Current Challenges Facing Recycling and Clearance of Fusion Radioactive Materials

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Abstract

The favorable 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 at end-of-life. In order to minimize (or eliminate) the quantity of such material that remains as waste requiring long-term storage (> 100 y), maximum use should be made of both recycling within the nuclear industry and "clearance" for scrapping or release to the commercial market as non-radioactive products. For the clearance of materials, the U.S. Nuclear Regulatory Commission, European Commission, Nuclear Safety Commission of Japan, and International Atomic Energy Agency recently issued revised clearance levels. In this paper the implications for fusion materials of these new levels are considered, with examples of re-evaluation of the clearance index for selected power plant concepts.

Concerning recycling within the nuclear industry, 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 this paper makes recommendations for revised criteria, and assesses the implications of their use.

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 at end-of-life. In order to minimize (or eliminate) 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 approach has typically been considered in conceptual fusion power plant studies in the last decade. This paper examines the feasibility of the current and state-of-the-art approach to the recycling and clearance of fusion activated materials.

Most radioactive materials generated from fusion power plant operation and decommissioning are 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 dominant radioactive material mass stream is generated in the decommissioning stage, but a significant amount is also produced by routine component replacements during operation. A great deal of the decommissioning material 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 radioactive 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 waste is the spent fuel or, in case of reprocessing, vitrified highly radioactive waste. Presenting the main environmental issue for nuclear power world-wide, these materials are very different from fusion activated materials, both in type of material and isotopic composition (1,2). For instance, fusion radioactive materials do not contain uranium, plutonium, long-lived transuranics, or fission products and have no proliferation relevance. Their global radiotoxicity is inferior and short-lived compared to fission. But despite these differences in the basic characteristics of the active material, the experience gained from the handling and management of fission activated materials will be very useful in the fusion context.

2. Clearance Regulations: a Review of Recent Issues

2.1 The concept and application of clearance

The International Basic Safety Standards (BSS) for Protection against Ionizing Radiation and for the Safety of Radiation Sources specify requirements for the protection of health against exposure to ionizing radiation and for the safety of radiation sources (3). The BSS are based on information provided by the United Nations Scientific Committee on the Effects of Atomic Radiation regarding the detrimental effects attributed to radiation exposure (4), as well as the recommendations of the International Commission on Radiological Protection, ICRP (5). The BSS define the terms and explain the use of the concepts of exclusion, exemption and clearance for establishing the scope of regulatory control (6):

- '**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.

In the case of clearance, the BSS define the concept and radiological criteria to be used as a basis for determining clearance levels, but leave their establishment to national authorities.

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). Such limits are generally very low (e.g. 0.4 Bq/g in the U.K.). 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 are a useful step towards this direction, and their implementation would result in higher (i.e., less stringent) limits than the current non-specific limits in many national regulations

A first example of IAEA-like national regulations can be found in the new German radiation protection ordinance (7): this regulation permits Clearance, using a nuclide-by-nuclide clearance index similar to the IAEA approach. Another recent regulation has been issued in Italy (8), concerning the "*Allontanamento*" (Italian word for "clearance") of solid radioactive spent materials. Recycling in Italy is permitted for cleared material only. Similar regulation will be enacted in Japan by the end of 2005. Concentration limits are issued for each relevant nuclide, however, they may be partially summarized 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.

An overview of the new IAEA clearance limits (9) and U.S. guidelines (10) is provided below for the reader's convenience.

2.2 IAEA 2004 clearance limits

The IAEA 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 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 (see Table 1), and 1000 Bq/g for ^{55}Fe and^{186}Re.

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) may be computed as the weighted sum of all nuclide specific activities divided by the corresponding clearance limits:

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

Nuclide	IAEA (9)	U.S. (10) (Steel / Concrete)
^{3}H	100	526 / 152
^{14}C	1	313 / 83
^{54}Mn	0.1	0.625 / 0.118
^{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
^{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

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

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 recommendations (9) appear to be more stringent – at least for some radionuclides of particular interest to fusion – than the previously issued guidelines (11), upon which former evaluations for fusion materials (12,13) were based. For instance, the 2004 guidelines (9) 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 (11). This means it takes longer times for these materials to reach clearance.

2.3 U.S. recent clearance limits

During the decade of the 1940s and continuing to the present, the Nuclear Regulatory Commission (NRC) and its predecessor agency have attempted to develop and 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 (10) 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.

2.4 Comparison of different guidelines

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 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. Even though the U.S. and IAEA recommended an individual dose standard of 10 μSv/y (1 mrem/y) for cleared solids, we observed a notable difference between the clearance limits for the 115 and 257 radionuclides developed by the U.S. and IAEA, respectively. 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, based on fusion-specific irradiation conditions and a selection of scenarios for final disposition of cleared material (ranging from landfill disposal to recycling in items of everyday use).

