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Environmental Aspects of Recent Trend in Managing Fusion Radwaste: Recycling and Clearance, Avoiding Disposal

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Abstract

Effective progress in the environmental field hinges on how any source of energy handles the waste: radioactive, chemical, or toxic. As we enter the nuclear era, the criteria that define an acceptable nuclear system are evolving. For over a half century, the nuclear industry struggled with the disposal of high and low level wastes as the prediction of geological conditions is less accurate for long time into the future. The mandate of fusion to promote nuclear power as a clean source of energy will be significantly strengthened by adopting recycling and clearance, avoiding geological disposal. This is the first time in many years that fusion designers have seriously given their full support to this aspect of radwaste management. At present, the experience with recycling and clearance is limited, but will be augmented significantly by advances in spent fuel reprocessing and fission reactor dismantling before fusion is committed to commercialization in the 21st century and beyond.

1. Introduction

After decades of designing magnetic and inertial fusion power plants, it is timely to develop a new framework for managing the large volume of activated (and contaminated) materials that will be generated during plant operation and after decommissioning – a framework that takes into account the lessons learned from numerous international fusion and fission studies and the environmental, political, and present reality in the U.S. and abroad. Since the inception of fusion projects in the early 1970s, the majority of power plant designs have focused on the disposal of active materials in geological repositories as the main option for handling the replaceable and life-of-plant components, adopting the preferred fission waste management approach of the 1960s. Because of the sizable amount of fusion active materials, limited capacity of existing repositories, and the political difficulty of constructing new repositories worldwide, managing the continual stream of radioactive fusion materials cannot be relegated to the back-end as only a disposal issue. Concerns about the environment, radwaste burden for future generations, lack of geological repositories, and high disposal cost direct our attention to more environmentally attractive scenarios, such as:

- Recycling and reuse within the nuclear industry
- Clearance or release to the commercial market, if materials contain traces of radioactivity.

There is a growing international effort in support of this new trend [1-6]. In recent years, recycling and clearance became more technically feasible with the development of advanced radiation-resistant remote handling (RH) tools that can recycle highly irradiated materials [2,4] and with the introduction of the clearance category for slightly radioactive materials by national and international nuclear agencies [7]. Such recent advances encouraged many designers to apply recycling and clearance to all fusion components that are subject to extreme radiation levels: very high levels near the plasma and very low levels at the bioshield.

2. How Much Radioactive Material Does Fusion Generate?

Fusion power cores generate a sizable volume of active materials (AM) relative to fission reactors. To put matters into perspective, we compared ITER [8], the advanced ARIES tokamak (ARIES-AT) [9], and a compact stellarator (ARIES-CS) [10] to ESBWR (Economic Simplified Boiling Water Reactor) – a Gen-III^{+} advanced fission reactor [11]. Figure 1 displays the notable difference in sizes and a typical classification into high-level waste (HLW), low-level waste (LLW), and clearable materials that contain traces of radioactivity. This AM volume problem is not new and has been recognized for decades by the fusion program since its inception in the early 1970s. Over the years, the ARIES team [12], however, has been moving forward to underscore their commitment to AM minimization by design, applying more advanced technology and physics operating regimes. For instance, the focus on ARIES compact devices contributed significantly to the 2-4 fold decrease in AM volume between the most recently developed power plants and previous designs delivered prior to 1995 (refer to Fig. 2).

