Evaluation of Disposal, Recycling, and Clearance Scenarios for Managing ARIES Radwaste after Plant Decommissioning

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Abstract

The wealth of experience accumulated over the past 30-40 years of fusion power plant studies must be forged into a new strategy to reshape all aspects of handling the continual stream of radioactive materials during operation and after power plant decommissioning. With tighter environmental controls and the political difficulty of building new repositories worldwide, the disposal option could be replaced with more environmentally attractive scenarios, such as recycling and clearance. We applied the three scenarios to the most recent ARIES compact stellarator power plant. All ARIES-CS components qualify as Class A or C low-level waste, according to the U.S. guidelines, and can potentially be recycled using conventional and advanced remote handling equipment. Approximately 80% of the total waste can be cleared for reuse within the nuclear industry or, preferably, release to the commercial market. This paper documents the recent developments in radwaste management of nuclear facilities and highlights the benefits and challenges of disposal, recycling, and clearance.

1. Introduction

Since the inception of the project in the early 1990s [1], the ARIES vision focused on the disposal of all active materials. In general, ARIES plants generate only low-level waste (Class A or C) that requires near-surface, shallow-land burial. The recent introduction of the clearance category for slightly radioactive materials and the development of radiation-hardened remote handling equipment opened the possibility to recycle and clear the majority of the ARIES radwaste. Scenarios for fusion radwaste management now include disposal in geological repositories, recycling and reuse within the nuclear industry, and clearance or release to the commercial market if the materials contain traces of radioactivity.

We applied the three scenarios to the most recent ARIES design, a compact stellarator. Launched in 2003, the study provides perspective on the benefits of optimizing the physics and engineering characteristics of the compact stellarator (CS) power plant [2]. The primary goal is to develop a more compact machine that retains the cost savings associated with the low recirculating power of stellarators, and benefits from the higher beta, smaller size, and higher power density, and hence lower cost of electricity, than was possible in earlier stellarator studies. The reference ARIES-CS design, shown in Fig. 1, has a power level of 1000 MW_e. The dual-cooled LiPb/FS/He blanket must breed sufficient tritium for plasma operation, recover the neutron energy, and protect the shield for the entire plant life (40 full power years). The blanket and shield help protect the vacuum vessel (VV) and all three components protect the superconducting magnets for life. The neutron wall loading (NWL) averages at 2.6 MW/m^2 and peaks at the outboard midplane at 4 MW/m^2, calling for blanket replacement every 3.9 FPY.

Over the past three decades, the waste volume aspect of fusion power plants continued to be of a concern. As such, the national ARIES project has been committed to the achievable goal of radwaste minimization. The focus on compact devices with radwaste reduction mechanisms (such as blanket segmentation and well-optimized components) contributed most significantly to the factor of 2-4 difference in radwaste volume between recent ARIES plants and previous designs developed prior to 1995. Recycling and clearance can be regarded as a more effective means to reduce the radwaste stream. The reason is that clearable materials will not be categorized as waste and the majority of the remaining non-clearable materials can potentially be recycled indefinitely, as discussed below, and therefore, will not be assigned for geological disposal. In support of this position, we suggest adopting the MRCB philosophy:

M – Minimize volume of active materials by design
R – Recycle in-vessel components, if economically and technologically feasible [3-5]
C – Clear slightly-irradiated materials [5-8]
B – Burn long-lived radionuclides in fusion devices [9].