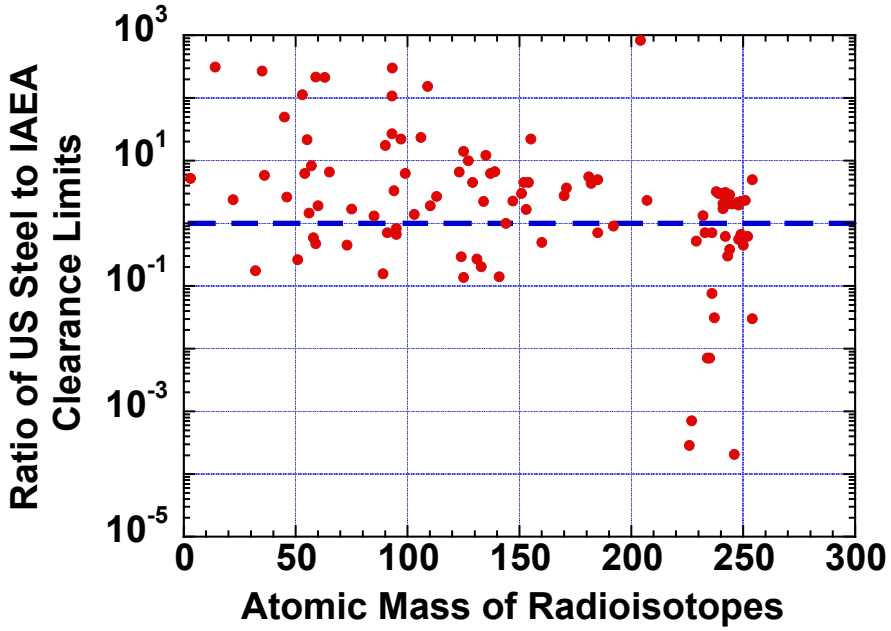

Fig. 1. Ratio of 2003 U.S. steel clearance limits to 2004 IAEA's.

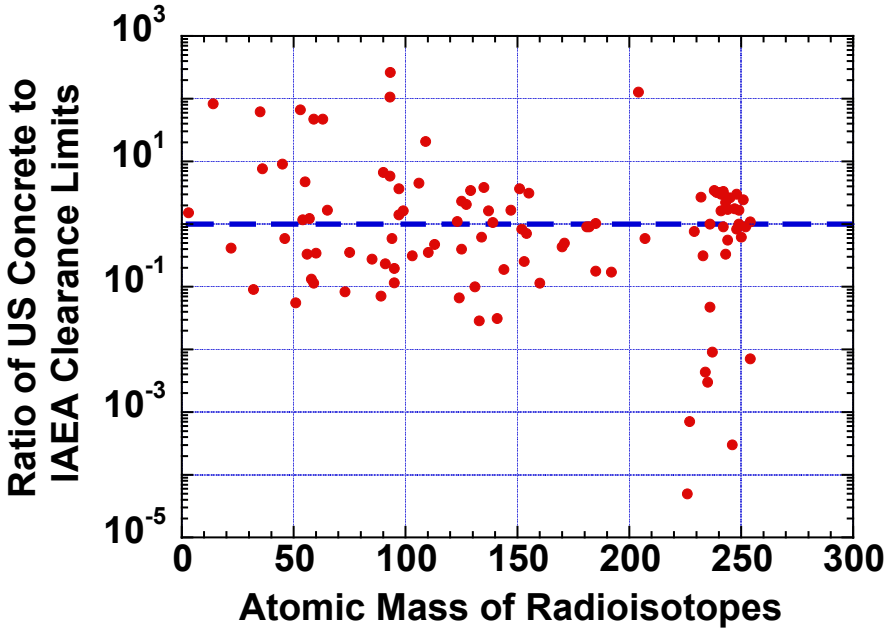

Fig. 2. Ratio of 2003 U.S. concrete clearance limits to 2004 IAEA's.

3. Implications for Fusion Materials of New Clearance Levels and Missing Elements in Clearance Standards

In this section, the implications for fusion materials of these new levels are considered, by re-evaluating the clearance index (CI) for selected power plant concepts.

3.1 ARIES – Advanced Research, Innovation, and Evaluation Study

The CI of each component depends strongly on the neutron flux level, neutron spectrum, composition, and service lifetime. Because of the compactness of the U.S. advanced designs (13,14) the CIs of all internal components (blanket, shield, vacuum vessel, and magnet) exceed the clearance limit by a wide margin. No changes have been made to deliberately clear the outer components as the addition of new shielding components outweighs the benefits and defeats the waste minimization goal (13). This means the internal components should be recycled or disposed of in repositories as low-level waste (LLW) according to the U.S. waste classification guidelines. Of interest is the 2 m thick external concrete building that surrounds the torus. In the ARIES-CS stellarator, the confinement building represents the largest single component of the decommissioning waste (74%). Fortunately, it 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 (CI < 1) is to re-evaluate the CIs for the constituents. This may cause a problem. The entire component could have a CI < 1, but 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 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

Table 2. Storage periods for constituents of innermost segment of ARIES-CS building.

