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Advanced management concepts for fusion waste

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Abstract

This paper presents fusion waste management studies carried out under the long-term actions on Safety and Environment of the European Fusion Technology Programme. The fusion-specific strategy proposed here aims at reducing the permanent radioactive waste. Recycling is the solution investigated for in-vessel materials, which have high activation levels. Limits on surface dose limits define the feasibility of recycling by remote handling and by hands-on operation. The feasibility of clearance for materials having lower activation levels, is assessed with limits of the concentration of the radionuclides contained in the waste, weighting their respective potential hazard. This strategy is applied to two power reactor designs: PM-1, PM-2, representing advanced solutions or moderate progress on present technologies. It is shown that the amount of permanent radioactive waste can be reduced by recycling and clearance in both designs, but with significant advantages in the case of PM-1.

1. Introduction

Fusion waste management aspects were assessed in the long-term safety and environmental actions SEAFP [1] and SEAL [2] of the European Fusion Technology Programme.

The present action in this field is SEAFP-2, which concentrates upon two main issues:

- Definition of a containment strategy, and implementation, to minimise releases in worst accidents.
- Definition of a waste management strategy, and implementation, to minimise repository volumes and hazards.

This paper deals with the second item, waste management, and presents SEAL and SEAFP-2 studies which improve results reported in [3,4].

2. A proposed waste management strategy for fusion activated waste

The analysis is based on the supposition of an initial period of 50 years of decay of the activated waste at the reactor site. After this period, three options may be applied depending on the residual radioactivity of the waste:

- Recycling: build new pieces for nuclear installations with the activated material, either keeping all residual radioactivity or eliminating previously the most noxious radionuclides.
- Clearance: the release of the activated material from regulatory control and its disposal as non-active waste.
- Permanent disposal as radioactive waste of the waste fraction which cannot be recycled or cleared.

3. Recycling

Only the radioactivity aspects of recycling linked with remote operation are analysed here, without dealing with the two possible options of forming the new pieces: (a) without reducing the residual radioactivity or, (b) by eliminating noxious radionuclides with reprocessing. In the SEAFP-2 study, like in SEAL, a contact dose rate of 10 μSv/h is taken to be the limit for hands on recycling (HOR), in compliance with the 1990 ICRP Recommendations [5], and remote handling recycling (RHR) is assumed feasible in the range 10 μSv/h – 10

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mSv/h with different grades of shielding precautions. These values were proposed in [6] and are a slight reduction of the limits proposed by the authors and adopted in SEAFP: 25 μSv/h and 20 mSv/h for HOR and RHR.

4. Clearance

In SEAL and SEAFP-2 studies limits on specific activity of waste allowing clearance are assigned taking into account the potential hazard of each radionuclide contained. Unconditional clearance levels of radionuclides are taken either directly or evaluated according to methods shown in [7] and explained in Appendix A. The feasibility of clearance for waste containing mixtures of radionuclides is evaluated in the same Appendix A with "clearance indices" obtained from weighted averages of the clearance levels.

The clearance levels in fusion-relevant radionuclides, derived from [7] and adopted in SEAL analyses may be found in [3]. In the SEAFP-2 study some safety factors are applied to the clearance levels adopted in SEAL, which are reduced as follows:

- clearance levels which are smaller than 1000 Bq/kg are unchanged,
- clearance levels between 1000 Bq/kg and 10000 Bq/kg are reduced to 1000 Bq/kg,
- clearance levels greater than 10000 Bq/kg are reduced by a factor 10.

These reduced clearance levels are shown in Table 1.

Table 1
Clearance levels L_c for the most important nuclides in fusion activated materials, reduced by safety factors. SEAFP-2 analyses

Nuclide	Half life years	L_c [a] Bq/kg
H_3	12.35	3×10^5
Be_{10}	1.6E6	4×10^3
C_{14}	5730	3×10^4
Al_{26}	7.16E5	4×10^2
Si_{32}	450	1×10^3
Cl_{36}	3.01E5	3×10^4
K_{40}	1.28E9	1×10^3
Ca_{41}	1.4E5	7×10^4
Mn_{53}	3.7E6	6×10^4
Fe_{55}	2.7	3×10^4
Co_{60}	5.271	3×10^2
Ni_{59}	7.5E4	3×10^4
Ni_{63}	96	3×10^5
Nb_{93m}	13.6	2×10^4
Nb_{94}	2.03E4	3×10^2
Mo_{93}	3.5E3	9×10^3
Tc_{99}	2.13E5	3×10^3
Ag_{108m}	127	6×10^2
Ag_{110m}	249.9	3×10^2
Sn_{119m}	0.802	5×10^3
Sb_{125m}	2.77	1×10^3
Ir_{192}	0.203	1×10^3
Ir_{192m}	241	1×10^3

[a] different from those adopted in SEAL which are shown in Ref. [3].

