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L. El-Guebaly, P. Wilson, D. Paige,
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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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ABSTRACT

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 early phase of the ARIES and Z-pinch projects, estimates were 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. A considerable challenge is the disposition of the very large volume of potentially clean materials. As an alternative to recycling or disposal in repositories, many countries are proceeding successfully with the process of developing clearance guidelines that allow solids 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 limits. This exercise is proving valuable in understanding the differences between the clearance standards. While US clearance standards now exist for a limited number of radionuclides that are important to the fission industry, no such standards are in place for radionuclides of interest to fusion facilities. Before fusion penetrates the energy market, the US should develop fusion-specific standards that address the safe release of fusion solids with trace levels of radioactive materials.

I. INTRODUCTION

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 the designers to examine the recycling and clearance options as a means to enhance the respository capacity by reducing the volume of solid waste requiring radioactive burial. The majority of nuclear waste (70-90%) contains traces of radioactive elements that represent no risk to the public health and safety. Nuclear researchers in 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 it is no longer radioactive, be unrestrictedly recycled into consumer products (tools, tables, chairs, building materials, etc.), and save the disposal cost (several thousand dollars per cubic meter). The clearance policy will be extremely important in the future as the decommissioning of nuclear 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 during the 1980s and 1990s are documented in a set of reports published by the Nuclear Regulatory Commission (NRC) in the US[1], International Atomic Energy Agency (IAEA) in Vienna[2], and EURATOM in Europe[3]. 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[4] to inertial fusion energy (IFE) applications[5-8]. With the emergence of the 1996 European Union (EU) clearance standards by EURATOM and the more recent US guidelines for solid materials by the NRC, we took the initiative to compare the three clearance standards in order to identify the implications on the waste management approach and highlight the areas of discrepancy and agreement for the isotopes of interest to fusion applications. For this purpose, we have applied the clearance criteria on two representative IFE and MFE power plants: Z-pinch[6,9] and ARIES-CS compact stellarator[10]. 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 current system of clearance standards.

This paper is organized as follows. We begin with a brief description of the Z-pinch and ARIES-CS designs. The next section compares the IAEA and EU clearance standards to the newly developed US-NRC guidelines. Sections V and VI summarize the clearance results and document the anticipated waste inventory. Section VII surveys the marketplace and highlights the industry reaction to clearance. At the end, we recommend additional evaluations to the US-NRC clearance standards that are deemed necessary for fusion applications.

Throughout this study, the neutron flux was evaluated with the DANTSYS[11] 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[12] and the FENDL-2 175 neutron group transmutation cross-section library[13]. 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 years (FPY) lifetime extensions, requiring an additional few centimeters of shield to protect the externals. Such minor modification to the design will not alter the conclusions of this study.

II. Z-PINCH OVERVIEW

Z-pinch IFE is relatively new, and has become part of the IFE community over the past five years. The magnetically insulated Recyclable Transmission Line (RTL) connects the driver to the target as shown in Fig. 1. The RTL is made from a material that is easily separable from the coolant (e.g., carbon steel) 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 “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 on-site. The key design parameters are given in Table I. Every 10 seconds, the RTL/target assembly is inserted into the chamber, the shot is fired, portions of the RTL are vaporized and

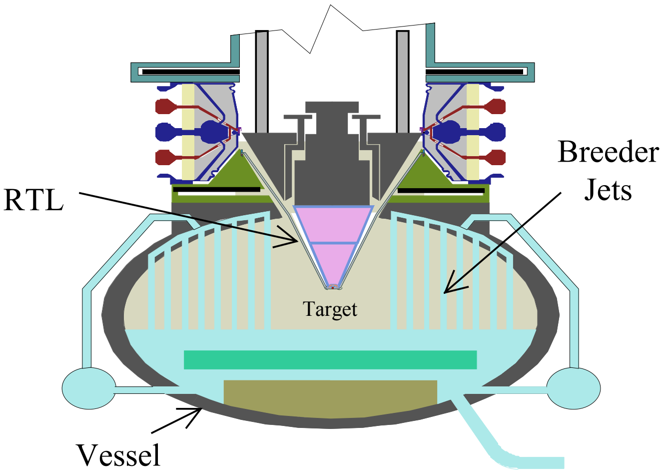

Figure 1. Z-pinch chamber and RTL connecting the target to the power supply.

end up mixed 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[12] modeled all pulses (~10,000) using the $6x10^{14}$ n/cm^{2}s space-average flux distributed over the conical RTL[6].

