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Technical note

The zero-waste option for nuclear fusion reactors: Advanced fuel cycles and clearance of radioactive materials

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Abstract

This paper deals with the radioactive waste issue for fusion reactors, proposing an innovative solution (the "zero-waste" option), which could be a clear advantage of fusion power versus fission, in view of its ultimate safety and public acceptance. Its goal is the Clearance (declassification to non-radioactive materials) of all reactor components, after a sufficient period of interim decay, according to the recommendations recently issued by IAEA.

Even if feasible in theory, a zero-waste option for fusion reactors using the Deuterium–Tritium fuel cycle will be difficult to obtain in practice: a relevant amount of radioactive materials from reactor decommissioning – even if recyclable within the nuclear industry – should be disposed of as low-level waste.

As a further step towards the zero-waste option, the features of fusion reactors based on alternative advanced fuel cycles have been examined, to assess whether that goal could be reached for such devices. Fusion reactors with advanced Deuterium–Helium-3 (DHe) fuel cycle have quite outstanding environmental advantages. Compact ignition tokamaks can be designed in order to achieve DHe ignition. Ignitor, a compact ignition experiment aimed at studying DT plasmas, may also be used in that direction. The extrapolation of Ignitor

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technologies towards a larger and more powerful experiment using advanced fuel cycles (Candor) is described. Results show that Candor does reach the zero-waste option.

A fusion power reactor based on the DHe cycle could be the ultimate correct response to the environmental requirements for future nuclear power plants.

1. Introduction

The attractive safety and environmental potential of fusion can be fully realised by a power plant design in which attention is paid to reducing the impact of materials activation. Activated materials, generated by neutron interactions with plant structure, will be removed from the plant during routine blanket and divertor replacements, and then in decommissioning at end-of-life. One of the main goals for fusion is the minimisation of radioactive waste originating from a power plant, with a waste management strategy including the maximum reasonably possible use of materials recycling – within the nuclear industry – and materials clearance (i.e., declassification to non-radioactive material).

This paper concentrates on the radioactive waste issue for fusion, proposing an approach (the "zero-waste" option), which could be a clear advantage for fusion power, in view of its ultimate safety and public acceptance. A recent publication from International Atomic Energy Agency (IAEA, 2004) defines reference levels of concentration of radionuclides in order to declassify materials to non-active ones: these levels will be used to define the requirements of the zero-waste option. It will be shown that the requirements cannot be fulfilled 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 obtained by those devices.

2. Fusion waste management and clearance

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. The dominating waste mass stream is generated in the decommissioning stage. A great deal of the decommissioning waste has a very low activity concentration, especially when a long period of intermediate decay is anticipated. Radioactive nuclides in fusion waste are mainly solid metallic activation products and tritium; it is quite different from fission waste, both in type of material and isotopic composition (Taylor et al., 2001; Cheng et al., 1998). The options for handling fusion waste must therefore be sharply different than those for fission. In most countries with a nuclear fission program, waste management strategies are based on deep geological disposal of high-level waste (HLW) and/or long lived waste, including spent fuel, while a less sophisticated disposal method, mostly a near-surface type repository is used for low-level or intermediate-level waste (LLW/ILW), short-lived or not-heat-generating waste. The acceptance criteria mainly deal with isotope specific or total activity concentration limits.

For fusion waste, however, it is appropriate to explore solutions that minimise the use of final repositories. For this purpose, a waste management strategy – adopted for fusion long-term studies such as SEAFP (Raeder et al., 1995) and PPCS – was developed (Rocco and Zucchetti, 2000). It was 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), based upon an extension to fusion of two documents emitted by IAEA and ICRP and available in that moment (IAEA, 1996; ICRP, 1998).

This recycling and clearance strategy appears to have a great potential interest, since its application could reduce the amount of permanent disposal waste (PDW) of SEAFP and PPCS plant models to almost zero: about 70% of the total could be recycled and 30% cleared to non-active material (Rocco and Zucchetti, 2000).

In particular, those studies have identified in recycling – after a long interim decay period (up to 100 year) – the main way for avoiding the production of permanent disposal waste, even for components close to the plasma.

In fact, the direct reuse or recycling of materials within the nuclear industry, usually after a decay period of up to 50 years, keep the material out of the waste stream. For example, recycled materials may be used to fabricate further components for nuclear power plants of any type.

The feasibility of recycling fusion materials has been the subject of studies for some years. It is generally assumed that the radiological criterion, which determines the possibility of recycling, is based on the gamma dose rate at the surface of the material (“contact” dose rate).

