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Abstract

The development of commercial fusion plants includes the demonstration that the waste burden for future generations would be avoided. In order to minimize the radioactive material requiring long-term storage, maximum emphasis should be placed on recycling and clearance, avoiding geologic disposal. Clearance is the most desirable option for components like the vessel, shield, magnets and bioshield, which make up a great part of the mass and are only mildly irradiated. Recently, the International Atomic Energy Agency, the U.S. Nuclear Regulatory Commission and other institutions have revised clearance guidelines for nuclear applications. In this paper, the implications of these new standards, particularly for slightly irradiated fusion materials, are considered. The amount of clearable materials is lower and/or the cooling period is longer than previously estimated. It becomes more evident now that improvements to the clearance data are needed to include many missing fusion-specific nuclides, and that the control and measurement of impurity levels, even for materials subjected to low neutron exposure, is important. Segregation of components into more basic parts also plays a key role in minimizing the amount of waste. Finally, the issue of public acceptability of cleared materials is discussed since the unrestricted release of radioactive materials to the market is still controversial, despite the extremely low level of activity ($\leq$ 10 μSv/y) – way below the natural background.

1. Introduction

To fully exploit the favorable inherent safety and environmental characteristics of fusion power, careful attention should be paid to the disposition of active materials during operation and after decommission. In order to minimize (or eliminate) the volume of activated materials that requires long-term storage (> 100 y), full use should be made of both recycling within the nuclear industry and "clearance" or release to the commercial market as non-radioactive material for general recycling. The latter has recently been considered in several conceptual fusion power plant studies over the last decade [1-8]. This paper examines the feasibility of applying the clearance approach to the slightly activated components of the newly developed U.S. and EU fusion power plants using the most recent clearance guidelines.

Most radioactive materials generated from fusion power plant operation and decommissioning are activated solid metallic materials from the main machine components and concrete from the biological shield. Some components will also have surface contamination including tritium. The dominant radioactive material mass stream is generated in the decommissioning stage, but a significant amount is also produced by routine blanket and divertor replacement during operation. A great deal of the decommissioning materials (up to 80%) has a very low activity concentration and can be cleared from regulatory control, especially when a long period (up to 100 y) of intermediate decay is anticipated. Radioactive nuclides in fusion activated materials are mainly solid metallic activation products and tritium. While the fission power industry also has to manage activated structural materials originating from the decommissioning phase, the main source of fission high-level waste is the spent fuel or, in case of reprocessing, vitrified highly radioactive waste. Presenting the main environmental issue for nuclear power worldwide, these materials are very different from fusion activated materials, both in type of material and isotopic composition [9]. For instance, fusion radioactive materials are classified as low-level waste, do not contain long-lived transuranics or fission products and have no proliferation relevance. Their global radiotoxicity is inferior and short-lived compared to fission. Despite these differences in the basic characteristics of the active materials, the reprocessing and recycling experience gained from handling and managing the fission activated materials will be very useful to the fusion industry.

2. Clearance Regulations

Clearance, as defined by the International Basic Safety Standards (BSS) for Protection against Ionizing Radiation and for the Safety of Radiation Sources [10], means the removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory agency. Removal from control in this context refers to control applied for radiation protection purposes.

For the clearance of materials, one approach has been to compute a clearance index by application of nuclide-by-nuclide clearance levels, based on various national or international guidelines. Although few countries yet have such an approach enshrined in law, guidelines have been issued by competent authorities, and over the past five years, the U.S. Nuclear Regulatory Commission, European Commission, and International Atomic Energy Agency (IAEA) have issued revised clearance levels, taking into account the previous guidelines.

Although the national regulations for many nuclear qualified countries include “exemption limits” that in some cases allow materials clearance, these regulations are typically in terms of a total specific activity (Bq/g or Bq/m^3). Where nuclide-specific limits are prescribed, these typically do not include some important fusion-relevant nuclides. There is clearly the need for an internationally-agreed set of clearance limits of relevance to fusion, especially if cleared materials could potentially be introduced into the international market. The newly issued IAEA international guidelines [11] are a useful step towards this direction.

Concentration limits for clearance are issued in the IAEA guidelines for each relevant nuclide for fission and fusion [11]. Activation products of steels and other candidate materials for fusion have a wide range of concentration limits, e.g., 0.1 Bq/g for ^{60}Co and most impurities' activation products, 100 Bq/g for tritium, and 1000 Bq/g for ^{55}Fe and ^{186}Re (see Table 1). For materials with more than one radioactive nuclide, given the specific activity A_i (in Bq/g) and the clearance level L_i of each nuclide contained in the material, a clearance index (CI) can be computed as the weighted sum of all nuclide specific activities divided by the corresponding clearance limits:

$$CI = \Sigma_i \ (A_i / L_i).$$

A material can be cleared if CI ≤ 1. Typically it would be an aim to achieve this during the 100 year storage period following decommissioning, and preferably within a few years.

The 2004 IAEA recommendations appear to be more stringent – at least for some radionuclides of particular interest to fusion – than the previously issued guidelines [12], upon which former evaluations for fusion materials [1-6] were based. For instance, the 2004 guidelines call for lower clearance limits (i.e., more stringent) for ^{14}C, T, and ^{60}Co (factors of 300, 30 and 3, respectively) compared to the previous 1996 standards [12]. This means it takes longer times for these materials to reach clearance.

For more than 50 years, the Nuclear Regulatory Commission (NRC) and its predecessor agency have attempted to give greater uniformity to the clearance standards while materials containing traces of radioactivity continued to be released to date on a case-by-case basis. More attempts by the NRC in the 1980s, 1990s, and just recently in 2003 declared materials with low concentrations of radioactivity could be deregulated. Based on a detailed technical study, the NUREG-1640 document [13] contains estimates of the total effective dose equivalent (from which the clearance index can be derived) for 115 radionuclides that could be present in activated steel, copper, aluminum, and concrete from decommissioning of nuclear facilities. The NRC has not yet issued an official policy on the unconditional release of specific materials. Herein, the proposed annual doses reported in the NUREG-1640 document will be referred to as the proposed U.S. limits.

