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Citation: Zucchetti, M., and L. Bonavigo. "Advanced fuel fusion reactors: Towards a zero-waste option." Nuclear & Renewable Energy Conference (INREC), 2010 1st International. 2010. 1-6. © 2010, IEEE

As Published: http://dx.doi.org/10.1109/INREC.2010.5462602

Publisher: Institute of Electrical and Electronics Engineers

Persistent URL: http://hdl.handle.net/1721.1/59541

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

ADVANCED FUEL FUSION REACTORS: TOWARDS A ZERO-WASTE OPTION

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ABSTRACT

Low activation materials are only a partial response to the requirement of a really environmentally sound fusion reactor: another way round to tackle the problem is the reduction of the neutron flux and subsequent material irradiation, possibly by exploring other possible fusion reactions such as the Deuterium-Helium-3 one.
Most of the studies and experiments on nuclear fusion are currently devoted to the Deuterium-Tritium (DT) fuel cycle. The recent stress on safety by the world community has stimulated the research on 'advanced' reactions, such as Deuterium-Helium-3 (DHe3). IGNITOR is a proposed compact high magnetic field tokamak. A design evolution of IGNITOR in the direction of a reactor using a DHe3 fuel cycle has led to the proposal of the Candor experiment.
This paper deals with the radioactive waste issue for fusion reactors, proposing an innovative solution (the "zero-waste" option), which is a clear advantage of fusion power versus fission, in view of its ultimate safety and public acceptance. Fusion reactors with advanced DHe3 fuel cycle turn out to have quite outstanding environmental advantages.

1. INTRODUCTION

Nuclear reactor studies are mostly devoted to the Deuterium-Tritium (DT) fuel cycle. Neutron-induced transmutation of materials in a DT fusion power plant will give rise to the potential for long-term activation, i.e. neutron-induced radioactivity in structures. To ensure that the attractive safety and environmental characteristics of fusion power are not degraded, careful design choices are necessary. An aim of optimising power plant design must be to minimise both the level of activation and the total volume of active material that might ultimately be categorised as waste requiring disposal. Materials selection is central to this optimisation, however the reliance on deuterium and tritium as the sole fusion fuels must be reconsidered too.

Public acceptance of fusion is tied to its pledge of cleaner energy. Therefore a low radioactive inventory in the reactor is essential to obtain this result. A number of approaches are currently being pursued to minimise the radioactive inventory, and therefore the waste, from a fusion power plant [1]: the common element of all approaches is the use of low activation materials. Vanadium-based alloys are an example of such materials [2].

If DT reaction is chosen, low activation materials allowing firstly a significant reduction in the risk of exposure of personnel to radiation damage in case of an accident and secondly partially solving the problem of long life wastes, are a widely studied solution for the close-to-plasma components in a commercial reactor. It has long been claimed that the development of high-performance, low activation materials for the first wall and structural components is the key to the successful attainment of safety, environmental and economical advantages of fusion power systems. Long lifetime under neutron-interactive environments and low activation characteristics are common requirements to candidate structural materials, and they are difficult to satisfy in conjunction with the other necessary characteristics: moreover, their quantitative demands depend on the fusion power system design and the strategy of handling neutron-activated materials from the reactors.

The selection of appropriate materials for fusion reactors relies on a trade-off between multiple requirements which are mainly driven by economic, safety and environmental factors, and are difficult to satisfy altogether. In addition to an extensive set of engineering property specifications, there is a range of possible radiological requirements on low-activation materials, not all of which may be satisfied simultaneously.

The selection of adequate materials is particularly difficult for the most highly exposed parts of the machine such as the first wall. The components need to be suitable for operating under severe thermomechanical loadings and intense irradiation by energetic neutrons up to high dose rate: fluence of up to 200 displacements per atom (dpa) are expected for these plasma-facing materials, if the DT reaction is foreseen to be used in a fusion power plant. Candidate structural materials for plasma facing and structural components have a chemical composition that is based on low activation elements (Fe, Cr, V, Ti, W, Si, C, Ta). They include mainly reduced activation ferritic/martensitic (RAFM) steels, oxide dispersion strengthened RAFM and RAF steels, vanadium-based alloys, tungsten-based materials, and fibre reinforced SiC/SiC ceramic composites. Each alternative alloy class exhibits specific problems arising from radiation damage.