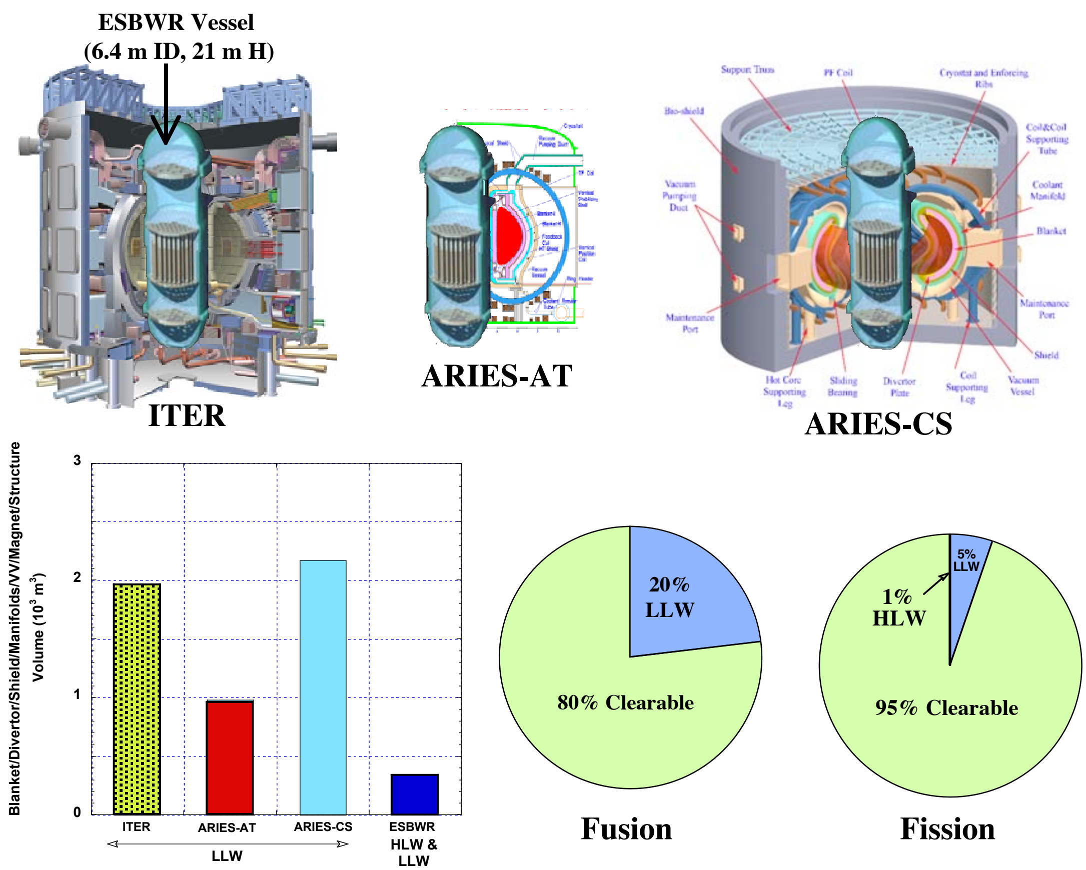

Figure 1. Comparison between selected fusion devices and vessel of advanced fission reactor.