3. Comparison of Different Guidelines and Missing Elements in Clearance Standards

Many different studies over the years, both national and international, have yielded sets of nuclide-specific clearance limits. The differences may be in part due to differences in data such as dose conversion coefficients, but more significantly they are based on different methodologies and scenarios for the way in which individuals may be exposed to radiation from the material. As an example, Figures 1 and 2 display the ratios of the U.S. limits to the IAEA's for steel and concrete. Even though the U.S. and IAEA recommended an individual dose standard of 10 μSv/y (1 mrem/y) for cleared solids, we observed notable differences between the two sets of clearance limits. Table 1 lists the clearance limits for selected radioisotopes encountered in fusion applications. Notice some limits are more restrictive while others are more liberal. The U.S. study incorporated realistic modeling of the current U.S. industrial practices as well as current data on the living habits in the U.S. in order to minimize unnecessary conservatism in the dose estimates. The IAEA study was based on a set of exposure scenarios including direct radiation, inhalation and ingestion, and also took into account some of the national studies (including the U.S. study).

Concerning some fusion-relevant nuclides, additional effort is needed to reduce the differences between the various standards and understand the technical reasons for the major disagreements. It would be particularly valuable to develop a set of clearance limits for use in fusion studies, with international consensus, including all relevant nuclides. Numerous fusion radioisotopes with $T_{1/2}$ ≥10 y are missing from the U.S. and IAEA standards and should be included in future evaluations. These missing radioisotopes include, but are not limited to, ^{10}Be, ^{26}Al, ^{32}Si, $^{91,92}Nb$, ^{98}Tc, ^{113m}Cd, ^{121m}Sn, ^{150}Eu, $^{157,158}Tb$, $^{163,166m}Ho$, ^{178n}Hf, $^{186m,187}Re$, ^{193}Pt,

^{208,210m,212}Bi, and ^{209}Po. The U.S. 2003 technical study (NRC 2003) did not address nuclides with half-lives < 30 days or gases (such as Ar and Kr) since they would not likely remain in the materials removed from nuclear facilities. Short-lived progenies (such as ^{108}Ag, ^{121}Sn, ^{137m}Ba, ^{208}Tl, ^{212}Pb, ^{210}Bi, and ^{209}Po) are assumed to be in secular equilibrium with their long-lived parents and are thus included in the analysis of the parents.

Table 1. IAEA AND U.S. CLEARANCE LIMITS (in Bq/g) FOR SOME FUSION-RELEVANT NUCLIDES

Nuclide	IAEA [11]	U.S. [13] (Steel / Concrete)
^{3}H	100	526 / 152
^{14}C	1	313 / 83
^{22}Na	0.1	0.238 / 0.0417
^{40}K	---	2.94 / 0.526
^{45}Ca	100	5000 / 909
^{53}Mn	100	11400 / 6670
^{54}Mn	0.1	0.625 / 0.118
^{55}Fe	1000	21700 / 4760
^{59}Fe	1	0.476 / 0.114
^{58}Co	1	0.588 / 0.133
^{60}Co	0.1	0.192 / 0.035
^{59}Ni	100	2.17e4 / 4.76e3
^{63}Ni	100	2.13e4 / 4.76e3
^{64}Cu	100	---
^{94}Nb	0.1	0.333 / 0.059
^{99}Mo	10	---
^{99}Tc	1	6.25 / 1.64
^{110m}Ag	0.1	0.192 / 0.0357
^{125}Sb	0.1	1.41 / 0.23
^{152}Eu	0.1	0.455 / 0.083
^{154}Eu	0.1	0.455 / 0.071
^{182}Ta	0.1	0.435 / 0.091
^{192}Ir	1	0.91 / 0.172
^{108m}Ag	---	0.345 / 0.0588
^{186}Re	1000	---

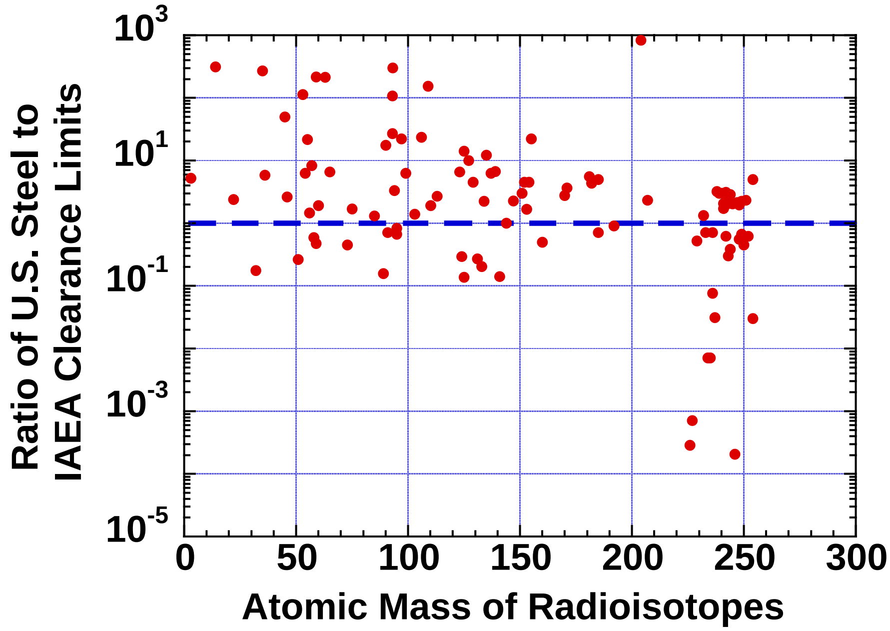

Fig. 1. Ratio of 2003 U.S. steel clearance limits to 2004 IAEA's.