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 traces of radioactivity and approximately 1000 m^3 of carbon steel can potentially be cleared from regulatory control after plant decommissioning. The 12 vessels and surrounding containment building represent other waste streams from the Z-pinch. The sizable building dominates the waste stream, followed by the 2000 m^3 vessels. An activation assessment is underway to estimate the various classifications for these components.

III. 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 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 2 is a top view of ARIES-CS showing the plasma boundary and the 18 TF coils while Fig. 3 displays an elevation view at the middle of a field period showing the arrangement of the internal components. Not shown is a 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 FS-based LiPb/He system) undertook the appropriate arrangement of ARIES-CS internal components (see Fig. 3). The physical and operating parameters of ARIES-CS are listed in Table I.

Table I. 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*

* Full power year.

Figure 2. Three field period ARIES-CS design option.

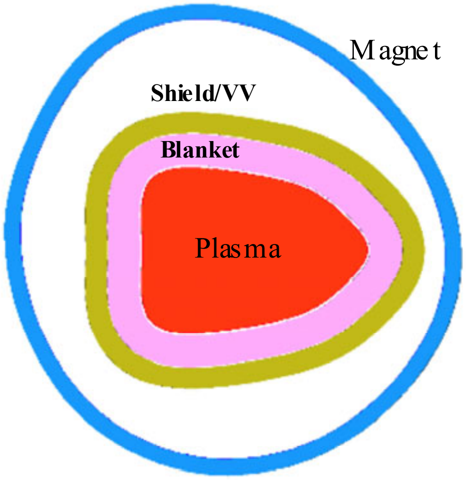

Figure 3. Vertical cross section of ARIES-CS at middle of field period.

IV. COMPARISON OF CLEARANCE LIMITS

In issuing the clearance standards, US-NRC has previously tried to set standards during the decades of the 1980s and 1990s. The most recent 1998 NRC document[1] includes specific standards for licensed US facilities, such as fission power reactors, fuel cycle units, hospitals, etc. Beginning in 1982, IAEA along with other European agencies published a number of recommendations for clearance of materials from regulatory control. There is a widespread agreement between US-NRC, IAEA, and EU on the primary dose standard and the negligible risk the cleared materials present to individuals. The three organizations recommended an individual dose standard of 10 μSv/y (1 mrem/y) for cleared solids. The United Nations recommends that radiation doses above background level to members of the public from radiation sources other than medical exposures should not exceed 1 mSv/y (100 mrem/y). 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 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).

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

Radionuclides	IAEA[2]	EU[3]	US-NRC[1]
H-3	3.00E+03	1.00E+06	2.00E+04
C-14	3.00E+02	1.00E+04	6.00E+02
Na-22	3.00E-01	1.00E+01	2.00E-02
Cl-36	3.00E+02	1.00E+04	4.00E+00
Ar-39	4.57E+01	---	---
K-40	4.78E+00	1.00E+02	2.00E-01
Mn-54	3.00E-01	1.00E+01	1.00E-01
Fe-55	3.00E+02	1.00E+04	1.00E+04
Fe-59	3.00E+00	1.00E+01	9.00E-02
Ni-59	3.33E+02	1.00E+04	2.00E+04
Co-60	3.00E-01	1.00E+01	4.00E-02
Ni-63	3.00E+03	1.00E+05	8.00E+03
Sr-90	3.00E+00	1.00E+02	1.00E+00
Mo-93	8.69E+01	1.00E+03	7.00E+02
Nb -93m	2.06E+02	1.00E+04	1.00E+03
Nb-94	3.00E-01	1.00E+01	6.00E-02
Nb-95	1.30E+00	1.00E+01	1.00E-01
Zr-95	1.35E+00	1.00E+01	1.00E-01
Tc-99	3.00E+02	1.00E+04	5.00E+01
I-129	3.00E+01	1.00E+02	2.00E-01
Cs-137	3.00E-01	1.00E+01	4.00E-02
Ir-192	3.00E+00	1.00E+01	8.00E-02
Ag-108m	6.13E-01	1.00E+01	6.00E-02
Ag-110m	3.00E-01	1.00E+01	4.00E-02