Constituents	U.S.	IAEA
Mild steel	3.5 y ^{54}Mn, ^{55}Fe, ^{60}Co	7 y ^{54}Mn,^{55}Fe
Concrete	1.3 y ^{22}Na, ^{54}Mn, ^{59}Fe, ^{41}Ca	1 y ^{54}Mn, ^{22}Na, ^{45}Ca, ^{55}Fe

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%. Figures 3 and 4 depict the CI's decrease with time for the innermost segment's steel and concrete according to the most recent U.S. and IAEA guidelines. The recommended storage periods are given in Table 2 along with the dominant radionuclides in descending order. Note that the inconsistencies in the clearance standards (refer to Table 1) have doubled the storage period for steel.

Numerous fusion radioisotopes with $T_{1/2} \geq 10$ 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 (10) 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. A detailed discussion of the methodology used to estimate the U.S. doses can be found in the appendices of NUREG-1640 (10).

3.2 PPCS – Power Plant Conceptual Study

The European Power Plant Conceptual Study (PPCS) (15), which was completed in 2004 (16) adopted the same strategy as the earlier Safety and Environmental Assessment of Fusion Power (SEAFP) (17), applying both clearance and recycling criteria to the disposition of active material (18). The clearance limits applied in the PPCS were those recommended by IAEA in 1996 (11). The results for the four power plant concepts studies (plus a fifth added in follow-on studies) show that in most cases all of the bulky toroidal field (TF) coils and their structure on the outboard side, together with much of that on the inboard side, reach clearance within 100 years (19). In some cases, parts of the vacuum vessel could also be cleared.

Selected analyses of some key regions of PPCS models have now been repeated using the clearance limits in the 2004 IAEA guidelines (9). A first example of the impact of the revised clearance limits is illustrated in Figure 5, which shows the evolution of the clearance index for a particular region of the TF coil structure in PPCS Plant Model A (which has a water-cooled lithium-lead blanket). This region is near the top of the coil structure in the 3-D model, where the neutron flux is relatively low. This is material that achieved clearance after 0.5 day in the original calculations, but with the new IAEA limits, clearance is only achieved after about 0.5 years. The uncertainty on the computed CI value due to the stochastic error on the Monte Carlo computation of neutron fluxes is 14% in this case, in addition to 11%

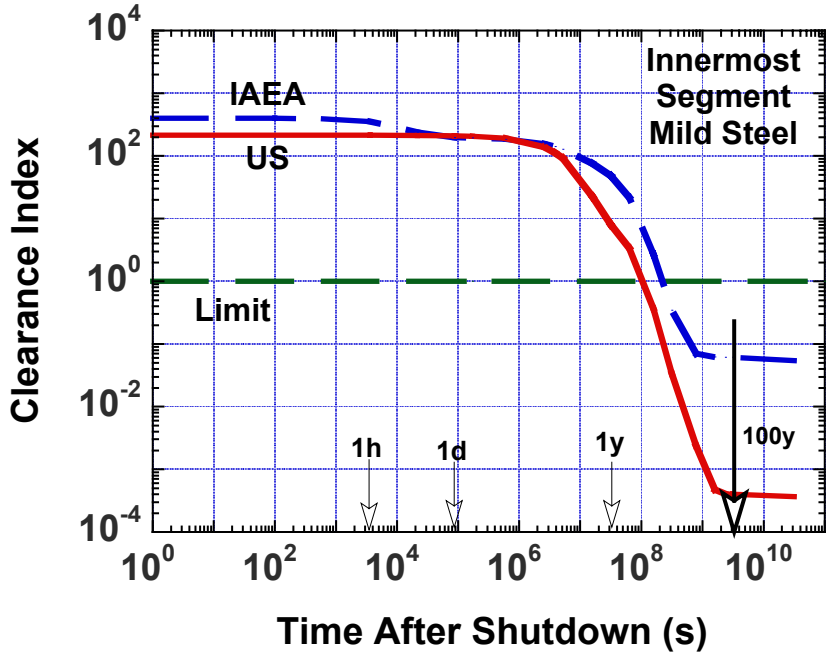

Fig. 3. Comparison of U.S. and IAEA clearance indices for steel of innermost segment of the confinement building.