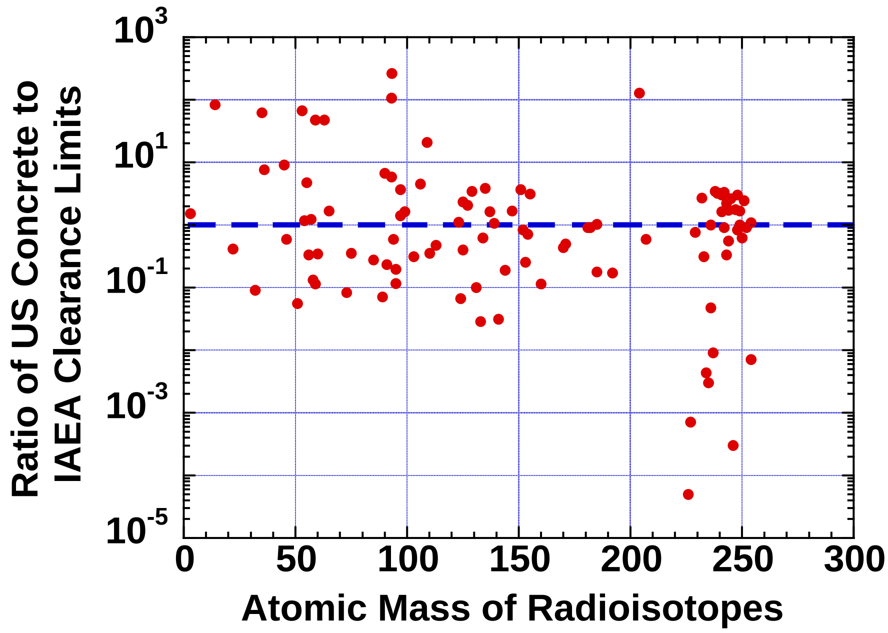

Fig. 2. Ratio of 2003 U.S. concrete clearance limits to 2004 IAEA's.

4. Implications of New Clearance Levels for Fusion Designs

The clearance strategy would appear to have great potential for fusion, since its application could greatly reduce the amount of materials to be disposed of or recycled. Recent studies have in fact shown the following:

a) ARIES power plants: about 80% of the activated material volume (mainly the magnet structure, magnet Cu stabilizer, cryostat, and bioshield) could be cleared while ~20% (the blanket, shield, manifolds, vacuum vessel, and Nb_3Sn superconductor) could either be recycled or disposed of as low-level waste [14].

b) PPCS plant models: between 17 and 24% of the activated material mass could be cleared, and between 76 and 83% recycled [15,16,17] after 100 years interim decay.

4.1 ARIES – Advanced Research, Innovation, and Evaluation Study

The multi-institutional ARIES team launched a study in 2003 to provide perspective on the benefits of optimizing the physics and engineering characteristics of the so-called compact stellarator (CS) power plant [18]. The primary goal of the study is to develop a more compact machine that retains the cost savings associated with the low recirculating power of stellarators, and benefits from the higher beta, smaller size, and higher power density, and hence lower cost of electricity, than was possible in earlier stellarator studies. The reference ARIES-CS design has a power level of 1000 MW_e. Figure 3 displays a vertical cross section at the beginning of the ARIES-CS field period. The dual-cooled LiPb/FS/He blanket must breed sufficient tritium for plasma operation, recover the neutron energy, and protect the shield for the entire plant life (40 full power years). The blanket and shield help protect the vacuum vessel (VV) and all three components protect the superconducting magnets for life. The neutron wall loading (NWL) peaks at the outboard midplane at 4 MW/m^2, calling for blanket replacement every 3.9 FPY, while the average NWL is 2.6 MW/m^2.

The clearance index of each component depends strongly on the neutron flux level, neutron spectrum, composition, and service lifetime. Because of the compactness of ARIES-CS, the CIs of all internal components (blanket, shield, manifolds, and vacuum vessel) exceed the clearance limit by a wide margin even after an extended period of 100 y (refer to Fig. 4). No changes have been made to deliberately clear these components as the addition of new shielding components outweighs the benefits and defeats the waste minimization goal. This means the in-vessel components should be recycled or disposed of in repositories as low-level waste (LLW) according to the U.S. waste classification guidelines [14]. Examining the magnet constituents indicates that the JK2LB steel structure and Cu stabilizer are clearable within 100 y according to the U.S. guidelines. Of interest is the 2 m thick external concrete building (bioshield) that surrounds the torus. It represents the largest single component of the decommissioned waste. Fortunately, the bioshield along with the 5 cm thick cryostat and some magnet constituents qualify for clearance, representing ~80% of the total active material volume.

Since the ultimate goal is to separate the constituents of the component for recycling and reuse by industry, the ARIES approach for handling the cleared components (CI < 1) is to re-evaluate the CIs for the constituents [3]. The entire component could have a CI < 1, but the individual constituents may not and vice versa, requiring further segregation of the active materials based on constituents rather than components. Figure 5 confirms the impossible clearance of Nb_3Sn superconductor. The remaining magnet constituents can be cleared, however, within 20-300 y.

We propose another approach to deal with sizable components, such as the 2 m thick bioshield. It should be segmented and reexamined. As such, the bioshield was divided into four segments (0.5 m each) and the CIs reevaluated for the constituents (85% concrete and 15% mild steel, by volume). The results indicate that the innermost segment has the highest CI while the outer three segments meet the clearance limit within a few days after decommissioning. As Figures 6 and 7 indicate, the mild steel is a major contributor to the CI although its volume fraction is only 15%. The recommended storage periods are given in Table 2 along with the dominant radionuclides in descending order. Note that the inconsistencies in the ^{14}C and ^{63}Ni clearance standards (refer to Table 1) result in a wide variation in the required storage period for the coil structure and mild steel.

