Evolution of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants

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July 2005
(revised August 2005)

UWFDM-1271

Accepted for publication in *Fusion Science and Technology*.

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ABSTRACT

The issue of radioactive waste management presents a top challenge for the nuclear industry. As an alternative to recycling or disposal in repositories, many countries are proceeding successfully with the process of developing clearance guidelines that allow solids and building rubble containing traces of radioisotopes to be cleared from regulatory control and unconditionally released to the commercial market after a specific storage period. With the emergence of new clearance standards, we took the initiative to compare the US to the European and other international limits. This exercise is proving valuable in understanding the differences between the clearance standards and their implications for the radwaste management of fusion power plants. While clearance standards now exist for most radionuclides that are mainly important to the fission industry, no such standards are in place for many radionuclides of interest to fusion facilities. Before fusion penetrates the energy market, fusion-specific standards should be developed to address the safe release of fusion materials with trace levels of radioactive contamination.

I. INTRODUCTION

The main focus of the waste management task is the efficient disposal of radwaste materials. This includes the careful distinction between radioactively contaminated and clean materials. During the course of MFE and IFE power plant studies, estimates are made of the total quantities of radioactive materials, including estimates of the various low-level waste classifications and the relative amounts of slightly radioactive materials. Despite the availability of shallow burial repositories in the US, the relatively large volume of radwaste that nuclear facilities generate compared to other sources of energy forces designers to examine the recycling and clearance options as a means to enhance the repository capacity by reducing the volume of solid waste requiring radioactive burial. The majority (70-90%) of the nuclear waste contains traces of radioactive nuclides that represent no risk to the public health and safety. Nuclear researchers in the US, Europe, and elsewhere have attempted to issue policy statements to deregulate materials with low concentrations of radioactive contamination. If this effort succeeds, the cleared materials will not be subject to regulatory control, be handled as if they are no longer radioactive, be unrestrictedly recycled into consumer products (tools, tables, chairs, building and road materials, etc.), and more importantly, save the disposal cost (several thousand dollars per cubic meter). The clearance policy will be extremely valuable in the future as the decommissioning of fission and fusion plants generates a large amount of slightly radioactive waste. Concrete constitutes the greatest volume of slightly radioactive solids resulting from decommissioning.

The clearance guidelines and standards developed since the early 1980s are documented in a set of reports published by the Nuclear Regulatory Commission (NRC) in the US, the International Atomic Energy Agency (IAEA) in Vienna, and European Commission (EC) in Europe. Japan is currently developing similar regulations. The IAEA clearance limits developed over the past two decades have been used worldwide for a diverse range of fusion concepts from magnetic fusion energy (MFE) tokamaks[1-5] to inertial fusion energy (IFE) applications[6-9]. With the emergence of the new IAEA clearance limits in 2004, the US guidelines in 2003, and the European Union (EU) standards in 2000, we took the initiative to compare the three clearance standards and identify the implications on the waste management approach, highlighting the areas of discrepancy and agreement for the isotopes of interest to fusion applications. For this purpose, we have applied the clearance criteria to two representative IFE and MFE power plants: Z-pinch[7,10] and the ARIES-CS compact stellarator[11]. The dominant questions this study set out to answer are the type of radioactive materials originating from these facilities and the feasibility of clearing the components that dominate the waste stream based on the most recent system of clearance standards developed during the decade of the 2000s.

This paper is organized as follows. We begin with the historic evolution of the clearance standards followed by a comparison between the most recent US, IAEA, and EU guidelines. The following sections briefly describe the Z-pinch and ARIES-CS designs. Sections VI and VII summarize the clearance results and document the anticipated waste inventory. Section VIII surveys the marketplace and highlights the reaction of the US industries and nuclear institutions to clearance. We conclude with specific remarks and recommend additional evaluations to the clearance standards that are deemed necessary for fusion applications.

Throughout this study, the neutron flux was evaluated with the DANTSYS[12] discrete ordinates transport code with the FENDL-2 175 neutron 42-gamma group coupled cross section library. The activation results reported herein were computed with the ALARA pulsed activation code[13] and the FENDL-2 175 neutron group transmutation cross-section library[14]. The activation model assumes the irradiation process continues for the entire plant life (40 full power years) with 85% availability. Future studies may call for 10-20 full power year (FPY) lifetime extensions to operate beyond the projected 40 FPY plant life. This extension may require an additional few centimeters of blanket/shield to protect the external components (vacuum vessel, magnets, building etc.) and such a minor modification to the design will not alter the conclusions of this study.

II. EVOLUTION OF CLEARANCE STANDARDS

II.A. US Documents

Since the 1940s, the Atomic Energy Commission (AEC) and its successor agency in the US, the NRC, have tried to set standards for release of slightly radioactive materials from regulatory control for licensed US facilities such as fission power reactors, fuel fabrication and reprocessing plants, accelerators, hospitals, etc. The original 1957 standards for protection against radiation by the AEC did not include criteria specifying a concentration of a radionuclide in a solid material below which the solid material would be exempt from regulatory control. However, an amendment was added later allowing the NRC to evaluate requests by licensees for permission to release solid materials on a case-by-case basis. During the decade of the 1970s, the NRC has attempted to give greater uniformity to the clearance standards while materials containing traces of radioactivity continued to be released to date using the case-by-case approach. More attempts by the NRC in 1980, 1990, 1998, and just recently in 2003 declared materials with low concentrations of radioactivity can be deregulated. The 1998 draft NUREG-1640 document[15] contains estimates of the total effective dose equivalent (from which the clearance index can be derived) for 67 radionuclides that could be present in metals from decommissioning of nuclear facilities. The draft NUREG-1640 document has been published in a final form[16] in 2003 where 58 limits were updated, 9 radionuclides eliminated, and 57 new radionuclides added, bringing the total number of radioisotopes to 115 for steel-based and concrete-based wastes. There are important differences between the 1998 draft and the 2003 final documents, as will be discussed shortly.

The 2003 technical study[16] did not address nuclides with half-lives < 30 days or gases (such as H, Ar, and Kr) since they would not be likely to remain in the materials removed from nuclear facilities. Short-lived progenies 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 annual doses can be found in the appendices of NUREG-1640[16]. Note that this 2003 report incorporated more realistic modeling of the current industrial practices in the US to minimize unnecessary conservatism, i.e., overestimation of annual doses. The results of the 2003 analysis can be used as part of the technical basis to support US regulatory considerations. However, this technical report[16] cannot be inferred to represent any US regulatory decision as 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 draft and final documents[15,16] will be referred to as the US limits.

Even though we are content to only use the proposed US limits in our analysis, it is pertinent to mention two important US documents: The American National Standards Institute (ANSI) 1999 document[17] that helped to spur on the NRC to finalize their NUREG document and the Department of Energy (DOE) 1997 handbook[18] that controls the recycling and reuse of slightly radioactive materials from 13 DOE sites not licensed by the NRC. In many instances, the DOE facilities are no longer functioning but still contain significant amounts of slightly radioactive materials. The DOE interim document[18] has not been finalized yet.

II.B. European and IAEA Documents

Beginning in 1996, the EC has published a number of reports[19-21] that deal with clearance issues. These reports address special cases of metals recycling, equipment and building reuse, and building demolition. The most recent EU clearance limits for 197 radionuclides that could be present in any type of materials are documented in the 2000 EC RP-122 report[22]. These limits are typically 1-4 orders of magnitude lower than those reported for 295 radionuclides in the previous 1996 document[20]. The most recent guidelines modified, eliminated, and added limits for 165, 130, and 32 radionuclides, respectively. An explicit assumption in the EC analysis that built into the EC recommendations is that it is forbidden to mix highly contaminated surfaces or rubble with the uncontaminated bulk of the structure.

