Clearance Issues for Advanced Fusion Power Plants

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ABSTRACT

Over the past 10 years, the ARIES team has been devoting a serious effort to reduce the volume of radwaste generated by fusion power plants. Recently, an initiative was launched in the U.S. and Europe to reduce the radwaste volume further by clearing the outer components from regulatory control. Before proceeding further with the development of a new strategy for the U.S. fusion waste management, it is essential to assess the implication of the clearance option on the waste generated by the U.S. advanced power plants. In this paper, we discuss the results of the analysis, the approach adopted by the ARIES team for handling the cleared components, and the U.S. market for cleared metals. Our results state that, because of the compactness of the design, none of the ARIES-AT fusion power core components has a clearance index below one at the end of the 100 year interim storage period and all components should be either recycled or disposed near surface as low-level waste. At present, the U.S. industry has zero tolerance for metals with very low radiation level, meaning the commercial market for cleared metals does not exist.

I. INTRODUCTION

The United States' decision of pursuing the clearance option for fusion materials should be examined in the content of a U.S. fusion power plant such as ARIES-AT,[1] the most recent advanced tokamak design developed by the ARIES team. By definition, clearance is the unconditional release of materials from radiologically controlled areas after an interim storage period of 50 or 100 years. In the U.S., the term "clearance" replaces the term "free release" previously used in the nuclear industry.

The primary options for managing the waste of the ARIES power plants[2] include near-surface disposal as Class A or Class C Low-Level Waste (LLW), recycling and reuse in nuclear facilities, and clearing of materials containing very low radioactivity. The emphasis on the approach of disposing, recycling, and clearing the waste differs between the various countries. In the U.S., the waste management system offers repositories for both shallow and deep geological burial, for low- and high-level wastes. In Europe, there is no shallow land burial. Thus, the extremely high cost of deep geological disposal drives a strong incentive for recycling and clearance.

The differences in the waste management approaches and the market for cleared metals somewhat influenced the design of the fusion power plants. For instance, compact, high power density machines with well optimized radial builds generating only LLW are being developed in the U.S. with less of an economic and social driver for clearance. On the other hand, relatively larger machines with greater radial builds are designed in Europe,[3] emphasizing the recycling and clearance options for radwaste. Despite the availability of shallow burial repositories in the U.S., the relatively large volume of waste that fusion generates compared to other sources of energy, forces the designers to examine the recycling and clearance options as means to enhance the respository capacity by reducing the volume of solid waste requiring radioactive burial. Just recently, we applied the clearance criterion to the most recent ARIES-AT design and surveyed the U.S. market for cleared metals. In the past, numerous studies have addressed the option of recycling and reuse of the waste in nuclear facilities, and readers can consult the references for a broader perspective on this option.[4, 5, 6]

II. NRC AND IAEA GUIDELINES

At present, the U.S. Nuclear Regulatory Commission (NRC) has not defined the standards for the volumetric contamination that guide the radiation protection program for clearnace of solid materials. Standards for release of contaminated liquid and gas effluents were incorporated into NRC regulatory guidelines that were applied for decades to routine operations of fission power plants, limiting exposures to the public to annual doses ranging from 4 to 25 mrem/y. The NRC has initiated rulemaking efforts to establish standards for release of solid materials containing small amounts of radioacitivity, but the process may not be complete for several years.[7]

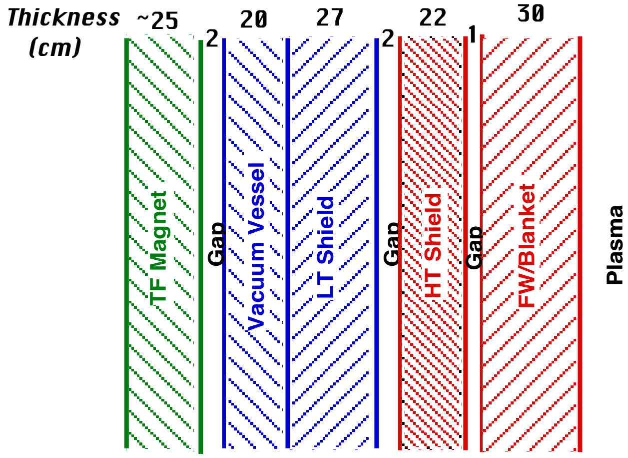

Figure 1a. Schematic of IB radial build at midplane.