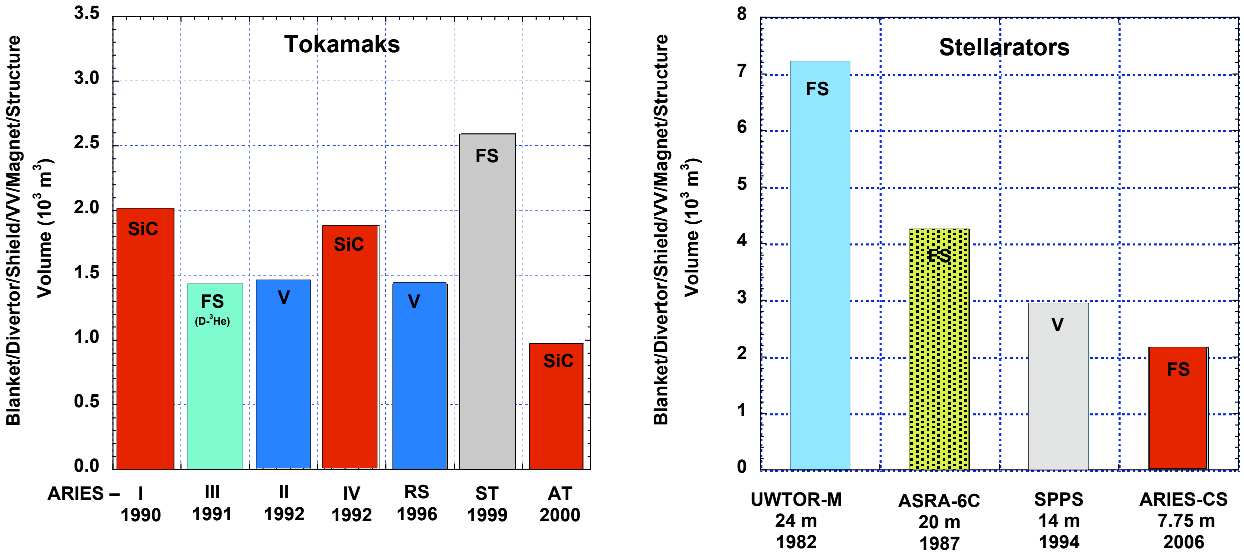

Figure 2. Evolution of fusion power core volumes for U.S. tokamaks and stellarators developed over past 30 years (actual volumes, no compactness, no replacements).

Surrounding the fusion power core is the bioshield, a 2-3 m thick, steel-reinforced concrete building that essentially protects the public and workers against radiation. Being away from the plasma source, the bioshield is subject to low radiation and contains very low radioactivity. However, its volume dominates the waste stream. Since burying such a huge volume of slightly activated materials in geological repositories is impractical, the U.S. Nuclear Regulatory Commission (NRC) and the International Atomic Energy Agency (IAEA) suggested the clearance concept where such components could temporarily be stored for the radioactivity to decay, then released to the commercial market for reuse as 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.

Fusion designers must increase attention to waste management issues associated with the large volume of AM discharged from fusion power plants. Specifically, they should strive to minimize the AM volume problem by design and reshape the fusion waste management approach, maximizing the reuse of AM through recycling and clearance, if technically and economically feasible. This means being strategic about active materials that can free ample space in repositories and, in the long run, save fusion billions of dollars for the high disposal cost. More importantly, this is the best way for the fusion community to promote fusion as an attractive energy source with minimal environmental impact.

3. The disposal option

To date, and after 50 years in the energy market, the nuclear industry continues to struggle with the management of radioactive waste from fission power plants. The reason is that, while radioactivity and toxic hazard can be estimated for many years, the prediction of geological and climatology conditions is less accurate for longer times into the future. This is probably one of the biggest advantages of fusion power vs. fission: it does not produce large volumes of long-lived radionuclides. Moreover, future availability of LLW disposal capacity [13] and disposal cost are highly uncertain and regulatory standards tend to become more stringent with time. Therefore, recent efforts suggest minimizing the AM sent to repositories by recycling and clearance.

The majority of fusion power plants will generate only low-level waste that requires near-surface, shallow-land burial as all fusion materials are carefully chosen to minimize the long-lived radioactive products. The LLW will decay to dismissal level during the period of active institutional control, typically around 100 years. As an example, the activity has been generated to classify the individual components of ARIES-CS [10] at the end of their service lifetimes (3 FPY for replaceable components (FW, blanket, and divertor) and 40 FPY for permanent components (shield, vacuum vessel, and magnet)). All ARIES-CS components qualify as LLW. This is not unique to stellarators as most tokamaks employing low-activation materials exhibit similar features. Table I identifies the Class A and C components according to the U.S. classification. The VV and externals are less radioactive than the in-vessel components, to the extent that they qualify as Class A LLW, the least hazardous type of waste. Excluding the clearable components (cryostat and bioshield), ~ 70% of the waste (blanket, shield, divertor and manifolds) is Class C LLW. The remaining ~30% (VV and magnet) would fall under the Class A LLW category.