5. Application to activated waste arising from fusion power plants

5.1. Power reactor models, calculations tools and hypotheses

Results of analyses presented here concern two reactor models, having a power of about 3000 Mw_{th}. PM-1 is an advanced design, with V–4Cr–4Ti as in-vessel structural material, Li_2O ceramic pebble bed breeder and helium coolant, whereas PM-2 represents a near-term development, with in-vessel structures made with low activation martensitic steel, Pb-17Li breeder and water coolant. Reactor outward zones are the same in both models. These two models analysed in SEAFP-2, apart some changes in the materials compositions, are intrinsically the same examined in SEAFP and SEAL studies. Reactor and materials data may be found in [8]. Activation levels are evaluated by the code FISPACT-4 [9], with 1-D neutron fluxes as inputs, a Mean Neutron Wall Loading of 2 MW/m^2 and a continuous irradiation of 5 years, 25 years, 15 months for in-vessel-, out-of-vessel-zones and divertor, respectively.

5.2. Sorting of activated waste

Table 2 shows the application of the management options indicated above for PM-1 and PM-2 as evaluated in SEAL [3]. All waste arising from PM-1 could either be recycled or cleared, whereas about 13% of the PM-2 waste should be disposed of. This result confirms the excellent low-activation characteristics of the V alloy. An increase to 100 years of the decay period would reduce the PM-2 waste to be disposed of to the divertor copper only.

PM-2 results show that the outboard zones of the vacuum vessel and toroidal field coil can be cleared, whereas the inboard zones, which are less effectively shielded, must be recycled. Inboard TFC could be cleared after an interim storage prolonged to 100 years. It has also to be noted that the material which can be cleared is less in PM-1 than in PM-2. This is due to the better shielding properties of the PM-2 blanket. The effect of recycling on the long-term contact dose of waste is shown in Table 3. It is seen that the the residual radioactivity of the recycled material is soon overwhelmed by the newly built radionuclides, thus the activation during operation and for short decay timesshutdown of a shield material does not change, either with a new or with a recycled material.

Table 2
Sorting of PM-1 and PM-2 activated waste. SEAL analyses

Management option	PM-1 weight, t(%)	PM-2 weight, t(%)
Disposal	[a]	8787 [d] (12.75)
Recycling	40288 [b] (69.6)	33122 [e] (48.05)
Clearance	17677 [c] (30.4)	27020 [f] (39.2)
Totalweight, t(%)	58265 (100)	68929 (100)

[a] No material to be disposed of.
[b] Blanket & divertor V–5Ti, vacuum vessel OPTSTAB, AISI316 of divertor plug; Be, Li_2O, Pb.
[c] All material not included in [b].
[d] Divertor copper, front-mid blanket martensitic steel.
[e] AISI316 of divertor plugs, mid-rear blanket, martensitic steel, Pb–17Li breeder, shield and inboard vacuum vessel OPTSTAB, 26% of Nb-Sn superconductors (inboard zone).
[f] Outboard vacuum vessel OPTSTAB, Pb, B_4C, toroidal field coil (TFC) casings AISI316, 74% of Nb–Sn superconductors (outboard zone), TFC insulators.

Conversely, the long-term radioactivity may change, depending on long-lived nuclides build-up. In the case of V–4Cr–4Ti, enough long-lived nuclides are produced during the first irradiation in blanket conditions, such that the 50-years contact dose rate of a recycled material (i.e., 130 years in total after the beginning of the first irradiation) is five times higher than the same figure for a first-use material. On the other hand, long-lived nuclides production in the low-activation martensitic steel is not enough to make a difference. In fact, no appreciable differences in the long-term dose rate are found between re-used and new material.

5.3. An alternative to recycling: Reprocessing and clearance

Recycling has the merit of a radical reduction of the radioactive waste, but the disadvantages linked with the use of ''old and radioactive'' materials in new plants. Evaluations presented in [3], proposed an alternative to recycling, consisting in the reprocessing of V–5Ti, the vanadium alloy adopted in PM-1 during the SEAL phase, with elimination of the noxious radionuclides, followed by clearance, i.e. the declassification to non-active waste after 50 years of cooling. The irradiation conditions were that of the average flux in the blanket. Nb_{94}, deriving from activation of 60 ppm of niobium impurity in the alloy, exceeded its clearance level by more than 2×10^4. Also other radionuclides exceeded, even if to much lesser extents, their clearance levels. Taking a 50% weight of Nb_{94} as contributor to the total hazard, It was found that the clearance could be possible if: (a) Nb_{94} activity were reduced by a factor 2.5×10^{-5} and, (b) the activities of the other radionuclides were reduced in such a way that the sum of all factors A_c/L_c, included that of Nb_{94}, be less than the unity. A reduction of the niobium concentration in the alloy to 0.1 ppm, reduces the Nb_{94} activity by a factor of 600. A further reduction by a factor of 70 should be obtained by reprocessing. A process based on elemental dilution with stable niobium and zone melting with suppression of niobium impurity could possibly be adopted. Nb_{93m} activity would be also reduced by the methods described above, other processes should be investigated to reduce

Table 3
Effect of recycling on surface dose rates (Blanket irradiated materials recycled as shield materials compared to new materials irradiated in shield). SEAFP-2 analyses