However, recycling is a question dealing not only with radiation protection, 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.

Economical assessment of waste recycling must be considered too. Recycling processes and long-time storage of fusion waste should raise the price of waste more than market prices of industrial waste. Economically viable strategies must be envisaged for recycling.

In conclusion, it seems that, even if feasible in theory, a zero-waste option for fusion reactors will not be possible: a relevant amount of radioactive materials from reactor decommissioning – even if “recyclable” – should be disposed of as radioactive waste. Most probably, those materials will meet requirements for classification as low-level waste; however, it must be stressed their difference from fission high-level waste, in terms of lower hazard during its transport and lower cost and requirements for its disposal.

However, the production of such waste cannot be avoided – for fusion power reactors – by means of the choice of their structural and constituting materials: it always occurs if a Deuterium–Tritium fuel cycle is used for fusion. Studies have shown (Ciampichetti et al., 2002) that even the adoption of low-activation materials, such as vanadium alloys, for the blanket and the first wall of fusion reactors (i.e., the structures most exposed to the neutron flux from the plasma, and the most activated ones) is not sufficient for the scope. It is practically impossible to reduce the long-term radioactivity of selected materials to levels allowing clearance of in-vessel structures. Even if vanadium-based alloys are at the moment the only material with sufficiently low-activation constituting elements, attainment of clearance conditions in activated in-vessel vanadium-based alloys structures would require very low concentrations of impurities, not achievable with the current purification methods and, in some cases, below the present detection limits, and to develop methods to reprocess the activated alloy for extracting radiotoxic nuclides.

A step forward – if the zero-waste result has to be achieved – is necessary. However, before that, the implementation of the new IAEA recommendations about materials clearance must be discussed, since rules have recently changed in the definition of clearance.

Although all national regulations have some "exemption limits" that allow materials clearance, some of them do not consider explicitly fusion-relevant nuclides, while other ones are too restrictive. Implementation into national regulations of clearance rules following the IAEA recommendations is the solution.[2] In some cases, they result in higher (i.e., less stringent) limits than the limit of 1000 Bq/kg, regardless the nuclide type, which is closer to typical national regulations definitions of de minimis.

The new IAEA clearance limits (IAEA, 2004) are a decisive progress in this direction and they will be briefly described here.

The International Basic Safety Standards for Protection against Ionising Radiation and for the Safety of Radiation Sources (the BSS) specify requirements for the protection of health against exposure to ionising radiation and for the safety of radiation sources (FAO, 1996). The BSS are based on information on the detrimental effects attributed to radiation exposure provided by the United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR (United Nations,

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[2] A first example of this can be found in the recent new German radiation protection ordnance (German Law, 2001), emitted in July 2001: this regulation permits Clearance, using a nuclide-by-nuclide clearance index similar to the IAEA approach. Another recent regulation has been issued in Italy (Italian Law, 2003), concerning the "*Allontanamento*" (Italian word for "clearance") of solid radioactive spent materials. This regulation is necessary for the ongoing decommissioning activities of the four shut down Italian fission reactors. Concentration limits are issued for each relevant nuclide, however, they may be partially summarised – for our purposes – as follows: a non-alpha-emitter metallic material may be cleared, if its specific activity is less than 1 Bq/g. For other materials than metallic ones and concrete, the limit is 0.1 Bq/g, while for concrete the limit is almost half-way, depending on the type of nuclides. Recycling in Italy is permitted for cleared material only.

Table 1
Clearance limits (Bq/g) according to IAEA recommendations (IAEA, 2004) for some relevant nuclides

Nuclide	Clearance limit (Bq/g)	Nuclide	Clearance limit (Bq/g)
H-3	100	Nb-94	0.1
Mn-54	0.1	Mo-99	10
Co-58	1	Ag-110m	0.1
Co-60	0.1	Eu-152	0.1
Ni-59	100	Eu-154	0.1
Ni-63	100	Ta-182	0.1
Cu-64	100	Ir-192	1

2000), as well as on the recommendations of the International Commission on Radiological Protection, ICRP (ICRP, 1991).

The BSS define the terms and explain the use of the concepts of exclusion, exemption and clearance[3] for establishing the scope of regulatory control (CEC, 1993). In the case of clearance, in particular, the BSS define the concept and the radiological criteria to be used as a basis for determining clearance levels but leave their establishment to national authorities.