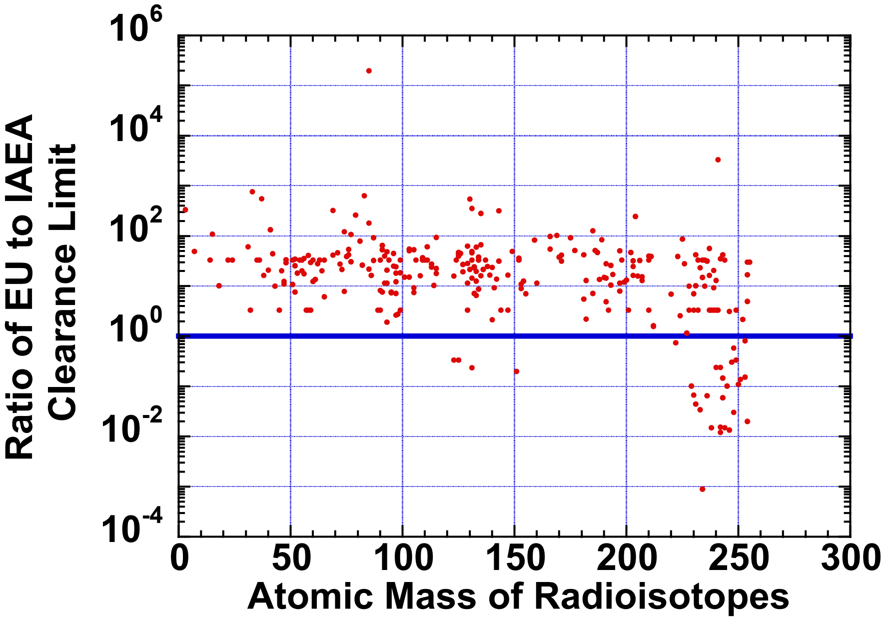

Figure 4. Ratio of EU clearance limits to IAEA's for 300 radioisotopes.

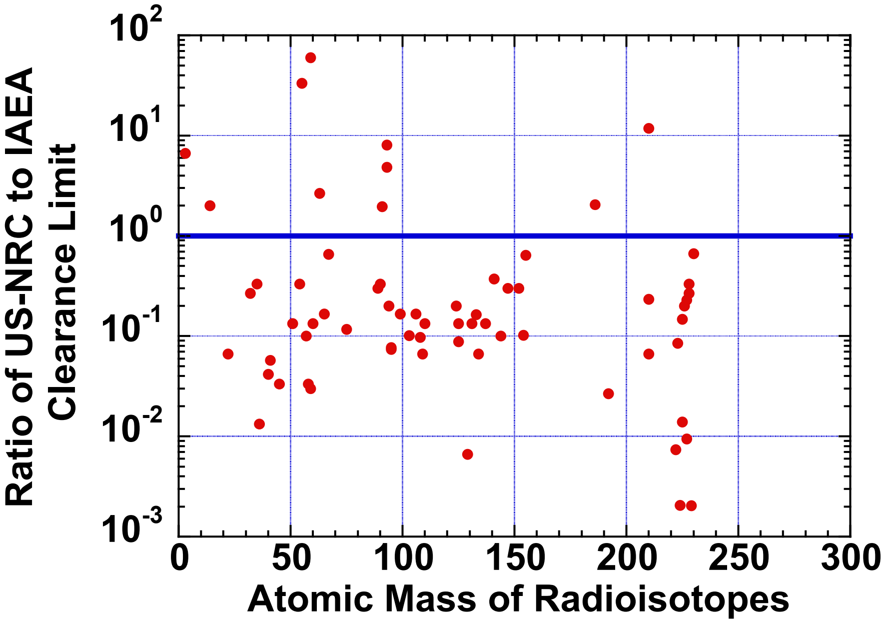

Figure 5. Ratio of US-NRC clearance limits to IAEA's for 67 radioisotopes.

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 clearance limits for the 1650, 300, and 67 radionuclides developed by IAEA, EU, and US-NRC, respectively. The three standards do not agree on the limits of almost all 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. However, it seems unlikely that an additional effort will be devoted to reduce the difference in the limits and understand the technical reasons for the major disagreements.