TABLE 2. STORAGE PERIODS FOR ARIES-CS INTERCOIL STRUCTURE, CRYOSTAT, AND CONSTITUENTS OF INNERMOST SEGMENT OF BIOSHIELD

Constituents	U.S.	IAEA
Cu Stabilizer	20 y ^{60}Co	~100 y ^{63}Ni
Inter-coil Structure (JK2LB)	10 y ^{54}Mn	~500 y ^{14}C, ^{63}Ni
Cryostat (304 SS)	64 y ^{60}Co	70 y ^{63}Ni, ^{60}Co
Bioshield:		
Mild steel	3.5 y ^{54}Mn, ^{55}Fe, ^{60}Co	7 y ^{54}Mn, ^{55}Fe
Concrete	0.6 y ^{22}Na, ^{54}Mn, ^{59}Fe, ^{41}Ca	0.6 y ^{54}Mn, ^{22}Na, ^{45}Ca, ^{55}Fe

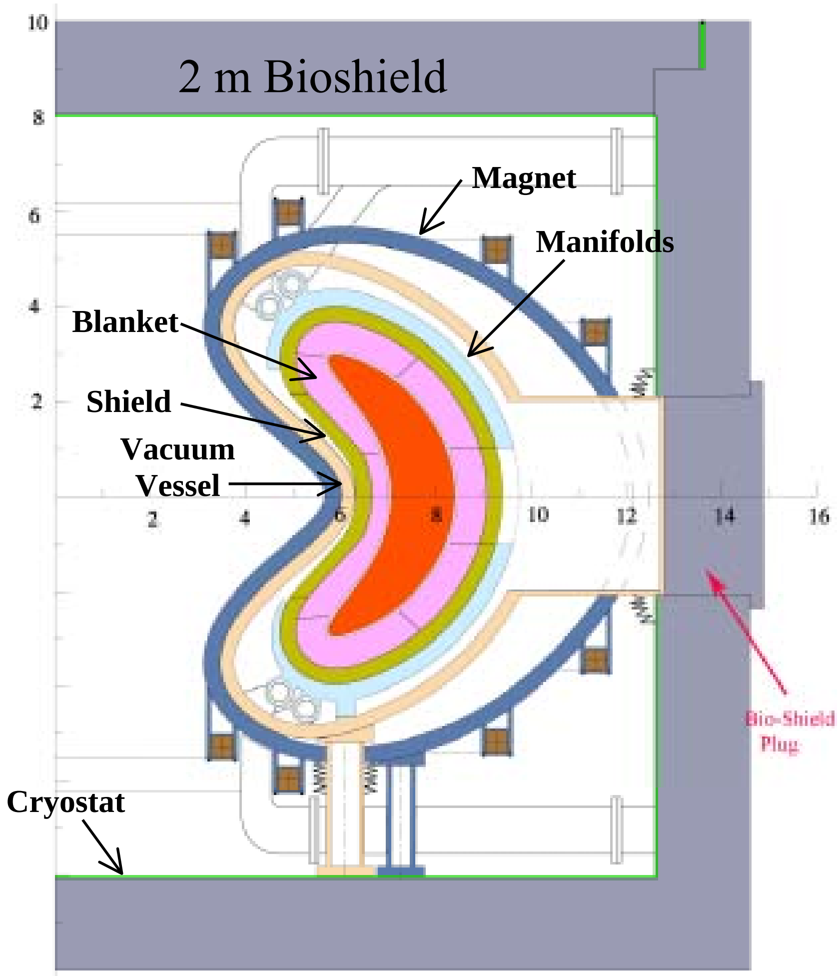

Fig. 3. Vertical cross section of ARIES-CS showing the main core components and the surrounding cryostat and bioshield.

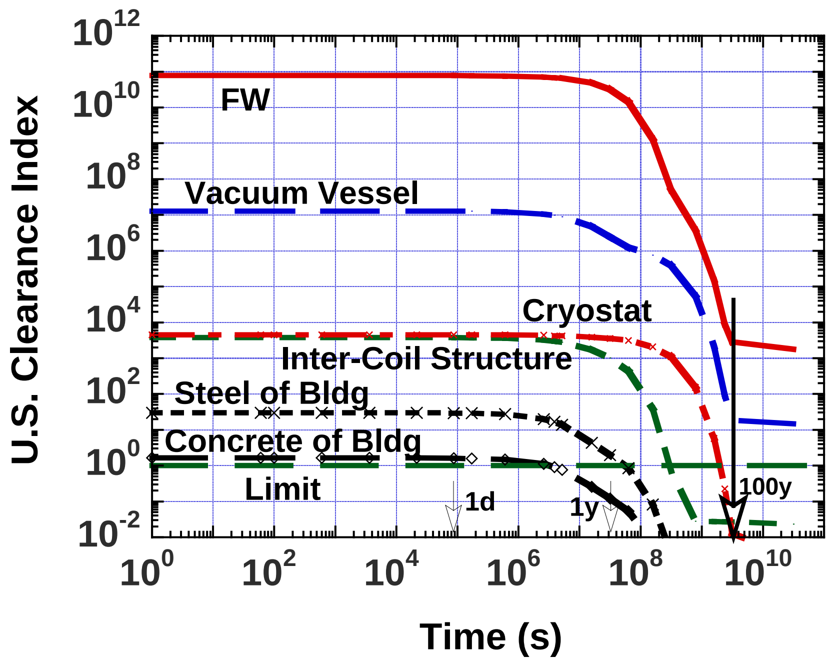

Fig. 4. Decrease of ARIES-CS clearance index with time after decommissioning.

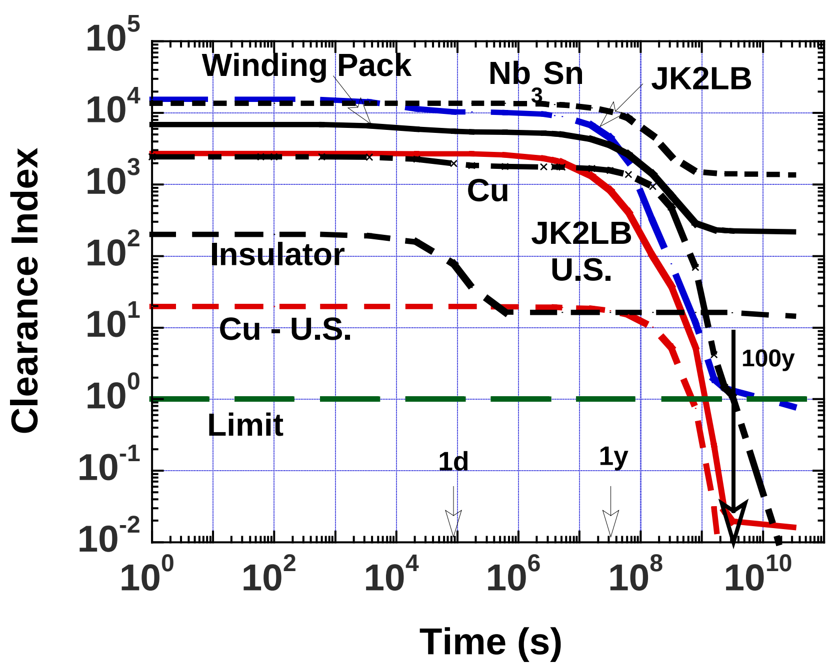

Fig. 5. Variation of IAEA CI of winding pack constituents with time after decommissioning. The U.S. CI for JK2LB steel and Cu stabilizer are included for comparison.

