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## **Abstract**

In order to minimize the quantity of active materials that require long-term storage, arising during operation and after fusion power plant decommissioning, maximum use should be made of both recycling within the nuclear industry and clearance. For the latter, revised limits have recently been issued at the international level and in the U.S. and Europe. In this paper the implications for fusion materials of these new levels are considered. Concerning recycling, power plant studies have employed criteria based solely on radiological parameters. Reviews of remote procedures currently used within the nuclear industry suggest that these criteria have been unduly conservative and should be revised.

## 1. Introduction

The favorable inherent safety and environmental characteristics of fusion power can be fully exploited only in a power plant design that pays careful attention to the disposition of active materials arising during operation and after decommissioning [1]. In order to minimize the quantity of activated material that requires long-term storage ( $> 100$  y), full use should be made of both recycling within the nuclear industry and “clearance” for scrapping or release to the commercial market as non-radioactive material for general recycling. This paper examines the feasibility of the current and state-of-the-art approach to the recycling and clearance of fusion activated materials. Further details and data are available in the collaborative study report [2].

## 2. Recent Clearance Regulations

Clearance is the removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body [3]. Removal from control in this context refers to control applied for radiation protection purposes.

Although many national regulations include “exemption limits” that in some cases allow materials clearance, these usually omit some important fusion-relevant nuclides.

Recently, the U.S. Nuclear Regulatory Commission (NRC) and the International Atomic Energy Agency (IAEA) have issued revised clearance levels, taking into account previous guidelines and studies. The U.S. study incorporated realistic modeling of the current U.S. industrial practices and current data on the living habits in the U.S., to minimize unnecessary conservatism in the dose estimates. The IAEA study was based on a set of exposure scenarios, and also took into account some of the national studies (including the U.S. study).

Concentration limits for clearance are issued in the 2004 IAEA guidelines for 257 nuclides [4]. Activation products of fusion materials have a wide range of concentration limits; 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 nuclide, a clearance index (CI) may be computed as the weighted sum of all  $A_i$  divided by the corresponding  $L_i$ . A material can be cleared if  $CI \leq 1$ .

The IAEA 2004 recommendations [4] appear to be more stringent – for some fusion-relevant radionuclides – than the previous IAEA guidelines [5], upon which former evaluations for fusion materials [6,7] were based. For instance, they call for lower clearance limits (i.e., more stringent) for  $^{14}\text{C}$ , T, and  $^{60}\text{Co}$  (factors of 300, 30 and 3, respectively).

Based on a detailed technical study, the NUREG-1640 document [8] by the U.S. NRC contains estimates of the total effective dose equivalent (from which the clearance index can be derived) for 115 radionuclides. The NRC has not yet issued an official policy on the unconditional release of specific materials. Herein, the proposed annual doses reported in Ref. 8 will be referred to as the proposed U.S. limits (see Table 1).

Numerous fusion radioisotopes with  $T_{1/2} \geq 10$  y are missing in the most recent standards [4,8] and should be included in future evaluations. These include  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{32}\text{Si}$ ,  $^{91,92}\text{Nb}$ ,  $^{98}\text{Tc}$ ,  $^{113\text{m}}\text{Cd}$ ,  $^{121\text{m}}\text{Sn}$ ,  $^{150}\text{Eu}$ ,  $^{157,158}\text{Tb}$ ,  $^{163,166\text{m}}\text{Ho}$ ,  $^{178\text{n}}\text{Hf}$ ,  $^{186\text{m},187}\text{Re}$ ,  $^{193}\text{Pt}$ ,  $^{208,210\text{m},212}\text{Bi}$ , and  $^{209}\text{Po}$ .

Even though the NRC and IAEA both recommended an individual dose standard of  $10 \mu\text{Sv/y}$  for cleared solids, we observed a notable difference between the clearance limits (see Table 1). As an example, Figure 1 displays the ratios of the U.S. limits to those of the IAEA for steel.

Table 1. IAEA and U.S. clearance limits (in Bq/g) for some fusion-relevant nuclides.