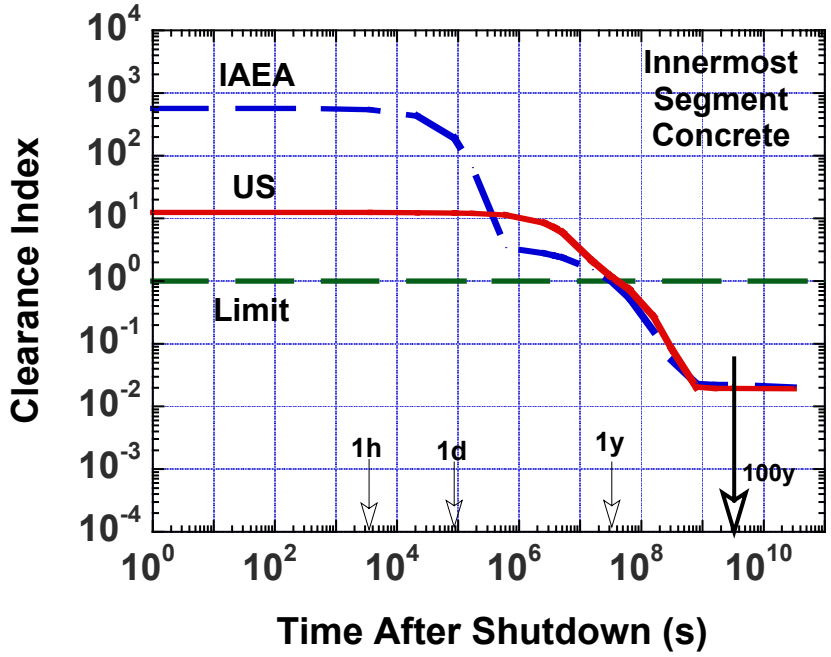

Fig. 4. Comparison of U.S. and IAEA clearance indices for concrete of innermost segment of the confinement building.

due to nuclear data uncertainties, plus the effects of modeling simplifications and assumptions about detailed material compositions.

At the other extreme, Figure 6 shows a similar comparison for a portion of the vacuum vessel for PPCS Plant Model C (with dual-coolant lithium-lead blanket), which only just achieved clearance within 100 years in the original calculations. The location of this region is poloidally about 60° above the mid-plane on the outboard side. With the new IAEA limits, clearance of this material 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}Ni. At later times, the decrease in the ^{14}C limit, by a factor of 300, becomes dominant. It is worth noting that while the Monte Carlo neutron flux uncertainty is less than 3% in this case, 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 ^{108m}Ag, for instance, has 78% uncertainty at this time. This is a reminder that improvements in nuclear data accuracy are needed for some fusion-specific nuclides and reactions, and also that control of the level of impurities in materials for fusion components 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; this applies in particular to Eu, Tb, Hf, Bi and Sm.