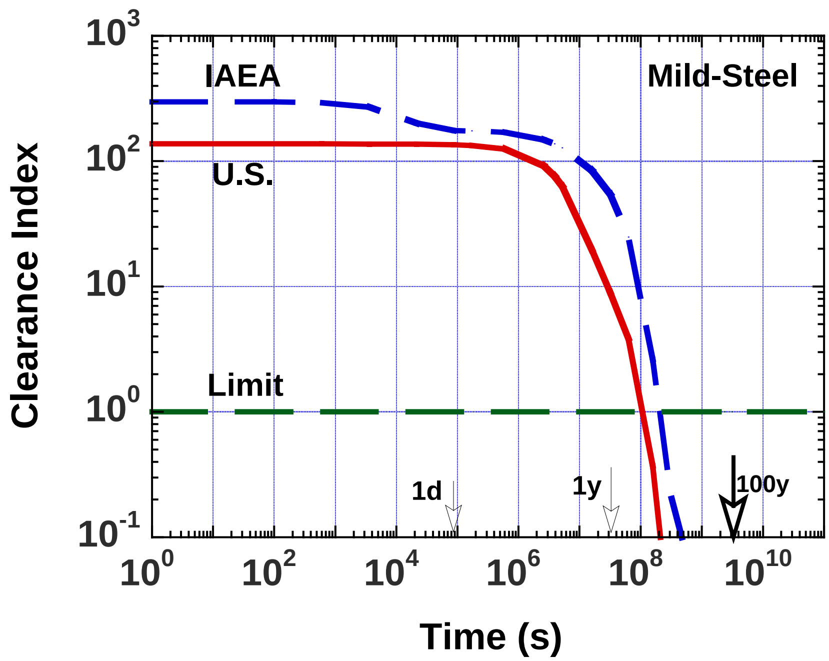

Fig. 6. Comparison of U.S. and IAEA clearance indices for steel of innermost segment of bioshield.

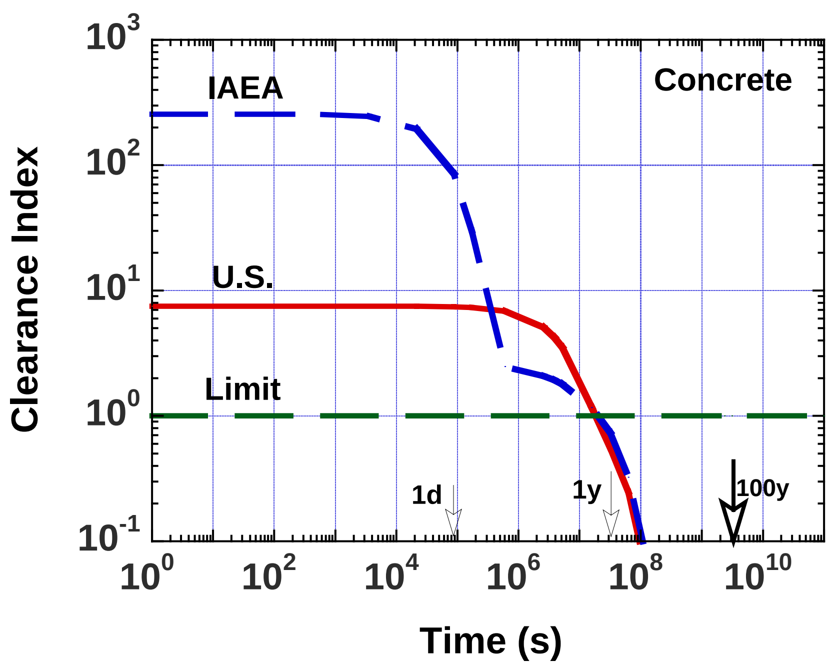

Fig. 7. Comparison of U.S. and IAEA clearance indices for concrete of innermost segment of bioshield.

4.2 PPCS – Power Plant Conceptual Study

The European Power Plant Conceptual Study (PPCS) applied both clearance and recycling criteria to the disposition of active material arising from five different power plant concepts [15]. Clearance was the strategy pursued for outer, bulky, lifetime components which are only mildly irradiated: usually the toroidal field coils (TFC), vacuum vessel (VV) and low temperature shields (LTS); clearance levels used were those recommended by IAEA in 1996 [10]. Results varied according to details of the plant design, materials and fusion power, but in general they showed that between 20 and 50% of the total amount of material to be disposed of reached clearance within 100 years, mostly TFC and VV and, only occasionally, parts of the LTS [16]. Both the TFC and VV in all PPCS models were scaled versions of ITER designs.

Revision is being made of the radioactive waste analysis of PPCS plants based on ITER test blanket modules [17], accounting for the latest design features and nuclear regulations; a more comprehensive approach to the overall clearance/recycling strategy is being developed. For the 1.5 GWe plant model PPCS-AB, based on a helium-cooled LiPb concept, previous analyses using 1996 IAEA levels [10] resulted in all of the outboard and parts of the inboard legs of the coils, and most of the outboard vacuum vessel, reaching clearance within 100 years (21% of the total waste, which is ~124000 tonnes) [16]. Under the 2004 IAEA guidelines, calculations performed so far have resulted in less parts of the inboard TFC, and none of the outboard VV, achieving clearance under the new levels. The fraction of clearable material in model AB after 100 years is now ~13%. Figure 8 shows time histories of the clearance index for the outer, lifetime components of this plant model: LTS, VV and TFC, at the inboard and outboard midplane.