It seems therefore that low activation materials are only a partial response to the requirement of a really environmentally sound fusion reactor: another way round to tackle the problem is the reduction of the neutron flux and subsequent materials irradiation, possibly by exploring other possible fusion reactions such as the advanced Deuterium-Helium-3 one.

A DT fusion power reactor, in fact, will be a nuclear power plant, similar in general aspects to a fission reactor, however different in many other ones. For instance, the radioactive

inventory in a fusion reactor does not contain plutonium and other transuranic elements, and the inventory of alpha-emitters is at minimal levels. Moreover, since neutron-induced radioactivity is the main component of fusion reactors radioactive inventory, this may be effectively reduced by a correct choice of the constituting materials. Furthermore, a fusion reactor has no proliferation-relevant materials, except for tritium, which however is currently not safeguarded under by the Non-Proliferation Treaty. Finally, fusion energy may be economically viable as a complementary source of energy and power, if developed on a large-scale basis, and as long as they can produce electricity more reliably and economically than renewable sources such as wind turbines and photovoltaic cells. The immense fuel resource is part of what makes fusion energy attractive in the long-term.

The attractive safety and environmental potential of fusion can be substantiated by a power plant design in which materials activation is minimised. Activated materials will be removed from the plant during routine components replacements, and then in decommissioning at end-of-life. Radioactive waste generation, management and final disposal is probably the main drawback for fission energy, and therefore it deserves the highest attention also in the case of fusion reactors. In this field, the main goal for fusion must be the minimisation of radioactive waste originating from a power plant: this minimisation may be interpreted as reducing both the total volume of active waste and its level of activation.

In Europe, the recommendations of the 1990 Fusion Evaluation Board [3] may be assumed as a standard: "Radioactive wastes from the operation of a fusion plant should not require isolation from the environment for a geological time span and therefore should not constitute a burden for future generations". This can be translated into a reduction of permanent waste, and into the assessment of the low hazard of fusion permanent waste, if any, when compared to fission waste.

In the first direction, an activated materials management strategy including the maximum reasonably possible use of materials recycling (within or outside the nuclear industry) and materials "clearance" (i.e., declassification to non-radioactive material) must be pursued, in order to minimise the production of permanent waste. Recycling may include reprocessing of materials with extraction of noxious radionuclides.

This paper concentrates on the radioactive waste issue for fusion: an innovative solution (the "zero-waste" option) will be proposed. This could be another crystal clear advantage of fusion power in view of its ultimate safety and public acceptance.

It will be shown that this option cannot be fully reached with fusion reactors using the Deuterium-Tritium fuel cycle. Then, the features of fusion reactors based on alternative advanced fuel cycles will be examined, in order to assess whether the zero-waste option could be a reachable goal for such devices.

2. FUSION WASTE MANAGEMENT STRATEGIES

Most radioactive waste generated from fusion power reactor operation and decommissioning is activated solid metallic material from the main machine components and concrete from the biological shield. Some components will also have surface contamination including tritium, however, as already mentioned, material detritiation will always be performed. The dominating waste mass stream is generated in the decommissioning stage. A great deal of the decommissioning radioactive materials has a very low activity concentration, especially if a long period of intermediate decay is anticipated. Radioactive nuclides in fusion waste are mainly solid metallic activation products and tritium. Therefore, fusion waste is quite different from fission waste, both in type of material and isotopic composition [1,2].