TABLE I: ARIES-CS CLASS A, CLASS C, AND CLEARABLE COMPONENTS

Structure	**Class C LLW**	**Class A LLW**	**Could be Cleared?**
FW/Blanket/Back Wall	√		no
Divertor System	√		no
Shield/Manifolds	√		no
Vacuum Vessel		√	no
Magnet:			
Nb_3Sn	√		no
Cu Stabilizer		√	√
JK2LB Steel		√	√
Insulator		√	√
Cryostat		√	√
Bioshield		√	√

In the U.S., the disposition of LLW by shallow-land burial is performed on a regular basis at three commercial land disposal facilities: the Barnwell facility in South Carolina, the Clive facility in Utah, and the Richland facility in Washington [13]. Beginning in July 2008, the Barnwell repository may limit the amount of LLW that they currently accept. Many nuclear facilities are currently storing their LLW and HLW onsite because of the limited and expensive offsite disposal options.

Several critical issues for the disposal option can be identified based on the outcome of numerous fusion studies:

- Large volume to be disposed of (7,000 - 8,000 m^3 per plant, including bioshield)
- Immediate or deferred dismantling?
- High disposal cost (for preparation, packaging, transportation, licensing, and

disposal)
– Limited capacity of existing LLW repositories
– Need for fusion-specific repositories designed for T-containing activated materials
– Political difficulty of building new repositories
– Tighter environmental controls
– Radwaste burden for future generations.

4. The recycling option

At present, a reasonable recycling experience exists within the fission industry. In the U.S., the Department of Energy (DOE) has operated small-scale "restricted" releases of mildly radioactive materials to the nuclear industry throughout the 1990s. With the renaissance of nuclear energy, it seems highly likely that recycling technology will continue to develop at a fast pace to support the mixed-oxide (MOX) fuel reprocessing system and the Global Nuclear Energy Partnership (GNEP) initiative that seeks expanding the worldwide use of fission nuclear power. Fusion has a much longer timescale than 30 years. Developing its long-term strategy, fusion will certainly benefit from the ongoing fission recycling experience and related governmental regulations. Recycling processes include storing in continuously monitored facilities, detritiation, segregation of various materials, crushing, melting, and re-fabrication [3]. Most fusion AM contains tritium that could introduce serious complications to the recycling process. Detritiation treatment prior to recycling is necessary for fusion components with high tritium content. Today, advanced RH equipment (that can handle up to 10,000 Sv/h) is available in the nuclear industry, in hot cells and reprocessing plants [4].
The vast majority of fusion components can potentially be recycled using conventional and advanced RH equipment. As an illustration, we applied the recycling approach to ARIES-CS components (blanket, shield, divertor and vacuum vessel). All components can potentially be recycled using conventional and advanced RH equipment that can handle 0.01 Sv/h (or 0.01 Gy/h; 10^3–10^4 fold the hands-on dose limit) and high doses of 10,000 Sv/h (10,000 Gy/h) or more, respectively. The variation with time of the recycling dose shows a strong material dependence (refer to Fig. 3). The ARIES-CS FW, made of modified F82H ferritic steel (FS), 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. The average FW/blanket dose is an order of magnitude lower. No further dose build-ups are expected for up to 50 y following FW/blanket replacement due to the reuse of these components after numerous life cycles as the dose is a flux dependent response function. In recent years, many plasma physicists called for attaching 2 mm W tiles to the FW to enhance the plasma performance. The W exihibits slightly lower recycling dose rates than a steel-based FW. ^{54}Mn (from Fe) is the main contributor to the dose of FS-based components (FW, blanket, shield, manifolds, and VV) at early cooling periods (<10 y), while impurities have no contribution to the recycling dose for the short cooling periods. Storing the FW/blanket temporarily for several years helps drop the dose by a few orders of magnitude before recycling. This indicates developing advanced recycling tools helps relax the stringent specifications imposed on fusion material impurities. In fact, this is an important choice: either stringent on impurities or on advanced RH equipment.
There is no doubt within the fusion community that recycling has a key role to play to help minimize the volume of radioactive materials assigned for geological disposal. However, some argue recycling could result in substantial technological difficulties, while others claiming the

environmental benefits far outweigh any adverse effects. In fact, there was a cost saving in recycling lead shielding bricks at INL versus disposal in U.S. LLW repositories [1]. Moreover, tests with INL shielding containers showed that millwright composition adjustments after slag removal in the foundry produced metal alloys with properties very similar to, or equal to, those of fresh alloys.