Sometimes an entire component does not achieve clearance but individual constituents and/or radial/poloidal parts of it do so. Such is the case of the inboard leg of the TFC in model AB, as seen in Figure 9; the lowermost and uppermost poloidal sectors achieve clearance, whereas the rest do not. Also the rear steel case, radial plates and epoxy-glass insulator achieve clearance all along the inboard side, whereas the front case, incoloy and superconductor cable do not; this is illustrated in Figure 10. A similar effect is found in the outboard side of the VV, where the average CI does not permit clearance but that of the outer wall does so. Segregation of components into more basic constituents/parts thus plays a key role in minimizing the amount of waste requiring disposal or recycling; results show that, if convenient separation is made, the amount of cleared material from PPCS-AB could be increased by ~40%, still under 2004 IAEA guidelines. This is illustrated in Figure 11.

Some specific effects of the more stringent IAEA levels have already been pointed out [8]. In particular, a 30-fold decrease of the ^{63}Ni level appears to become a particular concern in the case of conventional 316 grade steel used for the VV and TFC walls, casing and radial plates; its effect is crucial in the case of model AB outboard VV. Similar decreases in ^{125}Sb and ^{94}Nb levels also affect, although less dramatically, the superconductor strands, reducing the amount of clearable material from the TFC. These elements are main constituents of the original materials; in the case of the 316 steel for VV and TFC applications the use of ferritic, low-activation variants has been recommended. Traces of impurities at the level of detection limits have certain influence in some cases, providing the difference between clearance and disposal; in 316 steel, even prior to irradiation, naturally occurring radioisotopes of Rb and Re impurities provide a background CI of 0.22, according to the 2004 IAEA levels (see Figure 10). The majority of nuclides contributing to the CI up to 100 years, however, arise from isotopes in the main elements in the composition of the materials of interest such as those previously mentioned. Moreover, uncertainty in the nuclear data introduces a stochastic component in the overall analysis.

The original PPCS work did not assess the 15 cm thick cryostat, central solenoid (CS) or poloidal field coils (PF). The material mass in these lifetime components is rather small (~9400 tonnes in total), and recent analyses show that most of it could be released from regulatory control within a few decades from plant shutdown [17].

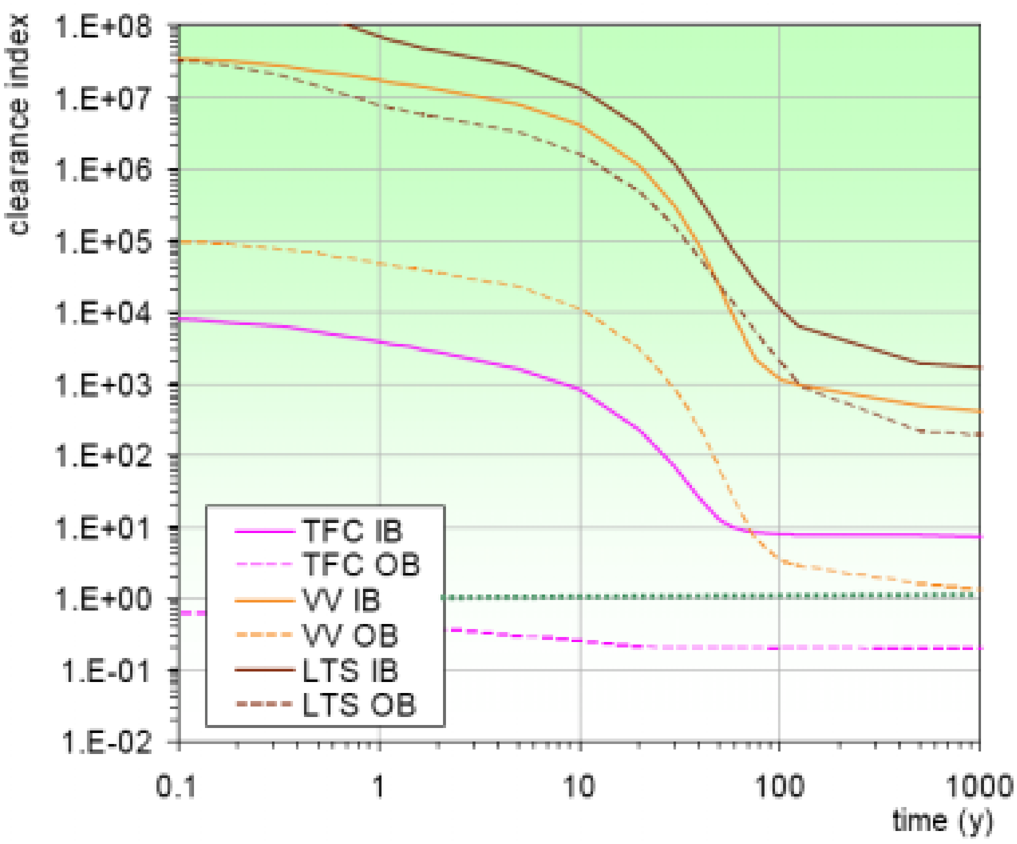

Fig. 8. CI time histories of lifetime components in PPCS-AB, at inboard and outboard midplane.