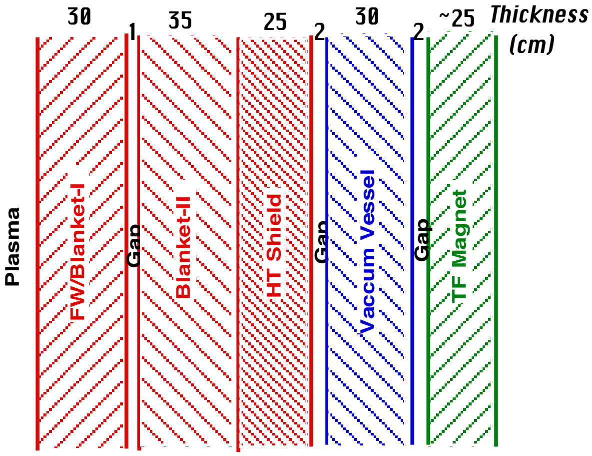

Figure 1b. Schematic of OB radial build at midplane.

Recently, the American National Standards Institute (ANSI) has published a consensus standard that provides guidance for clearance of solid materials.[8] The ANSI standard limits the dose to 1 mrem/y and has been the subject of significant controversy in some nuclear communities. Once the NRC nuclide-specific regulatory limits are established for release of solids, fusion designs will have to implement additional controls and apply a safety factor in the analysis to ensure that the actual dose is below the absolute limit. In addition to the U.S. activities, various organizations are working toward release standards for clearance. On the international level, the development of clearance standards for solids has made a significant improvement over the past several years. In conjunction with various organizations, the International Atomic Energy Agency (IAEA) has developed clearance standards for 1650 radioisotopes of interest to nuclear applications[9] based on a dose limit of 1 mrem/y. During the course of the ARIES studies, we have adopted a U.S. approach for the waste management aspect of the ARIES designs. However, the U.S. clearance standards for solids are lacking and may take years to develop and complete. Due to the absence of official U.S. guidelines, we have temporarily adopted the IAEA nuclide-specific clearance limits and applied those limits to the ARIES-AT design. This approach could be optimistic as the U.S. standards may call for a more stringent limit regarding the public dose.

III. OVERVIEW OF ARIES-AT AND COMPUTATIONAL MODEL

ARIES-AT is a 1000 MW$_e$ power plant using $Li_{17}Pb_{83}$ breeder/coolant in a blanket made entirely of the low activation SiC/SiC composites. A high-temperature (HT) shield, followed by a vacuum vessel (V.V.), surrounds the blanket. The three components provide a shielding function for the HT superconducting TF magnets. The clearance calculations to be presented here have been performed for an interim design developed before March 2000. Figures 1a and 1b illustrate the details of the radial builds and Table 1 lists the specific composition of the individual components. The low activation FS 9Cr-2WVTa developed by ORNL[10] is employed for the low-temperature components. The final design is now complete and incorporates several design improvements that will not alter the conclusion of this study.

We performed a series of 1-D activation analyses using the newly developed ALARA code[11] and the most recent data library based on FENDL-2 evaluation with 175 neutron group structure. The model includes the inboard (IB) and outboard (OB) components with first wall radii of 3.55 and 6.05 m, and average neutron wall loadings of 2.8 and 5.2 MW/m^2, respectively.

Table 1. Composition of Components Comprising ARIES-AT Radial Build

Blanket	15% SiC, 85% LiPb*
HT shield	15% SiC, 10% LiPb*, 75% B-FS
LT shield	15% FS, 10% H_2O, 75% WC
Vacuum vessel	25% FS, 75% H_2O
TF magnet #	87% 316SS, 2.5% $YBa_2Cu_3O_5$, 0.5% Ag, 10% LN

* 90 % enriched Li
\# Electric insulator not included

IV. ARIES APPROACH

At the end of the service lifetime, individual components or constituents could be stored for 50-100 years, then cleared from regulatory control if the clearance index (CI) is below unity. By definition, the CI is the ratio of the activity (in Bq/kg) to the allowable limit summed over all radioisotopes. Since the ultimate goal is to separate the constituents of the component for recycling and reuse by industry, our 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 waste based on constituents rather than components. Constituents with CI > 1 will be stored in LLW repositories while cleared solids could be shipped to the industry for recycling.

