Evaluation of Recent Scenarios for Managing Fusion Activated Materials: Recycling and Clearance, Avoiding Disposal

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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L. El-Guebaly, V. Massaut[1], K. Tobita[2], L. Cadwallader[3]

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

http://fti.neep.wisc.edu

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[1] SCK•CEN, Belgian Nuclear Research Center, Belgium
[2] Japan Atomic Energy Agency, Ibaraki, Japan
[3] Idaho National Laboratory, Idaho Falls, ID, U.S.A.

Abstract

After decades of designing magnetic and inertial fusion power plants, it is timely to develop a new framework for managing the 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., Europe, and Japan. This will clearly demonstrate that designers and scientists developing fusion processes and facilities will be dealing with the back end of this type of energy production from the beginning of the conceptual design of power plants. It is becoming evident that future regulations for geological burial will be upgraded to assure tighter environmental controls. Along with the political difficulty of constructing new repositories worldwide, the current reality suggests reshaping all aspects of handling the continual stream of fusion active materials. Beginning in the mid 1980s and continuing to the present, numerous fusion designs examined replacing the disposal option with more environmentally attractive approaches, redirecting their attention to recycling and clearance while continuing the development of materials with low activation potential. There is a growing international effort in support of this new trend. In this paper, recent history is analyzed, a new fusion waste management scheme is covered, and possibilities for how its prospects can be improved are examined.

1. Introduction

Since the inception of the 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. Now, after ~40 year experience in designing fusion power plants, it is timely to think of a new framework to handle the sizable volume of activated materials (AM) that fusion will generate during operation and after decommissioning. Concerns about the environment, radwaste burden for future generations, lack of geological repositories, and high disposal cost directed our attention to recycling of the AM (for reuse within the nuclear industry) and clearance (the unconditional release to the commercial market or disposal in a non-nuclear landfill). In fact, the recycling and clearance options have been investigated by fusion researchers in the late 1980s and 1990s, focusing on selected materials or components [1-6], then examining almost all fusion components in the late 1990s and 2000s [7-15]. Recycling and clearance became more technically feasible with the development of advanced radiation-hardened remote handling (RH) tools that can recycle highly irradiated materials [16-18] and with the introduction of the clearance category for slightly radioactive materials by national and international nuclear agencies [19,20]. Such recent advances encouraged many fusion designers [17,21-28] 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.

We recognize the value of recycling and clearance as an effective means to control the volume of fusion AM, second to waste minimization by design. Clearable materials are not labeled waste and the majority of the remaining non-clearable materials can potentially be recycled and therefore, will not be assigned for geological disposal. This means the volume of AM that any fusion power plant will generate is influenced by the adequate choice of materials and design and the implementation of the recycling and clearance approaches in the design from the beginning. Nevertheless, the disposal scheme could be the preferred option for specific components for several reasons, including economics, occupational dose minimization, and chemical toxicity. This suggests that the technical and economical aspects, along with the environmental and safety-related concerns, must all be addressed during the selection process of the most suitable AM handling approach for individual components: disposal, recycling, with or without clearance, as given in Table I.

There is a growing international effort in support of recycling and clearance. Numerous researchers applied this new trend to magnetic fusion energy (MFE) power plants [29,30,9-13,30,31,14,33-35,22-24,27], inertial fusion energy (IFE) power plants [36-38,16,39,40], and experimental devices [41-43] fuelled with either D-T or advanced D-^{3}He fuel [44-46]. As an illustration of the environmental benefits and impact of the recent AM management approaches, we applied all three scenarios (disposal, recycling, and clearance) to the most recent U.S. MFE power plant: ARIES-CS [47,48,27] – a compact stellarator with a net electric power of 1000 MW$_e$ and 7.75 m average major radius, approaching that of tokamaks. The dual-cooled LiPb/FS/He blanket breeds sufficient tritium for plasma operation, recovers the neutron energy, and protects the shield for the entire plant life (40 full power years). The blanket and

Table I. Classification of clearable and non-clearable materials for disposal and recycling

	Non-cleared materials	**Cleared materials**
Dispose of	In controlled disposal sites	In non-nuclear industrial landfill
Recycle	Within nuclear industry	In commercial market

shield help protect the manifolds and vacuum vessel (VV) and all four components protect the superconducting magnets for life. The neutron wall loading (NWL) averages 2.6 MW/m^2. Based on the 5.3 MW/m^2 peak NWL, the first wall (FW), blanket, and divertor will be replaced every 3 FPY. The details of the radial dimensions, compositions, alloying elements, and impurities are all given in Ref. 49.

In addition to applying the three scenarios to ARIES-CS, we explored the technical elements supporting the future management of fusion active materials, as well as the policy, regulatory, and concerns for each option: disposal, recycling, and clearance. This paper intends to complement a series of recent documents related to the new trend in radwaste management activities. In particular, it addresses the fusion AM volume problem, introduces the distinct benefits of developing advanced RH recycling equipment, and highlights the positive implications of clearing the sizable bioshield that surrounds the fusion torus. To enhance prospects for a successful waste management scheme, several tasks received considerable attention during this collaborative study and will be discussed in this paper. These include the key issues and challenges for disposal, recycling, and clearance, the limited capacity of existing repositories, the status of the recycling and clearance infrastructure, the need for new clearance guidelines for fusion-specific radioisotopes, the ongoing European R&D program to optimize the fusion AM management scheme, the availability of a commercial market for recycled and cleared materials, and the acceptability of the nuclear industry to recyclable materials.

2. How much radioactive material does fusion generate?

Fusion power cores generate a sizable volume of AM relative to fission reactors. To put matters into perspective, we compared ITER [50], the advanced ARIES tokamak (ARIES-AT) [51], the European Power Plant Conceptual Study (PPCS) [52], the Japanese VECTOR tokamak [53,54], and a compact stellarator (ARIES-CS) [47,48] to ESBWR (Economic Simplified Boiling Water Reactor) – a Gen-III$^+$ advanced fission reactor [55]. Table II provides the breakdown of the volumes while Figs. 1 and 2 display 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 [56], 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. 3).

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. It is constructed to withstand natural phenomena, such as earthquakes, tornados, floods, and an airplane crash. 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 US-NRC and 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.

Depending on the fusion dismantling strategy, a large storage facility will be needed to safely store the sizable fusion components for up to 100 y to reduce the radiological hazards. Options include immediate dismantling and deferred dismantling. Pertinent questions are: how long would a fusion plant remain intact before dismantling? Is it preferable to store the AM onsite or transport them to centralized storage and reprocessing facilities? What would be the support ratio for such facilities?

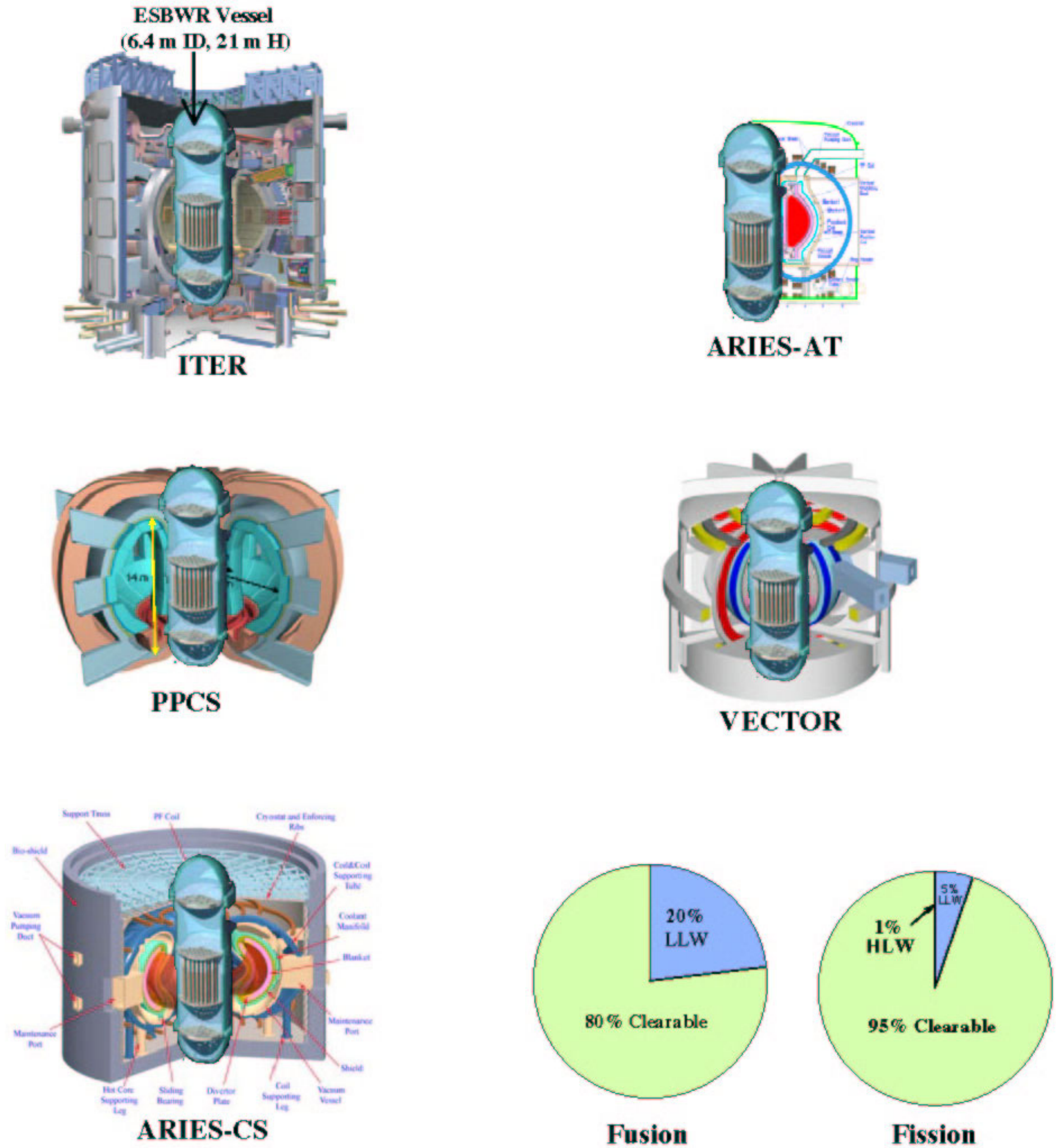


Figure 1. Comparison between selected fusion devices and vessel of advanced fission reactor.