Figures 4 and 5 compare the ratios of the EU and US-NRC limits to the IAEA's. At first glance, we noticed that the US-NRC standards are the most conservative, followed by the IAEA's, then the EU's. In other words, the US-NRC standards seem more protective. However, applying the limits to the Z-pinch and ARIES-CS designs, this trend was reversed for some components as will be shown shortly.

The clearance limits are normally expressed in becquerel per gram for each radionuclide. Table II compares the IAEA, EU, and US-NRC clearance limits for selected radioisotopes encountered in fusion designs. By definition, the clearance index (CI) is the ratio of the activity (in Bq/g) to the allowable clearance limit summed over all radioisotopes. Our approach for handling the cleared component (CI < 1) is to reevaluate the CIs for the constituents. 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 LLW in repositories while cleared solids can be shipped to the industry or marketplace for reuse.

V. RESULTS

V.A. Z-Pinch

The drop of the RTL CI with time after shutdown is shown in Fig. 6. Note the rapid drop in the CI on a time scale of a century. The CI reaches the limit of one at 30, 35, and 50 y after plant decommissioning, according to the EU, US-NRC, and IAEA guidelines, respectively. The dominant radionuclides are ^{54}Mn,

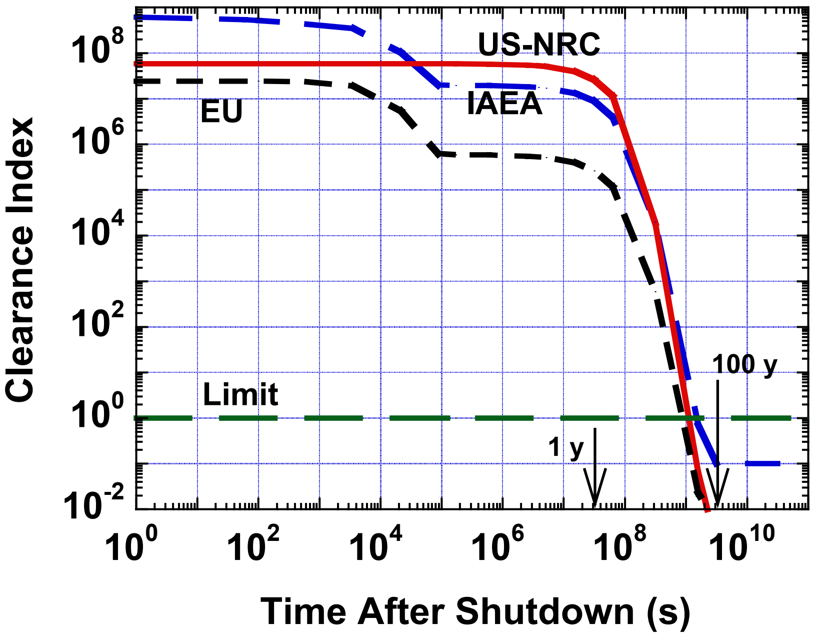

Figure 6. Drop of RTL clearance index with time.

^{55}Fe, and ^{60}Co, respectively. The results are conservative as no credit is given to the removal of the slag that may contain some of the transmutation products. A CI < 1 means the RTL carbon steel contains traces of radioactive elements and represents no risk to the public health and safety. On this basis, the ~10,000 tons RTL radwaste can be cleared after 30-50 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 more 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[6,7], it is recommended not to remove the transmutation products to simplify the recycling process and reduce its cost.

V.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, compositions, and lifetime. We used a lifetime of 5 FPY for the blanket and 40 FPY for all other components. The CI results for the LiPb/FS design option are plotted in Fig. 7 using the IAEA standards. Because of the compactness of the machine, the CIs of all internal components 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[4]. This means the ARIES-CS internal components should be disposed of in repositories[14] 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. 8). The outer segments meet the clearance limit within a few days or less after shutdown. We then applied the IAEA, EU, and US-NRC clearance standards to the innermost segment. As