In a series of documents issued in the early 1980s and continuing through the 1990s, the IAEA established the principles that underlie its technical estimates of the dose factors and clearance limits[23,24] for the recycling of steel, aluminum, and concrete. Results using limits established prior to 1995 tend to overpredict the doses as parameters were assigned values from the upper end of their expected range. In 1996, the IAEA prepared an interim report on recommended clearance limits for solid materials[25] for 1650 radionuclides of interest to fission and fusion applications. Just recently, the IAEA published revised clearance standards[26] for 257 radionuclides, claiming to take into account the US NUREG-1640[16] and the EU EC-RP-122[22] evaluations.

III. COMPARISON OF CLEARANCE LIMITS

There is widespread agreement between the US, IAEA, and EU organizations on the primary dose standard and the negligible risk the cleared materials present to individuals. They all recommended an individual dose standard of 10 μSv/y (1 mrem/y) for cleared solids. According to the United Nations recommendations, the radiation dose above background level to members of the public from radiation sources other than medical exposures should not exceed 1 mSv/y (100 mrem/y). This means the 10 μSv/y dose limit for cleared solids represents 1% of the total allowable excess dose, < 0.5% of the radiation received each year from natural background sources (2.4-3.6 mSv/y), and significantly less than the amount of radiation that we receive from our own body[27] from radioactive potassium-40 (0.18 mSv/y), from routine medical procedures (0.55 mSv/y), for living in a brick house (70 μSv/y), or for flying across the country (25 μSv).

Even though all three standards recommend an annual dose of 10 μSv as the basis for clearance of solids from regulatory control, we observed a notable difference between the most recent clearance limits for the 115, 257, and 197 radionuclides developed by US[16], IAEA[26], and EU[22], respectively. Furthermore, numerous fusion radioisotopes with $T_{1/2} \geq 10$ y are missing and should be included in future evaluations as they may be important for determining the long-term disposition of materials from decommissioned fusion power plants. These 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.

As will be shown shortly, the three standards do not agree on the limits for many radioisotopes because different approximations are used to compute these limits and different exposure scenarios are selected to model the doses. Consistency of clearance standards is certainly desirable, particularly for materials that may end up in the international market. Given the complexity of the scenarios used to develop the clearance standards with so much effort having gone into these studies over the past 25 years, it seems unlikely that additional, reasonable effort will be able to dramatically reduce the differences and understand the technical reasons for the major disagreements at least until there is real-world experience that can be used for benchmarking purposes.

Figures 1-3 display the evolution of the US, IAEA, and EU clearance standards, comparing the new to old limits developed during the 1996-2004 period. Ratios < 1 are clearly an important indicator for the degree of conservatism built in issuing the new limits. Note that the EU[20,22] and new IAEA[26] limits are rounded to the power of 10, the new EU limits are 1-4 orders of magnitude lower than the old limits, and the new US standards are becoming less conservative. The motivation for the extreme divergence of the new EU limits being more restrictive while the new US limits being more liberal - is stated in the reports. Reference 22 mentions that the most restrictive scenario was adopted to define the EU clearance standards, selecting low doses in case an individual is exposed to multiple objects produced from cleared materials. The US study[16] incorporated realistic modeling of the current US industrial practices as well as current data on the living habits in the US in order to minimize unnecessary conservatism in the dose estimates.

To make a comparison across the three standards, Figs. 4-6 display the ratios of the new EU and US limits to the IAEA's. At first glance, we noticed that the EU standards are the most conservative, followed by IAEA's, then US. In other words, the EU standards are more restrictive and protective to the public. However, applying the limits to actual designs, the trend could be reversed, depending on the dominant radioisotopes. Table I lists the old and new clearance limits for selected radioisotopes encountered in fusion applications. Normally, the clearance limit is expressed in becquerel per gram and can be derived by dividing the recommended 10 μSv/y dose standard by the mass-based effective dose equivalent (in μSv/y per Bq/g) for the individual radionuclide.

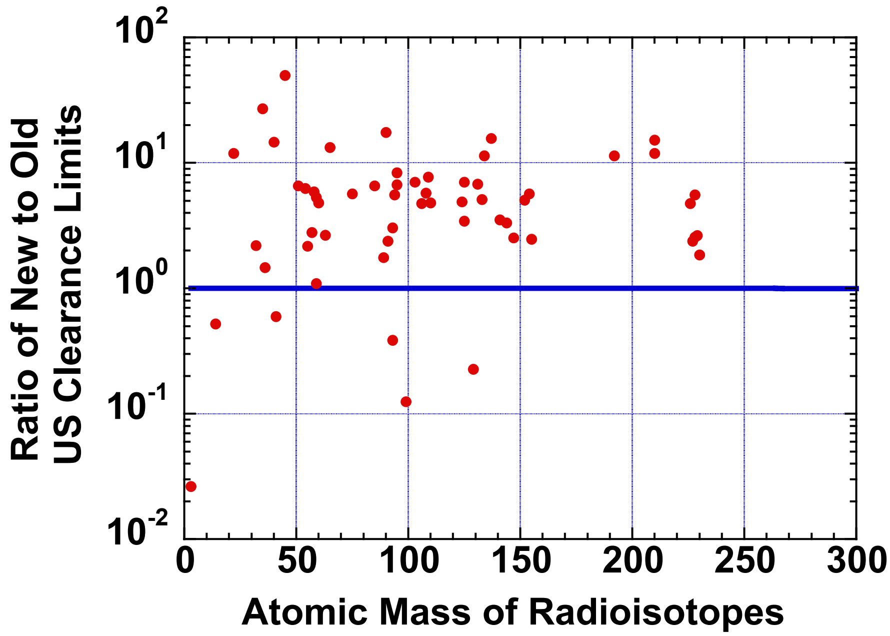

Fig. 1. Ratio of 2003 to 1998 US clearance limits for steel.

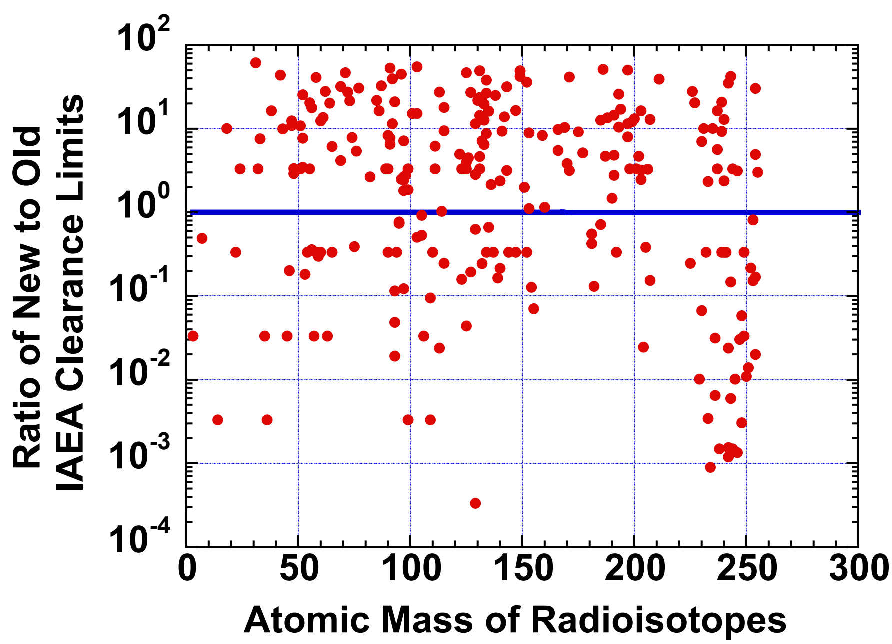

Fig. 2. Ratio of 2004 to 1996 IAEA clearance limits.