Irradiation and/or cooling periods	Surface dose rate of recycled material	Surface dose rate of new material
V-4Cr-4Ti in PM-1 [a]		
5 years of irradiation in outboard blanket	2.6×10^4 Sv/h	–
50 years of cooling	1.38 mSv/h	–
25 y of irradiation in outboard shield	7.6×10^3 Sv/h	7.6×10^3 Sv/h
50 years of cooling	1.3 mSv/h	0.25 mSv/h
Low-activation Martensitic Steel in PM-2		
5 years of irradiation in outboard blanket	6.3×10^3 Sv/h	–
50 years of cooling	20 mSv/h	–
25 y of irradiation in outboard shield	1.6×10^2 Sv/h	1.6×10^2 Sv/h
50 years of cooling	8.1 mSv/h	8.0 mSv/h

[a] V–4Cr–4Ti substitutes V–5Ti adopted in SEAFP and SEAL.

the activities of C_{14}, Ni_{63} and other noxious radionuclides. It is envisaged to deepen the same analysis on the V–4Cr–4Ti–alloy adopted in SEAFP-2.

5.4. Tritium effects

Management options defined previously are based on activation level only. Complementary evaluations concern the influence of the tritium permeated in the activated materials. By developing results of French experiments it is shown in [3] that, after detritiation procedures, steel reprocessed from in-vessel zones and formed into new pieces will have residual tritium outgassing rates of less than 2×10^5 Bq/kg per day. 1000 kg of such pieces in a 350 m^3 laboratory with 5 air changes per hour will produce a tritium concentration of less than 5×10^3 Bq/m^3. According to [10] the dose rate due to this concentration is 0.15 μSv/h which is negligible, thus lower rates of air changes could be adopted without harm. It is also shown that tritium occasionally present in out-of-vessel zones cannot hamper clearance. The tritium expected concentrations in these zones are of thousands of Bq/kg, at maximum. They may be compared with the clearance levels of tritium of Table 2: 3×10^5 Bq/kg. Hence, following the method indicated in Appendix A, it is seen that tritium contributions to the clearance indices of these zones are small fractions of the total and may be neglected.

6. Conclusions

- The proposed waste management strategy is based upon recycling and clearance as ways to reduce/eliminate permanent radioactive waste.
- Feasibility of recycling is assessed from limits on the waste contact dose rate. Additional assessments should include:
  1. Recycling by keeping radioactivity within the new pieces, or
  2. Recycling by previous reprocessing to extract the noxious radioisotopes.
- Whereas in SEAFP the feasibility of clearance was based on the compliance of waste with a fixed activity limit, in SEAL and SEAFP-2 clearance depends upon the relative hazards of the nuclides contained in the waste. Clearance levels adopted in SEAL and SEAFP-2 derive from an IAEA interim proposal. Clearance levels of radionuclides and waste clearance indices used in calculations on real cases should be agreed by the Regulatory Authorities. To be on the safe side, SEAFP-2 evaluations also consider safety factors on clearance levels proposed by IAEA.
- The proposed management strategy has been applied successively to plant models defined in SEAFP, SEAL and SEAFP-2, and irradiated materials have been sorted following the various options.
- It turns out that most materials may be recycled or cleared. For instance, in PM-1, about 70% in weight can be recycled, and 30% can be cleared. In PM-2 a 13% amount should be disposed of.
- An alternative to material recycling, consisting in its reprocessing (to eliminate noxious nuclides), followed by clearance, has been considered, and applied to the V–5Ti alloy adopted in SEAL in-vessel structures. This analysis will be deepened on the V–4Cr–4Ti alloy adopted in SEAFP-2.
- The effect on materials activation of multiple recycling has been studied: it turns out that it is appreciable, for certain materials such as V-alloys, only in the long term after the end of the last irradiation.
- The effect of tritium presence in the activated material has been taken into account, turning out to be negligible.

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Appendix A. Unconditional clearance levels of radionuclides according to Ref. [7] and clearance indices

Clearance levels of many radionuclides are given in [7]. They are obtained from various safety analyses of radioactive waste repositories, where 10 μSv/a and 100 μSv/a are taken as dose limits for the Most Exposed Individual of the public in "likely" and "unlikely" accidents scenarios.

Clearance levels of radionuclides not given in [7] may be evaluated taking the minimal value among the following three expressions

$$\left\{ \frac{1}{E_\gamma + 0.1E_\beta} \; \frac{\mathrm{ALIinh}}{1,000} \; \frac{\mathrm{ALIing}}{100,000} \right\} (\mathrm{Bq/g}),$$

where Bq/g is the bulk activity, $E\gamma$ and E_β are the effective energy of the beta and gamma emission in MeV, ALI_{inh} and ALI_{ing} are the most restrictive values of the Annual Limit of Intake by inhalation and ingestion, Bq. An irradiated material contains a mixture of radionuclides. The authors propose to evaluate a "clearance index" I_c in the following way: given the specific activity A_i of the z radionuclides contained in the material after 50 years of decay and the related clearance levels L_i, I_c is given by

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

The material can be cleared if: $I_c < 1$.

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