Nuclide	IAEA [4]	U.S. [8] (Steel / Concrete)
$^3\text{H}$	100	526 / 152
$^{14}\text{C}$	1	313 / 83
$^{54}\text{Mn}$	0.1	0.625 / 0.118
$^{58}\text{Co}$	1	0.588 / 0.133
$^{60}\text{Co}$	0.1	0.192 / 0.035
$^{59}\text{Ni}$	100	2.17e4 / 4.76e3
$^{63}\text{Ni}$	100	2.13e4 / 4.76e3
$^{64}\text{Cu}$	100	---
$^{94}\text{Nb}$	0.1	0.333 / 0.059
$^{99}\text{Mo}$	10	---
$^{99}\text{Tc}$	1	6.25 / 1.64
$^{110\text{m}}\text{Ag}$	0.1	0.192 / 0.0357
$^{152}\text{Eu}$	0.1	0.455 / 0.083
$^{154}\text{Eu}$	0.1	0.455 / 0.071
$^{182}\text{Ta}$	0.1	0.435 / 0.091
$^{192}\text{Ir}$	1	0.91 / 0.172

Concerning some fusion-relevant nuclides, additional effort is needed to reduce the differences between the standards and understand the technical reasons for the major disagreements. It is recommended to develop a set of clearance limits for use in fusion studies, with international consensus, including all relevant nuclides, based on fusion-specific irradiation conditions and a selection of scenarios for the final disposition of cleared material.

### 3. Clearance of Fusion Materials: US, European, and Japanese Studies

Because of the compactness of the U.S. ARIES advanced designs [7,9] the CIs of all internal components (blanket, shield, vacuum vessel, and magnet) exceed the clearance limit by a wide margin. No changes were made to deliberately clear the outer components as the addition of new shielding components outweighs the benefits and defeats the waste minimization goal [7]. This means the internal components should be recycled or disposed of in repositories as low-level waste (LLW). However, for the ARIES-CS stellarator, the 2 m thick confinement building that represents the largest single component of the decommissioning waste (74%) qualifies for clearance.

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 ( $\text{CI} < 1$ ) is to reevaluate the CIs for the constituents. Even though the entire component could have a  $\text{CI} < 1$ , the individual constituents may not, requiring further segregation of the active materials based on constituents rather than components. Therefore, the ARIES-CS building was further divided into four segments (0.5 m each) and the CIs

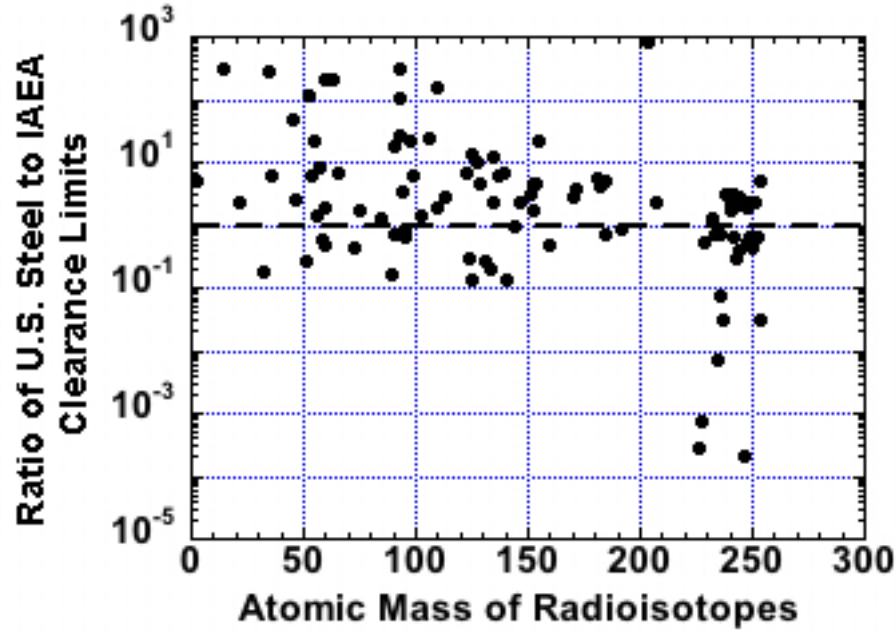


Fig. 1. Ratio of U.S. 2003 steel clearance limits to those of IAEA 2004.

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. The mild steel is a major contributor to the CI although its volume fraction is only 15%. Figure 2 depicts the CI's decrease with time for the innermost segment's steel according to the most recent U.S. and IAEA guidelines. The recommended storage periods are 3.5 y according to the NRC guidelines and 7 y according to the IAEA standards.