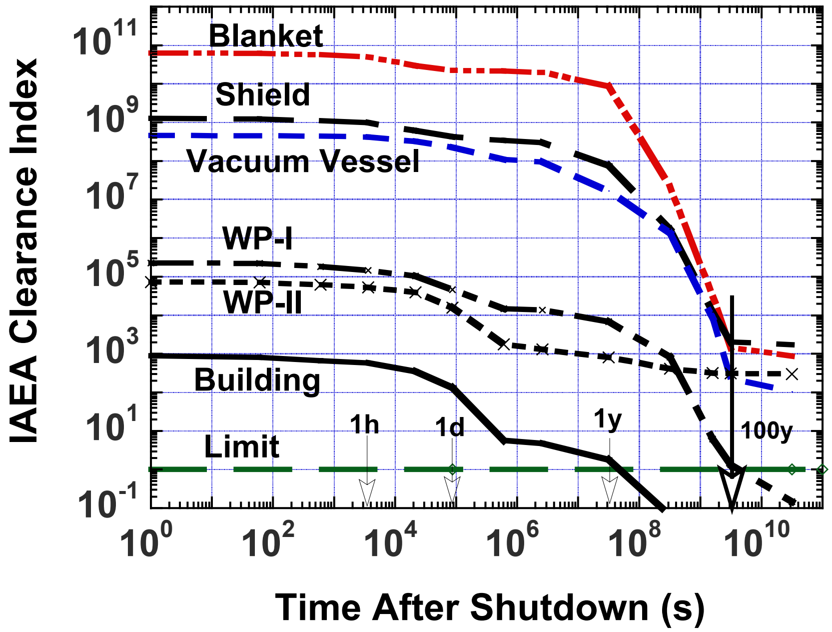

Figure 7. Drop of ARIES-CS clearance index with time.

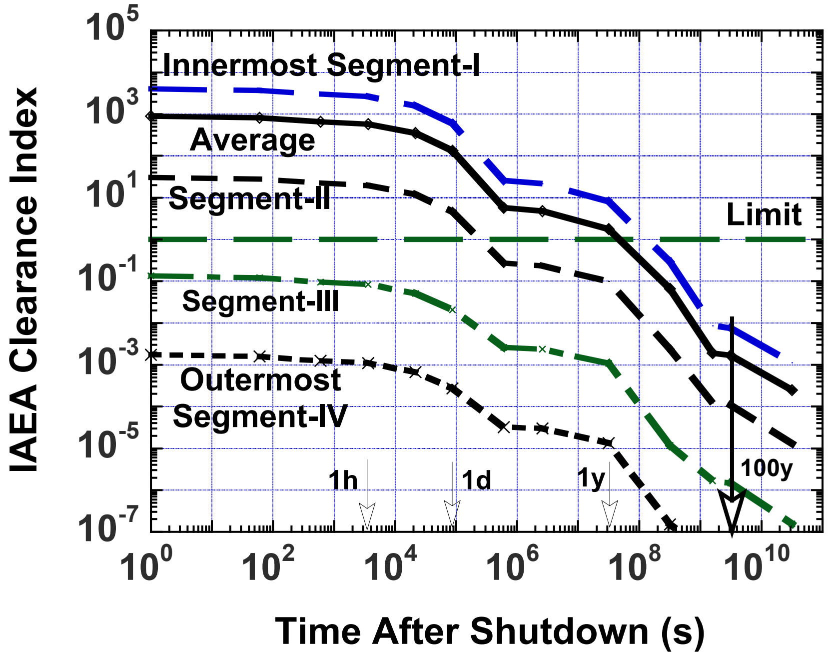

Figure 8. Clearance index for individual segments of the concrete building.