The options for handling fusion waste have therefore to be different than those for fission. In particular, it is appropriate to explore solutions that minimise the use of final repositories. For this purpose, a waste management strategy was developed [4]. It is based upon two main concepts:

1. Recycling of moderately radioactive materials within the nuclear industry.
2. Declassification of the lowest activated materials to non-active material (Clearance). The IAEA Clearance Limits [5] are taken as a reference in this study. Concentration limits for clearance are issued for most relevant nuclides for fission and fusion, however some data for relatively important nuclides are missing. For materials with more than one radioactive nuclide, given the specific activity A_i and the clearance level L_i of each one of the z nuclides contained in the material, an index $CI = I_c$ may be computed as:

$$I_c = \sum_{i=1}^{Z} \frac{A_i}{L_i} \qquad (1)$$

The material can be cleared if $I_c \leq 1$

This "recycling and clearance" strategy appears to have a great potential interest. If we apply the management strategy, for instance, to the Power Plant Conceptual Study (PPCS) [6], it turns out that the amount of Permanent Disposal Waste (PDW) of PPCS plant models can be reduced to almost zero, while about two thirds of the total could be recycled and one third cleared to non-active material [1,2,4,6].

Those studies have identified therefore in recycling - after a long interim decay period (up to 100 y) – for moderately activated materials, the main way for avoiding the production of Permanent Disposal Waste. In fact, the direct reuse or recycling of materials within the nuclear industry, usually after a decay period of up to 50 years, keeps the material out of the waste stream.

However, recycling is a question dealing not only with radiological feasibility, but also with metallurgy, materials science, shielding and remote handling techniques. A wide experience in these fields is available from fission research. Not all the "recyclable" material, from a merely radioactive concentration viewpoint, is effectively worth recycling: it must be assessed whether and when recycling of such materials is feasible or convenient; radiological, technical, and economical questions should be considered. Recycling processes and long-time storage of fusion waste should raise the price of reprocessed materials more than market prices of industrial waste.

In conclusion, it seems that, even if feasible in theory, a zero-waste option for fusion DT-powered reactors will not be possible: a relevant amount of radioactive materials from reactor decommissioning – even if "recyclable" from the radiological point of view – should be disposed of as radioactive waste. Most probably, those materials will meet requirements for classification as Low Level Waste, and it should be stressed their difference from fission High-Level Waste, in terms of lower hazard during its transport, lower cost and requirements for its disposal, lower environmental impact of repositories.

However, a further step – if the zero-waste option has to be achieved - is necessary: the adoption of advanced fuel cycles, such as the Deuterium-Helium-3 one.

3. ADVANCED FUEL CYCLES FOR FUSION

Nuclear reactor studies are currently devoted mostly to the Deuterium-Tritium (DT) fuel cycle, since it is the easiest way to reach ignition or a high energy gain.

The recent stress on safety by the world's community has however stimulated the research on other fuel cycles than the DT one, based on 'advanced' reactions, such as Deuterium-Deuterium (DD) and Deuterium-Helium-3 (DHe3). With these cycles, it is not necessary to breed and fuel tritium. The DHe3 cycle, moreover, has a very low presence of fusion neutrons. In fact, the DHe3 cycle is not completely aneutronic, due to DD side reactions generating 2.45 MeV neutrons and tritium, and to DT side reactions generating 14.07 MeV neutrons [7].

Given the drastically different conditions under which tritium-poor or tritium-less plasmas can reach ignition compared to DT, it is of particular interest to explore the physics of plasmas in which DHe3 reactions play an important role [8]. These reactions have their own set of problems, such as the availability on Earth of ^{3}He (which may be found in a sufficient abundance on the surface of the Moon) and the attainment of the higher plasma parameters that are required for burning [9]: for instance, a typical a typical ion temperature for DHe3 is 50-100 keV vs. 10-20 keV for D-T. Concerning ^{3}He availability, a commercial lunar ^{3}He fusion power infrastructure has been fully assessed and it seems attainable. ^{3}He seems the only valid commercial reason for going back to the Moon and start a mining activity [10]. ^{3}He is also made available from the decay of tritium produced for nuclear weapons. In DHe3 fusion reactors, finally, more severe problem should be heat load on the first wall as well as Plasma Facing Components rather than activation. Heat load analyses are therefore recommendable.