The European PPCS [10] applied the 1996 clearance [5] and recycling criteria to the disposition of active material [11]. The results show that in most cases the bulky toroidal field coils and their structure on the outboard side, together with much of that on the inboard side, reach clearance within 100 years [12]. In some cases, parts of the vacuum vessel could also be cleared.

Selected analyses of some key regions of PPCS models were repeated using the 2004 IAEA guidelines [4]. An example is illustrated in Figure 3, showing the evolution of the clearance index for a portion of the vessel for PPCS Plant Model C, which achieved clearance within 100 years in the original calculations. With the new limits, clearance is not achieved on any practical timescale. The largest contributor to the increase in the CI at 100 years is the 30-fold lower limit for  $^{63}\text{Ni}$ . At later times, the decrease in the  $^{14}\text{C}$  limit becomes dominant. It is worth noting that the error introduced by nuclear data uncertainties is 41%. The high data uncertainty is due to the importance of certain activated impurities; the activity of  $^{108\text{m}}\text{Ag}$ , for instance, has 78% uncertainty at this time. Improvements in nuclear data accuracy are needed for some fusion-specific nuclides and reactions, and also the control of impurities in low activation materials will be crucial. Improved measurement of the level of specific impurities is also needed, as present assumptions, that trace elements are present at the current limit of detection, lead to an overprediction of activity.

In Japan, clearance of radioactive materials was assessed for SiC/SiC-based A-SSTR2 [13] and steel-based DEMO-2001 [14]. For both plants, reinforced shielding is adopted to clear the ex-shield

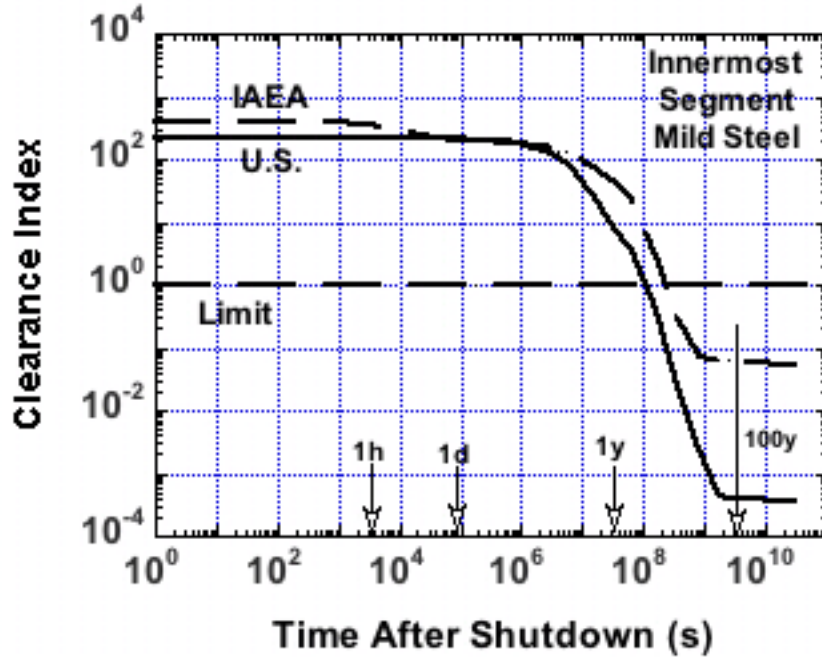


Fig. 2. Comparison of U.S. and IAEA clearance indices for steel of innermost segment of the confinement building.

components from regulatory control as much as possible [15]. In principle, 75% of the radioactive materials from both reactors are qualified for clearance after 50 year storage. However, according to the Japanese clearance regulation, there is little prospect to clear inhomogeneous radioactive materials, to avoid accumulation of particular isotopes contained in the radioactive materials beyond the clearance level when the materials are disassembled for recycling. Then, large portions of the toroidal and poloidal magnets cannot be cleared. In order to overcome this problem, advanced disassembling technology must be developed.