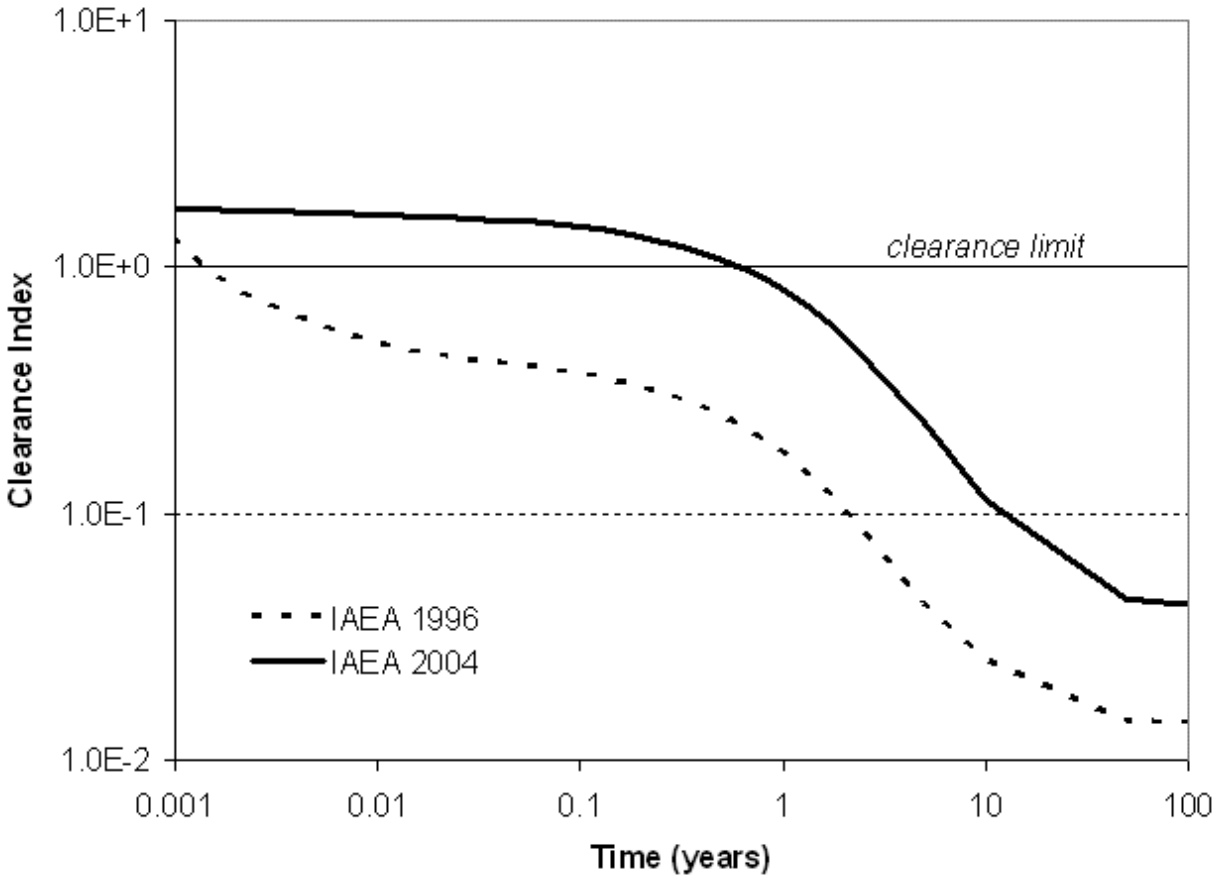

Fig. 5. Clearance index of material from a part of the toroidal field coil of PPCS Plant Model A.

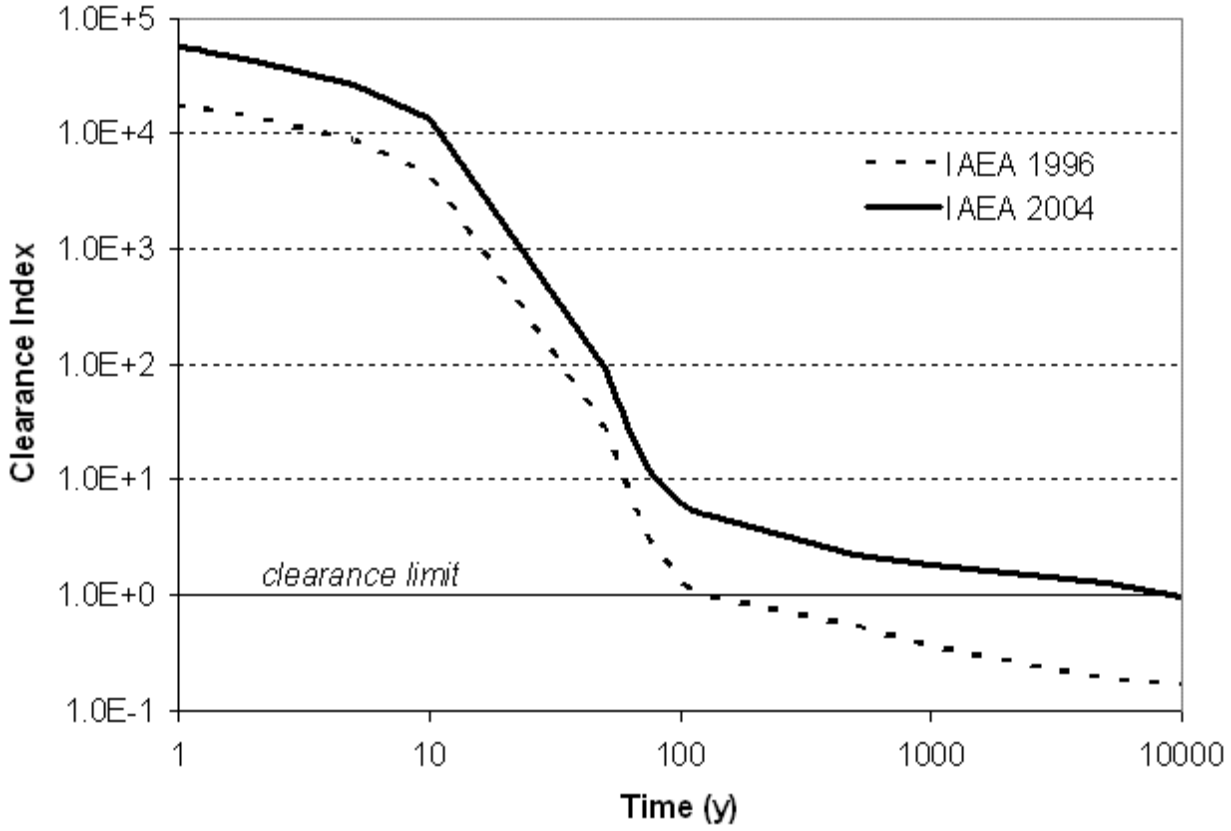

Fig. 6. Clearance index of material from part of the vacuum vessel of PPCS Plant Model C.