The safety guide includes specific values of activity concentration for both radionuclides of natural origin and those of artificial origin that may be used for bulk amounts of material for the purpose of applying exclusion or exemption. It also elaborates on the possible application of these values to clearance.

Concentration limits for clearance are issued in the IAEA guide for each relevant nuclide for fission and fusion. Activation products of steels and other candidate materials for fusion have concentration limits that range from 0.1 Bq/g (e.g., Co-60 and most impurities activation products) to 100 Bq/g, that is also the limit for Tritium (see Table 1).

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 I_c may be computed as

$$I_c = \sum_{i=1}^{Z} \frac{A_i}{L_i}.$$

The material can be cleared if: $I_c \leqslant 1$.

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[3] 'Exclusion' means the deliberate exclusion of a particular category of exposure from the scope of an instrument of regulatory control on the grounds that it is not considered amenable to control through the regulatory instrument in question. Such exposure is termed excluded exposure. 'Exemption' means the determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure (including potential exposure) due to the source or practice is too small to warrant the application of those aspects. 'Clearance' means the removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body. Removal from control in this context refers to control applied for radiation protection purposes.

These recommendations are likely to be implemented in national regulations. They appear to be generally a bit more stringent than the previously issued ones (IAEA, 1996), upon which the above-mentioned evaluations for fusion materials (Rocco and Zucchetti, 2000) were based.

Therefore, also if the new clearance limits were applied, it is confirmed that, if a total clearance of fusion reactor materials is our goal, a further progress is necessary. That must necessarily consist in avoiding the use of the Deuterium–Tritium fuel cycle, in order to minimise neutron fluxes and then neutron-induced radioactivity in plant components.

3. Advanced fuel cycles and the zero-waste option

Most of the studies and experiments on nuclear fusion are currently devoted to the Deuterium–Tritium (DT) fuel cycle, since it is the easiest way to reach ignition. Even if physical and technological demonstration of fusion power has yet to be obtained, some of the main technological questions of future DT fusion reactors have been identified already. Among those, in particular, the radioactive inventory in such reactors is due, besides tritium, to the neutron-induced radioactivity in the reactor structures.

The recent stress on safety by the world's community has stimulated the research on other fuel cycles than the DT one, based on 'advanced' reactions, such as Deuterium–Deuterium (DD) and Deuterium–Helium-3 (DHe). With these cycles, it is not necessary to breed and fuel tritium. The DHe cycle, moreover, has a very low presence of fusion neutrons. In fact, the DHe cycle is not completely aneutronic, due to DD side reactions generating 2.45 MeV neutrons and T, and to DT side reactions generating 14.07 MeV neutrons. Neutron fluxes are, however, much lower than for DT reactions (Zucchetti, 1991).

The inherent cost of a fusion power reactor will hardly make it competitive with fission reactors from the economic viewpoint: a clear environmental excellence must be one of the strong points to make fusion competitive. At the long term, this excellence can be obtained by means of DHe reactors.

DHe fusion has its own set of problems, such as the availability of ^{3}He and the attainment of the higher plasma parameters that are required for burning. However, they have also other advantages, like for instance the possibility to obtain electrical power by direct energy conversion of proton. A fusion power reactor based with DHe plasmas would not need a blanket to breed tritium, and also it would not need to produce electrical power indirectly, via the usual heating of a thermo-vector fluid (such as water of liquid metal) and its use in a thermodynamic cycle with a turbine (Zucchetti, 1998).

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

To begin to explore the possibilities of DHe 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 (Coppi, 1982).

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 (Boxman et al., 1975) and Frascati Torus Upgrade (FT/FTU) at ENEA in Italy (FTU, 2005).

Ignitor is a proposed compact high magnetic field tokamak, and it is aimed at reaching ignition in DT plasmas and at studying them for periods of a few seconds (Coppi et al., 1992; Coppi and Airoldi, 1999; Ignitor, 2005). However, 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 DHe 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 DHe reactions can supply thermal energy to a well-confined plasma (Coppi et al., 1994). 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 (Coppi et al., 2000). In particular, as a start, Ignitor can allow initial studies at the level of $\approx$1 MW of power in charged particles from the DHe reaction in a mostly DT plasma (Coppi et al., 1994, 2000; Sugiyama, 1989).

A design evolution of Ignitor in the direction of a power reactor using a DHe fuel cycle has been proposed. A feasibility study of a high-field DHe 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 (Coppi, 1982; Coppi et al., 1994). The main characteristics of the Candor machine are the following:: the major radius R_0 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. The toroidal field coils are divided into two sets of coils and that the central solenoid (air core transformer) is placed between them in the inboard part.