However, DHe3 reactors have also other advantages, like for instance the possibility to obtain electrical power by direct energy conversion of protons. A fusion power reactor based with DHe3 plasmas would not need a blanket to breed tritium, and also it would not need to produce electrical power indirectly, via the heating of a thermo vector fluid (such as water of liquid metal) and its use in a thermodynamic cycle with a turbine. Also, waste handling costs should be reduced relative to fission due to the lack of radioactive fusion products, and the reduction in neutron irradiation due to using DHe3 instead of DT.

In conclusion, we do not find in a fusion power reactor with DHe3 plasmas any similarity left with nuclear fission reactors.

4. COMPACT HIGH MAGNETIC FIELD TOKAMAKS

As a first step to explore the possibilities of DHe3 plasmas, a DT burning plasma experiment at high field and plasma densities, which can be much closer to the required parameters than present-day experiments, is particularly attractive.

Compact high-field experiments were the first to be proposed in order to achieve fusion ignition conditions on the basis of existing technology and the known properties of high-density plasmas. Good confinement and high purity plasmas have been obtained by high field machines Alcator/Alcator C/Alcator C-MOD at the Massachusetts Institute of Technology [11] and Frascati Torus Upgrade (FT/FTU) at ENEA in Italy [12].

IGNITOR is a proposed compact high magnetic field tokamak, and it is conceived as an experiment aimed at reaching ignition in DT plasmas and at studying them for periods of a few seconds [13-15]. The plasma density limit in IGNITOR is well above the optimal density for DT ignition, and it is suitable to the higher densities required for DHe3 burning. In fact, IGNITOR has been also designed to satisfy conditions where 14.7-MeV protons and 3.6-MeV alpha particles produced by the DHe3 reactions can supply thermal energy to a well-confined plasma [16]. In particular, IGNITOR can sustain plasma current exceeding that required to confine proton orbits at birth, and has more than sufficiently high densities so that the slowing-down time of both the protons and alpha particles is shorter than the electron energy replacement time of the thermal plasma in which they are produced. Preliminary analyses show that a fusion power $P_F \cong 2$ MW may be reached [13]. In particular, as a start, IGNITOR can allow initial studies at the level of approximately 1 MW of power in charged particles from the DHe3 reaction in a mostly DT plasma [13,16,17].

As a further step towards the study of a DHe3 reactor, a feasibility study of a high-field DHe3 experiment of larger dimensions and higher fusion power than IGNITOR, however based on IGNITOR technologies, has brought to the proposal of the Candor fusion experiment [8,16]. The main characteristics of the Candor machine are the following: the major radius R_o is about double than IGNITOR, plasma currents up to 25 MA with toroidal magnetic fields $B_T \cong 13$ T can be produced. Unlike IGNITOR, Candor would operate with values of poloidal beta around unity and the central part of the plasma column in the Second Stability region [16]. The toroidal field coils are divided into two sets of coils and the central solenoid (air core transformer) is placed between them in the inboard part.

The DHe3 ignition regime can be reached by a combination of ICRF heating and alpha particle heating due to DT fusion reactions that take the role of a trigger. Thanks to this fact, and unlike other proposed DHe3 fusion experiments, Candor is capable of reaching DHe3 ignition on the basis of existing technologies and knowledge of plasma, without any optimistic extrapolation. With this method, the need for an intense auxiliary heating, which is one of the main technological drawbacks of DHe3 ignition, would be considerably alleviated, becoming feasible with the present technology. However, this method has the disadvantage of using tritium and of presenting a higher neutron flux (due to DT reactions) than 'pure' DHe3 plasmas, and a neutron flux transient when passing from the initial DT trigger reaction to the final DHe3 burning plasma. The characteristic times over which the plasma discharge can be sustained are longer by more than a factor of 4 than those of IGNITOR.

Tritium inventory in Candor is expected to be very small and not to be a problem from the safety viewpoint.

The main characteristics of the Candor experiment are listed in Table 1.

The reactor model included coupled neutron transport and activation calculations. Neutron transport calculations have been performed with the SCALENEA-1 radiation transport system [18]. Neutron activation has been calculated by means of the EASY 2005.1 package (FISPACT code) [19]. The irradiation

history is simulated as follows: 100 cycles, each made of a 16-seconds pulse and a 6-hours dwell time.