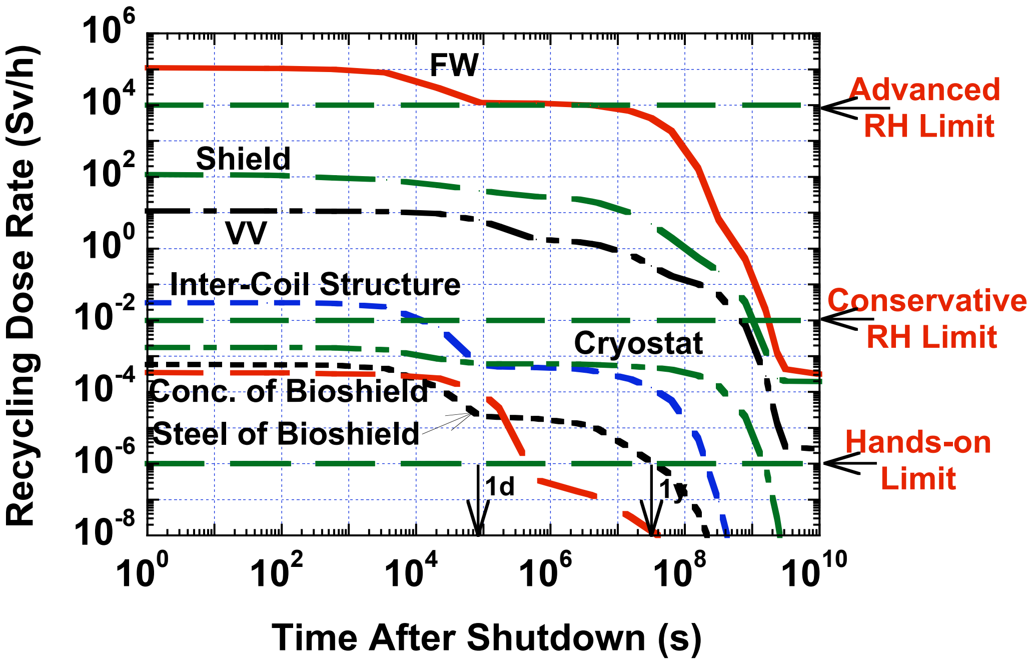

Figure 3. Reduction of recycling dose with time after shutdown.

Recycling should be pursued despite the lack of detail on how to implement it now. In order to provide a broader perspective of the relevant issues involved in the recycling process, several critical issues should be examined with dedicated R&D programs:

- Development of radiation-resistant RH equipment (> 10,000 Sv/h)
- Large interim storage facility
- Energy demand for recycling process
- Cost of recycled materials
- Treatment and complex remote re-fabrication of radioactive materials
- Radiochemical or isotopic separation processes for some materials, if needed
- Efficiency of detritiation system
- Any materials for disposal? Volume? Radwaste level?
- Properties of recycled materials? Any structural role? Reuse as filler?
- Aspects of radioisotope buildup by subsequent reuse and radiotoxicity buildup
- Recycling plant capacity and support ratio
- Acceptability of nuclear industry to recycled materials
- Recycling infrastructure.

5. The clearance option

Several regulatory agencies suggested the unconditional clearance option where slightly radioactive components (such as the bioshield) after decontamination can be handled as if it is no longer radioactive. This means solid materials containing traces of radioactivity can be reused without restrictions, recycled into a consumer product, or disposed of in a non-nuclear landfill, with no controls. If necessary, it could be stored safely at an onsite (or offsite) interim storage facility for a specific period, beyond the licensed operational life of the plant, then released to the commercial market for reuse.