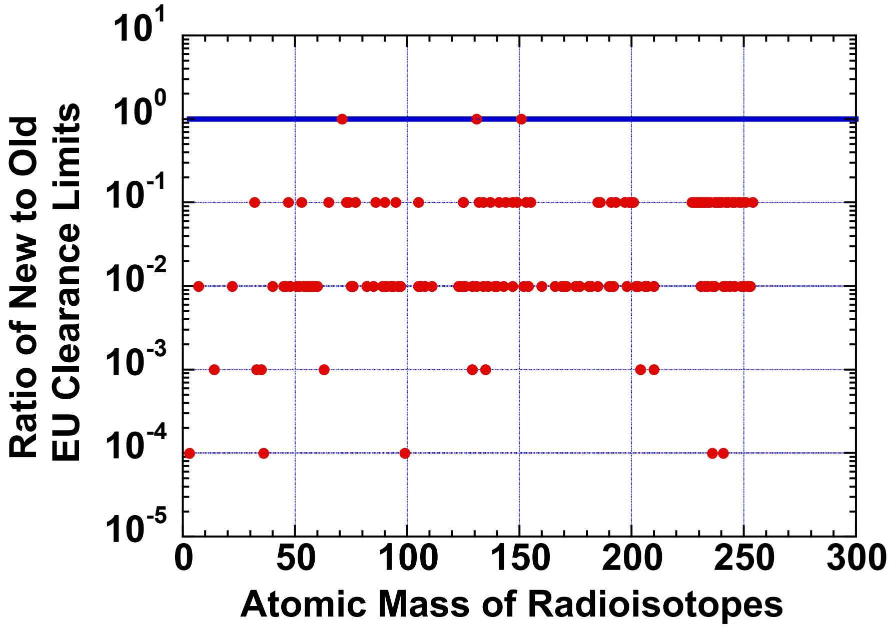

Fig. 3. Ratio of 2000 to 1996 EU clearance limits.

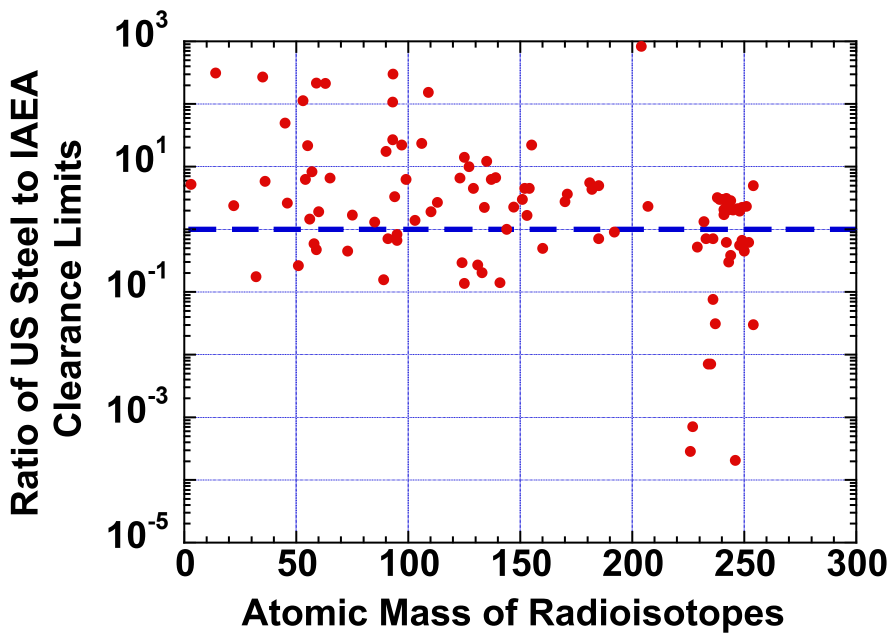

Fig. 4. Ratio of 2003 US steel clearance limits to 2004 IAEA's.

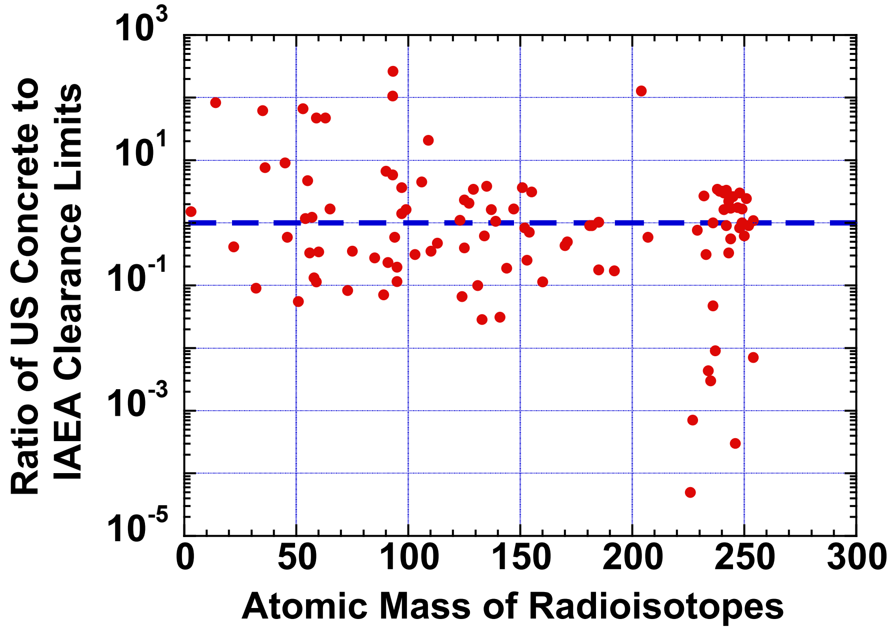

Fig. 5. Ratio of 2003 US concrete clearance limits to 2004 IAEA's.

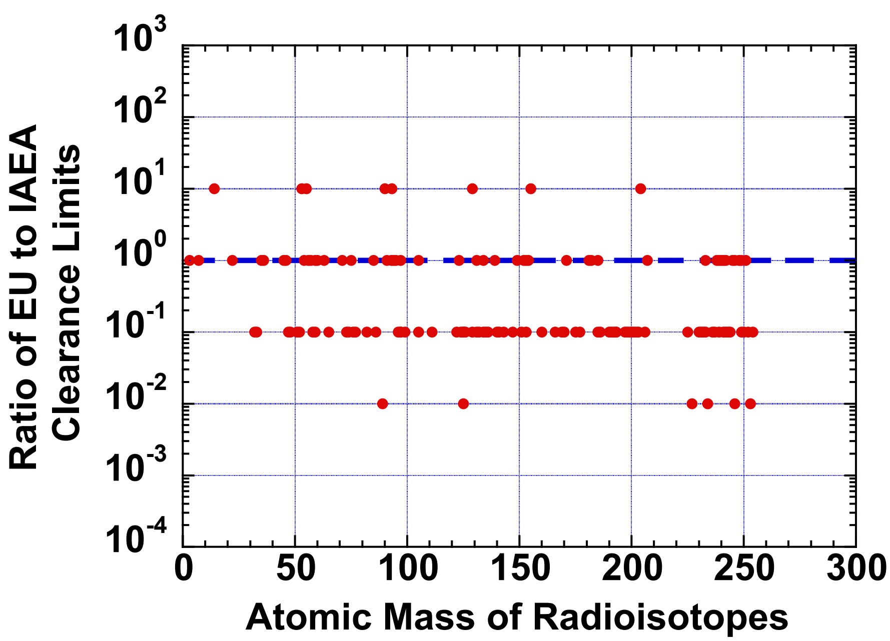

Fig. 6. Ratio of 2000 EU clearance limits to 2004 IAEA's.