Table 1 - Main characteristics of the Candor machine [16].

$R_0 \cong 2{,}5$ m	Major radius of the plasma column
a x b $\cong 0{,}92 \times 1{,}75$ m^2	Minor radii of the plasma cross section
$\delta_G \cong 0{,}36$	Triangularity
$I_p \leq 25$ MA	Plasma current in the toroidal direction
$B_T \cong 13$ T	Vacuum toroidal field at R_0
$V_0 \cong 80$ m^3	Plasma volume
$S_0 \cong 150$ m^2	Plasma surface area
$T_o \cong 65$ keV	Peak plasma temperature
$n_{e0} \cong 2\ 10^{21}$ m^{-3}	Peak electron density
$\beta_p \cong 1{,}2$	Poloidal beta
$W \cong 1$ GJ	Plasma internal energy

The zero-waste option for Candor activated materials has been verified: our goal is the clearance of all materials, even if obtained after long cooling times. Recycling within the nuclear industry is also considered, however as a less desirable alternative. The results for average materials/components are given in table 2: clearance is possible within less than 50 years of decay for SS316 and in about 100 years for Copper. All the components can be declassified as non-radioactive materials ("cleared") within cooling times varying from 50 to 100 y.

Table 2 – Clearance index for Candor materials (average)

Material	Clearance Index		
	30 y	50 y	100 y
Cu (Toroidal Field Coils average)	193	15	1.0
Cu (Reactor Average)	95	7,5	0,50
SS316 C-Clamp average	6,2	0,46	0,012

Results for contact dose rates are also reported for completing the analysis on recycling possibilities. Recycling within the nuclear industry is possible for all materials after less than 20 years of decay only (see Table 3)

Table 3 – Dose Rate for Candor materials (average)

Material	Contact dose rate (μSv/h)		
	20 y	30 y	50 y
Cu (Toroidal Field Coils average)	51,8	13,9	1,0
Cu (Reactor Average)	25,6	6,9	0,5
SS316 (C-Clamp average)	1,6 (6,1 at 10 y)	0,44	0,03

Therefore, if a much shorter decay time is seen as the preferable solution, the option of recycling the Candor materials, if they turn out to be valuable ones, might also be considered.

5. MATERIALS ACTIVATION ASSESSMENT

Activation behaviour of structural materials after service in a DHe3 advanced fuel fusion experiment like Candor will be investigated in this section, to assess whether their use in such experiments would be compatible with the zero-waste option.

We have simulated the irradiation in the Candor reactor plasma chamber wall (External Toroidal Field Coil Magnet flux) of the following structural materials:

- AISI 316L austenitic stainless steel
- EUROFER martensitic steel
- SiC/SiC composite material
- V-5Cr-5Ti vanadium alloy

Results for AISI 316L are listed in Table 4. The Clearance Index CI has been computed, according to the definition of CI discussed in section 2. It turns out that the CI for the material with impurities is higher than unity also for long decay times, such as 100 years and even 200 years. W define from now on as "Most responsible nuclides" those ones that contribute more to the clearance limit. The most responsible nuclides after 100 y of decay for AISI 316L are Ni-63 (an activation product of Ni), C-14 (a product of N), Mo-93 (a product of Mo) and Nb-93m (a product of Nb and Mo). Then, AISI 316L suffers the presence of Ni and N (alloying elements) and of Nb and Mo (impurities).

Table 4 – Clearance Index CI for AISI 316L, with and without impurities

Decay Time	Material with impurities	Material without impurities
30 years	407	406
50 years	32,1	30,8
100 years	2,68	1,35
200 years	2,23	0,92

The CI for EUROFER martensitic steel has been computed when irradiated in Candor. Results are available in Table 5. It turns out that EUROFER can be declassified to non-radioactive material (CI < 1) after about 60 years of decay, when the presence of impurities is taken into account. The most responsible nuclide after 30 and 50 y of decay is Co-60 (an activation product of Co, an impurity in EUROFER). If Co is removed or reduced, clearance of EUROFER may become possible after less than 30 y of interim decay.