3.3 A-SSTR2 and DEMO-2001

In Japan, the impact of clearance of radioactive materials was assessed for SiC/SiC-based A-SSTR2 (20) and steel-based DEMO-2001 (21). For both reactors, reinforced shielding is adopted to clear the ex-shield components from regulatory control as much as possible (22). The assessment indicates that fusion isotopes missing from the IAEA standards include ^{10}Be, ^{26}Al, ^{32}Si, ^{60}Fe, ^{91}Nb, ^{98}Tc, ^{108m}Ag, ^{178n}Hf, ^{186m}Re, ^{192n}Ir and ^{193}Pt. ^{108m}Ag is produced when Bi high temperature superconductor is used. ^{26}Al and ^{32}Si are SiC/SiC origin, and ^{186m}Re, ^{192n}Ir and ^{193}Pt are produced by multi-step reactions of W.

In principle, three quarters 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 for the sake of avoiding an accumulation of particular isotopes contained in the radioactive materials beyond the clearance level when the materials are disassembled to sort out into identical materials for recycling. Based on this policy, large portions of the toroidal and poloidal magnetic coils cannot be cleared from regulatory control. In order to overcome this problem, advanced disassembling technology must be developed.

4. Recycling Approaches and Dose Limit

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

a) SEAFP and 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 (12,15,19).

b) 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 (14).

c) Advanced D-^{3}He and ^{3}He-^{3}He fuelled power plants: almost all activated materials qualify for clearance. The zero-waste option is a reachable goal for such designs (23).

4.1 PPCS plant models

Concerning the Power Plant Conceptual Study, clearance feasibility of spent materials was evaluated according to the IAEA 1996 specifications (11). If a material could not be clearable, it must be either recycled or disposed of in repositories. Accordingly, four categories of materials were defined as:

- Non-Active Waste (NAW), satisfying the clearance condition,
- Simple Recycle Material (SRM),
- Complex Recycle Material (CRM), and
- Permanent Disposal Waste (PDW).

The definitions of these categories are equivalent to those adopted in earlier studies such as SEAFP. SRM has a contact dose rate below 2 mSv/h, and a specific decay heat below 1 W/m^3, after no more than 50 y of interim decay. CRM corresponding limits are 20 mSv/h and 10 W/m^3. The recycling of some SRM and all CRM materials could require remote handling procedures. An alternative, not evaluated in PPCS studies, could be a shallow land burial, after a decay time (approximately 100 years) depending on the nuclides contained in the materials and the local regulations. PDW is a material that does not satisfy any of the above conditions. The non-active waste can be processed as normal scrap metal, while simple and complex recycle material can be recycled for further use – employing straightforward processes in the case of SRM.

The activation of the materials in all four PPCS Models decays very rapidly at the beginning and then broadly by a factor of ten thousand over a hundred years. The radiotoxicity of the materials (namely, the biological hazard potential associated with their activation) decays by a factor of ten thousand over a hundred years. An important conclusion of PPCS was that for all four Plant Models, and a fifth one added in follow-on studies, if full use is made of the potential to recycle materials, then after 100 years there would be no material requiring permanent repository disposal (19). Whether or not such recycling operations would be feasible and economically viable for all candidate materials, is yet to be determined.

4.2 Possibilities for transmutation of fusion waste

It is anticipated that recycling will be mandated for all fusion activated material to minimize the volume of material assigned for geological burial. 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. In general, the public is likely to accept the nuclear industry if the waste is minimized and the HLW issue in particular is resolved. El-Guebaly has developed a plan for transmuting the fusion HLW to avoid sending the long-lived nuclides to HLW repositories (24). 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, attempting to transmute the majority of the long-lived radionuclides into short-lived or preferably, stable isotopes. ^{94}Nb was selected to illustrate the sensitivity of the burn-up fraction to ARIES design parameters (see Fig. 7). With 10 MW/m^2, the irradiation period needed for 90% burn-up is more than halved (50 y, instead of 120 y for 3 MW/m^2). Mixing beryllium with ^{94}Nb has remarkably improved the burn-up process (24). Inspection of the products reveals that stable nuclides comprise 87 atom% of the waste while the remaining 13 atom% represents ~7 atom% unburned ^{94}Nb, ~6 atom% other long-lived isotopes, and < 1 atom% short lived isotopes that decay rapidly within a few years. Admittedly, 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, therefore could be committed to LLW disposal along with the majority of the fusion activated materials, recycled within the nuclear industry, or hopefully, cleared from regulatory control and released to the commercial market. 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. Other compelling reasons for developing the concept include:

- Extending the service lifetime of LLW-limited components (such as the massive center-post of spherical tokamaks)
- Clearing many components from regulatory control by removing and burning the troublesome elements
- Employing high-temperature refractory metals to improve the design performance
- Relaxing stringent specifications imposed on impurity and alloying element concentrations (such as Nb, Ir, Ni, Ag, Cu, Co, Re, and Mo) that are based on LLW criteria, meaning no need to develop low-activation materials
- Employing off-shelf materials and shorten the pathway to fusion commercialization.