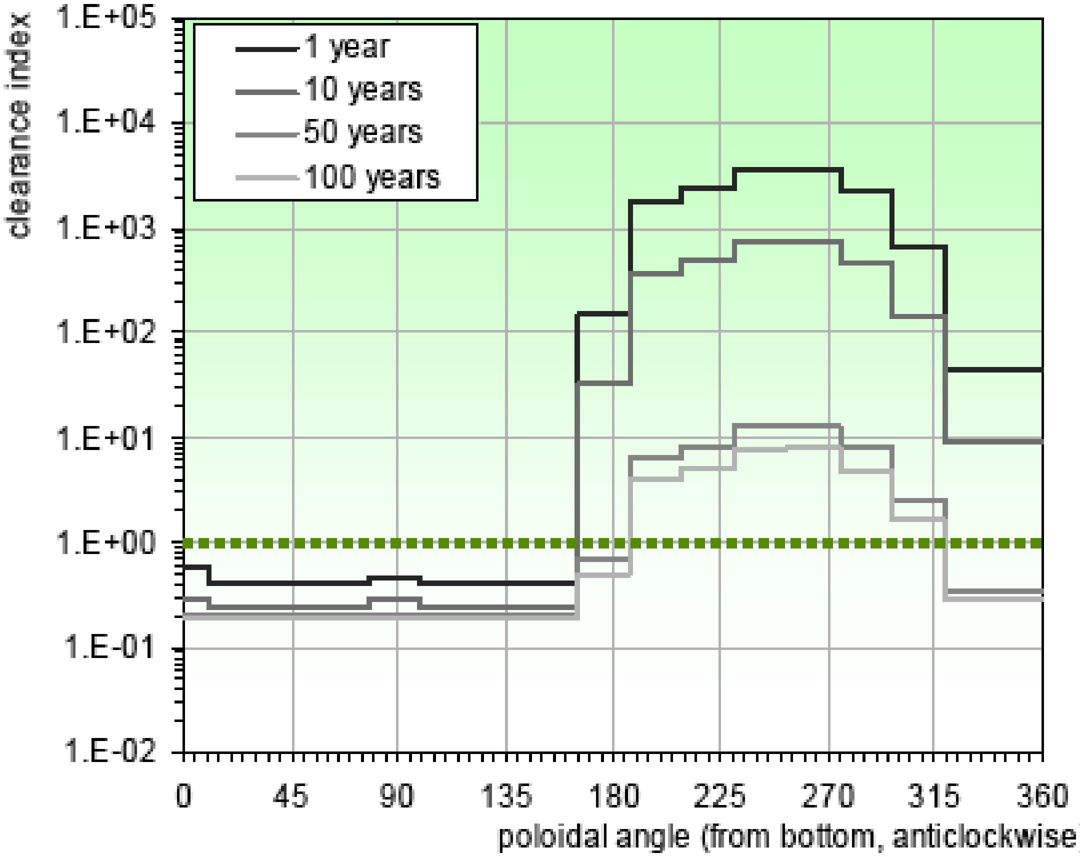

Fig. 9. Poloidal variation of the TFC CI in PPCS-AB at different times after shutdown.

5. Public Acceptability of Clearance

Further aspects must be considered for clearance, besides the question of its radiological feasibility. The issue of public acceptability of cleared material must be considered, since it is not assured that any radioactive material would be accepted for unrestricted release to the commercial market, despite its extremely low level of activity.

At present, there is no commercial market for the free (unconditional or unrestricted) release of slightly contaminated materials anywhere in the world [6,7]. Such a market will become increasingly important in this new millennium as the eventual decommissioning of fission and fusion power plants generates large amounts of slightly radioactive materials. The free release problem does not seem insurmountable. The alternate approach of restricted or conditional release of the slightly radioactive materials appears to be less controversial relative to the free release. In this category, the slightly radioactive materials are not recycled into a consumer

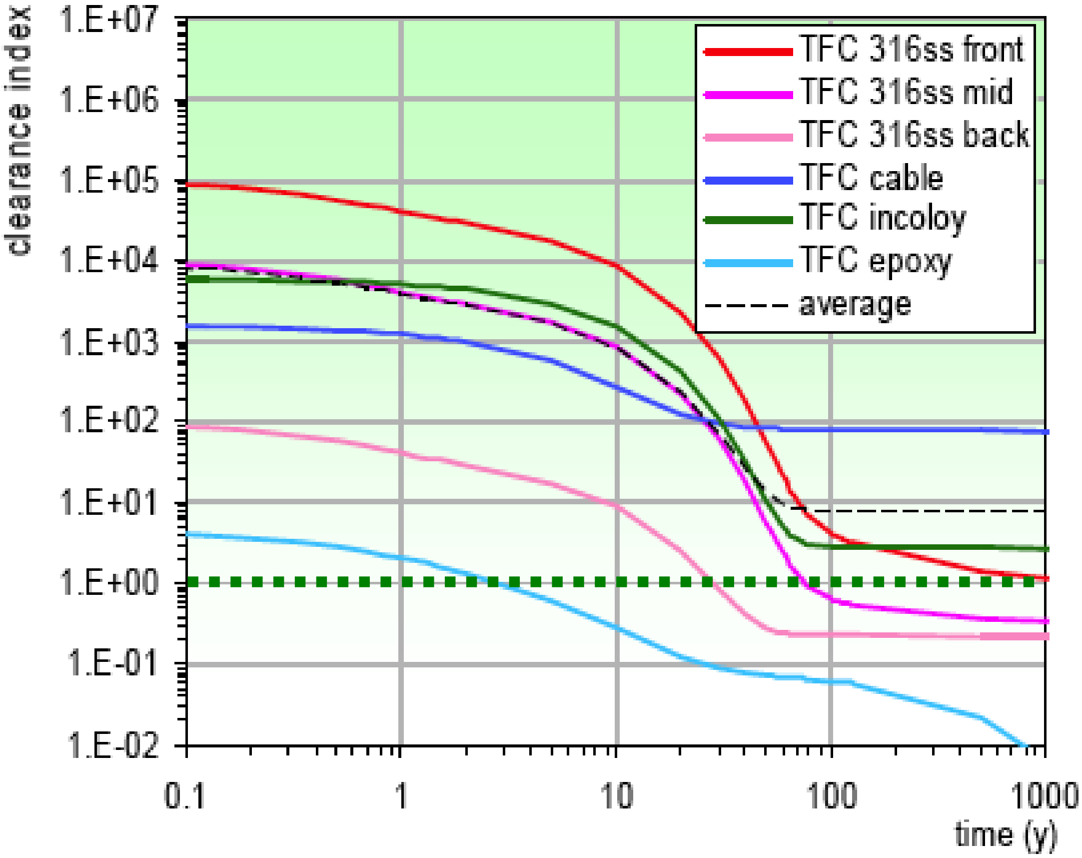

Fig. 10. CI time histories of the different TFC materials at the inboard midplane of PPCS-AB.

product, but rather released to dedicated nuclear-related facilities under continuing regulatory control or to specific applications where contact for exposure of the general public is minimal. Such contaminated materials have been released and continue to be released under existing practices on a case-by-case basis.