Table 5 – Clearance Index CI for EUROFER, with and without impurities

Decay Time	Material with impurities	Material without impurities
30 years	40	0,31
50 years	3,18	0,23
100 years	0,31	0,22
200 years	0,30	0,22

The activation behaviour of the composite material SiC/SiC has been investigated too, when irradiated in Candor. Results are listed in Table 6. Clearance of SiC/SiC is possible after less than 30 years of decay, even if the presence of impurities is taken into account. The most responsible nuclide at 30 y of decay is C-14 (mainly an activation product of N, and of C and O in minor relevance).

Finally, the Clearance Index for V-5Cr-5Ti vanadium alloy has been computed, when irradiated in Candor (see Table 7). It turns out that most of the activation of V-5Cr-5Ti is due to

impurities. If their presence is taken into account, the material needs about 50 years of decay to reach a CI < 1, while without impurities the same result is reached in a few (less than 5) years.

Table 6 – Clearance Index CI for SiC/SiC, with and without impurities

Decay Time	Material with impurities	Material without impurities
30 years	0,958	0,564
50 years	0,757	0,549
100 years	0,673	0,539
200 years	0,636	0,532

At 50 years of decay, if the presence of impurities is accounted for, the most responsible nuclides are Eu-152 and Eu-154, two activation products of Eu, an impurity in the vanadium alloy.

Table 7 – Clearance Index CI for V-5Cr-5Ti, with and without impurities

Decay Time	Material with impurities	Material without impurities
30 years	4,47	0,0013
50 years	0,825	< 0,001
100 years	0,096	< 0,001
200 years	0,059	< 0,001

Concerning AISI316L material, the only one with important activation problems, we have deepened our analysis: we have examined its activation behaviour after 100 y of interim decay, to assess which are the most relevant nuclides and their formation pathways. Results of this assessment may be seen in the following table 8.

Table 8 – Detailed activation behaviour of AISI316L after 100 y of decay.

Nuclide	Clearance Index	Original element
Ni-63	0,76	Ni 99%, Cu 0.64%
C-14	0,51	N
Mo-93	0,47	Mo
Nb-93m	0,40	Nb 82%, Mo 17.2%
Tc-99	0,22	Mo
Nb-94	0,20	Nb 78.4%, Mo 21%

It turns out that:

- Mo and Nb are the two main impurities affecting the clearance index
- Even without impurities, we have a CI > 1 due to activation of Ni and N, two alloying elements of AISI 316L

It is therefore impossible, even with impurity reduction, to reach the clearance goal for this material when irradiated as the plasma chamber constituent of Candor.

In conclusion, EUROFER, SiC/SiC and V-Cr-Ti materials have shown the possibility of being declassified to non-radioactive material (clearance) after their irradiation in the reactor plasma chamber wall, if a sufficient interim cooling time is allotted. AISI 316L, on the contrary, suffers the presence of Ni and N (alloying elements) and Nb and Mo (impurities).

6. CLEARANCE INDEX OF PURE ELEMENTS

It may be interesting to check the activation behaviour, as far as clearance index is concerned, of pure elements in DHe3 reactors materials.

We have simulated the irradiation of an ideal material, containing 100 % of one element, in the Candor vacuum chamber wall. Results may be seen in Table 9.

Table 9 – Clearance Indices for pure materials in Candor plasma chamber wall, after different intermediate decay times.