Table II. Breakdown of actual volumes of fusion and fission power cores (not compacted; no replacements included)

Design	ITER	ARIES-AT	PPCS-Model-C	VECTOR	ARIEC-CS	ESBWR
Concept	Tokamak	Tokamak	Tokamak	Tokamak	Stellarator	Fission
Output power (MWe)	---	1000	1450	1000	1000	1550
Major radius (m)	6.2	5.2	7.5	3.2	7.75	
Minor radius (m)	2.0	1.3	2.5	1.4	1.7	
Volumes (m^3):						
FW, blanket, and divertor	89*	270	1391	483	494	
Shield	273	160	238	678	436	
Manifolds	---	---	385	---	318	
Vacuum vessel	580	295	1188	82	362	
Magnets and support structure	1018	256	1663	356	558	
Fission core and vessel	---	---	---	---	---	~350
Total	~1960	~980	~4870	~1600	~2170	~350

*Divertor only.

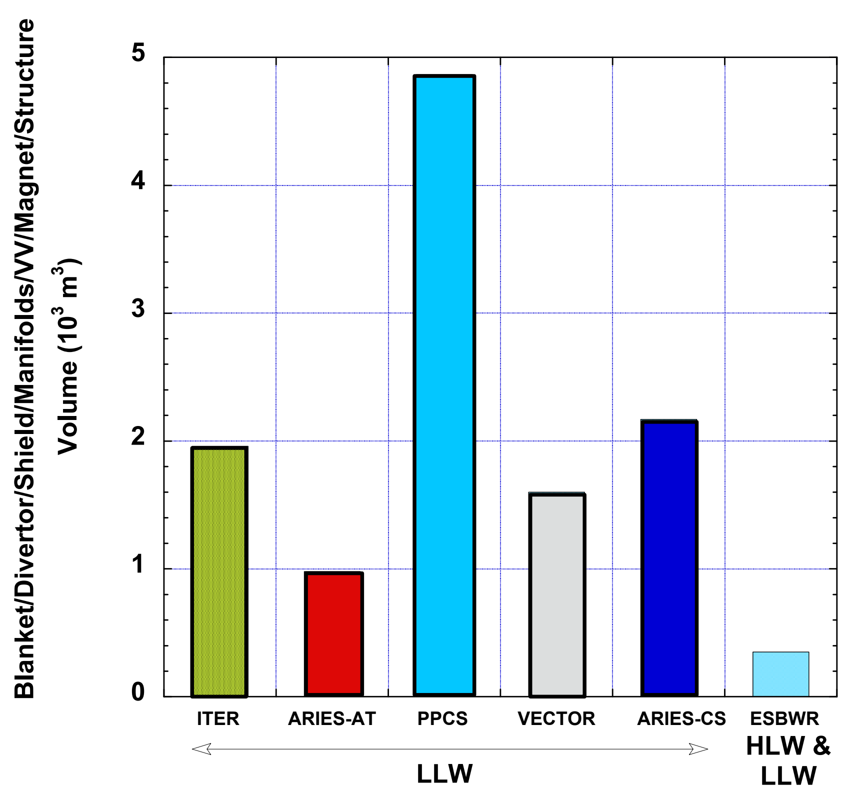
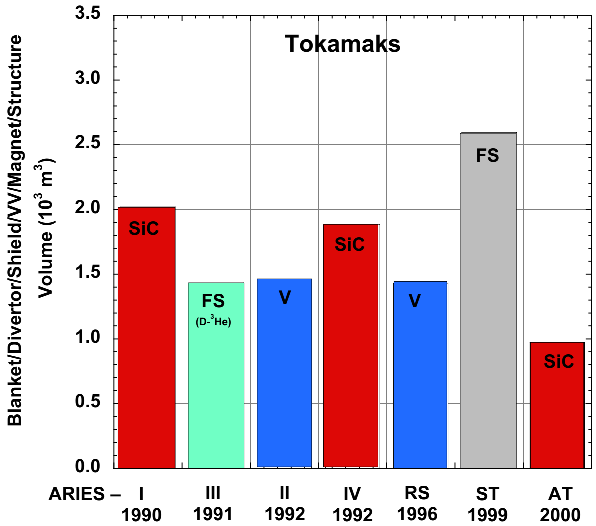


Figure 2. Total volume of major components comprising fusion power core. ESBWR fission core and vessel included for comparison.



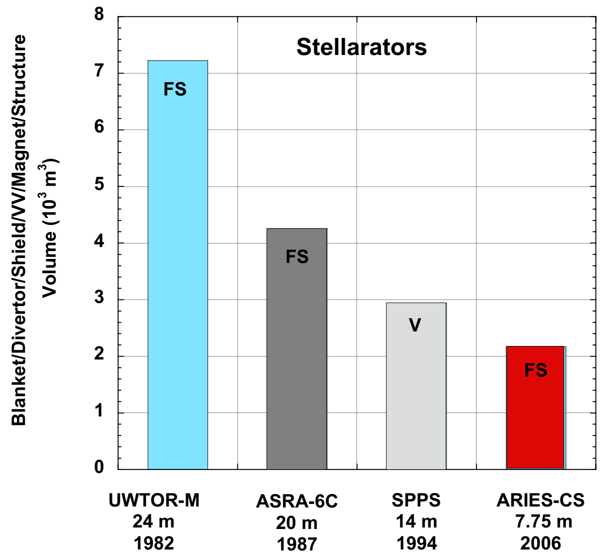


Figure 3. Evolution of fusion power core volumes for U.S. tokamaks and stellarators developed over past 30 years (actual volumes, no compactness, no replacements).

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

One of the key issues to the promotion of the nuclear industry worldwide is the political support for underground repositories and the availability of funding to build new ones. The disposal option attracted growing attention in the late 1960s as the preferred option for handling nuclear radwaste. 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 disposal capacity and disposal cost is highly uncertain and regulatory standards tend to become more stringent with time. Therefore, recent efforts suggest minimizing the AM sent to repositories by reprocessing, if feasible.

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. For the various fusion concepts, reprocessing of AM appeared technically attractive and judged, in many cases, a must requirement

Table III. 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		√	√

to control the radwaste stream [40,27,24]. In specific cases, even though reprocessing seemed technically feasible for certain components, the disposal scheme emerged as the preferred option for economic reasons [16]. To strengthen the overall feasibility of disposal, we summarized below the status of geological repositories in the U.S., Europe, and Japan. As expected, there are commonalities and differences internationally [8,57,34]. Thus, identifying a common basis for a universal repository seems impossible because of the great diversity in technical and geological repository settings, and in disposal requirements (specific radioactivity, contact dose rate, and decay heat level). Nevertheless, we made a number of observations and provided at the end the most critical disposal issues facing the international fusion community.

As an example, the activity has been generated to classify the individual components of ARIES-CS 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 III identifies the Class A and C components according to the U.S. classification (discussed below). 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.

3.1 Status of geological repositories

In the U.S., the radwaste is divided into three main types (LLW, TRU, HLW) based on where it comes from and classified according to activity, heat generation, and physical content. In other countries, the radwaste is categorized as LLW, ILW, and HLW according to what the effects of the radwaste might be. In all countries, LLW represents about 90% of all radwaste volume. This LLW could be safely disposed of in near surface disposal facilities as it decays to dismissal level during the period of active institutional control, typically around 100 years. To our knowledge, few countries are likely to have a deep-mined geological repository. In the 1990s, only one such repository was granted a license: the U.S. Waste Isolation Pilot Plant (WIPP) [58,59].

3.1.1 U.S.

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 U.S. 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. The lower level Class A waste must only meet the minimum packaging requirements. An intrusion barrier, such as a thick concrete slab, is added to Class C waste trenches.

The disposition of LLW by shallow land burial is performed in the U.S. on a regular basis at the Barnwell facility in South Carolina, the Clive facility in Utah, and the Hanford facility in Washington. Disposition of transuranic waste (TRU, the principal constituent of HLW) by placement in deep geologic storage is performed at the Waste Isolation Pilot Plant (WIPP) in New Mexico [58,59].

A fourth U.S. waste storage site, the Waste Control Specialists, LLC, site near Andrews, Texas, is working to obtain federal and State approvals to become a Class A waste disposal site similar to the EnergySolutions site at Clive, Utah [60]. Presently, the Andrews site can only temporarily store waste until final disposal has been arranged at a licensed site. It should also be noted that from 1971 to December 2006, the Barnwell site has disposed of 28.03 million cubic feet (~800,000 m^3) of LLW. The Barnwell site has between 1.2 and 2.2 million cubic feet of disposal space remaining in its 235 acres, depending on how trenching is undertaken at the site [61]. Beginning in 2008, the Barnwell South Carolina repository may limit the amount of LLW that they currently accept.

Waste disposal costs at U.S. disposal sites are typically \$3 per cubic foot for Class A LLW and \$300 per cubic foot for Class C waste, but this cost is only ~15% of the total waste life cycle cost [60]. The other costs include waste characterization, packaging, interim storage, and transportation. Many nuclear facilities are currently storing their LLW and HLW onsite because of the limited and expensive offsite disposal options.

For all ARIES fusion designs, we normally evaluate the waste disposal rating (WDR) for a compacted waste using the most conservative waste disposal limits developed by NRC-10CFR61 [62] and Fetter [63]. The NRC waste classification is based largely on radionuclides that are produced in fission reactors, hospitals, research laboratories, and food irradiation facilities. In the early 1990s, Fetter and others [63] performed analyses to determine the Class C specific activity limits for all long-lived radionuclides of interest to fusion using a methodology similar to that used in 10CFR 61 [62]. Although Fetter's calculations carry no regulatory acceptance, they are useful because they include fusion-specific isotopes. The ARIES approach requires all components to meet both NRC and Fetter's limits until the NRC develops official guidelines for fusion waste. Also, in ARIES, we report the WDR at 100 y after shutdown, allowing the short-lived radionuclides to decay. A WDR < 1 means LLW and WDR > 1 means HLW.