V. CLEARANCE RESULTS

The variation of CI with time after shutdown is shown in Figure 2 for the OB components. The CI depends strongly on the neutron flux level, spectrum, materials, operation time, and cooling period. The IB and divertor components exhibit similar behavior. We used a lifetime of 3 full power years (FPY) for both the inner blanket segment and divertor system and 40 FPY for all other components. The results at 100 years after shutdown are plotted in Figures 3a and 3b. Because of the compactness of the design, the CIs of all components exceed the limit by a large margin. This means the ARIES-AT components cannot be released as cleared metals; therefore, they could either be recycled or disposed near-surface as LLW. We attempted to clear the OB ex-vessel components (vacuum vessel, TF magnets, PF magnets, and cryostat) by adding a new water-cooled shielding component on the OB side and we assessed the impact of the added shield on the total waste volume of ARIES-AT. Re-examining the TF magnet reveals that the silver constituent is a major contributor to the magnet CI although its volume fraction amounts to only 0.5% (Figure 4). Excluding the silver, it would drop the magnet CI from 230 to 17. A 70 cm thick additional shield on the OB side (~160 m^3) would clear the silver (0.5 m^3) in particular as well as the other magnet constituents and OB ex-vessel components. A more attractive, practical option is to remove the silver and dispose it separately as nuclear waste. In this case, the additional shield required to clear the OB ex-vessel components is ~25 cm thick. This thinner shield calls for a slightly modified vacuum vessel composition (25% FS, 40% H_2O, and 35% B-FS).

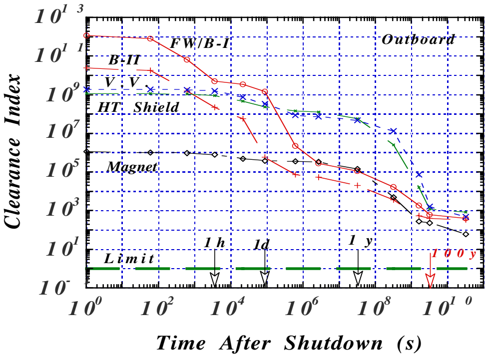

Figure 2. Reduction of clearance index with time after shutdown due to the decay of radionuclides.

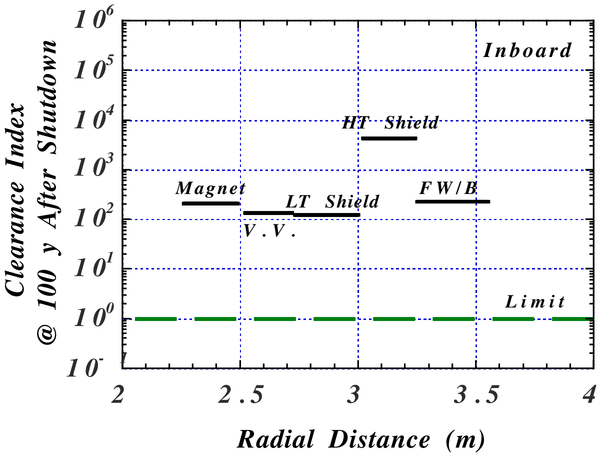

Figure 3a. Clearance indices for IB components evaluated at 100 years after shutdown.

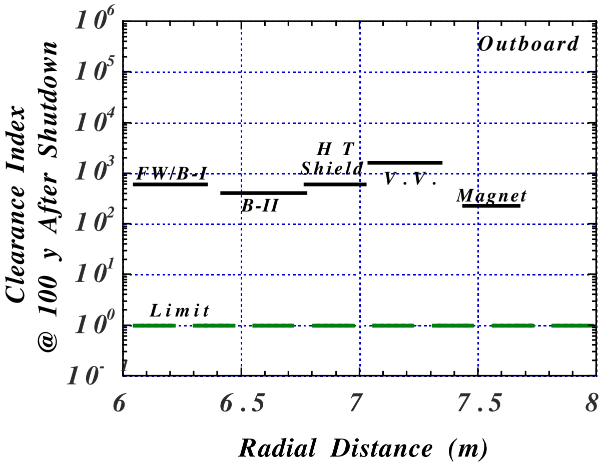

Figure 3b. Clearance indices for OB components evaluated at 100 years after shutdown.