Recent clearance guidelines have been issued by several national and international organizations [7]. They all recommend an individual dose for cleared solids of 10 μSv/y (< 1% of the natural background radiation). Nevertheless, the clearance limits developed by the different organizations show a wide variation for almost all radioisotopes because different approximations were used to compute these limits and different exposure scenarios were selected to model the doses. Other shortcomings include the lack of consideration for numerous fusion radioisotopes and their possible effect on the prediction of the clearance index (defined as the ratio of the activity (in Bq/g) of the individual radioisotope to the allowable clearance limit summed over all radioisotopes). Efforts by the US-NRC, IAEA, and others should continue to develop clearance standards for all radioisotopes of interest to fusion applications [7].

For the ARIES-CS example as well as for almost all tokamaks, the clearance indices for all internal components (blanket, shield, manifolds, and vacuum vessel) exceed unity by a wide margin even after an extended period of 100 y (refer to Fig. 4). ^{94}Nb is the main contributor to the CI after 100 y. Controlling the 3.3 wppm Nb and 21 wppm Mo impurities in MF82H helps CI approach unity. In the absence of impurity control, the in-vessel components should either be recycled or disposed of in repositories as LLW. Examining ARIES-CS magnet constituents confirms the impossible clearance of the Nb_3Sn superconductor (because of ^{94}Nb from Nb) and polyimide insulator (because of ^{14}C from N). The remaining magnet constituents can be cleared, however, within 100 y. Two candidate steels were originally proposed for the magnet structure: Incoloy-908 and JK2LB. The former contains 3 wt% Nb as an alloying element that raised an activation concern. Even though both Incoloy and JK2LB qualify as LLW, the JK2LB steel can be recycled with hands-on and cleared after ~1 year following shutdown, while the Incoloy steel cannot because of the high Nb content. Based on its favorable environmental (and economic) characteristics, the Japanese JK2LB steel is preferable, not only for ARIES-CS magnets, but also for future ARIES designs. The 2 m thick external concrete building (bioshield) that surrounds the torus represents the largest single component of the decommissioned radwaste. Fortunately, the bioshield along with the 5 cm thick cryostat and some magnet constituents qualify for clearance, representing ~80% of the total active material volume. The bioshield was divided into four segments (0.5 m each) and the CIs reevaluated for the constituents (85% Type-04 ordinary concrete, 10% mild steel, and 5% He by volume). Our results indicate that the innermost segment has the highest CI and can be cleared after about one year, while the outer three segments meet the clearance limit within a few days after shutdown.

As clearance is highly desirable for the nuclear industry, the US-NRC, IAEA, and other organizations should continue developing clearance standards for all radioisotopes of interest to fission and fusion applications. There is no established clearance market in the U.S. Nevertheless, some experience already exists in several European countries: Sweden, Germany, Spain, and Belgium. Currently, the U.S. industries do not support unconditional clearance claiming it could erode public confidence in their products and damage their markets. However, there have been some steps forward in clearance. For instance, several U.S. societies and organizations have published guidance on clearance indicating it can be conducted safely with no risk to public health. And clearance has been performed in the U.S. since the 1990s only on a case-by-case basis during decommissioning projects.