3.1.2 Europe

In Europe, the classification of waste and the waste management policies are coordinated at the national level, and only some guidelines and exchange of data are carried out at the European level [64]. Nevertheless, in general, most of the countries are following, more or less, the IAEA categorization [65] into low and intermediate level waste ($LILW_{SL}$, $LILW_{LL}$) and HLW (the subscripts SL and LL refer respectively to Short Lived and Long Lived, the limit between both being at 30 years half-life). Some countries like Spain, France, Finland, and Sweden are also introducing the concept of VLLW (Very Low Level Waste) for materials above the clearance level, but not requiring as much protection and engineering as the LILW. It has also to be noticed that France does not allow clearing materials but has based its classification on an *a priori* categorization of the materials and an extension of the VLLW class (TFA for Très Faiblement Actif) towards the lowest levels.

There is no disposal facility for High Level Waste currently operational in Europe. Most spent fuel and fuel reprocessing waste are stored either on the power plant site (dry or wet storage) or in centralized national storage. On the other hand there are LILW repositories currently operating in France (CSA), Spain (El Cabril), Sweden (SFR), United Kingdom (Drigg), and Finland (at each nuclear power plant site). Formerly, there was also a repository operational in Germany (ERAM in Morsleben) but it has been closed down prematurely in 1998 by a juridical decision following a claim from nuclear opponents. A specific disposal site for VLLW has been open in France since 2003 [66].

3.1.3 Japan

In Japan, the classification of radwaste is HLW, TRU, and LLW. In addition, LLW is divided into LLW(I), LLW(II), and LLW(III) according to the activity of radionuclides. The only existing repository is located in Rokkasho where LLW(II) is deposited in concrete pit storage. LLW(III) is for higher level radwaste to be deposited 50-100 m below the ground surface. The Rokkasho repository is also a candidate site for LLW(III). Unlined trench burial for LLW(I) is under investigation using the radwaste from the Japan Power Demonstration Reactor (JPDR) of JAEA. There is no candidate repository yet for the HLW and TRU wastes.

3.2 Disposal critical issues

Several critical issues for the disposal option can be identified based on the outcome of numerous power plant studies and the assessment of disposal situations in several countries:

- Large volume to be disposed of (7,000 - 8,000 m^3 per plant, including bioshield)
- Immediate dismantling 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 AM
- Political difficulty of building new repositories
- Tighter environmental controls
- Radwaste burden for future generations.

4. The recycling option – an alternate approach to disposal

Recycling is a real indicator of whether the nuclear industry is serious about reducing its radioactive waste. Currently, there is no unanimous consensus within the fusion community regarding recycling. The debate is similar to that occurring within the fission community with some arguing recycling could result in substantial technological difficulties, while others claiming the environmental benefits far outweigh any adverse effects. A recent Russian

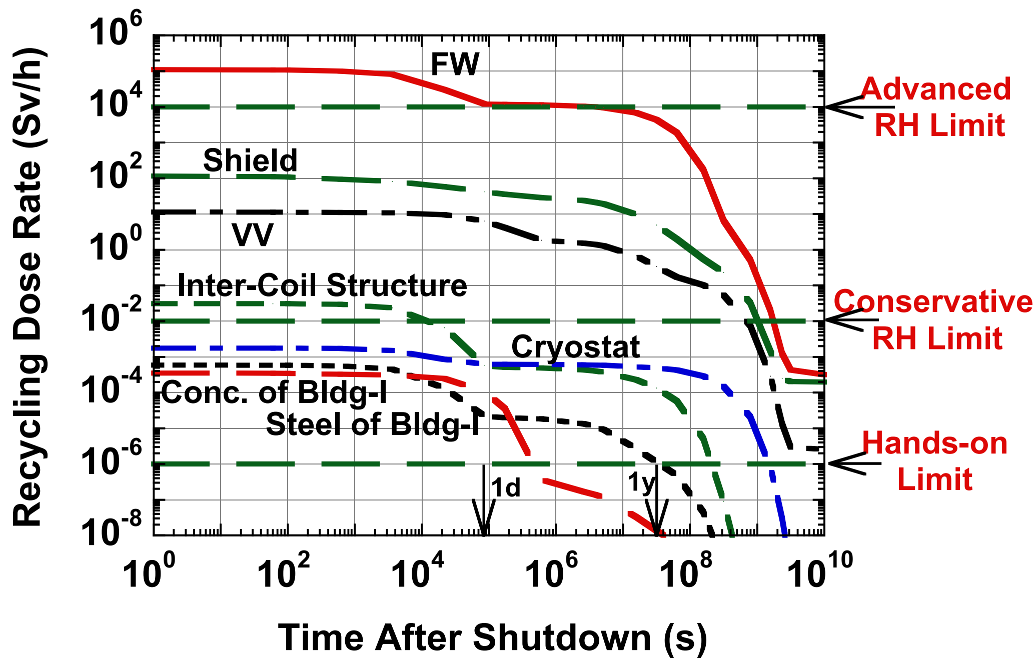


Figure 4. Reduction of recycling dose with time after shutdown.

study concluded that recycling is cheaper than disposal [67]. Furthermore, there was a cost saving in recycling lead shielding bricks versus disposal in U.S. LLW repositories, as will be discussed shortly.

At present, a reasonable recycling experience exists within the fission industry. 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 recycling strategy, fusion will certainly benefit from the ongoing fission recycling experience and related governmental regulations.

Recycling processes include storing in continuously monitored facilities, segregation of various materials, crushing, melting, and re-fabrication [68,26]. Fusion plasma facing components are highly radioactive and require special shielding during handling and transportation. Some may even need cooling for several days to remove the decay heat. Most fusion AM contains tritium that could introduce serious complications to the recycling process. Detritiation treatment prior to recycling is assumed for fusion components with high tritium content. Here, the technical feasibility of recycling is based on the dose rate to the RH equipment. Essentially, the dose determines the RH needs (hands-on, conventional, or advanced tools) and the interim storage period necessary to meet the dose limit while the presence and quantity of tritium and activated dust determine the confinement needs. Beside the recycling dose, other important criteria include the decay heat level during reprocessing, economics of fabricating complex shapes remotely, the physical properties of the recycled products, and the acceptability of the nuclear industry to recycled materials.

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. 4). The ARIES-CS FW, made of modified F82H ferritic steel (FS) [69], is an integral part of the blanket. It is shown in Fig. 4 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.

4.1 Advanced RH equipment

Today, advanced RH equipment is currently used in the nuclear industry, in hot cells and reprocessing plants. Components and remote handling systems capable of withstanding up to 10^4 to 10^5 Sv (10^4 to 10^5 Gy) in one year are currently used in spent fuel facilities [70]. Moreover, the first remote handling action to be carried out should be the removal and de-coupling of the component (from its position in the tokamak) prior to bringing it into the hot cell for further treatment. The main dose rate constraint would then be at this point of the process (moreover the ambient dose rate should be much higher there as the concerned component is still surrounded by others) rather than during further handling or recycling process. Therewith, one can conclude that, if the component can be removed, it can thus be further handled (providing the necessary shielding to limit the integrated dose).

Reviews of remote procedures currently used within the nuclear industry suggest that the 0.01 Sv/h criteria (10^3–10^4 fold the hands-on dose limit) have been unduly conservative [18]. The re-melting of wastes from fission power plants has already been carried out on materials with a contact dose rate of 0.12 Sv/h [18]. Much higher dose rates are present in routine operations in the reprocessing of spent fuel in vitrification facilities. Contact dose rates of 3,000 – 10,000 Sv/h exist at the outside surfaces of cylinders during operations such as weighing, welding, cleaning, contamination monitoring, and transfer to flasks [18,71]. While the fission processes have no direct relevance to the recycling of fusion materials, their success gives confidence that advanced remote handling techniques could be developed for the recycling of radioactive fusion components.

4.2 Recycling market

4.2.1 U.S.

The American scrap metal industry is highly concerned about radioactivity in their products [72,73]. Therefore, at present in the U.S. the most promising method to recycle radioactive materials is "constrained" or "restricted" release of mildly radioactive materials; that is, recycling these mildly radioactive materials back into the nuclear industry. The Department of Energy (DOE) has operated small-scale constrained releases to the nuclear industry throughout the 1990s. A few cases of successful free release and constrained release recycling are described below:

- About 150 tons of copper from the magnets in the decommissioned 184-inch cyclotron at Lawrence Berkeley Laboratory had mild activation, reading between 0 and 20 pCi/g (0-0.7 Bq/g), with an average of 3 pCi/g (0.1 Bq/g), due to approximately 0.42 mCi (15 MBq) of Co-60 dispersed volumetrically in the copper. The California Department of Health Services considered this copper to be non-radioactive and permitted free release of this copper to the recycle market [74].

- At the Idaho National Laboratory (INL), lead has been retrieved from shielding casks and recycled into both the nuclear industry and the commercial industry as free release material. In 1999, the INL identified, characterized, and shipped lead-and-steel casks to the GTS-Duratek firm in Oak Ridge, Tennessee for recycling. GTS-Duratek recycled nearly 100 tons of lead from those casks on the open market. GTS-Duratek has also recycled over one hundred tons of mildly activated steel from the Belgian BR3 reactor and fabricated steel shielding bricks for use at DOE accelerator facilities [75]. Note that GTS-Duratek was purchased by the EnergySolutions company in 2006.

- The INL recycled more cask shielding with the GTS-Duratek firm in 2001 to fabricate another 100 tons of lead bricks for nuclear industry use as an accelerator target shielding wall at the Idaho Accelerator Center on the campus of Idaho State University. Each shielding brick weighed 26.25 pounds (11.9 kg). The estimated cost of LLW disposal of the lead was about $5 USD/pound while the approximate cost of recycling was $4.30 USD/pound, which included fabrication into brick shapes. Therefore, there was a cost saving in recycle versus disposal and the savings of disposal volume. The cost to purchase brand new shielding bricks rather than obtain recycled bricks was estimated to be $46.00 USD per brick, so there was the savings of not requiring the purchase of new bricks.

- Recycling stainless steel and lead has also been carried out within the nuclear industry at the INL. In 1996, a program to utilize mildly radioactive (surface and volumetric) stainless steel and mildly radioactive lead to fabricate small shielding containers sized to accommodate one 30-gallon or one 55-gallon waste drum was carried out and several prototype casks were fabricated [76]. The drums contained transuranic waste (TRU) that read on the order of 50 mSv/h (5 rems/h). The casks were designed, built, and tested for strength and impact [77,78]. After passing the tests, the casks were used to shield the drums to the INL 'hands-on' contact handling level of 2 mSv/h (200 mrem/h). The casks were put in service at the Radioactive Waste Management Complex at the INL. The prototype casks functioned well and are still in use.