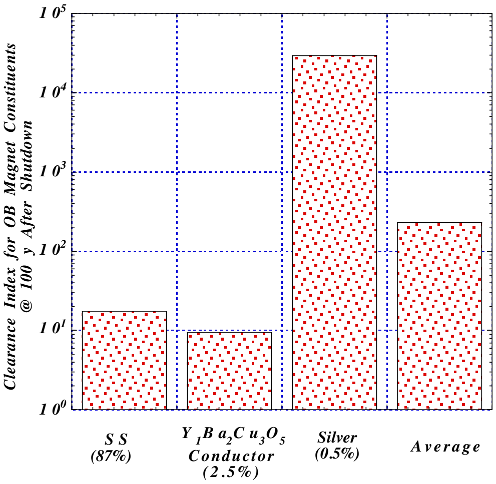

Figure 4. Contribution of individual constituents to the average clearance index of TF magnet.

Figure 5 compares the volumes of the reference OB ex-vessel components and the modified case where the 25 cm thick shield is added on the OB side to clear the OB ex-vessel components. Admittedly, the additional shield helps reduce the waste volume of the OB ex-vessel components by a factor of 4, but those components comprise only 18% of the total ARIES-AT waste produced over the 40 FPY plant life. The volume breakdown of the reference design is illustrated in Figure 6 for the fusion power core (FPC) components, excluding the spares. The cumulative volume reflects the 13 blanket and divertor replacements required during operation. The 25 cm additional OB shield would add ~50 m^3 but clear ~200 m^3 out of the ~1200 m^3 cumulative, compacted volume. We have extended the tradeoff study to the IB side. A 20 cm thicker LT shield would be needed to clear the IB ex-vessel components. Our results indicate that the reduction in the IB waste volume is relatively small while the impact on the overall size and cost of the machine is significant. A machine with a larger IB standoff will certainly generate more waste. On this basis, we do not recommend applying the approach of adding shield to the IB side to clear the IB ex-vessel components as it defeats the waste minimization goal of the study. In our analysis, we made several optimistic assumptions such as the use of the IAEA clearance guidelines without consideration for a safety factor, a 100 year storage period instead of 50 years, and perfect shielding components without penetrations or assembly gaps. Yet, the results showed < 20% waste saving that is somewhat less than desired. It appears likely that future analyses applying more realistic assumptions along with the U.S. NRC standards will demonstrate that the additional sizable shield offsets the waste saving and outweighs the benefits. This certainly supports our argument that a compact device is more attractive than a larger machine generating comparable (or more) waste in addition to cleared metals that may have a very limited marketplace.

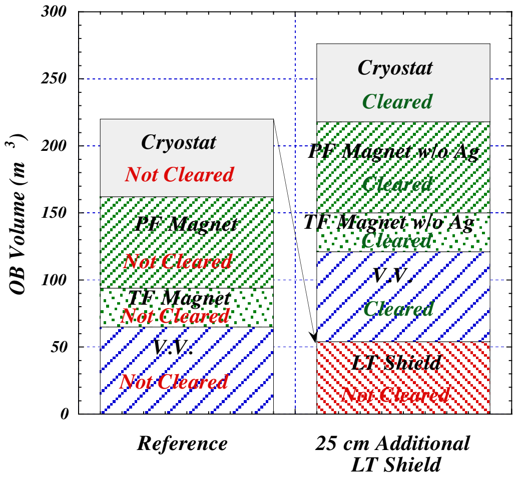

Figure 5. Effect of added OB shield on waste classification of OB ex-vessel components.