The success of this approach depends on the availability of reasonable space in fusion machines to burn their own HLW. The work recognizes fusion’s potential role in providing HLW-free energy, but stresses that advanced activated material reprocessing technology and isotope separation systems must be developed in 50-100 years _ by the time fusion joins the energy market.

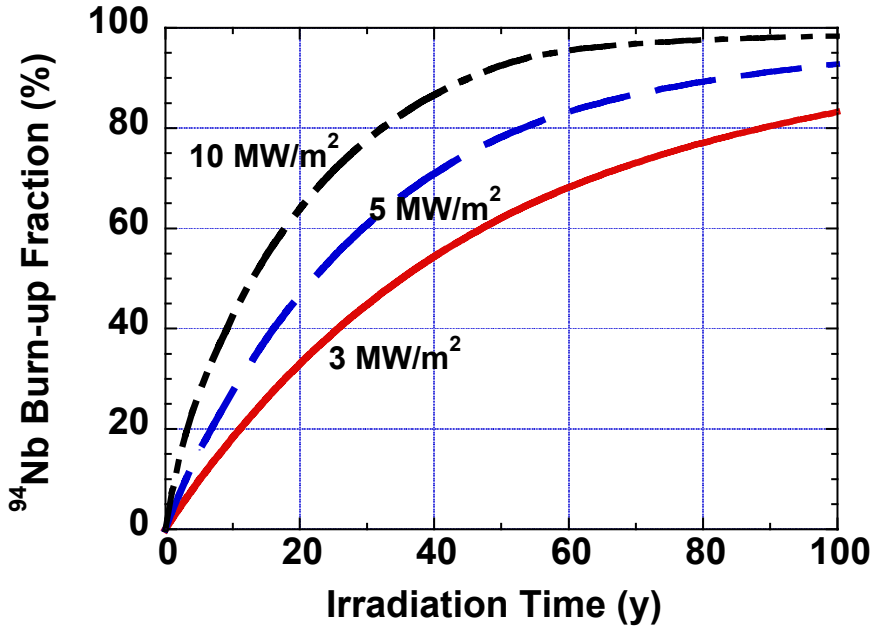

Fig. 7. Increase of ^{94}Nb burn-up fraction with neutron wall loading and irradiation time.

4.3 Advanced fuel cycles for complete clearance

The results presented in Sections 4.1 and 4.2 show that a complete (100%) clearance of activated materials is almost impossible for a D-T fueled power plant. A substantial quantity of activated materials would have to be recycled within the nuclear industry or, alternatively, disposed of as LLW. The production of such materials is difficult to avoid by means of materials selection (25).

The goal of 100% clearance could be achieved by modifying the fuel cycle and exploring the use of advanced fuel cycles, such as D-^{3}He, P-^{11}B, and ^{3}He-^{3}He. No tritium breeding is necessary with these cycles, eliminating the need for the blanket and its R&D programs. The presence of fusion neutrons is null for ^{3}He-^{3}He and very low for P-^{11}B and D-^{3}He. The P-^{11}B and D-^{3}He fuel cycles are not completely aneutronic due to the side reactions. Neutron wall loadings, however, can be kept low (by orders of magnitude) compared to D-T fuelled plants with the same output power (26). Nevertheless, burning advanced fuels requires substantial, continued progress in plasma physics and the scarcity of ^{3}He on earth raises the question of whether the time frame for acquiring the large lunar ^{3}He resource will be compatible with the fusion pathway to commercialization.

High beta and/or high field innovative confinement concepts, such as the field-reversed configuration and, to a lesser extent, the tokamaks are suitable devices for advanced fuel cycles. In the early 1990s, the ARIES-III D-^{3}He tokamak was developed within the framework of the ARIES study (27). The D-^{3}He Apollo series, along with ARIES-III, demonstrated attractive safety characteristics (28,29,30), including low activity and decay heat levels, low-level waste (WDR < 0.1), and low releasable radioactive inventory from credible accidents. Due to the lack of data, no clearance indices were evaluated in the early 1990s. Recent research, however, provided some insights on the clearance level for such D-^{3}He concepts. Zucchetti (23) examined the D-^{3}He Candor power plant and concluded that 100% clearance of materials is an achievable goal. The unconditional release of the slightly activated materials with no need for radioactive waste disposal is the key result of the Candor assessment. This suggests that studies for the development of advanced fuel cycles should be carried out in parallel with the present mainstream D-T

fusion power development, as the low neutron production helps overcome some of the engineering, materials, and safety hurdles to fusion development.