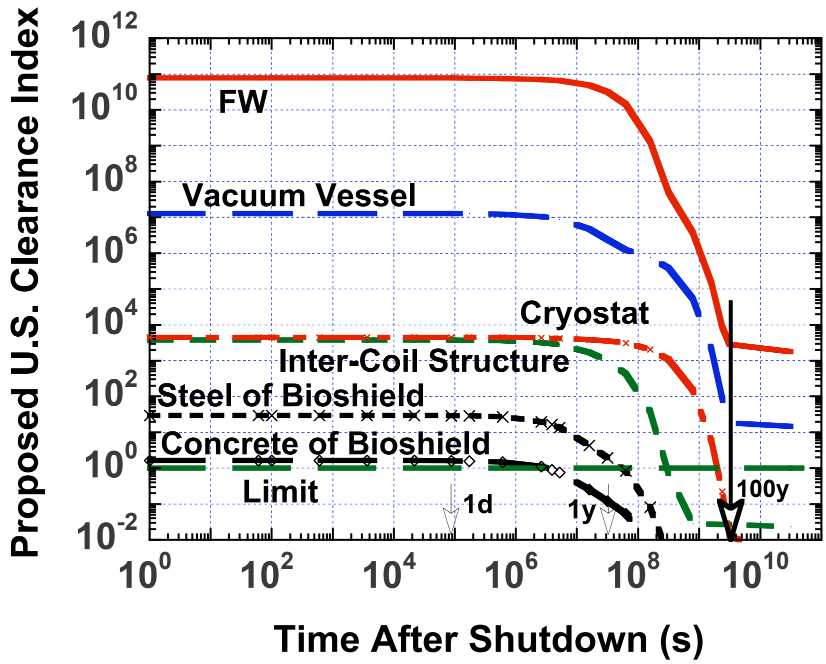

Figure 4. Decrease of clearance index of ARIES-CS components with time after shutdown.

Other clearance-related issues that need further assessment include:

- Discrepancies between US-NRC & IAEA clearance standards [7]
- Impact of missing radioisotopes on CI prediction
- Need for fusion-specific clearance limits
- Large interim storage facility
- Clearance infrastructure
- Availability of clearance market.

6. Integration of recycling/clearance process

The integration of the recycling and clearance processes in fusion power plants is at an early stage of development. Figure 5 depicts the essential elements of the recycling/clearance process. Examining the various steps, one could envision the following:

1. After extraction from the power core, components are taken to the Hot Cell to disassemble and remove any parts that will be reused, separate into like materials, detritiate, and consolidate into a condensed form.
2. Ship materials to a temporary onsite or centralized facility to store for a period of ~1 year or less.
3. If the CI does not reach unity in less than e.g. 100 y, transfer the materials to a recycling

center to refabricate remotely into useful forms. Fresh supply of materials could be added as needed.

4. If the CI can reach unity in less than e.g. 100 y, store the materials for 1-100 y then release to the public sector to reuse without restriction.

Due to the lack of experience, it is almost impossible to state how long it will take to refabricate components out of AM. The minimum time that one can expect is one year temporary storage and two years for fabrication, assembly, inspection, and testing. All processes must be done remotely with no personnel access to fabrication facilities.