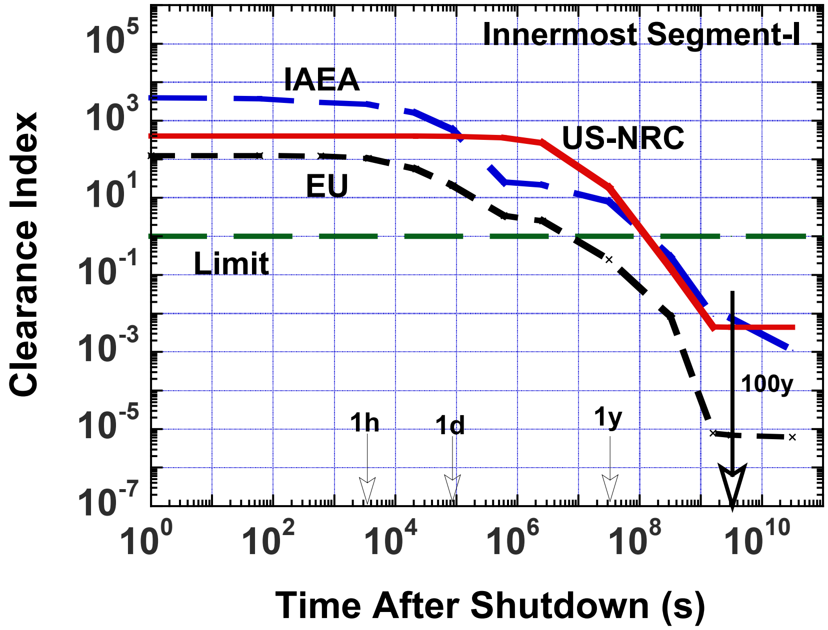

Figure 9. Comparison of IAEA, EU, and US-NRC clearance indices for the innermost segment-I of the building.

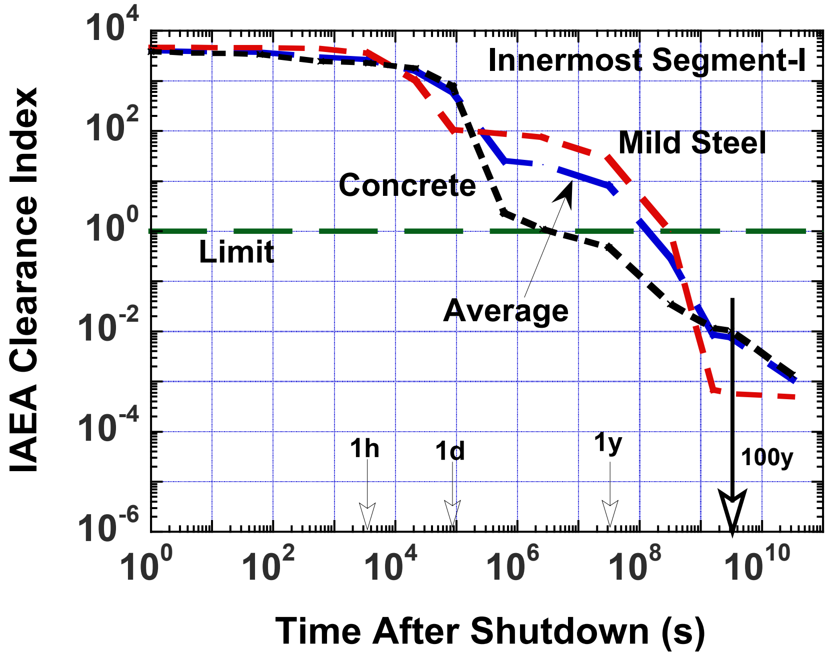

Figure 10. IAEA clearance index for constituents.

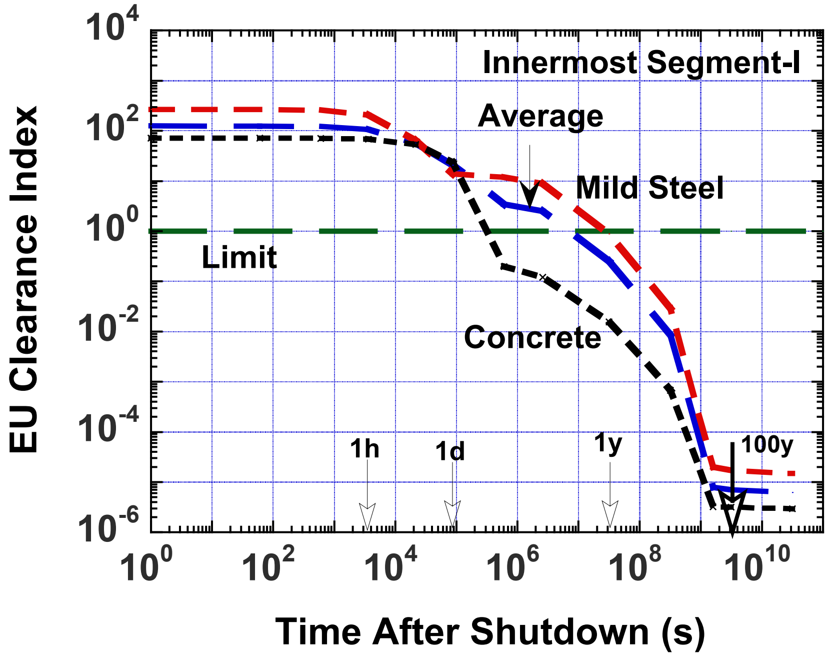

Figure 11. EU clearance index for constituents.