Table I. Clearance Limits (in Bq/g) for Selected Radionuclides

Radionuclides	US-1998[15] Metals	US-2003[16] Steel	Concrete	IAEA-1996[25]	IAEA-2004[26]	EU-1996[20]	EU-2000[22]
H-3	2.00E+04	5.26E+02	1.52E+02	3.00E+03	1.00E+02	1.00E+06	1.00E+02
C-14	6.00E+02	3.13E+02	8.30E+01	3.00E+02	1.00E+00	1.00E+04	1.00E+01
Na-22	2.00E-02	2.38E-01	4.17E-02	3.00E-01	1.00E-01	1.00E+01	1.00E-01
Cl-36	4.00E+00	5.88E+00	7.69E+00	3.00E+02	1.00E+00	1.00E+04	1.00E+00
Ar-39	---	---	---	4.57E+01	---	---	---
K-40	2.00E-01	2.94E+00	5.26E-01	4.78E+00	---	1.00E+02	1.00E+00
Ca-45	1.00E+02	5.00E+03	9.09E+02	3.00E+03	1.00E+02	1.00E+04	1.00E+02
Mn-53	---	1.14E+04	6.67E+03	5.49E+02	1.00E+02	1.00E+04	1.00E+03
Mn-54	1.00E-01	6.25E-01	1.18E-01	3.00E-01	1.00E-01	1.00E+01	1.00E-01
Fe-55	1.00E+04	2.17E+04	4.76E+03	3.00E+02	1.00E+03	1.00E+04	1.00E+02
Fe-59	9.00E-02	4.76E-01	1.14E-01	3.00E+00	1.00E+00	1.00E+01	1.00E-01
Ni-59	2.00E+04	2.17E+04	4.76E+03	3.33E+02	1.00E+02	1.00E+04	1.00E+02
Co-60	4.00E-02	1.92E-01	3.45E-02	3.00E-01	1.00E-01	1.00E+01	1.00E-01
Ni-63	8.00E+03	2.13E+04	4.76E+03	3.00E+03	1.00E+02	1.00E+05	1.00E+02
Sr-90	1.00E+00	1.75E+01	6.67E+00	3.00E+00	1.00E+00	1.00E+02	1.00E+00
Mo-93	7.00E+02	2.70E+02	5.88E+01	8.69E+01	1.00E+01	1.00E+03	1.00E+01
Nb-93m	1.00E+03	3.03E+03	2.63E+03	2.06E+02	1.00E+01	1.00E+04	1.00E+02
Nb-94	6.00E-02	3.33E-01	5.88E-02	3.00E-01	1.00E-01	1.00E+01	1.00E-01
Nb-95	1.00E-01	8.33E-01	1.96E-01	1.30E+00	1.00E+00	1.00E+01	1.00E+00
Zr-95	1.00E-01	6.67E-01	1.16E-01	1.35E+00	1.00E+00	1.00E+01	1.00E-01
Tc-99	5.00E+01	6.25E+00	1.64E+00	3.00E+02	1.00E+00	1.00E+04	1.00E+00
I-129	2.00E-01	4.55E-02	3.45E-02	3.00E+01	1.00E-02	1.00E+02	1.00E-01
Cs-137	4.00E-02	6.25E-01	1.64E-01	3.00E-01	1.00E-01	1.00E+01	1.00E+00
Ir-192	8.00E-02	9.09E-01	1.72E-01	3.00E+00	1.00E+00	1.00E+01	1.00E-01
Ag-108m	6.00E-02	3.45E-01	5.88E-02	6.13E-01	---	1.00E+01	1.00E-01
Ag-110m	4.00E-02	1.92E-01	3.57E-02	3.00E-01	1.00E-01	1.00E+01	1.00E-01
Re-186	4.00E+01	---	---	1.95E+01	1.00E+03	1.00E+03	1.00E+02

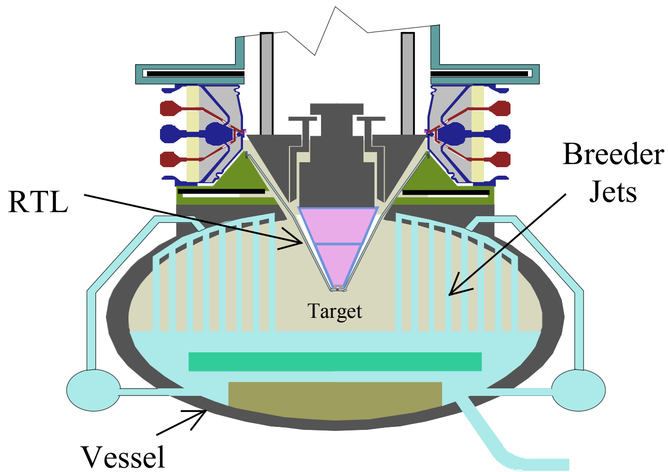

Fig. 7. Z-pinch chamber and RTL connecting the target to the power supply.

By definition, the clearance index (CI) for a particular component is the ratio of the activity (in Bq/g) of the individual radioisotope to the allowable clearance limit summed over all radioisotopes. A component qualifies for clearance if the CI drops below one at any time during a 100 year storage period following decommissioning. This means the component contains traces of radioactive nuclides and represents no risk to the public health and safety. The clearance indices of the various components comprising fusion devices vary widely, depending on the constituents, radioactivity level, and proximity to the plasma. Plasma facing components tend to exhibit very high clearance indices. Our approach for handling the cleared component (CI < 1) is to reevaluate the CIs for the constituents of the component (structure, filler, breeder, conductor, etc.). This may cause a problem. Even though the entire component could qualify for clearance, the individual constituents may not. If so, constituents with CI > 1 should be disposed of as low-level waste in geologic repositories while cleared solids (CI < 1) can be shipped to industry or the marketplace for reuse.

IV. Z-PINCH OVERVIEW

Z-pinch IFE is relatively new, and has become an essential part of the IFE community over the past five years[10]. The magnetically insulated Recyclable Transmission Line (RTL) connects the driver to the target as shown in Fig. 7. The RTL is made from a material that is easily separable from the coolant and would enter the 5 m radius chamber through a 1 m radius single hole at the top of the chamber. Since the inception of the Z study, recycling of the RTLs has been recognized as a

Table II. Key Design Parameters

Parameters	Z-Pinch	ARIES-CS
Net electric power	1 GW_e	1 GW_e
Target yield	3 GJ	---
# of units	12	1
Rep rate	0.1 Hz	---
# of shots / y	38 million	---
Average first wall radius	5 m	1.85 m
Neutron Wall Loading	---	2 MW/m^2
Availability	85%	85%
Plant lifetime	40 FPY	40 FPY

"must" requirement to control the radwaste stream and limit the RTL inventory to less than ten thousand tons. The RTL is made of carbon steel and manufactured onsite. The key design parameters are given in Table II. Every 10 seconds, the RTL/target assembly is inserted into the chamber, the shot is fired, portions of the RTL are vaporized and mix with the coolant to be recycled, the upper remnant of the RTL is removed, and the cycle is repeated. An online separation of the elements leaving the chamber would sort out the breeding material and target debris from the RTL shrapnel. The RTL materials spend 38 hr outside the chamber for remanufacturing, assembly, and inspection. Remote operation seems feasible using robots to pick up the ignited RTL and insert a new one into the chamber. The ALARA activation code[13] modeled all pulses (~10,000) using the $6x10^{14}$ n/cm^2s space-average flux distributed over the conical RTL[7].