VI. U.S. MARKET FOR CLEARED SOLIDS

Although circumstances may change prior to building a first ARIES power plant in 50 years, it is illustrative to consider the current market situation in the U.S. At present, the status of cleared metals in the U.S. is uncertain. The clearance issue is controversial and extensive discussions and meetings to develop consensus standards have been held with the NRC, Department of Energy (DOE), ANSI, health physics society, metal industries, and other organizations. So far, there are more questions than answers. What level of radioactivity is safe for workers and the public? Will NRC national standards be more stringent than the IAEA's? Is there a U.S. market for cleared metals? Will cleared metals be restricted to nuclear facilities or can they be released to commercial markets as clean scrap? There currently is strong opposition for converting the mildly radioactive metals from nuclear facilities and the defense program into a vast array of consumer products (toys, spoons, cars, pans, etc). Advocates argued that there are huge savings (several hundred million dollars) to be made by exempting slightly contaminated materials (e.g., cleared metals, concrete, roofing materials and furniture) from requirements of burying them in dumps designed specifically for radioactive items. Critics and environmentalists claim that any amount of radiation in metals for consumer use is too much. The U.S. labor unions and metal, scrap, and cement industries are demanding that the free release of the slightly contaminated materials be stopped because of potential risk, health, and economic impacts. In January 2000, the Specialty Steel Industry of North American (SSINA) voiced its opposition in this statement, "SSINA members have not and will not accept scrap that is known or perceived to be radioactively contaminated and will continue to monitor and reject materials that violate the industry 'zero tolerance' policy."

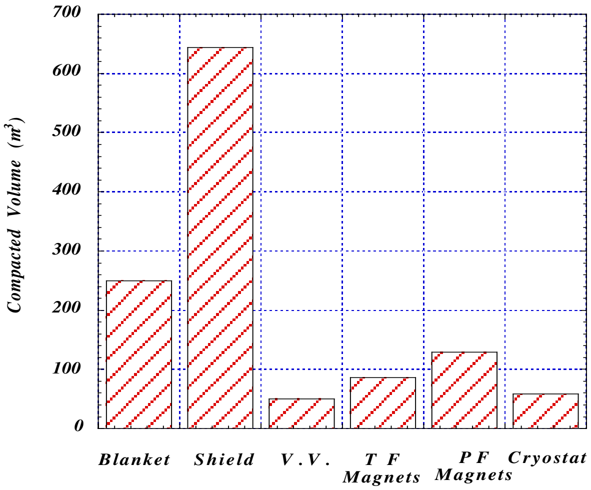

Figure 6. Cumulative volumes of ARIES-AT components.

Just recently, the clearance dilemma forced DOE to establish a new policy prohibiting the release of all volumetrically contaminated metals to the marketplace. DOE is also studying alternative options such as a restricted-release of metals for use only at DOE facilities or nuclear fuel cycle facilities, perhaps re-fabricated into storage containers for other contaminated materials.

Presently, the U.S. commercial market for cleared solids does not exist and the release of slightly contaminated materials is limited only to DOE recycling facilities. The U.S. industry may change its policy in the future if the new NRC national standards restrict the radiation dose to a safe level for workers and the public.

VII. CONCLUSIONS

We examined the clearance options of ARIES waste in the context of other waste management options such as disposal in repositories and recycling. Lacking a national standard for the release of cleared metals, we temporarily applied the IAEA clearance criterion to the ARIES power plants. Because of the compactness of the ARIES-AT machine, all FPC components possess high clearance indices that exceed the IAEA limit by a factor of several hundreds to several thousands. No changes have been made to the final design to clear any component. There is a need for a national standard for cleared solids. The U.S. DOE and NRC are in the process of developing rigorous standards and it is not known when those standards will be issued. The preliminary evidence indicates that the national guidelines could call for extremely low radioactivity levels for cleared solids (< 1 mrem/y), lower than the background level found in nature.

Aiming to protect the U.S. industry and public, the DOE had recently limited the shipment of slightly contaminated solids to DOE recycling facilities. Currently, the commercial market for recycling radioactively contaminated materials does not exist in the U.S. However, the national policy may change in the next 50 years before the start of ARIES power plant construction. Therefore, we will not rule out the clearance option, will continue monitoring the clearance level for future ARIES designs, and will apply the national NRC clearance standards when released.

ACKNOWLEDGEMENT

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