- The Savannah River National Laboratory (SRNL) also experimented with recycle and beneficial reuse within the DOE community [79,80]. Some large parts, e.g., reactor coolant pumps from decommissioned production reactors, were melted and cast as ingots; these steel ingots were shaped appropriately for later use as shielding blocks. The SRNL also examined construction of TRU and HLW waste casks using recycled materials, and has fabricated some casks similar to those at INL [79].

An unexpected benefit of the scrap metal melting process was that the slag tended to collect some of, or a majority of, the radionuclides and when the slag was removed from the melt the resulting ingots contained only very low levels of radioactivity. The slag would be sent to LLW disposal, but as a greatly reduced volume. The tests with the 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 virgin alloys. These experiences prove the feasibility of recycling metals within the nuclear industry.

Another issue is the recycle of concrete. On-site disposal and unrestricted landfill disposal of concrete are the primary methods used in the commercial industry at present [81]. The DOE also has large amounts of used concrete for disposal, roughly estimated to be more than a million cubic meters. Tripp [82] described a protocol that has been developed and used to assess disposal options for concrete within the DOE nuclear community. The options include:

1. Decontaminate the concrete structure, disposing of all LLW in shallow land burial, and crushing then reusing the decontaminated concrete as roadbed material. This only applies to surface contaminated concrete that can be decontaminated.
2. Crush the concrete without decontamination and reuse it as roadbed material.
3. Decontaminate the concrete material, dispose of all LLW, demolish the structure or material, and dispose of the decontaminated material as construction debris. The debris could be placed in a non-radiological landfill or used as a backfill material in new construction.
4. Demolish the concrete material and either dispose of it without decontamination as construction debris at a non-restricted landfill or reuse it as new construction backfill.
5. Demolish the concrete without decontamination and dispose of all material as LLW.
6. Decontaminate the concrete building structure and reuse it for some other purpose, e.g., an office building.
7. Demolish the concrete material with or without decontamination and entomb the demolished material.

There are other alternatives besides those listed here, but the seven listed above offer a wide range of solutions to the concrete disposition. Alternatives are assessed by minimizing the dose to members of the public while also minimizing the total cost of the effort. The concrete is profiled for radionuclides [83] and the corresponding dose of pCi/g per isotope present is summed and compared to a total 10 μSv/y (1 mrem/y) dose to members of the public. If the concrete dose is greater than 10 μSv/y for a given alternative, the DOE Assistant Secretary of Environment, Safety and Health would have to give approval for the project release limit, and if the dose is less than 10 μSv/y the DOE Field Office with project responsibility can approve the project release limit. A consensus standard [84] has been written about concrete disposal options.

Chen [85] pointed out that releasing mildly radioactive materials from regulatory control to the commercial metals industry could result in these materials finding their way into consumer products (e.g., strollers, toys, etc.). This possible migration, no matter how dilute, has engendered negative perceptions among the materials industries due to potentially negative economic impacts of U.S. consumer fear of the items and refusal to purchase the items. For example, Lubenau [86] described several widespread events in the U.S. where consumers and mill workers have suffered debilitating radiation exposures from inadvertent radioactive contamination in recycled consumer materials. For these reasons, the U.S. recycling market for AM is presently very small. The non-radiological portions of power plants (e.g., cooling tower rebar, unirradiated steam cycle equipment, etc.) are recycled. In 2000, the DOE imposed a moratorium on DOE-based recycling of radioactive materials to commercial markets due to the concerns of the U.S. metal industry [87]. The commercial nuclear industry has faced the same issue of reluctance of industry to recycle mildly radioactive materials. Currently in the U.S., the only acceptable 'de minimus' level of radioactivity in the commercial markets is zero.

4.2.2 Europe

Presently, the market of recycling radioactive material is still very little developed. First of all because only few power plants and facilities are being dismantled and secondly because the building of new facilities is almost stopped, and thus the need for components and material is rather low. Even for recycling into casks for spent fuel or shielded containers for radiating radwaste, the manufacturers are not very open to use recycled materials, for quality control purposes even though these materials may not be highly radioactive. After melting, the slag tends to collect numerous radionuclides. Several European fission reports published in the 1990s addressed this specific topic. Normally, the radionuclides in the slag are the heavy nuclides (U and TRU) while ^{137}Cs was found in the fumes and aerosols (i.e. in filters) and ^{60}Co or Ni remained in the bulk metal.

Up to now, the very narrow market for recycling concerned only very low value materials (concrete rubble and scrap metals) [88] or on the other hand the spent fuel, being a highly valuable material. The main market today is probably the recycling after clearance, providing an ad hoc system is in place for anonymizing the origin of the scrap or rubble.

4.2.3 Japan

Because the decommissioning of the first fission power station is in progress, there is no social need for recycling radioactive materials. It is expected that the Rokkasho repository can accommodate the LLW from fission power stations until 2030. For this reason, research is currently scarce on technologies for recycling of radioactive materials.

4.3 Recycling critical issues

There is no doubt within the fusion community that recycling has a key role to play to help minimize the volume of active materials. It 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, we identified several critical issues for the international fusion community to examine with dedicated R&D programs in key areas:

- Development of radiation-hardened RH equipment (10,000 Sv/h)
- Energy demand and cost of recycling process
- Radiochemical or isotopic separation processes for some materials, if needed
- Efficiency of detritiation system
- Any materials for disposal? Volume? Waste level?
- Properties of recycled materials? Reuse as filler? No structural role?
- Aspects of isotope buildup, radiotoxicity buildup, and impurities
- Recycling plant capacity and support ratio
- Acceptability of nuclear industry to recycled materials
- Recycling infrastructure.

5. The clearance option – an alternate approach to disposal

Several regulatory agencies suggested the unconditional clearance option where slightly radioactive components (such as the bioshield) or contaminated components, after decontamination (such as the primary coolant system), 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.

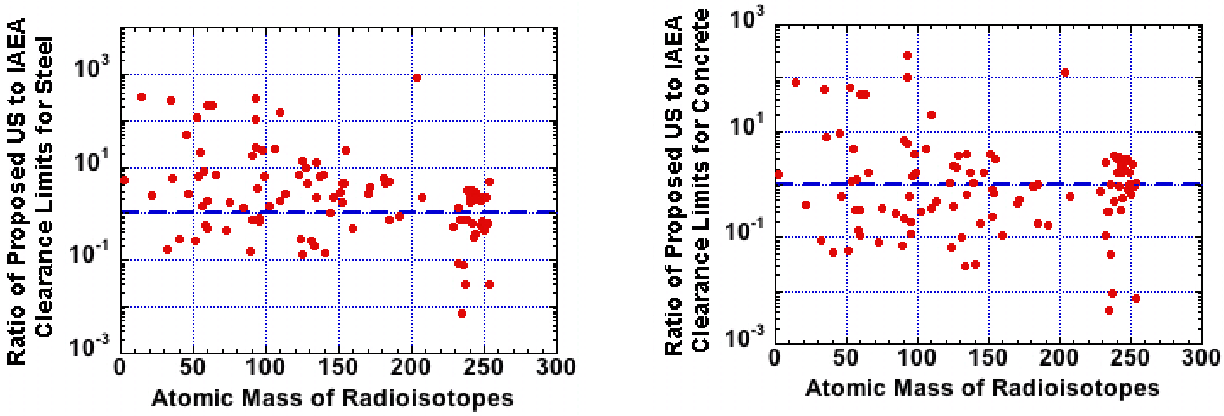


Figure 5. Ratio of proposed U.S. clearance limits to IAEA clearance limits.

Recent clearance guidelines have been issued by the US-NRC [19], IAEA [20], and other national organizations. The US-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 [19] will be referred to as the proposed U.S. limits. There is widespread agreement between the US-NRC and IAEA 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. This is very low in comparison with the variation in natural background radiation (2.4 - 3.6 mSv/y), representing less than 1% of the allowable. Nevertheless, as Fig. 5 indicates, the clearance limits developed by the different organizations show a wide variation for almost all radioisotopes [21] because different approximations were used to compute these limits and different exposure scenarios were selected to model the doses [19,20]. Other shortcomings include the lack of consideration for numerous fusion radioisotopes and their possible effect on the clearance index prediction. Efforts by the NRC, IAEA, and others should continue to develop clearance standards for all radioisotopes of interest to fusion applications.

By definition, the clearance index (CI) for any material 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 defined storage period following decommissioning. 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 segregate and re-evaluate the CIs for the constituents [11,21,23,35]. Essentially, segregation can either expedite or delay the clearance after the interim storage. Sizable components, such as the 2-3 m thick bioshield, should be segmented into 4-6 layers with the CI for each layer reexamined.

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. 6). ^{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, Fig. 7 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. The inconsistencies in the ^{14}C, ^{54}Mn, and ^{63}Ni clearance standards (refer to Table IV) result in a wide variation in the required storage period for the Cu stabilizer, coil structure, and mild steel, as displayed in Figs. 6-9.

Table IV. IAEA and U.S. proposed clearance limits (in Bq/g) for selected fusion-relevant nuclides

Nuclide	IAEA [20]	U.S. [19] (Steel / Cu / Concrete)
^{3}H	100	526 / 1e5 / 152
^{14}C	1	313 / 4.17e4 / 83
^{22}Na	0.1	0.238 / 8.33 / 0.0417
^{40}K	---	2.94 / 153.8 / 0.526
^{41}Ca	---	47.6 / 9.1e3 / 13.9
^{45}Ca	100	5e3 / 7e4 / 909
^{53}Mn	100	1.14e4 / 7.1e5 / 6.67e3
^{54}Mn	0.1	0.625 / 23.26 / 0.118
^{55}Fe	1000	2.17e4 / 2.33e5 / 4.76e3
^{59}Fe	1	0.476 / 22.7 / 0.114
^{58}Co	1	0.588 / 28.57 / 0.133
^{60}Co	0.1	0.192 / 9.1 / 0.035
^{59}Ni	100	2.17e4 / 3.57e5 / 4.76e3
^{63}Ni	100	2.13e4 / 1.85e5 / 4.76e3
^{64}Cu	100	---
^{94}Nb	0.1	0.333 / 11.5 / 0.059
^{99}Mo	10	---
^{99}Tc	1	6.25 / 1.05e3 / 1.64
^{108m}Ag	---	0.345 / 18.18 /0.0588
^{110m}Ag	0.1	0.192 / 10.3 / 0.0357
^{125}Sb	0.1	1.41 / 62.5 / 0.23
^{152}Eu	0.1	0.455 / 16.4 /0.083
^{154}Eu	0.1	0.455 / 16.67 /0.071
^{182}Ta	0.1	0.435 / 16.95 /0.091
^{192}Ir	1	0.91 / 52.63 /0.172
^{186}Re	1000	---

Two candidate steels were originally proposed for the magnet structure: Incoloy-908 and JK2LB [89]. 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. Figure 8 displays the clearance results showing the very slow decay rate for Incoloy. 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.