#### 4. Recycling Approaches and Dose Limits

The recycling and clearance strategy would appear to have great potential for fusion, since its application could reduce the amount of Permanent Disposal Waste to almost zero. Recent studies have in fact shown the following:

- a) ARIES power plants: about 75% of the activated materials (mainly the bioshield) could be cleared while ~25% (the blanket, shield, vacuum vessel, and magnet) could either be recycled or disposed of as low-level waste [9].
- b) PPCS plant models: between 30 and 50% of the activated material could be cleared (excluding the bioshield, which was not assessed in these studies), and between 50 and 70% recycled [10, 12]. Adopted recycling categories [11] were the following: Simple Recycling Material (SRM, dose < 2 mSv/h, and decay heat < 1 W/m<sup>3</sup>), Complex Recycling Material (CRM, dose < 20 mSv/h, and decay heat < 10 W/m<sup>3</sup>), after up to 100 y of interim decay.

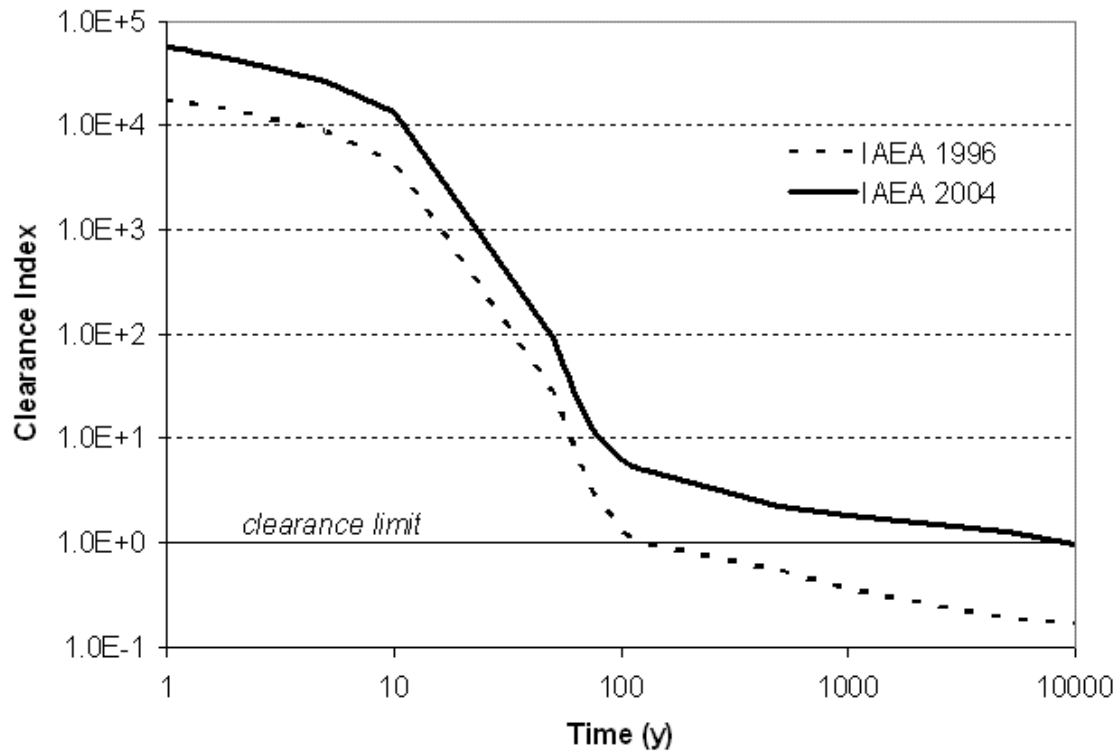


Fig. 3. Clearance index of material from part of the vacuum vessel of PPCS Plant Model C.

#### 4.1 Possibilities for transmutation of fusion waste

Separation of the highly radioactive radionuclides during the recycling process may eventually accumulate a limited amount of high-level waste (HLW) that may raise safety and environmental concerns. El-Guebaly has developed a plan for transmuting the fusion HLW to avoid its disposal [16]. The proposed concept requires advanced fusion power plants to burn their own HLW in a specially designed burning module. The process involves separation of the long-lived radionuclides from the waste stream, followed by irradiation with fusion neutrons to transmute the majority of the long-lived radionuclides into short-lived or preferably, stable isotopes.  $^{94}\text{Nb}$  was selected to illustrate the sensitivity of the burnup fraction to ARIES design parameters. With  $10 \text{ MW/m}^2$ , the irradiation period needed for 90% burnup is about 50 y, while it is 120 y for  $3 \text{ MW/m}^2$ . Inspection of the products reveals that the first irradiation process will not entirely transmute the long-lived radionuclides and therefore, a subsequent separation process and re-irradiation of the unburned radionuclides and other long-lived byproducts would be required. The final products could be committed to LLW disposal, or recycled. Extrapolations in activated material reprocessing technology would have to be considered in concert with similar ground rules being adopted in advanced fusion designs.