4.4 Recycling criteria

The feasibility of recycling fusion materials has been the subject of studies for some years. These studies have identified in recycling – after a long interim decay period up to 100 y – the main approach for avoiding the production of PWD, even for components close to the plasma. In fact, the direct reuse or recycling of low-activation materials within the nuclear industry, usually after a decay period of up to 100 years, keeps the material out of the waste stream, provided the separation of more active nuclides during the recycling process is avoided (31). Recycled materials could be used to fabricate new components for nuclear power plants of any type, for example radwaste containers, confinement buildings, shielding fillers, etc.

When determining the suitability of active material for recycling within the nuclear industry, power plant studies have employed criteria based solely on radiological parameters such as contact gamma dose-rate, intended to reflect the ability to handle the materials for processing by remote handling means if necessary. Reviews of remote procedures currently used within the nuclear industry suggest that these criteria have been unduly conservative. For example, as noted in section 4.1, European studies have assumed that the upper limit of gamma dose rate for a material to be suitable for recycling is 20 mSv/hr, whereas re-melting of wastes from fission power plants has already been carried out on material with a contact dose rate of 120 mSv/hr. Much higher dose rates than this are present in routine operations in the reprocessing of fission reactor fuel, for example in vitrification facilities. Contact dose rates of 3000 Sv/hr may be present at the outside surfaces of cylinders during operations such as weighing, welding, cleaning, contamination monitoring and transfer to flasks. A recent U.S. study has demonstrated the usefulness of recycling fusion components under the high dose rate condition of 3000 Sv/hr (32).

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 the recycling of active fusion components. The re-melting of steels, routinely performed using small-scale furnaces in the fission decommissioning industry, should present few problems. Of greater concern is the need to recycle components made of several materials. For example, the need to segregate the magnet and bioshield (13,14) into their original constituents and to separate the beryllium (or tungsten) armor from the first wall, particularly because these are the components with the highest level of activity. A review of recycling of blanket and divertor components, performed as part of PPCS (33) 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. A new study of possibilities for recycling active fusion material is now being launched in Europe.

The conservative radiological criteria applied in power plant studies for recycling suitability should be revised. The 2 mSv/hr dose limit for SRM does seem appropriate, as this corresponds to the acceptance criteria in some existing melting facilities (34), however, as the above discussion indicates, the 20 mSv/hr CRM limit could be increased, probably by one or two orders of magnitude. The feasibility of recycling active materials from a fusion power plant 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. The new European studies will consider metrics that could be applied to quantitatively evaluate these issues.

Handling of tritiated materials is another issue to be considered for recycling. Because of high diffusivity and high permeability of tritium in ferritic steel, the in-vessel components, even the vacuum vessel located far away from the plasma, will contain tritium at a much higher level than the clearance level (100 Bq/g for IAEA recommendation). In order to handle these tritiated materials for recycling, a guideline of tritium concentration will be necessary. The IAEA standards for safe transport (35) can be a guideline for this purpose (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. When the materials have a possibility of containing tritium beyond the guideline for the package, they should be pre-detritiated before transportation. After the radioactive materials are transported to the recycling plant, tritium concentration in the material can be reduced to an acceptable level for recycling by bubbling in a melting furnace.

5. Socio-economic Aspects

Further aspects must be considered for both clearance and recycling, besides the question of their radiological feasibility. Regarding clearance, the issue of public acceptability of cleared material must be considered, since it is not assured that formerly radioactive material would be accepted for unrestricted use, despite its extremely low level of activity. This is not an issue, of course, if the cleared material is simply disposed of in landfill sites.

At present, there is no market for the free (unconditional or unrestricted) release of slightly contaminated materials anywhere in the world. 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 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.

Concerning recycling, it 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 activated material recycling must be considered too. Recycling processes and long-time storage of activated fusion materials may result in the

price of recycled activated materials not being competitively priced with industrial recycled non-radioactive materials. Therefore, economically viable strategies must be envisaged for recycling.

6. Conclusions

One of the main goals for fusion is the minimization of radioactive materials, originating from a power plant, that need permanent disposal with a 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 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, PPCS, and advanced fuel cycles) shows excellent potential results: total recycling and clearance of these power plant materials seem a reachable goal, in principle.

For materials clearance, revised limits have been recently issued at the international level and in the US 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 points can be noted with regard to clearance:

1) 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.
2) 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.
3) 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.
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 of active material within the nuclear industry, power plant studies have employed criteria based on radiological parameters only, such as contact gamma dose-rate, intended to reflect the ability to handle the materials for processing by remote handling means if necessary. The following questions must be pointed out, however:

1) Reviews of current practices within the nuclear industry show that these radiological criteria for recycling 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 particular issues of removal and transportation of tritium need to be fully addressed.

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