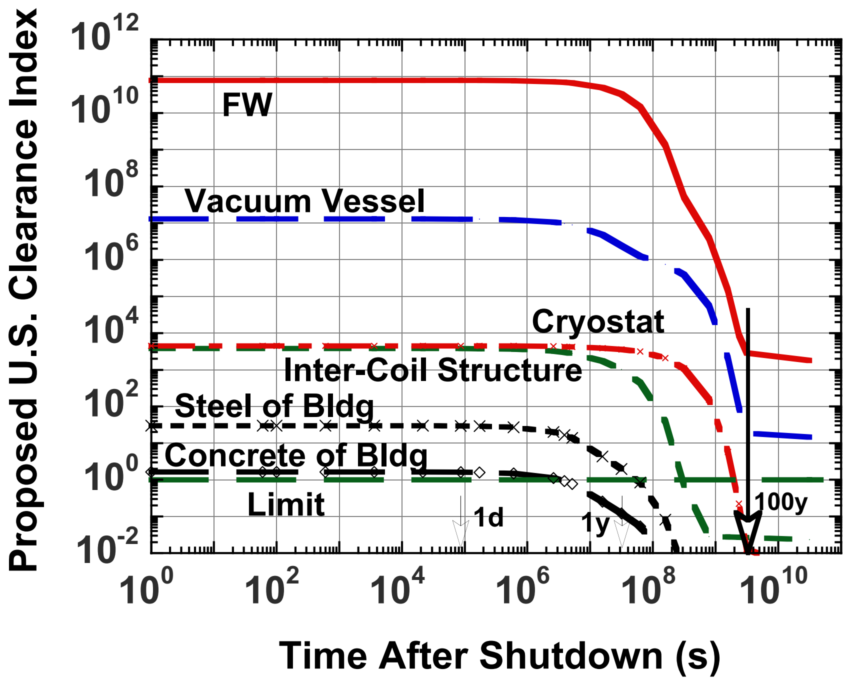


Figure 6. Decrease of clearance index of ARIES-CS components with time after shutdown.

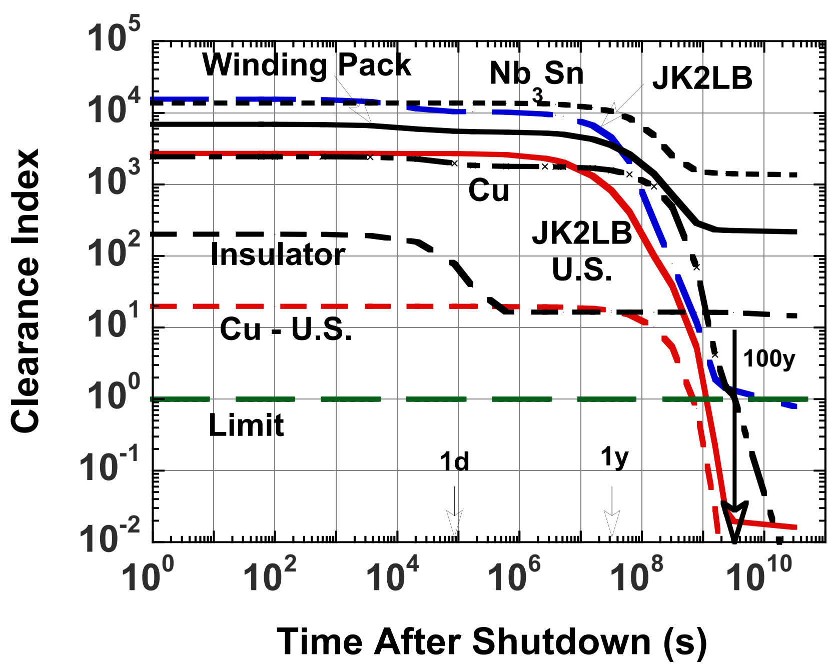


Figure 7. Variation of CI of winding pack constituents with time after shutdown.

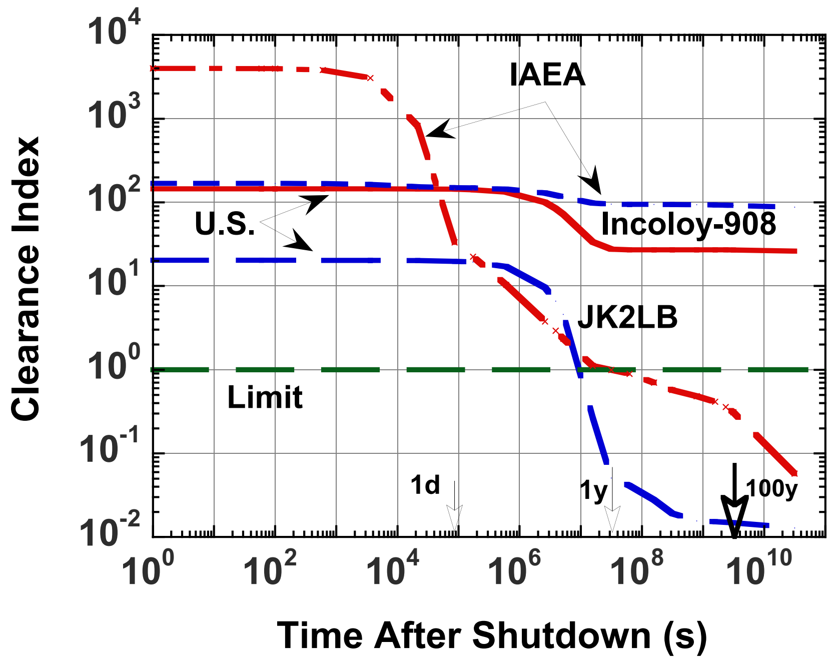


Figure 8. CI comparison of Incoloy-908 and JK2LB.

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% concrete, 10% mild steel, and 5% He by volume). Our results indicate that the innermost segment has the highest CI while the outer three segments meet the clearance limit within a few days after shutdown. This is probably impractical as the bioshield is commonly part of the building infrastructure and cannot be dismantled before all internal components are removed.

As Fig. 9 indicates, the mild steel is a major contributor to the CI of the bioshield if used with Type-04 ordinary concrete, although its volume fraction is only 10%. A variation was studied that affects the cooling period: a concrete with a more comprehensive list of constituents and impurities based on data from European Presurized Water Reactor (PWR) [68]. The results are shown in Fig. 9. Compared to Type-04 ordinary concrete, the EU PWR concrete calls for longer cooling period of ~50 y mainly for the CI of ^{152}Eu to drop below one. This finding is in general agreement with Ref. 68.

5.1 Clearance market

5.1.1 U.S.

The U.S. has three guidance documents on clearance of mildly radioactive materials. The first is NRC Regulatory Guide 1.86 [90], the second is NUREG-1640 [19], and the third is DOE Order 5400.5 [91]. The first and third of these documents address surface contamination but do not specifically address volumetrically activated material. The second document makes no distinction of surface or volumetric contamination, just doses to exposed persons from cleared materials. Clearance, or release from regulatory control to the open market (i.e., free release) for

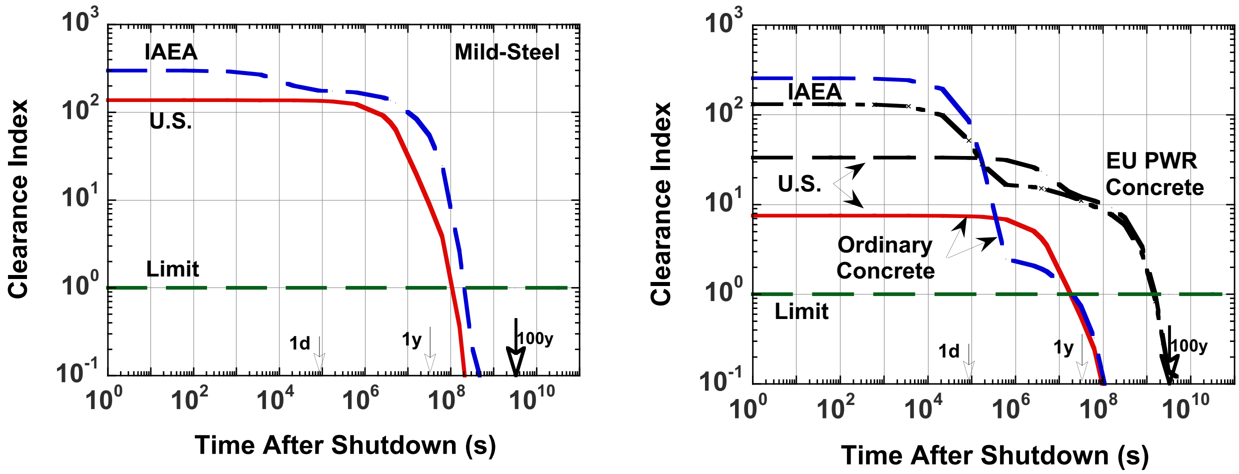


Figure 9. Comparison of US-NRC and IAEA CI for constituents of innermost segment of bioshield.

volumetrically activated or contaminated materials, has been performed only on a case-by-case basis during decommissioning projects since the 1990s. Chen [92] has pointed out that there is a lack of uniform release standards and NUREG-1640 is an attempt to provide a calculation from a dose endpoint as suggested in some clearance documents for radionuclide concentrations in the material to be cleared.