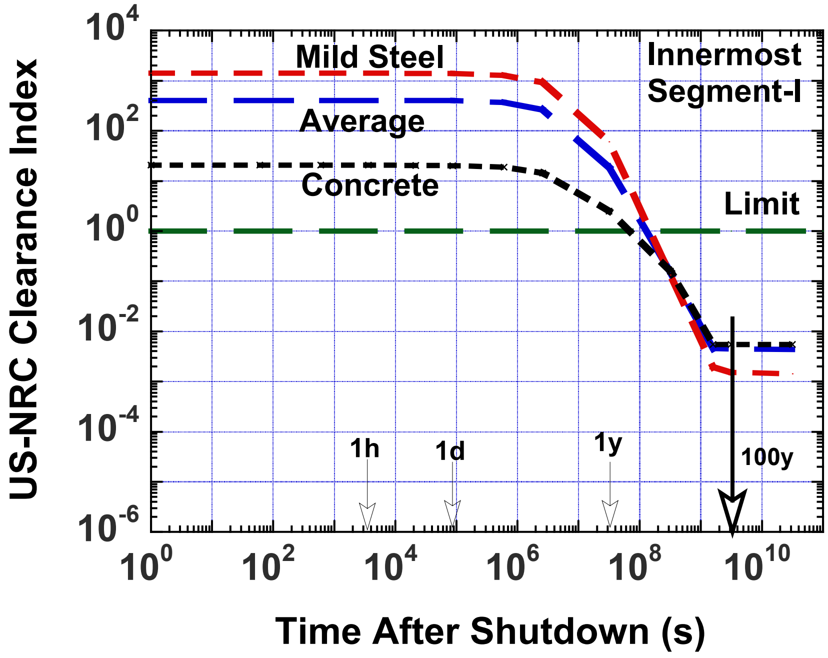

Figure 12. US-NRC clearance index for constituents.

Fig. 9 illustrates, the EU standards require the shortest storage period. 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 10-12 depict the evolution of the CI with time for the building constituents according to the IAEA, EU, and US-NRC guidelines. The storage periods are given in Table III along with the dominant radionuclides for the clearance indices. The inconsistencies in the clearance limits between the countries (refer to Table II) have resulted in widely varying storage periods contradicting the notion that more recent standards tend to shorten the storage period.

Table III. Storage Period for Constituents of Innermost Segment of ARIES-CS Building

Constituents	IAEA	EU	US-NRC
Mild steel	10 y ^{55}Fe	1 y ^{54}Mn, ^{55}Fe	5 y ^{60}Co, ^{54}Mn
Concrete	1 month ^{55}Fe, ^{22}Na, ^{39}Ar	5 days ^{55}Fe, ^{22}Na	2.5 y ^{22}Na

VI. WASTE INVENTORY

This section summarizes the inventory of LLW and cleared solids expected from the ARIES-CS power plant. Figure 13 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 building represents the largest single component of the decommissioning wastes. 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[15] (see Fig. 14). Note that if the lifetime of the fission and fusion plants can be extended for 20-30 more years, which seems probable, less materials will be generated from decommissioning. Disposal of all slightly radioactive solids into LLW disposal sites would cost several billion dollars. Clearance could reduce this disposal cost to nearly zero.