Although the nuclear industry favors some form of clearance standards, many consumer and environmental groups do not. For instance, the U.S. metals and concrete industries do not support clearance that unconditionally allows slightly radioactive solids to enter the commercial market, no matter how restrictive the clearance standards might be. Both industries expressed serious concerns that the presence of radioactive materials in their products could negatively affect their sales due to public fear. However, they would support a restricted use scenario in which radwaste reuse would be limited to selected purposes (e.g., nuclear facilities or radioactive waste containers) and subject to a high degree of control by the NRC. As clearance is highly desirable for both fission and fusion facilities, the national and international organizations are urged to continue their efforts to convince industrial as well as environmental groups that clearance of slightly radioactive solids can be conducted safely with no risk to the public health.

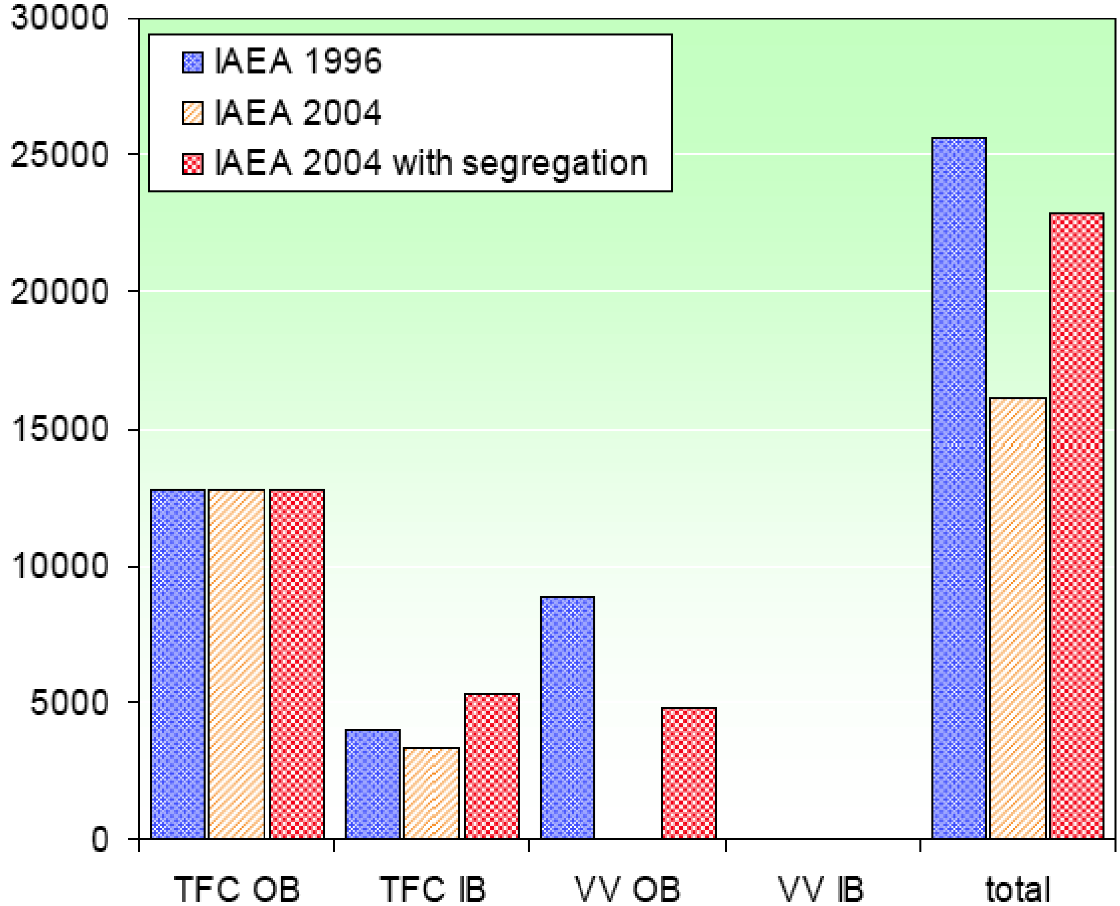

Fig. 11. Amounts of clearable material in PPCS-AB under (a) IAEA 1996 levels, (b) IAEA 2004 levels, and (c) IAEA 2004 levels applying segregation of materials.

6. Conclusions

One of the main goals for fusion should be the minimization of radioactive materials that need permanent disposal with a management strategy including the maximum reasonably possible use of materials clearance (i.e., declassification to non-radioactive material). This could result in a clear advantage for fusion power, in view of its ultimate safety and public acceptance. A review of power plant studies results in this field (ARIES and PPCS) shows excellent potential results as the majority of these power plant materials seem clearable, in principle.

Revised clearance limits have been recently issued at the international level and in the U.S. and Europe. The implications for fusion materials of these new levels are of interest. Some examples of reevaluation of the clearance indices for selected power plant concepts show that the amount of clearable material could be lower than previously estimated. However, the following general points can be noted:

- Differences between the various standards are relevant, and – for fusion-related materials – further studies are recommended to understand the technical reasons for the major disagreements.
- It is understood that a single set of international clearance limits – for all countries and for all radioactive materials – could be hardly obtained. However, an internationally agreed and complete set of fusion-specific clearance limits should be developed, as a result of further research in this field. In the meantime, we recommend incorporating both national and IAEA standards in fusion clearance evaluations.
- The interim decay time needed for reaching clearance (i.e., clearance index below unity) must not be fixed *a priori*, but chosen according to an optimization process where many factors are accounted for. Then, in particular, a 50 y or 100 y limit choice seems arbitrary from this viewpoint.
- It is necessary to dismantle and segment the components for declassifying the individual materials as non-active, with the possibility that some constituents may not achieve clearance.
- It is important to control and improve detection limits of impurities, even in materials irradiated only mildly, as these can make the difference between clearance or disposal of the material.

Acknowledgement

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