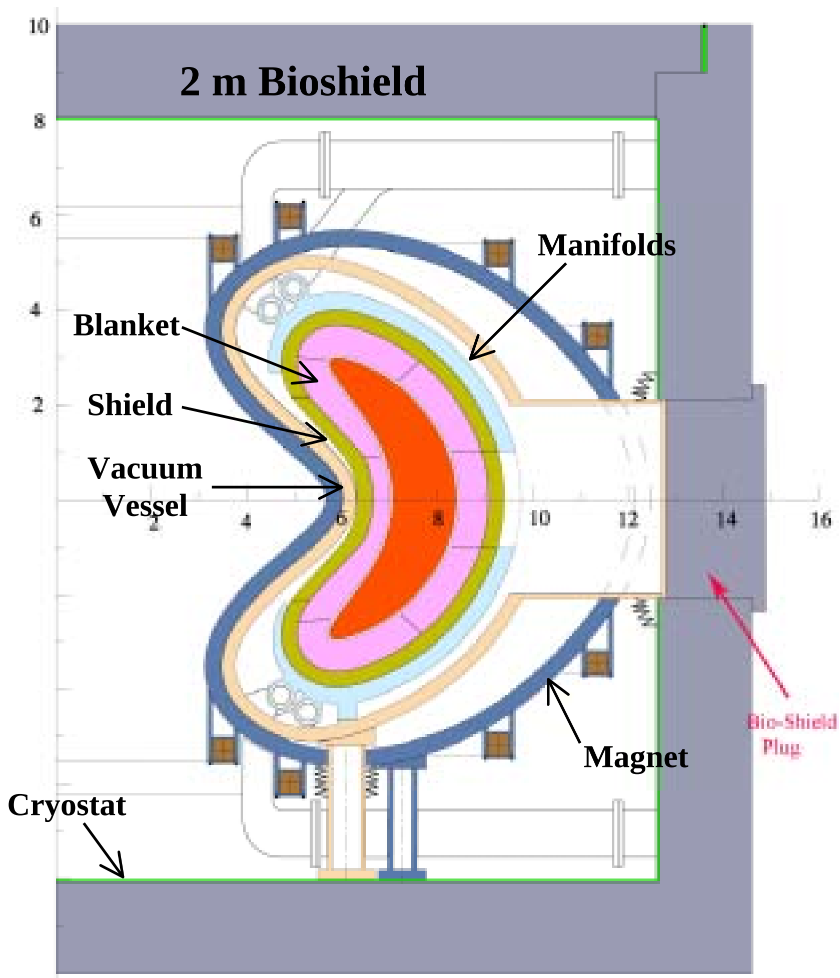

Fig. 1. Vertical cross section at the beginning of ARIES-CS field period.

The following sections summarize the disposal, clearance, and recycling results and highlight the technical issues and concerns for each option. At the end, we conclude with specific remarks and recommendations for fusion applications. Throughout this study, the neutron flux was evaluated with the DANTSYS discrete ordinates transport code [10] with the IAEA FENDL-2

175 neutron 42-gamma group coupled cross-section library. The activation results were computed with the ALARA pulsed activation code [11] and the IAEA FENDL-2 175 neutron group transmutation cross-section library. The activation model assumes the irradiation process continues for 3.9 FPY for the replaceable components and 40 FPY for the permanent components with 85% availability.

2. Geological Disposal

There are two categories of materials that are candidates for disposal according to the U.S. official criteria: high-level waste (HLW) and low-level waste (LLW). The Nuclear Regulatory Commission (NRC) has defined three more categories for LLW: Class A, B, and C. For each type, there is a specific disposal requirement. Class A is the least hazardous type of waste. The LLW containers are placed 8 m or more deep in the ground. An intrusion barrier, such as a thick concrete slab, is added to Class C waste trenches.

We evaluated the waste disposal rating (WDR) for a fully compacted waste using the most conservative waste disposal limits developed by Fetter and NRC-10CFR61 [4]. By definition, the WDR is the ratio of the specific activity (in Ci/m^3 at 100 y after shutdown) to the allowable limit summed over all radioisotopes. The ARIES-CS WDRs are less than one, meaning all components qualify as Class C LLW. The WDRs of the VV and external components are very low (< 0.1), to the extent that these components could qualify as Class A LLW. Excluding the cryostat and bioshield, ~ 70% of the waste (blanket, shield, and manifolds) is Class C. The remaining ~30% (VV and magnet) would fall under the Class A LLW category.

3. Clearance

Over the past five years, clearance guidelines [6] have been issued by the U.S. Nuclear Regulatory Commission (NRC) [12], European Commission, and International Atomic Energy Agency (IAEA) [13]. Based on a detailed technical study, the 2003 NUREG-1640 document [12] 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. A clearance index (CI) can be computed as the weighted sum of all nuclide specific activities (in Bq/g) divided by the corresponding clearance limits.

As Fig. 2 indicates, the majority of the ARIES-CS in-vessel components (blanket, shield, manifolds, and VV) cannot be cleared from regulatory control even after an extended storage of 100 y, according to the proposed U.S. clearance guidelines. This statement holds true as well for the IAEA clearance standards [8]. The bioshield, cryostat, and magnet constituents, except the Nb_3Sn superconductor, qualify for clearance [7,8]. Representing 80% of the total volume, the cleared materials save a substantial disposal cost and, more importantly, free ample space in the repositories for other radwaste.