There is no established U.S. market for clearable materials and, as stated earlier, there isconsiderable reluctance from the U.S. commercial sector to begin recycling these free release materials. The reluctance stems from the concern that U.S. consumers will not purchase products that could possibly be 'tainted' by radioactivity, no matter how small the radioactivity. Despite this concern, there have been some steps forward in clearance. The Health Physics Society and the ASTM have published guidance on clearance [93,94] which focuses on a dose limit of less than 10 μSv/y (1 mrem/y) to any individual member of the public from these materials, which follows the EU and IAEA established doses. NUREG-1640 gives additional direction on calculating potential annual doses from released material for a wide number of exposure scenarios. Attaining < 10 μSv/y (1 mrem/y) dose generally requires on the order of pCi/g (0.03 Bq/g) magnitude level of activity for each of the dominant volumetric radionuclides.

Comprehensive studies in the past few years have emphasized the issues with clearance:

- The National Academy of Sciences stated that there is no clear, overarching policy statement for management and disposition of waste. Volume contaminated waste is addressed on a case-by-case basis and can lead to inconsistent determinations. The nuclear industry could generate up to 50,000 metric tons of scrap metal per year in the coming decades and that amount represents about 0.1% of the total obsolete steel scrap metal that might be recycled during that time period [95].

- The National Council on Radiation Protection noted that recycling is a positive policy for environmental and public health. Harmony with the international community in setting universal clearance standards is needed to preclude issues of receiving scrap metal from abroad that has higher-than-allowable radioactivity. The scrap metal industry and the public have concerns with this issue and the concerns must be addressed [96].

The U.S. has had some very small successes with free release as mentioned in Section 4, and more success with ‘restricted release’, or clearance of materials to be re-used within the nuclear industry or the DOE community. 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.

5.1.2 Europe

There is no uniform or harmonized regulation on clearance in the European Union. Although the European Commission has published several guidelines on clearance of materials from regulatory control [97-101], each European country can issue its own regulation (see e.g. [102,103]). Since the 1990s and following the ongoing decommissioning program and projects, several countries have already issued regulations on clearance and projects have cleared materials in industrial quantities (mostly metals and concrete rubble):

- Sweden was among the first to apply clearance on metals and installed a "nuclear" furnace in its research center Studsvik. The Swedish regulation allows clearing of materials, but also even to treat (smelt) metals from abroad and clear them providing the material can be released within 10 years; the decay storage and subsequent release being carried out at the site of Studsvik.
- Germany has a rather complex and complete set of regulations for conditional and unconditional release. With several large decommissioning projects (like the Greifswald EWN, Stade, Gunremmingen A, Kahl, etc.), the amount of cleared materials amounts already in the thousands of tons.
- Spain started industrial clearance of metallic material, with its Vandellos decommissioning project. It must also be noticed that there is a convention signed between the Spanish government and the steel industry for enhancing the acceptance of cleared materials by the steel recyclers.
- Belgium has also introduced clearance levels into its regulation and has cleared thousands of tons of steel and concrete from the BR3 and Eurochemic projects.
- Italy also applies clearance, based on a case-by-case basis.

5.1.3 Japan

In Japan, the application of clearance was legislated in 2005 for radwaste from nuclear facilities. Note that the purpose of clearance is not only to encourage recycling of the waste, but also to dispose of it as industrial non-nuclear waste. Not all wastes fit recycling from the point of view of supply-demand balance, as indicated by the fact that concrete waste is in a state of excess supply in the present recycling market. In this sense, metal waste is considered as a useful resource for recycling.

The only example of recycling of cleared waste in Japan is the steel from the first commercial nuclear power plant (Tokai Power Station). Shielding blocks, tables, and benches were fabricated from the recycled steel for use in the Japan Proton Accelerator Research Complex (J-PARC) of JAEA [104]. The potential of the clearance market will be explored in the 2010s when the decommissioning of light water reactors is anticipated to begin in earnest.

5.2 Clearance critical issues

Efforts by the NRC, IAEA, and others should continue to develop clearance standards for all radioisotopes of interest to fusion applications. 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. Other clearance-related issues that need further assessment include:

- Discrepancies between NRC, EU, and IAEA clearance standards
- Impact on CI prediction of missing radioisotopes (such as ^{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)
- 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 10 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.

7. European R&D program

Fusion studies developed to date indicated recycling and clearance are technically feasible providing enhanced confidence in alternate means to keep the radioactive waste levels to a minimum, after an adequate decay period and proper handling and treatment. As a step forward, the recent EU R&D program [26,105] allows further optimization of the waste management scheme, enhancing the possibility of recycling and clearance as much as practically possible. The waste treatment includes detritiation, separation and sorting of different materials, among others.

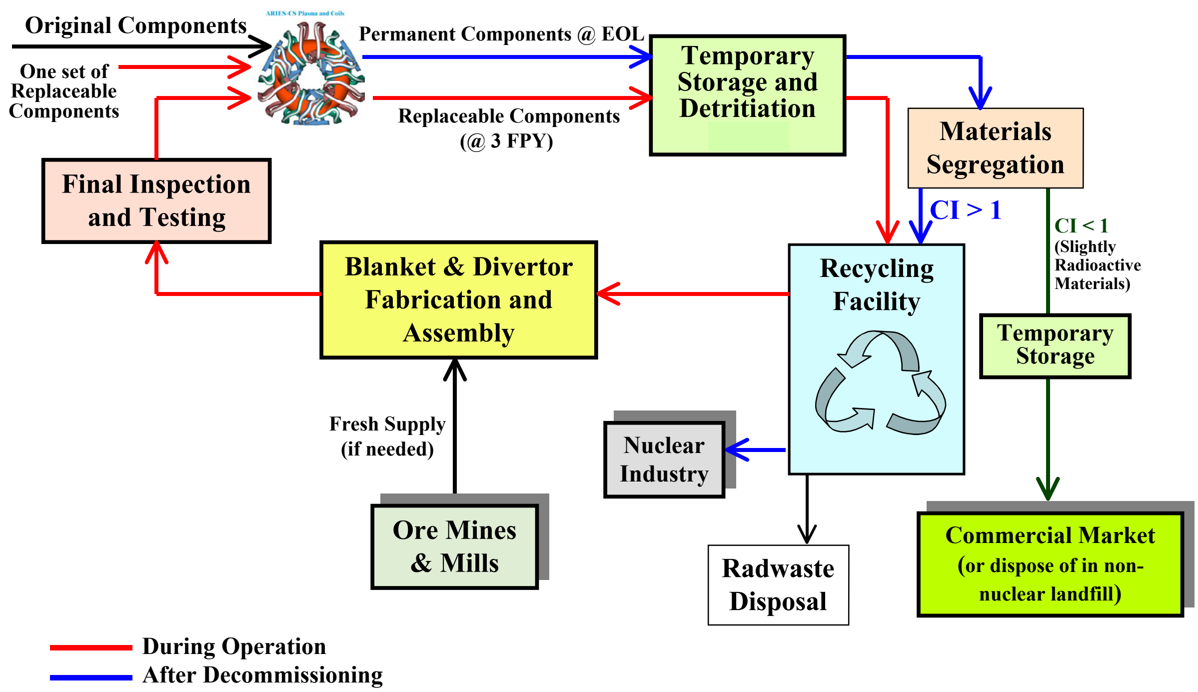


Figure 10. Diagram of recycling and clearance processes.

Moreover, if recycling or reuse is foreseen, processes for reuse and refabrication have to be made on an industrial scale.

The European study comprises a review of the current situation and state-of-the-art recycling methods for typical materials and components of fusion plants based on current European conceptual design studies. It focuses attention on R&D issues to be addressed in order to be able to recycle as much material as possible in a safe, economical and environmentally friendly manner. Recycling of fusion materials is a huge challenge and presents important spin-offs for the fusion industry. The conclusion of this first study is that the solutions and the routes to follow should be developed as soon as possible in order to tackle this important issue as it arises.

8. Observations and concluding remarks

We explored the technical elements supporting the future management of fusion active materials, as well as the policy, regulatory, and concerns for each option: disposal, recycling, and clearance. We described how the fusion development strategy should be set up to accommodate the new AM management trend. Our work recognizes the value of recycling and clearance as the most environmentally attractive solution, offering a significant advantage to fusion energy, and avoiding the waste burden for future generations. Fusion power plants developed to date will generate a sizable amount of active materials, compared to fission reactors. Adopting the 1960s fission preferred option of geological disposal or shallow land burial is not an environmentally attractive option. Also not acceptable is considering only pre-financing and generating disposal funds for future generations (50-100 y from even being born) to dispose of our radioactive waste. More environmentally attractive means to keep the volume of fusion radioactive wastes to a minimum should be developed and pursued.

Our intent is to raise awareness within the fusion community and call upon the worldwide conceptual power plant designers to minimize the volume of active waste by 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. We are forecasting an advanced recycling technology some 50-100 y in the future based on current accomplishments and near term developments within the fission industry in support of the GNEP, MOX fuel, and Partitioning and Transmutation activities. 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 in Europe and at several U.S. national laboratories. A clearance market currently exists in Germany, Spain, Sweden, Belgium, and other countries in Europe. In the U.S., the free release has been performed only on a case-by-case basis during decommissioning projects since the 1990s.

To enhance prospects for a successful AM management strategy, we applied all three scenarios (disposal, recycling, and clearance) to selected fusion studies. While recycling and clearance appeared technically attractive and judged, in many cases, a must requirement to control the AM stream, the disposal scheme emerged in other fusion studies as the preferred option for specific components for several reasons, including economics, occupational dose minimization, and chemical toxicity. This suggests that the technical and economic aspects, along with the environmental and safety related concerns, must all be addressed during the selection process of the most suitable waste management approach for individual components and that probably a mix of both strategies will present the best economical and technical option.

A dedicated R&D program should 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
    - Minimize radwaste volume by design
    - Promote environmentally attractive scenarios such as recycling and clearance, and avoid geological burial; therefore design easily replaceable components
    - 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 rad-hard 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.

Acknowledgement

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References

1. C. Ponti, Recycling and shallow land burial as goals for fusion reactor materials development, Fusion Technology 13 (1988) 157-164.