The IFE Z-pinch is worth consideration because of the possible advantages for clearing the RTL, an in-vessel component. Unlike all other IFE concepts (driven by laser or heavy ion beams), the Z-pinch illustrates for the first time that an internal component inside the containment building contains only traces of radioactivity and approximately 1000 m^3 of carbon steel can potentially be cleared from regulatory control after plant decommissioning. The ten vessels and surrounding containment building represent other waste streams for the Z-pinch. The sizable building dominates the waste stream, followed by the 2000 m^3 vessels and 1000 m^3 RTL. An activation assessment is underway to estimate the various classifications for the building and vessel components.

V. ARIES-CS OVERVIEW

Advances in physics and technology have yielded the compact stellarator – a promising new configuration for magnetic fusion. It combines the best features of tokamaks with the inherently steady-state operation of stellarators to avoid disruptions. The geometry follows a helical pattern shaped by the external toroidal field (TF) coils. Due to their 3-D

Fig. 8. Three field period ARIES-CS design option.

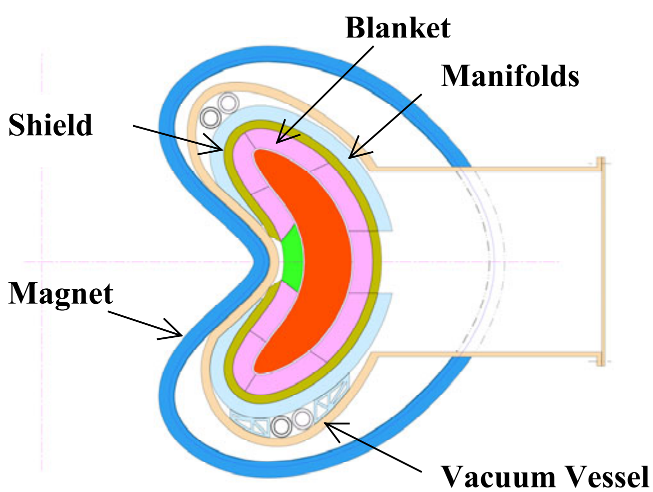

Fig. 9. Vertical cross section of ARIES-CS at beginning of field period.

topology, stellarators don't necessarily have the same poloidal cross-section found in tokamaks. The plasma boundary and first wall (FW) assume different cross-sections as one moves toroidally through the device. Figure 8 is a top view of ARIES-CS showing the plasma boundary and the 18 TF coils while Fig. 9 displays an elevation view at the beginning of a field period, showing the arrangement of the internal components. Not shown is the 2 m thick concrete building surrounding the torus to protect the workers and public. For this analysis, we employed a simplified cylindrical model in which one of the leading candidate blankets (the dual-cooled ferritic steel-based LiPb/He system) undertook the appropriate arrangement of ARIES-CS internal components shown in Fig. 9. The physical and operating parameters of ARIES-CS are listed in Table II.

Table III. Storage Periods for RTLs of Z-pinch

Material	US-1998[15]	US-2003[16]	IAEA-1996[25]	IAEA-2004[26]	EU-1996[20]	EU-2000[22]
Carbon steel	35 y ^{55}Fe	40 y T, ^{55}Fe, ^{60}Co	50 y ^{60}Co	70 y ^{53}Mn	30 y ^{54}Mn	60 y ^{55}Fe , T

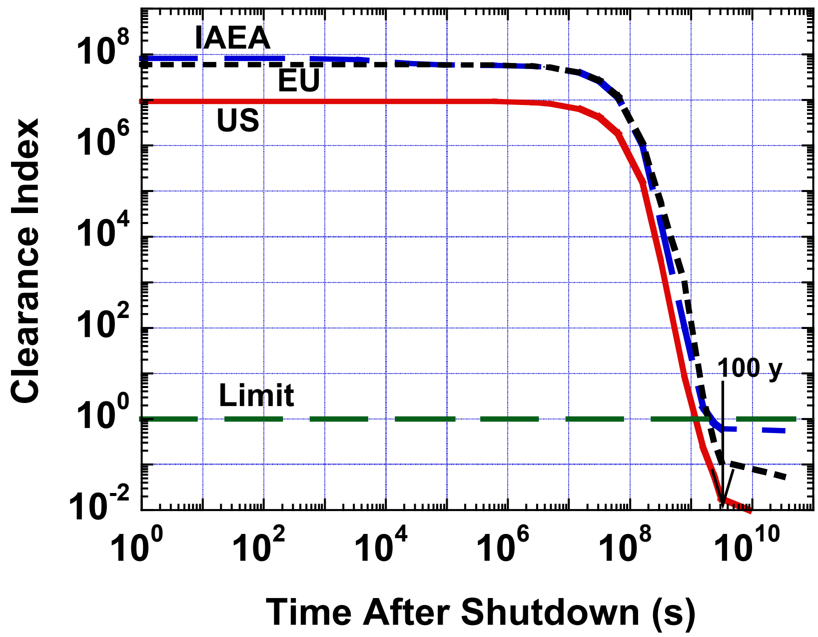

Fig. 10. Decrease of RTL clearance index with time after decommissioning.

VI. RESULTS OF CLEARANCE ANALYSIS

VI.A. Z-Pinch

The variation of the RTL CI with time after shutdown is shown in Fig. 10. Note the rapid drop in the CI on a time scale of a century. The CI reaches the limit of one at 40, 70, and 60 y after decommissioning, according to the US, IAEA, and EU guidelines, respectively. Table III documents the dominant radionuclides (in descending order) and compares the results of the new and old standards[28]. As noted, the new guidelines suggest a longer storage period. This observation is unique to the RTLs of the Z-pinch as the trend could be reversed for other components and designs. The analysis assumes the tritium is trapped in the RTL structure and continues to build up with time. In reality, a considerable fraction of the tritium is likely to diffuse out during reprocessing. Thus, the results reported herein are conservative as no credit is given to the release of T and/or the removal of the slag that may contain some of the transmutation products.

A CI < 1 means the RTL carbon steel can be cleared after 40-70 y and released to the nuclear industry or commercial market for reuse. Of interest is that the release saves a substantial disposal cost for such a large quantity, freeing ample space in the repositories for other radioactive wastes. Continual removal of the transmutation products during recycling would shorten the storage period, but generates an undesirable small amount of highly radioactive waste. Since the end products pose no radiological hazards and satisfy the recycling criteria[7,8], it is recommended not to deliberately separate the transmutation products to simplify the recycling process and reduce its cost.

VI.B. ARIES-CS

The activation and subsequent radiological and clearance analyses of ARIES-CS are more complex than that of the Z-pinch RTL as we deal with multiple components, numerous constituents, and various service lifetimes. The CI of each component depends strongly on the neutron flux level, neutron spectrum, composition, and lifetime. We used a lifetime of 5 full power years (FPY) for the blanket and 40 FPY for all other components. The CI results for the dual-cooled LiPb/FS/He design option are plotted in Fig. 11 using the IAEA standards. Because of the compactness of the machine, the CIs of all internal components (blanket, shield, vacuum vessel, and magnet) exceed the clearance limit by a wide margin. These findings are not unique to stellarators as similar conclusions have been reached for the internals of advanced tokamaks[1]. This means the ARIES-CS internal components should be disposed of in repositories[29] as low-level waste (LLW).