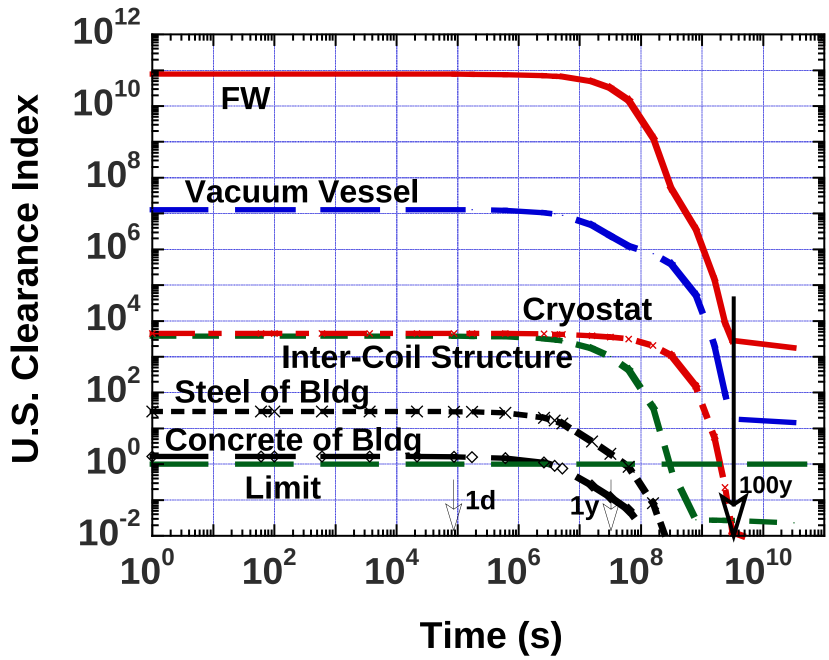

Fig. 2. Decrease of ARIES-CS clearance index with time after decommissioning. Blanket, shield, and manifold curves (not shown) fit between FW and VV curves.

4. Recycling

We applied the recycling approach to the non-clearable in-vessel components (blanket, shield, and vacuum vessel). All components can potentially be recycled using conventional and advanced remote handling (RH) equipment. The variation with time of the recycling dose shows a strong material dependence (refer to Fig. 3). The first wall (FW) is an integral part of the blanket. It is shown in Fig. 3 as a separate component to provide the highest possible dose to the RH equipment. ^{54}Mn (from Fe) is the main contributor to the dose of FS-based components (FW, blanket, shield, manifolds, and VV). Storing the FW/blanket temporarily for several years helps drop the dose by a few orders of magnitude before recycling. After several life cycles, advanced RH equipment could handle the shield, manifolds, and VV. For the SiC inserts, the main contributors to the dose are ^{58,60}Co, ^{54}Mn, and ^{65}Zn, originating from SiC impurities. More strict impurity control may allow hands-on recycling of SiC.

5. Technical Issues and Concerns

The developmental stages for the three radwaste management approaches are at different levels of maturity. The disposition of high and low-level wastes is performed in the U.S. on a regular basis at the South Carolina, Utah, New Mexico, and Washington repositories. Beginning in 2008, the Barnwell repository will severely curtail the amount of LLW that they currently accept and there is no plan for a replacement site yet. Recently, the Yucca Mountain project has proven how politically difficult it is to develop an acceptable repository. Many U.S. nuclear facilities are currently storing their LLW onsite because of the limited and expensive offsite disposal options.