2. E.T. Cheng, D.K. Sze, J.A. Sommers, O.T. Farmer III, Materials recycling considerations for D-T fusion reactors, Fusion Technology 21 (1992) 2001-2008.

3. G.J. Butterworth, Can we recycle fusion materials, Fusion Technology 21 (1992) 1994-2000.

4. T.J. Dolan and G.J. Butterworth, Vanadium recycling, Fusion Technology 26 (1994) 1014-1020.

5. G.J. Butterworth, C.B.A. Forty, A.D. Turner, A.J. Junkinson, Recycling of copper used in fusion power plants, Fusion Engineering and Design 38 (1998) 441-458.

6. E.T. Cheng, Waste management aspects of low activation materials, Fusion Engineering and Design 48 (2000) 455-465.

7. P. Rocco, M. Zucchetti, Advanced management concepts for fusion waste, Journal of Nuclear Materials 258-263 (1998) 1773-1777.

8. E.T. Cheng, P. Rocco, M. Zucchetti, Y. Seki, T. Tabara, Waste management aspects of low activation materials, Fusion Technology 34 (1998) 721-727.

9. P. Rocco, M. Zucchetti, Waste management for different fusion reactor designs, Journal of Nuclear Materials 283-287 (2000) 1473-1478.

10. D. Petti, K. McCarthy, N. Taylor, C.B.A. Forty, R.A. Forrest, Re-evaluation of the use of low activation materials in waste management strategies for fusion, Fusion Engineering and Design 51-52 (2000) 435-444.

11. L. El-Guebaly, D. Henderson, A. Abdou, P. Wilson, Clearance issues for advanced fusion power plants, Fusion Technology 39, No. 2 (2001) 986-990.

12. Y. Asaoka, K. Okano, T. Yoshida, R. Hieatari, S. Mori, Evaluation of radioactive waste generated from the compact reversed shear tokamak reactor (CREST), Fusion Technology 39, No. 2 (2001) 1018-1022.

13. M. Zucchetti, R. Forrest, C. Forty, W. Golden, P. Rocco, S. Rosanvallon, Clearance, recycling and disposal of fusion activated material, Fusion Engineering and Design 54 (2001) 635-643.

14. K. Tobita, S. Nishio, S. Konishi, S. Jitsukawa, Waste management for JAERI fusion reactors, Journal of Nuclear Materials 329-333 (2004) 1610-1614.

15. S.A.Bartenev, A. Ciampichetti, N.G. Firsin, R.A. Forrest, B.N. Kolbasov, I.B. Kvasnitskij et al., Recycling and clearance of vanadium alloys in fusion reactors, to be published in Journal of Nuclear Materials.

16. L. El-Guebaly, P. Wilson, D. Henderson, A. Varuttamaseni, Feasibility of target materials recycling as waste management alternative, Fusion Science & Technology 46, No. 3 (2004) 506-518.

17. M. Zucchetti, L. El-Guebaly, R. Forrest, T. Marshall, N. Taylor, K. Tobita, The feasibility of recycling and clearance of active materials from a fusion power plant, Journal of Nuclear Materials 367-370 (2007) 1355-1360. Available at: http://fti.neep.wisc.edu/pdf/fdm1286.pdf.

18. L. El-Guebaly, R.A. Forrest, T.D. Marshall, N.P. Taylor, K. Tobita, M. Zucchetti, Current challenges facing recycling and clearance of fusion radioactive materials, University of Wisconsin Fusion Technology Institute Report, UWFDM-1285 (2005). Available at: http://fti.neep.wisc.edu/pdf/fdm1285.pdf

19. Nuclear Regulatory Commission, Radiological assessments for clearance of materials from nuclear facilities, Washington, D.C., Main Report NUREG-1640 (2003). Available at: http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1640/

20. International Atomic Energy Agency, Application of the concepts of exclusion, exemption and clearance, IAEA Safety Standards Series, No. RS-G-1.7 (2004). Available at: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1202_web.pdf

21. L. El-Guebaly, P. Wilson, D. Paige, Evolution of clearance standards and implications for radwaste management of fusion power plants, Fusion Science & Technology 49 (2006) 62-73.

22. L. El-Guebaly, Evaluation of disposal, recycling, and clearance scenarios for managing ARIES radwaste after plant decommissioning, Nuclear Fusion 47 (2007) 485-488.

23. L. El-Guebaly, R. Pampin, M. Zucchetti, Clearance considerations for slightly-irradiated components of fusion power plants, Nuclear Fusion 47 (2007) 480-484.

24. R. Pampin, V. Massaut, N.P. Taylor, Revision of the inventory and recycling scenario of active materials in near-term PPCS models, Nuclear Fusion 47 (2007) 469-476.

25. M. Zucchetti, S.A. Bartenev, A. Ciampichetti, R. Forrest, B.N. Kolbasov, P.V. Romanov, V.N. Romanovskij, A zero-waste option: recycling and clearance of activated vanadium alloys, Nuclear Fusion 47 (2007) 477-479.

26. V. Massaut, R. Bestwick, K. Brodén, L. Di Pace, L. Ooms, R. Pampin, State of the art of fusion material recycling and remaining issues, Fusion Engineering and Design 82 (2007) 2844-2849.

27. B.J. Merrill, L. El-Guebaly, C. Martin, R.L. Moore, A.R. Raffray, D.A. Petti, Safety assessment of the ARIES compact stellarator design, to be published in Fusion Science and Technology.

28. M. Zucchetti, L. Di Pace, L. El-Guebaly, B.N. Kolbasov, V. Massaut, R. Pampin, P. Wilson, An integrated approach to the back-end of the fusion materials cycle, to be published.

29. P. Rocco, M. Zucchetti, Recycling and clearance possibilities – final report of task 4.2, SEAFP2/4.2/JRC/4 (Rev. 1), September 1998.

30. P. Rocco, M. Zucchetti, Integrated approach to recycling and clearance (more realistic management of activated materials), Final Report of the SEAFP Project, Task S5.2, UKAEA report, SEAFP99/S5.2/JRC/1 (Rev. 1) (1999).

31. R.A. Forrest, Alternative options - categorization of activated materials for PPCS plant models C and D, PPCS/UKAEA/PPCS5D2-1, UHAEA (2003).

32. R.A. Forrest, Categorization of activated materials for PPCS plant models A and B, PPCS/UKAEA/PPCS15D2-1, UHAEA (2003).

33. L. El-Guebaly, P. Wilson, and D. Paige, Initial activation assessment of ARIES compact stellarator power plant, Fusion Science & Technology 47, No. 3 (2005) 440-444.

34. K. Brodén, G. Olsson, Categorization of activated material from fusion power reactors and acceptability for final disposal, Fusion Engineering and Design 75-79 (2005) 1229-1232.

35. L. El-Guebaly, R. Pampin, and M. Zucchetti, Insights from clearance assessments of fusion power plants: ARIES and PPCS, University of Wisconsin Fusion Technology Institute Report, UWFDM-1292 (2006). Available at: http://fti.neep.wisc.edu/pdf/fdm1292.pdf

36. L.A. El-Guebaly, D.L. Henderson, P.P.H. Wilson, A.E. Abdou, Activation of target coatings/hohlraums and influence on waste management of IFE chambers, University of Wisconsin Fusion Technology Institute Report, UWFDM-1154 (2001). Available at: http://fti.neep.wisc.edu/pdf/fdm1154.pdf

37. L.A. El-Guebaly, D.L. Henderson, P.P.H. Wilson, A.E. Abdou, Target activation and radiological response of ARIES-IFE dry wall chamber, Fusion Engineering and Design 63-64 (2002) 653-658.

38. S. Reyes, J. Sanz, J. Latkowski, Use of clearance indexes to assess waste disposal issues for the HYLIFE-II inertial fusion energy power plant design, Fusion Engineering and Design 63-64 (2002) 257-261.

39. L. El-Guebaly, P. Wilson, M. Sawan, D. Henderson, A. Varuttamaseni, Recycling issues facing target and RTL materials of inertial fusion designs, Nuclear Instruments & Methods in Physics Research, Section A, 544 (2005) 104-110.

40. L. El-Guebaly, P. Wilson, M. Sawan, Activation and waste stream analysis for RTL of Z-Pinch power plant, to be published in Fusion Science and Technology.

41. P. Rocco, M. Zucchetti, ITER waste management: the recycling and clearance option, Fusion Technology 30 (1996) 1550-1555.

42. E.T. Cheng, P. Rocco, M. Zucchetti, Application of SEAFP waste recycling and clearance strategies to ITER, Fusion Engineering and Design 51-52 (2000) 485-491.

43. K. Brodén, E. Eriksson, M. Linberg, G. Olsson, Clearance and disposal of ITER radioactive waste components, Fusion Engineering and Design 58-59 (2001) 945-947.

44. A. Ciampichetti, P. Rocco, M. Zucchetti, The zero waste option: clearance of activated and first wall/blanket materials, J. Nucl. Mater. 307-311 (2002) 1047-1051.

45. M. Zucchetti, The zero-waste option for nuclear fusion reactors: advanced fuel cycles and clearance of radioactive materials, Annals of Nuclear Energy 32/14 (2005) 1584-1593.

46. L. El-Guebaly, M. Zucchetti, Recent developments in environmental aspects of D-^{3}He fuelled fusion devices, Fusion Engineering and Design 82, # 4 (2007) 351-361.

47. F. Najmabadi et al., Overview of ARIES-CS power plant study, to be published in Fusion Science and Technology.

48. L. El-Guebaly, P. Wilson, D. Henderson, M. Sawan, G. Sviatoslavsky, T. Tautges et al., Designing ARIES-CS compact radial build and nuclear system: neutronics, shielding, and activation, to be published in Fusion Science and Technology.

49. Available at: http://fti.neep.wisc.edu/aries-cs/builds/build.html.

50. The ITER Project: http://www.iter.org/a/index_nav_1.htm

51. F. Najmabadi, A. Abdou, L. Bromberg, T. Brown, V.C. Chan, M.C. Chu et al., The ARIES-AT advanced tokamak, advanced technology fusion power plant, Fusion Engineering and Design 80 (2006) 3-23.

52. D. Maisonnier, I. Cook, P. Sardain, R. Andreani, L. Di Pace, R. Forrest et al., A conceptual study of commercial fusion power plants. Final Report of the European Fusion Power Plant Conceptual Study (PPCS), Report EFDA-RP-RE-5.0 (2005).