The DHe 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 DHe fusion experiments, Candor is capable of reaching DHe ignition on the basis of existing technologies and knowledge of plasma. With this method, the need for an intense auxiliary heating, which is one of the main technological drawbacks of DHe 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' DHe plasmas, and a neutron flux transient when passing from the initial DT trigger reaction to the final DHe 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.

Table 2
Neutron activation in Candor main components

Component	Zero	1 day	1 week	1 month	1 year	10 years	25 years
Internal toroidal magnets	4.3×10^6	8.0×10^5	9.2×10^2	5.1×10^2	3.9×10^2	1.3×10^2	40
Transformer coils	3.0×10^5	5.9×10^4	5.1×10^1	2.4×10^1	1.7×10^1	5.0	1.7
External toroidal magnets	9.7×10^4	1.9×10^4	1.3×10^1	5.4	2.8	0.47	0.18
Structure (C-clamp)	1.4×10^3	9.6×10^2	2.6×10^2	4.2×10^1	2.0	0.21	0.023

Activity concentration (Bq/g) at different decay times after maximum (end-of-life) irradiation.

Tritium inventory in Candor is expected to be very small and not to be a problem from the safety viewpoint. Neutron power fractions in a Maxwellian plasma for various ion temperatures and fuel mixtures have been determined for instance in (Fundamenski and Harms, 1996). For Candor, neutron transport calculations to determine its neutronics were performed, and the results are available in (Zucchetti, 1998). Neutron activation has been calculated there too: activity concentrations and dose rates are the main output of the simulation. Table 1 shows some activation data at end-of-life (maximum) irradiation. The main result of the study is that neutron activation is quite moderate.

The quantity and quality of radioactive waste from the machine operation and decommissioning has been estimated: total radioactivity concentrations in Table 2, nuclides concentrations and gamma dose rates show that no Candor spent material will need to be disposed of as permanent waste in underground repositories. All materials may be recycled, if convenient, after a short interim decay.

Concerning clearance, we have that most of the components far from the plasma could be immediately cleared. However, we obtain a further most important result: all the components – even those closer to the plasma chamber – if a longer interim decay is accorded, can be eligible for clearance, according to the new IAEA limits. In particular, all components but internal magnets may be declassified after less than 10 years of decay. For internal magnets, 20 years of interim decay are necessary.

In other words, Candor does reach the zero-waste option, without the need of any materials selection, low-activation materials, or further shielding.

The final design of a fusion power reactor with DHe plasmas has yet to be conceived. However, the zero-waste option is a reachable goal for such reactors, as the results for Candor have indicated.

4. Conclusions

Concerning the radioactive waste issue for fusion, the “zero-waste” option – proposed in this paper – can be a clear advantage for fusion power, in view of its ultimate safety and public acceptance. It deals with Clearance (declassification to non-radioactive materials) of all reactor components, after a sufficient period of interim decay, according to the clearance indices recently recommended by IAEA.

Even if feasible in theory, a zero-waste option for fusion reactors using the Deuterium–Tritium fuel cycle will be hard to obtain.

As a further step towards this goal, the features of fusion reactors based on alternative advanced fuel cycles have been analysed. Fusion reactors with advanced Deuterium–Helium-3 (DHe) fuel cycle have quite outstanding environmental advantages, such as the quite low presence of Tritium, neutrons and activated materials.

Compact high-field ignition tokamaks can be designed in order to achieve DHe ignition. Ignitor, a compact ignition experiment aimed at studying DT plasmas, may also be used in that direction. The extrapolation of Ignitor technologies towards a larger and more powerful experiment using advanced fuel cycles (Candor) has been described.

Results obtained for Candor show that, even with the presence of DT plasmas triggering, Candor does reach the zero-waste option.

The final design of a fusion power reactor with DHe plasmas has yet to be conceived. However, the zero-waste option is a reachable goal for such reactors, as the results for Candor have indicated.

Studies for the development of compact ignition tokamaks and advanced fuel cycles must be carried out in parallel with the current mainstream development line, which deals with larger tokamaks and DT plasmas, i.e., the International Tokamak Experimental Reactor (ITER) and DEMO designs.

We think, in fact, that a fusion power reactor based on the DHe cycle could be the ultimate correct response to the environmental requirements for future nuclear power plants.

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