Of interest is the 2 m thick external concrete building that surrounds the torus. It qualifies for clearance. We further divided the building into four segments (0.5 m each) and reevaluated the CIs for the constituents (85% concrete and 15% mild steel, by volume) of each segment since the ultimate goal of clearance is to reuse the constituents by industry. The results indicate that, as expected, the innermost segment has the highest CI (see Fig. 12). The outer three segments meet the clearance limit within a few days after decommissioning. We then applied the US, IAEA, and EU clearance standards to the innermost segment. Further segregation of the constituents reveals that the mild steel is a major contributor to the CI although its volume fraction is only 15%. Figures 13 and 14 depict the drop of the CI with time for the innermost segment's steel and concrete according to the US, IAEA, and EU guidelines. Note that the US standards call for the shortest storage period. The recommended storage periods are given in Table IV along with the dominant radionuclides in descending

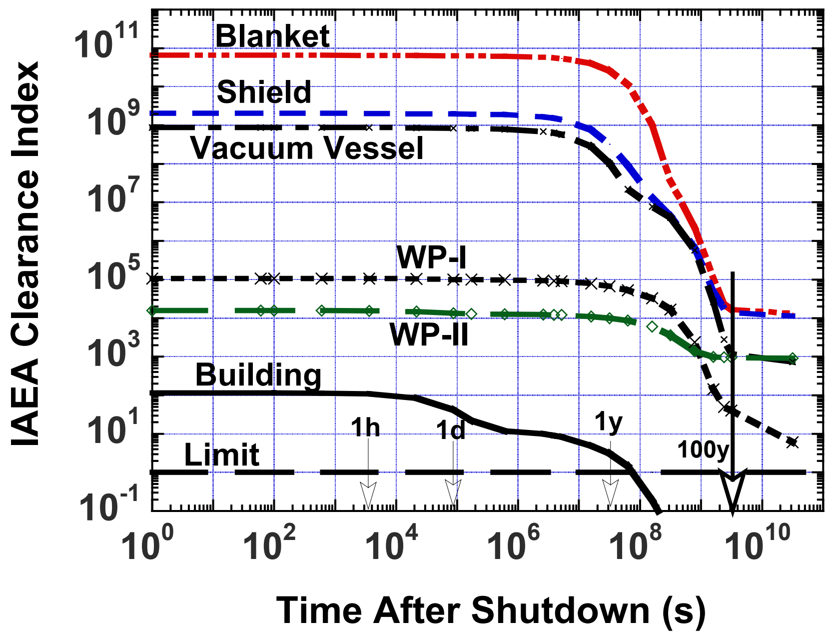

Fig. 11. Decrease of ARIES-CS clearance index with time after decommissioning

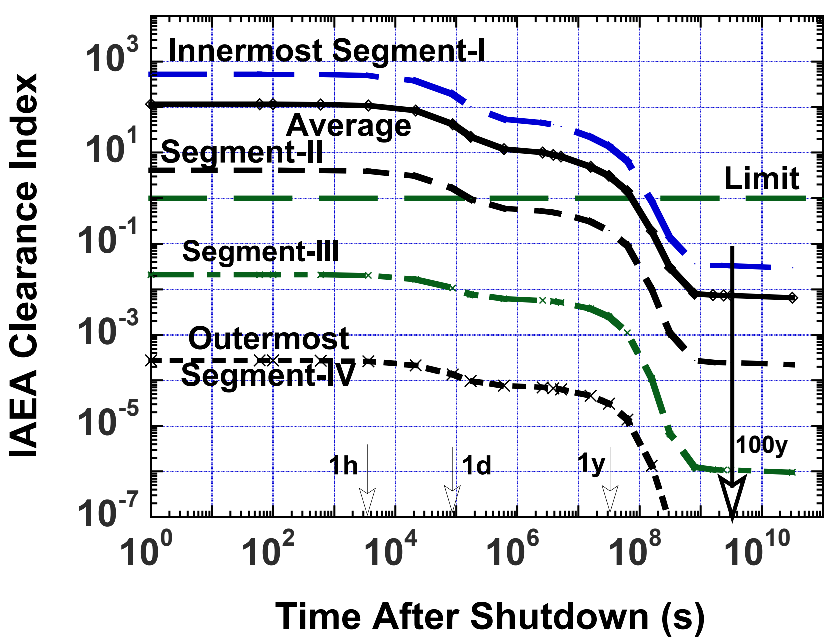

Fig. 12. Clearance index for individual segments of concrete building.

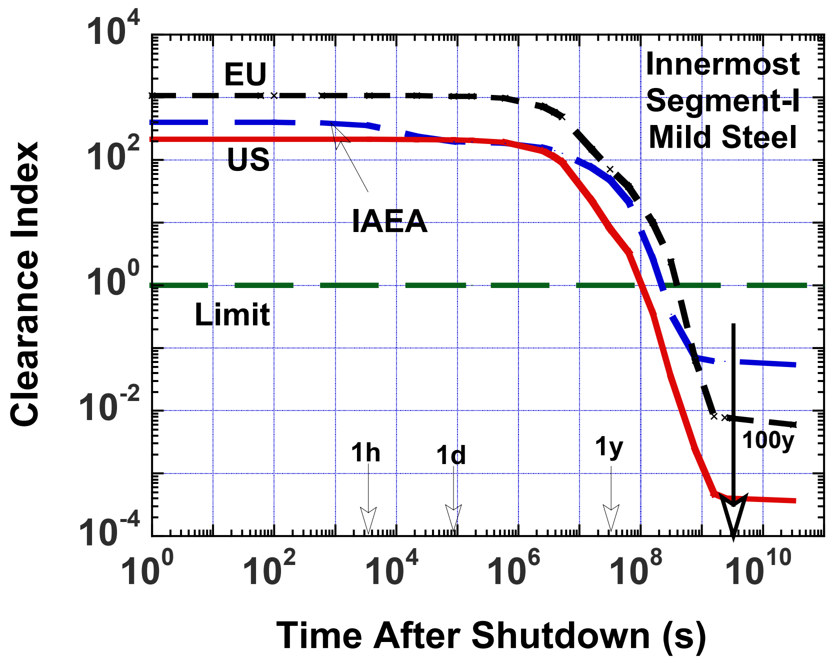

Fig. 13. Comparison of US, IAEA, and EU clearance indices for steel of innermost segment-I of the confinement building.