This new approach may allow the ARIES designs to relax the LLW top-level requirement and permit the production of HLW, pending that recycling is a “must” requirement for all fusion activated material.



## 4.2 Recycling criteria

For recycling of fusion materials within the nuclear industry, power plant studies have employed feasibility criteria based solely on radiological parameters such as contact gamma dose-rate [1]. Reviews of remote procedures currently used within the nuclear industry suggest that these criteria have been unduly conservative. For example, for PPCS, the CRM dose limit is 20 mSv/h, whereas re-melting of wastes from fission power plants has already been carried out on material with 120 mSv/h. Much higher dose rates than this (up to of 3000 Sv/h) are present in routine operations in the reprocessing of fission reactor fuel. A recent U.S. study has demonstrated the usefulness of recycling fusion components under the high dose rate condition of 3000 Sv/h [17].

While the fission processes have no direct relevance to the recycling of fusion materials, their success gives confidence that remote handling techniques could be developed for fusion materials recycling. The re-melting of steels, routinely performed using small-scale furnaces in the fission decommissioning industry, should be straightforward, while of greater concern is recycling components made of several materials. For example, the need to segregate the magnet and bioshield [7,9] into their original constituents and to separate the armor from the first wall. A review of recycling of blanket and divertor components [18] noted this point and other aspects of fusion which differ from current fission waste re-melting practice: the higher melting point of some materials, the need to trap and treat off-gases containing tritium, and handling difficulties with some items of high specific activity.

The conservative radiological criteria applied in power plant studies for recycling suitability should be revised. The 2 mSv/h dose limit for SRM seems appropriate, as this corresponds to the acceptance criteria in some existing melting facilities [19], however, the 20 mSv/h CRM limit could be increased, probably by one-two orders of magnitude. Recycling practicability depends not only on these radiological criteria, however. The possibility of waste reprocessing and isotope separation systems being available on the industrial scale, for fabrication of new components, as well as the economic viability of these processes, will ultimately determine the extent of fusion materials recycling.

Handling of tritiated materials is another issue. Since the in-vessel components will be tritiated, a guideline for tritium concentration will be necessary. The IAEA standards for safe transport [20] could be appropriate (preferably,  $< 0.11$  g T for Type-A package transport, or otherwise  $< 330$  g T for Type-B(U) packages) because the radioactive materials should be transported to a recycling plant in most cases located outside a fusion power plant. If the materials contain tritium beyond the guideline, they should be pre-detritiated before transportation. Before recycling, tritium concentration can be reduced to an acceptable level by bubbling in a melting furnace.

## 5. Conclusions

One of the main goals for fusion is the minimization of radioactive materials that need permanent disposal. A strategy maximizing the use of materials recycling (within the nuclear industry) and clearance could result in a clear advantage for fusion power, in view of its ultimate safety and public acceptance. Recent power plant studies show excellent results in this field.

Concerning materials clearance, in particular:

- 1) Some examples of reevaluation of the clearance indices, based on recently issued limits, show that the amount of clearable material could be lower than previously estimated or may require a longer cooling period.

- 2) Differences between standards are relevant, and – for fusion-related materials – further studies are needed to understand the reasons for the disagreements. An internationally agreed and complete set of fusion-specific clearance limits should be developed.
- 3) The interim decay time before clearance must not be fixed *a priori*, but chosen according to an optimization process where many factors are accounted for.
- 4) It is necessary to dismantle and segment the components for recycling of individual materials as non-active, with the possibility that some constituents may not achieve clearance while the bulk of the material does.

Concerning recycling within the nuclear industry:

- 1) Power plant studies adopted criteria based on radiological parameters only, such as contact gamma dose-rate. Reviews of current practices within the nuclear industry show that these criteria have been unduly conservative. Moreover, factors other than contact gamma dose-rate must be considered.
- 2) Handling, cutting and dismantling of active material using remote techniques prior to re-melting, particularly the separation of high activity items, could present a particular challenge.
- 3) The control and accurate measurement of impurities in low activation materials will be key to achieving CI and dose levels low enough to facilitate recycling.
- 4) The issues of removal and transportation of tritium need to be fully addressed.

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