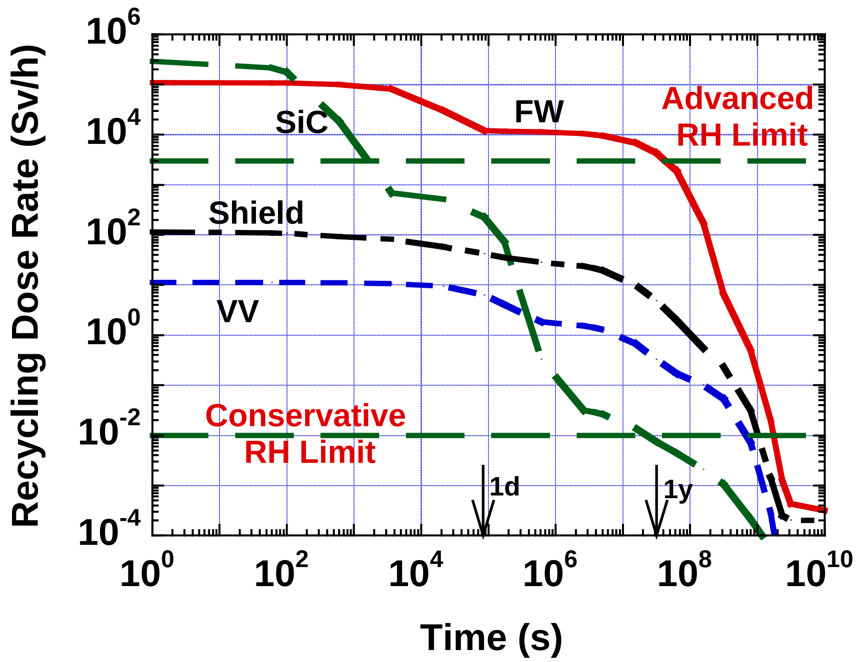

Fig. 3. Variation of dose with time at end of service lifetime of ARIES-CS in-vessel, non-clearable components.

At present, there is no clearance market anywhere in the world. Even though the nuclear industry favors some form of clearance standards, many consumer and environmental groups do not. Moreover, the U.S. industries do not support clearance claiming it could erode public confidence in their products and damage their markets [6]. The dose level of 10 μSv/y (1 mrem/y) for cleared solids is very small in comparison with the variation in natural background radiation (2.4-3.6 mSv/y). As clearance is highly desirable to minimize the radwaste assigned for geological disposal, we urge the 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.

Recycling is an essential step toward achieving the goal of radwaste minimization. It should be pursued despite the lack of details on how to implement it now. We expect significant advancements in recycling technologies some 50-100 y in the future based on current accomplishments and near-term developments in the rapidly growing area of fission fuel reprocessing. Fusion will certainly benefit from fission developments and accomplishments.

To enhance the prospects for a successful radwaste management strategy, we compiled a list of key issues and concerns that need further investigation and assessment:

Disposal:

- Large volume to be disposed of (7,000 - 8,000 m^3 per plant, including bioshield)
- High disposal cost (for preparation, packaging, transportation, licensing, and disposal)
- Existing LLW repositories may become limited

- Political difficulty of building new repositories
- Tighter environmental controls
- Radwaste burden for future generations.

Recycling:

- Development of radiation-hardened RH equipment (> 3000 Sv/h)
- Energy demand and cost
- Chemical or isotopic separation processes, if needed
- Any materials for disposal? Volume? Waste level?
- Properties of recycled materials?
- Recycling plant capacity and support ratio.

Clearance:

- No market worldwide
- Discrepancies between clearance standards [6]
- Lack of consideration for numerous fusion radioisotopes [6]
- Impact of missing radioisotopes on clearance index prediction.

6. Concluding Remarks

The waste aspect of fusion energy should be recognized as an issue that is significant not only to the fusion community, but also to the global environment. Managing the many thousand cubic meters of active materials after plant decommissioning represents a real challenge and cannot be relegated to the back-end as only a disposal issue. With tighter environmental controls and the political difficulty of building new repositories worldwide, the disposal option could be replaced with more environmentally attractive scenarios, such as:

1. Recycle and reuse within the nuclear industry
2. Clear or release to the commercial market if materials contain traces of radioactivity.

The introduction of the clearance category for slightly radioactive materials is an important recent development to accommodate most decommissioned waste (~80%) at a cost much lower than that for traditional LLW. The development of radiation-hardened remote handling equipment that can handle high doses of 3000 Sv/h opened the possibility to recycle almost all in-vessel, non-clearable components.

There is a growing international effort in support of the recycling/clearance trend [5-8] in order to make fusion a viable energy source with minimal environmental impact. We highly recommend minimizing the radwaste by design, and recycling/clearing all fusion components, if economically and technologically feasible, avoiding the disposal option. These recommendations help earn public acceptance for fusion as government agencies and public ask for energy sources that:

- Are safe ⇒ no evacuation plan
- Generate little or no waste ⇒ no burden for future generations
- Do not deplete natural resources ⇒ recycle all radwaste
- Have minimal environmental impact ⇒ avoid geological disposal.

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