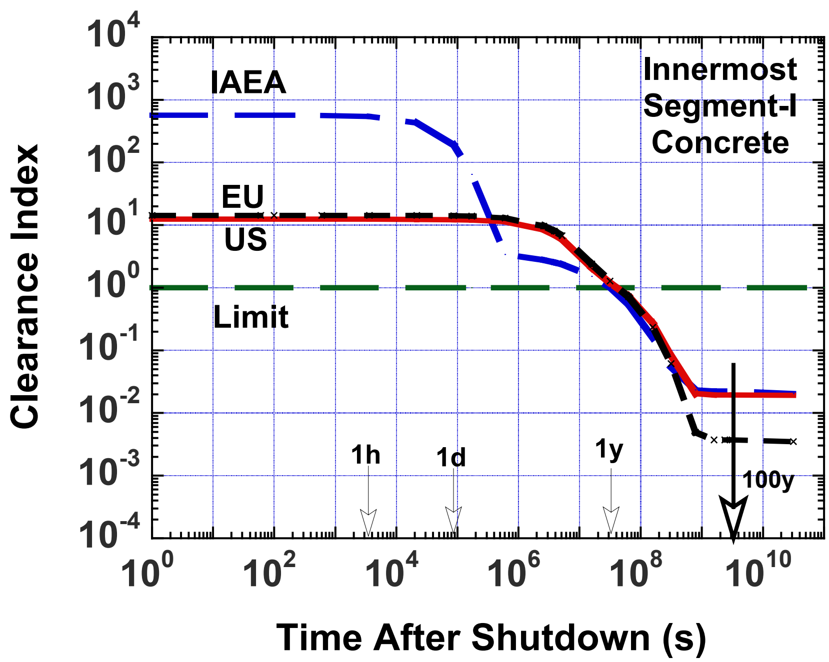

Fig. 14. Comparison of US, IAEA, and EU clearance indices for concrete of innermost segment-I of the confinement building.

Table IV. Storage Periods for Constituents of Innermost Segment-I of ARIES-CS Building

Constituents	US-1998[15]	US-2003[16]	IAEA-1996[25]	IAEA-2004[26]	EU-1996[20]	EU-2000[22]
Mild steel	5 y ^{60}Co, ^{54}Mn	3.5 y ^{54}Mn, ^{55}Fe, ^{60}Co	10 y ^{55}Fe	7 y ^{54}Mn,^{55}Fe	1 y ^{54}Mn, ^{55}Fe	13 y ^{55}Fe
Concrete	N/A	1.3 y ^{22}Na, ^{54}Mn, ^{59}Fe, ^{41}Ca	1 month ^{55}Fe, ^{22}Na, ^{39}Ar	1 y ^{54}Mn, ^{22}Na, ^{45}Ca, ^{55}Fe	5 days ^{55}Fe, ^{22}Na	1.3 y ^{54}Mn, ^{22}Na, ^{55}Fe, ^{45}Ca

order. The inconsistencies in the clearance standards (refer to Table I) have resulted in widely varying storage periods for steel (3-13 y) and a comparable storage period (~ 1 y) for concrete. An effort was made to compare these storage periods with that of reference 28 where the pre-2000 standards[15,25,20] have been used to evaluate the CIs. As Table IV indicates, the new, less conservative US standards tend to shorten the storage period for the ARIES-CS building while the new, more restrictive EU standards extend it by 1-2 orders of magnitude.

VII. WASTE INVENTORY

This section summarizes the inventory of LLW and cleared solids expected from the ARIES-CS power plant. Figure 15 displays the breakdown of the fully compacted volume of the internal and external components of ARIES-CS. The blanket volume reflects the seven replacements required during operation. The confinement building represents the largest single component of the decommissioning waste (74%). As mentioned earlier, it includes materials in which radioactive contamination is so low that clearance is warranted. Similar observations have been made for fission power plants where ~95% of the US fission waste is essentially uncontaminated and suitable for clearance[27] (see Fig. 16). Note that if the lifetime of the fusion (or fission) plants can be extended for 10-20 more FPY, which seems probable, less inventory of materials would be expected to arise over a few hundred years from the decommissioning of fewer power plants, despite the slight increase in blanket/shield size necessary to protect the externals for > 40 FPY. Disposal of all slightly radioactive solids into LLW disposal sites would cost several billion dollars. Clearance could reduce this disposal cost to nearly zero.

VIII. SURVEY OF MARKETPLACE AND REACTIONS TO CLEARANCE IN THE US

VIII.A. Marketplace

At present, there is no market for the free (unconditional or unrestricted) release of slightly contaminated materials either in the US or abroad. Such a market will become increasingly important in this new millennium as the eventual

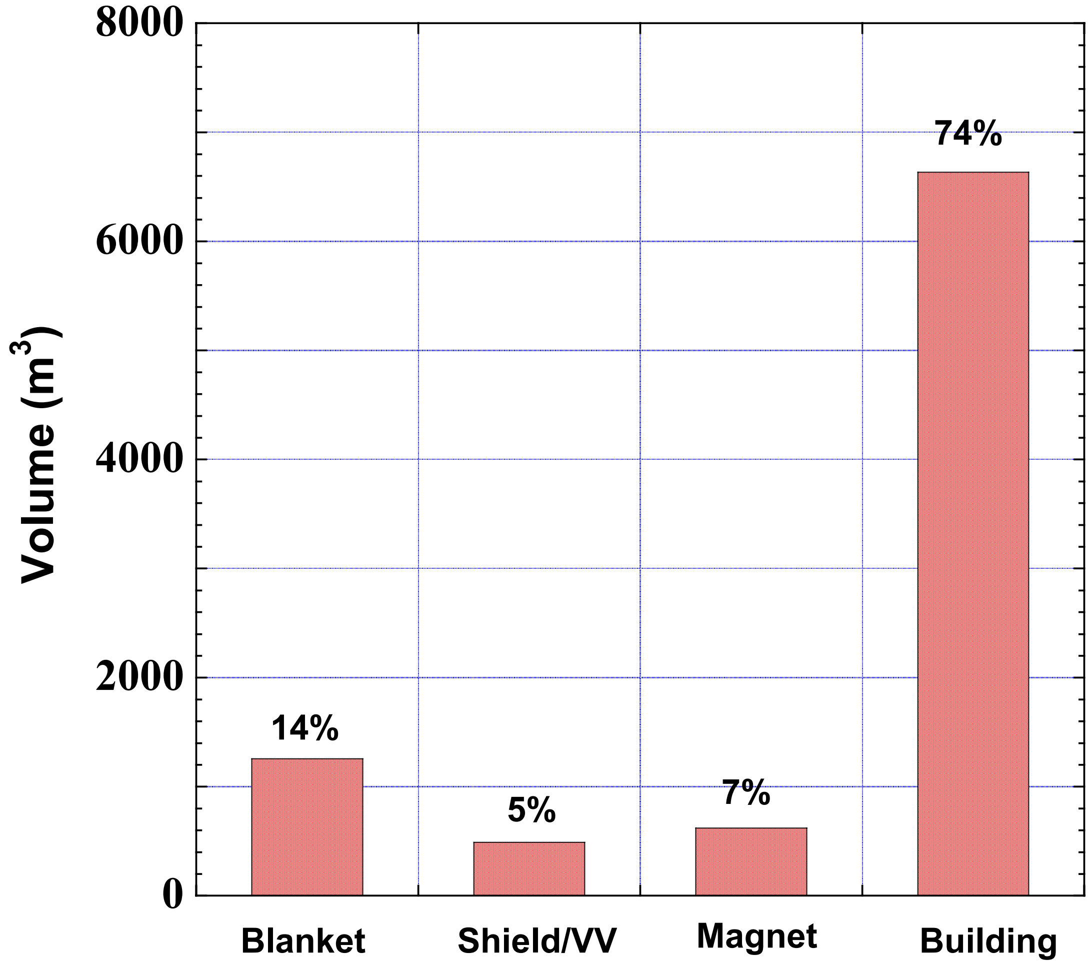

Fig. 15. Volume of ARIES-CS low-level waste.