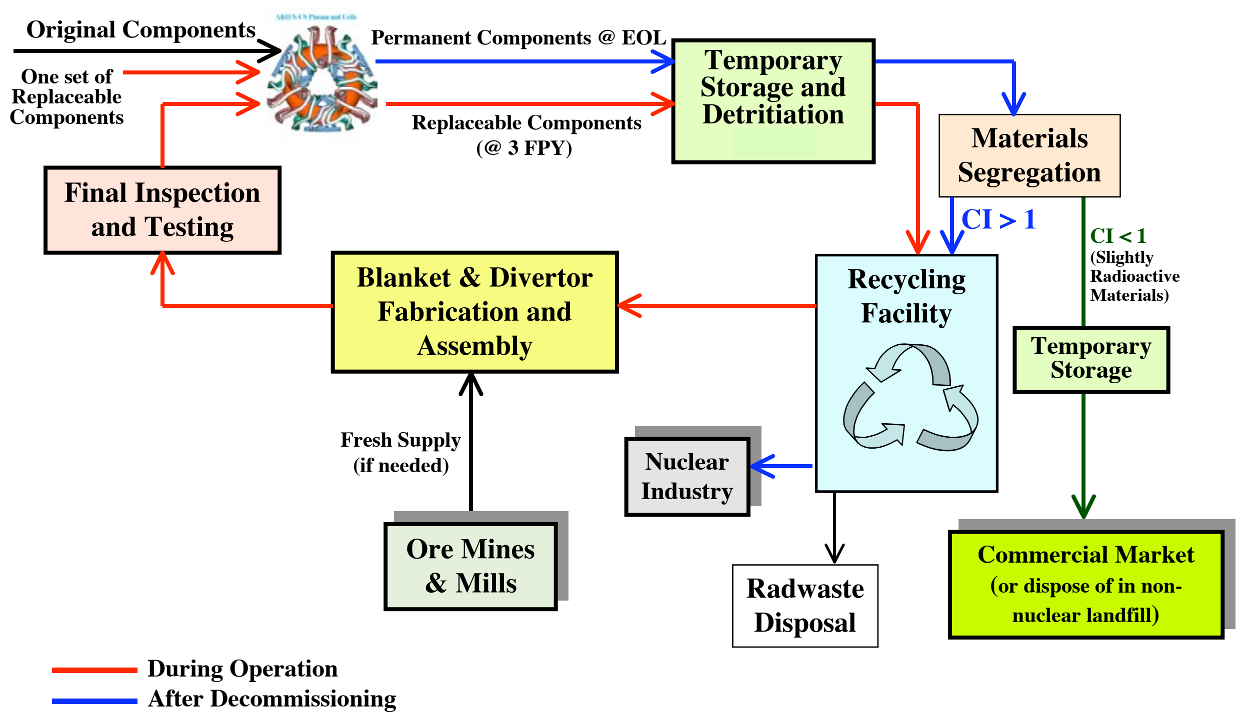

Figure 5. Diagram of recycling and clearance processes.

7. Observations and recommendations

Recycling and clearance are the most environmentally attractive solutions, offering a significant advantage in terms of minimizing the volume of fusion radwaste and avoiding the waste burden for future generations. We call upon the worldwide conceptual power plant designers to minimize the volume of active waste by clever design and choice of material, mandating the use of recycling and clearance, if technically and economically feasible, even if we lack the details of how to implement them today in our designs. At present, the experience with recycling and clearance is limited, but will be augmented significantly by advances in spent fuel reprocessing (that deals with highly radioative materials), fission reactor dismantling, and bioshield clearing before fusion is committed to commercialization in the 21st century and beyond.

While recycling/clearance is a tense, contentious political situation, there has been some progress. For instance, limited scale recycling within the nuclear industry has been proven feasible at several U.S. national laboratories and in Europe. A clearance market currently exists in Spain, Germany, Sweden, Belgium, and other European countries. In the U.S., the free release has been performed only on a case-by-case basis during decommissioning projects since the 1990s. While the clearance process has been ongoing for decades, a more uniform and universal process is highly desirable.

To promote fusion as a nuclear source of energy with minimal environmental impact, the fusion development strategy should be set up to accommodate this new active material management trend. A dedicated R&D program could optimize the waste management scheme further and address the critical issues identified for each option. Seeking a bright future for fusion, we provide the following general recommendations for making sound decisions to restructure the framework of handling fusion active materials:

- Fusion designers:
    - Continue developing low-activation materials. Stringent specifications on impurities could be relaxed by developing advanced recycling tools
    - Minimize radwaste volume by clever design
    - Promote environmentally attractive scenarios such as recycling and clearance, and avoid geological burial
    - Identified critical issues should be investigated for all three options
    - Technical and economic aspects must be addressed before selecting the most suitable radwaste management approach for any fusion component.
- Nuclear industry and organizations:
    - Continue developing advanced radiation-resistant remote handling equipment capable of handling 10,000 Sv/h or more
    - Nuclear industry should accept recycled materials from dismantled nuclear facilities
    - National and international organizations (US-NRC, IAEA, etc.) should continue their efforts to show that clearance can be conducted safely with no risk to public health
    - Regulatory agencies should seriously take into account fusion-specific and advanced nuclear materials and issue official guidelines for the unconditional release of clearable materials.

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