Element	CI T = 30 y	CI T = 50 y	CI T = 100 y	CI T = 200 y
Fe	0,0951	0,0012	< 0,001	< 0,001
Co	795000	57000	79,5	< 0,001
Ni	1270	99	6,1	3,1
Mo	45	45	45	45
C	0,23	0,21	0,20	0,19
Nb	11000	9470	8370	8200
N	756	743	734	725
Al	0,553	0,203	0,045	0,035
Cu	932	73,6	4,96	2,42
Mn	0,1	0,033	0,002	< 0,001
Ti	< 0,001	< 0,001	< 0,001	< 0,001
Si	0,0013	< 0,001	< 0,001	< 0,001
Cr	0,001	< 0,001	< 0,001	< 0,001
W	0,011	0,0059	0,0018	< 0,001
B	103	33	2,0	0,0096
O	0,64	0,63	0,63	0,62

The following comments may be derived from the data reported in Table 9:

- Pure iron has a quite moderate activation.
- Cobalt activation is due to Co-60, hence its sudden decay between 100 and 200 y (Co-60 has a half-life of about 5,2 y)
- Nickel activation at 30 and 50 y is mainly due to Co-60, while Ni-63 is the most responsible nuclide at 100 and 200 y.
- Molybdenum activation is practically stable, due to Mo-93, Nb-94 and Nb-93m
- Carbon activation is due to C-14, at shorter term tritium is also important
- Concerning Nb activation, Nb-94 is the most responsible nuclide at long term, while at 30 y at 50 y Nb-93m is also relevant
- Nitrogen activation, almost stable too, is totally due to C-14
- Aluminium activation is mostly due to tritium. The contribution of Al-26 (CI = 0,035) is evident at 200 y only.
- Copper activation is quite high. It is mainly due to Co-60 at short term (30 and 50 y) and to Ni-63 at long term (100 and 200 y).
- Manganese activation is all due to tritium
- Titanium activation is negligible
- Silicon activation is very low, and all due to tritium
- Chromium activation is very low, and all due to tritium
- Tungsten activation at 30 y is due to Hf178m (68%), and T (30%)
- Boron activation is quite high, and all due to tritium
- Oxygen activation is all due to C-14

7. CONCLUSIONS

Innovative solutions in the field of radioactive waste could be a clear advantage of fusion in view of its ultimate safety and public acceptance: recycling and/or clearance (i.e., declassification to non-radioactive materials) of all components, after a sufficient period of interim decay, should be the goals for an environmentally attractive fusion power plant.

As a further step towards the waste minimization, the features of fusion devices based on alternative advanced fuel cycles have been examined. In particular, the advanced D-^{3}He fuel cycle offers several environmental advantages, such as the quite low presence of tritium, neutrons, and activated materials. Ignition of D-^{3}He plasmas, however, is more difficult to achieve compared to D-T plasmas and ^{3}He is not available on Earth, but from the decay of tritium in thermonuclear bombs.

Candor is a study of a compact high-magnetic field tokamak, extrapolated from IGNITOR technologies. Results obtained for the D-^{3}He Candor experiment show that no environmental problems arise from such a device, from the radiological point of view, even with the presence of D-T plasma triggering: Candor does reach the zero-waste option as all wastes can be cleared within 100 y.

Activation behaviour of materials after service in a D-He3 advanced fuel fusion experiment has been investigated. EUROFER, SiC/SiC and V-Cr-Ti materials have show the possibility of being declassified to non-radioactive material (clearance) after their irradiation in the reactor plasma chamber wall, if a sufficient interim cooling time is allotted. AISI 316L, on the contrary, suffers the presence of Ni and N (alloying elements) and Nb and Mo (impurities).

Concerning pure elements, it is of particular interest the high activation of Copper, used in the reactors as conducting material for magnets: Cu activation products are Co-60 and Ni-63: they could be eliminated from the material after service in the reactor. Activation of pure iron, on the contrary, is quite moderate, and this permits in principle to steels to aim at the clearance goal.

The DHe3 cycle offers safety advantages and could be the ultimate response to the environmental requirements for future nuclear power plants. Furthermore, the low neutron production helps overcome some of the engineering and material hurdles to fusion development. Studies for the development of advanced fuel cycles should be carried out in parallel with the current mainstream fusion pathway that primarily focuses on DT tokamaks, such as ITER, test facilities, DEMO, and power plants.

In conclusion, a correct choice of materials for DHe3 reactors permits to select those ones which can be declassified to non-radioactive material when used in the first wall structure: this result is not obtainable in the case of DT reactors.

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