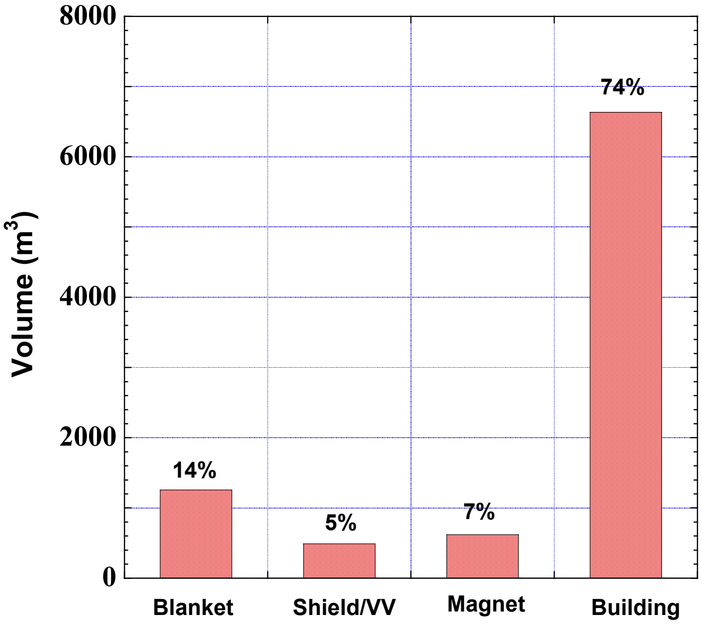

Figure 13. Volume of ARIES-CS low-level waste.

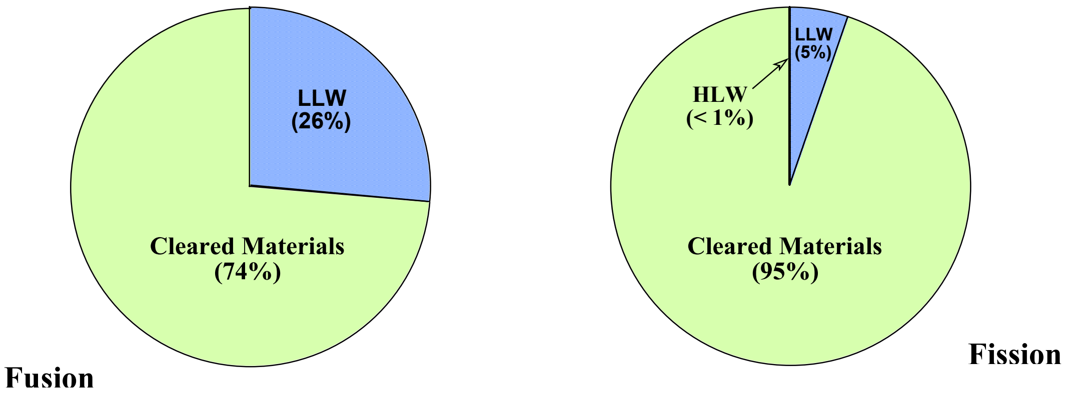

Figure 14. Breakdown of low-level waste and cleared solids for typical fission and fusion designs.

VII. SURVEY OF MARKETPLACE AND REACTIONS TO CLEARANCE

VII.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 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 the 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 or on a case-by-case basis where guidance documents do not apply.

VII.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 metals (steel, copper, nickel, aluminum, etc.) 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.

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 US-NRC 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 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 NRC.

VII.C. ANS Support for Clearance

The American Nuclear Society (ANS) normally reviews draft regulations and provides input to the rulemaking process. On March 2003, the ANS issued a position statement[16] 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.

VIII. 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 the 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 IAEA, EU, and US-NRC organizations, representing less than 1% of the allowable. However, the clearance limits developed prior to the year 2000 by the different countries show a wide variation. The US-NRC clearance standards issued for only 67 radioisotopes seem more restrictive (i.e., the allowable activity level is lower) than the IAEA and EU standards. Nevertheless, the IAEA guidelines call for the longest storage period before releasing the cleared metals for the majority of cases considered in this study.

We have applied the clearance standards to the internal components on the Z-pinch design as well as to the externals of ARIES-CS in an attempt to minimize the volume of fusion waste assigned for geological burial. 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 (30-50 y, depending on the 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. 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 and its release saves a substantial disposal cost for such a large quantity, freeing ample space in the repositories for more radioactive wastes.

Despite the development of the US clearance standards by NRC, we found limitations in the 1998 guidelines, including lack of consideration for numerous fusion radioisotopes of interest to fusion facilities and their possible effect on the clearance index prediction. This means the clearance issue within the US fusion community is still under controversy. Efforts by the NRC 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, update the US-NRC, IAEA, and EU 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.

The environmental and consumer groups remain concerned with radiation effects on public health despite the economic benefits of clearance. The industrial groups expressed 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 supported clearance. The national and international organizations must continue their efforts to convince the industrial as well as the environmental groups that clearance of slightly radioactive solids can be conducted safely with no risk to the public health and is highly desirable for the nuclear industry.

ACKNOWLEDGMENTS

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