal and separate release of are therefore particularly effective for dealing with such transmutation mechanism. Isotopic tailoring seems to be effective also for the first wall made of tungsten. The material could be recycled in less than a decade. Nonetheless, a deeper impurity analysis is required.

V-4Cr-4Ti displayed also better radiation resistance data. Its dpa rate is comparable with Inconel 718 one, in similar conditions, but the threshold is expected to be much higher. Furthermore, the gas generation is significantly reduced with respect Inconel. Considering that light gas atoms can diffuse in the solid and merge in bubbles, a structure subjected to huge heat loads that could raise the gas partial pressure is expected to be initiate a crack in a short time. Such aspect suggests that V-Cr-Ti systems would be more reliable as structure than Inconel, from neutron irradiation viewpoint. It is thus advantageous to keep considering vanadium alloys for fusion application. In the case of ARC, it is suggested to evaluate a low-activation and high radiation resistance vessel, made of V-Cr-Ti system, alongside the baseline configuration made of Inconel.

Lastly, it is here highlighted that damage mechanisms of fusion neutrons are very different from fission neutrons. Transmutation goes in the different directions, namely heavier atoms turn into lighter ones, displacement per atoms are almost doubled and gas generation is increased by about two orders of magnitude. Hence, it is clear that experimental data given by irradiation with fission machines, albeit being necessary, cause a significant uncertainty when it comes to apply them for predicting failure in fusion reactors. It is therefore here concluded that it would be necessary a facility able to simulate irradiation of 14 MeV neutrons at high fluences or, to evaluate the implementation of particularly precautionary safety coefficients when it comes to design structural components of a fusion machine.

Acknowledgements

The authors would like to thank professors Dennis Whyte, Zachary Hartwig and Michael Short from MIT for sharing their knowledge in fruitful conversations and elucidating suggestions.

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