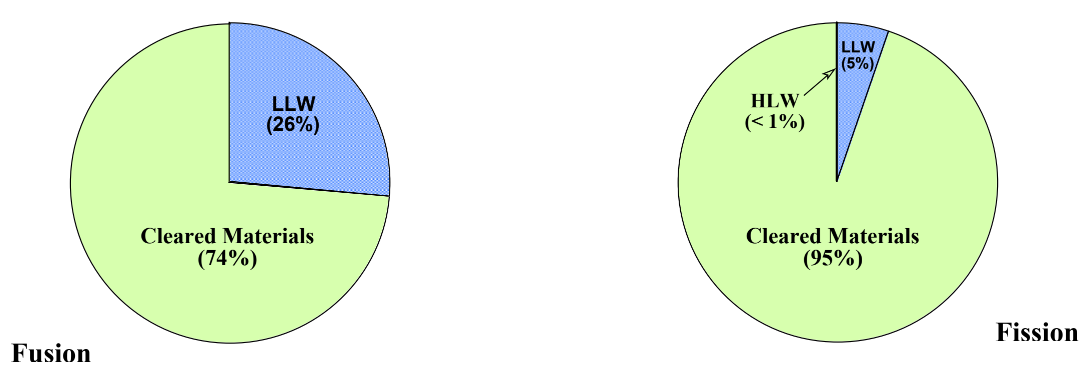

Fig. 16. Breakdown of low-level waste and cleared solids for typical fission and fusion power plants.

decommissioning of fission and fusion power plants generates large amounts of slightly radioactive materials. The free release problem does not seem insurmountable. During the decade of the 1990s and continuing to the present, the NRC has attempted to formalize its policies on the disposition of the slightly radioactive materials and in the meantime convince consumer, environmental, and industrial groups that clearance is desirable and can be done safely. The alternate approach of restricted or conditional release of the slightly radioactive materials appears to be less controversial relative to the free release. In fact, the NRC does have guidance documents regarding how such materials are cleared from regulatory control (a practice that US licensed facilities make use of routinely). 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. Examples include shielding blocks for containment buildings of licensed nuclear facilities, concrete rubble base for roads, deep concrete foundations, non-water supply dams for flood control, etc. Such contaminated materials have been released and continue to be released in the US under existing practices on a case-by-case basis where guidance documents do not apply.

VIII.B. Opposition of Industry and Environmental Groups

Although the nuclear industry favors some form of clearance standards, many consumer and environmental groups do not. For instance, the US metals (steel, copper, nickel, aluminum, etc.) and concrete industries do not support clearance that unconditionally allow 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.

In June 2000, the steel industry in particular voiced its opposition to unconditional clearance stating that it will not accept radioactively contaminated scrap metals and will continue to monitor and reject materials that violate the industry "zero tolerance" policy. However, it would support a restricted use scenario in which steel waste 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.

The environmental groups tend to share the following perceptions:

- The NRC's true intent is economic, that is to enable recycling of large amounts of contaminated materials, which will benefit no one but the nuclear industry.

- Multiple effects are possible from a release that is recycled into numerous sources for public use, and these effects have not been well characterized by the NRC.

- Releases of radioactive materials cannot be tracked or controlled in a way to protect the public health and safety.
- The concept of buildings made with radioactive materials exposing people to radiation greater than background exposure is contrary to the charter of the NRC.

VIII.C. ANS Support for Clearance

The American Nuclear Society (ANS) normally reviews draft regulations and provides input to the rulemaking process. In March 2003, the ANS issued a position statement[30] that supports the clearance of solid materials from nuclear facilities, stating that:

- Absolutely prohibiting the release of all solid materials that manifest a small amount of radioactivity is not reasonable.
- Unrestricted release of materials with slight levels of radioactivity can be accomplished with negligible or no risk to the public health and safety.
- The 10 μSv/y (1 mrem/y) standard is unreasonably low and without a firm scientific justification.
- Scientific evidence would seem to support a dose limit several times larger than the proposed 10 μSv/y (1 mrem/y).

Moreover, ANS along with the Health Physics Society and other institutions recommended some exceptions. Even though they support the development of clearance standards, they argue for special consideration to be given to the steel recycling industry in particular because radioactive sources could present a risk to public health and steel workers. The special exception for other metals and concrete industries was not uniformly shared by all members of these institutions.

IX. CONCLUDING REMARKS

As an alternate option to disposal in a geological repository, we have explored the potential of clearing, recycling, and then releasing to the commercial market the majority of the solid materials after fusion facilities are decommissioned. Circumstances considered for clearance (unrestricted release) include materials in which radioactive contamination is so low that clearance is warranted. These slightly radioactive materials need not be treated as waste and can be released from regulatory control into the marketplace.

It is believed that a dose level that is small in comparison with the variation in natural background radiation (2.4-3.6 mSv/y) can be considered trivial. Therefore, an individual dose standard of 10 μSv/y (1 mrem/y) for cleared solids is widely accepted by the US, IAEA, and EU organizations, representing less than 1% of the allowable. Nevertheless, the clearance limits developed by the different countries show a wide variation. For particular radionuclides, the disagreement between the limits can be much greater than a factor of 10. The US clearance standards issued for 115 radioisotopes seem less restrictive (i.e., the allowable activity level is higher) than the IAEA and EU standards issued for 257 and 197 radioisotopes, respectively. However, it seems unlikely that an additional effort will be devoted in the near future to reduce the difference in the limits and understand the technical reasons for the major disagreements.

We have applied all three clearance standards to two US power plant concepts: the internals of the IFE Z-pinch design and the internals as well as the externals of the MFE ARIES-CS design. Even though waste classification assessments have been carried out worldwide in the past mainly using the IAEA guidelines, results of the three standards have never been compared this thoroughly for the same fusion designs and operating conditions. Internal components are normally assigned for geological burial as Class A or C LLW. The Z-pinch case represents the first time an internal component (the recyclable transmission lines) can be released from regulatory control after a relatively short storage period (40-70 y, depending on the clearance limit). According to all three standards, none of the ARIES-CS power core components (blanket, shield, vacuum vessel, and magnet) can be cleared even after an extended storage period of 100 y as their clearance indexes exceed unity by a wide margin. Note that these findings may be different if the evaluation is carried out for the European or Japanese power plants. The building that surrounds the power core is subject to a less severe radiation environment, contains residual radioactivity, and thus can be cleared. Of interest is that the building dominates the waste stream volume and its release along with the RTLs saves a substantial disposal cost for such a large quantity, freeing ample space in the repositories for other radioactive fusion wastes.

Despite the development of new clearance standards, we found limitations in the most recent guidelines, including lack of consideration for numerous fusion radioisotopes and their possible effect on the clearance index prediction. Efforts by the NRC, IAEA, and EU should continue to develop clearance standards for all radioisotopes of interest to fusion applications. In the meantime, we will continue pursuing the development of the clearance standards in the US and abroad, incorporate the most recent US, IAEA, and EU clearance limits in the ALARA activation code, and monitor the clearance index for the ARIES power plants and the like until the NRC issues fusion-specific clearance guidelines.

Environmental and consumer groups remain concerned with radiation effects on public health despite the economic benefits of clearance. Industrial groups express serious concerns about the potential economic damage to their markets from free release as it could erode public confidence in the safety of their products. However, professional societies (such as ANS) associated with the nuclear industry support clearance. As clearance is highly desirable for both fission and fusion facilities, we urge national and international organizations 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.

ACKNOWLEDGMENTS

This work was performed under the auspices of the US Department of Energy (contract #DE-FG02-98ER54462) and Sandia National Laboratory (contract #297000). The authors wish to thank Drs. B. Merrill, L. Cadwallader (Idaho National Laboratory), and R. Anigstein (S. Cohen & Associates, Inc.) for helpful discussions during the preparation of this manuscript.

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