53. S. Nishio, K. Tobita, S. Konishi, T. Ando, S. Hiroki, Tight aspect ratio tokamak power reactor with superconducting TF coils, Proc. of 19th IAEA Fusion Energy Conf., Lyon, FT/P/1-21 (2002). Available at: http://www-pub.iaea.org/MTCD/publications/PDF/csp_019c/html/node362.htm#74213

54. S. Nishio, K. Tobita, K. Tokimatsu, K. Shiniya, I. Senda, Technological and environmental prospects of low aspect ratio tokamak reactor "VECTOR", Proc. of 20th IAEA Fusion Energy Conf., Vilamoura, FT/P7-35 (2004). Available at: http://www-naweb.iaea.org/napc/physics/fec/fec2004/datasets/FT_P7-35.html

55. The ESBWR Design : http://www.gepower.com/prod_serv/products/nuclear_energy/en/new_reactors/esbwr.htm

56. The ARIES Project: http://aries.ucsd.edu/ARIES/

57. N. Taylor, E.T. Cheng, D. Petti, M. Zucchetti, Overview of international waste management activities in fusion, Fusion Technology 39 (2001) 350-356.

58. New Mexico Environmental Department, Hazardous waste facility permit - waste isolation pilot plant, EPA-NM-4890139088, Sante Fe, NM (1999).

59. Environmental Protection Agency, criteria for the certification and recertification of the waste isolation pilot plant's compliance with the disposal regulations: certification decision, Federal Register 27354-27364, 63, #95 (1998).

60. N. Zacha, Low-level waste disposal in the United States – status update, Radwaste Solutions, 10, # 3 (July/August 2003) 18-20.

61. South Carolina Department of Health and Environmental Control, Bureau of Land and Waste Management, Status of the Barnwell low-level radioactive waste disposal facility (2007). Available at: http://www.scdhec.net/lwm/pubs/barnwell_llwdf_status.pdf.

62. Nuclear Regulatory Commission, 10CFR61, Licensing requirements for land disposal of radioactive waste, Federal Register FR47 (1982) 57446.

63. S. Fetter, E. T. Cheng, F. M. Mann, Long term radioactive waste from fusion reactors: part II, Fusion Engineering and Design 13 (1990) 239-246.

64. International Atomic Energy Agency, Categorizing operational radioactive wastes, IAEA Tecdoc-1538 (April 2007).

65. P. Vankerckhoven, Radioactive waste categories - current position (1998) in the EU member states and in the Baltic and central European countries, EUR 18324 EN (1998).

66. The national fact sheets on radioactive waste management and their update, OECD/NEA document, ref. NEA/RWMC(2005)-15 (on CD-ROM) (2005).

67. S.A. Bartenev, I.B. Kvasnitskij, B.N. Kolbasov, P.V. Romanov, V.N. Romanovskij, Radiochemical reprocessing of V-Cr-Ti alloy and its feasibility study, Journal of Nuclear Materials 329-333 (2004) 406-410.

68. L. Ooms, V. Massaut, Feasibility of fusion waste recycling, SCK-CEN Report, R-4056, 276/05-01 (2005).

69. R. Klueh, E.T. Cheng, M.L. Grossbeck, E.E. Bloom, Impurity effects on reduced-activation ferritic steels developed for fusion applications, Journal of Nuclear Materials 280 (2000) 353-359.

70. P. Desbats, H. Toubon, G. Piolain, Status of development of remote technologies applied to Cogema spent fuel management facilities in France, ANS 10th International Topical Meeting on Robotics and Remote Systems for Hazardous Environments, Gainesville, Florida (March 2004).

71. R. Pampin, R.A. Forrest, R. Bestwick, Consideration of strategies, industry experience, processes and time scales for the recycling of fusion irradiated material, UKAEA report FUS-539 (2006).

72. Activists, industry barrage radioactive scrap end run, American Metal Market, 109, No. 341 (December 13, 2001).

73. D. Sandoval, Casting a nuclear shadow, Recycling Today 41, No. 12 (December 2003) 42-46.

74. U.S. Department of Energy, Environmental assessment for the slightly activated copper coil windings from the 184-inch cyclotron at Lawrence Berkeley Laboratory, Berkeley, California, DOE/EA-0851 (August 2, 1993).

75. M. Klein, J. Dadoumont, Y. Demeulemeester, V. Massaut, Experience in decommissioning activities at the BR3 site, Fusion Engineering and Design 54 (2001) 443-449.

76. W. D. Richins, T. E. Fewell, H. J. Welland, H. R. Sheely, Jr., Shielded containers for radioactive waste using recycled contaminated metals, Nuclear Engineering and Design 197 (2000) 183-195.

77. W. D. Richins, Impact and structural analysis of the INEL 30 gallon recycled shielded storage container, Idaho National Laboratory report, INEL-96/0141 (May 1996).

78. W. D. Richins, Impact and structural analysis of the INEL 55 gallon recycled shielded storage container, Idaho National Laboratory report, INEL-96/0272 (July 1996).

79. W. L. Boettinger, Beneficially reusing low level regulated waste, the Savannah River Site Stainless Steel Program, CONF-931207-1, Westinghouse Savannah River Company (1993).

80. W. L. Boettinger, G. Mishra, Stainless steel RSM beneficial reuse technical feasibility to business reality, WSRC-RP-97-292, Westinghouse Savannah River Company (1997).

81. Ten spectacular seconds, successful cooling tower implosion at Trojan reflects careful planning, Radwaste Solutions 13, No. 4 (2006) 36-38.

82. J. L. Tripp, A. M. Phillips, R. H. Meservey, S.Y. Chen, S. Kamboj, J. Arnish, Reuse of concrete within DOE from decontamination and decommissioning projects, Argonne National Laboratory report, ANL/EA/CP-102944 (September 2000).

83. S. Aggarwal, G. Charters, D. Thacker, Building material characterization using a concrete floor and wall contamination profiling technology, Proceedings of Waste Management 2003 Symposium (WM'03), Tucson, AZ (February 23-27, 2003) 69.

84. Standard guide for evaluating disposal options for concrete from nuclear facility decommissioning, ASTM E2216-02, American Society for Testing and Materials, West Conshohocken, PA (October 2002).

85. S.Y. Chen, Managing the disposition of potentially radioactive scrap metal, Health Physics, 91 (2006) 461-469.

86. J. O. Lubenau, J. G. Yusko, Radioactive materials in recycled metals, Health Physics, 68 (1995) 440-451.

87. S.Y. Chen, N. Ranek, S. Kamboj, J. Hensley, A. Wallo, Authorized release of DOE's non-real property: process and approach, Health Physics 77 (supplement 1) (1999) 40-48.

88. Lise-Lotte Spontón, Summary on the whole process and cycle of materials, Report Studsvik, N-06/229, EFDA task TW5-TSW-001/D5 (December 2006).

89. Nakajima, H., K. Hamada, K. Takano, N. Fujitsuna, Development of low carbon and boron added 22Mn-13Cr-9Ni-1Mo-0.24N steel (JK2LB) for jacket which undergoes Nb_3Sn heat treatment, IEEE Transactions on Applied Superconductivity 14 (2004) 1145-1148.

90. U.S. Nuclear Regulatory Commission, Termination of operating licenses for nuclear reactors, Regulatory Guide 1.86 (June 1974).

91. U.S. Department of Energy, Radiation protection of the public and environment, DOE Order 5400.5 (February 8, 1990, revised January 7, 1992) (change 2).

92. S.Y. Chen, Evaluation of US radiation protection standards for release of properties containing residual radionuclides, Proceedings of the 8th International Conference on Radioactive Waste Management and

Environmental Remediation (ICEM'01), Bruges, Belgium, September 30-October 4, 2001, ASME, New York (2001) 397-400.

93. Health Physics Society, Surface and volume radioactivity standards for clearance, HPS/ANSI N13.12, McLean, Virginia (1999).

94. American Society for Testing Materials, Standard guide for unrestricted disposition of bulk materials containing residual amounts of radioactivity, ASTM E1760-96 (reapproved 2003), ASTM International, West Conshohocken, PA (1996).

95. National Academy of Sciences, Disposition dilemma: controlling the release of solid materials from nuclear regulatory commission-licensed facilities, National Academy Press, Washington, DC (2002).

96. National Council on Radiation Protection, Managing potentially radioactive scrap metal, NCRP Report No. 141, Bethesda, Maryland (2002).

97. Radiation Protection RP 89; Recommended radiological protection criteria for the recycling of metals from the dismantling of nuclear installations; Recommendations of the group of experts set up under the terms of Article 31 of the Euratom Treaty, European Communities (1998).

98. Radiation Protection RP 113; Recommended radiological protection criteria for the recycling of buildings and building rubble from the dismantling of nuclear installations; Recommendations of the group of experts set up under the terms of Article 31 of the Euratom Treaty, European Communities (2000).

99. A. Deckert, S. Thierfeldt, E. Kugeler, I. Neuhaus, Radiation Protection RP 114; Definition of clearance levels for the release of radioactively contaminated buildings and building rubble; Final Report, European Communities (May 05, 1999).

100. S.F. Mobbs and M.P. Harvey, Radiation Protection RP 117; Methodology and models used to calculate individual and collective doses from the recycling of metals from the dismantling of nuclear installations, Final Report Contract No. 94-ET-009, European Communities (2000).

101. Radiation Protection RP 122, Practical use of the concept of clearance and exemption (Part I and II); Recommendations of the group of experts set up under the terms of Article 31 of the Euratom Treaty, European Communities (2000).

102. C. Küppers, Comparison of clearance criteria in different countries, 4th International Symposium, Release of Radioactive Material from Regulatory Control - Harmonisation of Clearance Levels and Release Procedures, Hamburg (March 20-22, 2006).

103. Radiation Protection RP 134, Evaluation of the application of the concepts of exemption and clearance for practices according to title III of Council Directive 96/29/Euratom of 13 May 1996 in EU Member States, Volume 1: Main Report, Issue No. 134, European Communities (2003).

104. Japan Proton Accelerator Research Complex: http://j-parc.jp/index-e.html

105. G. Ollson, L-L. Sponton, L.Ooms, Mid-long term R&D step by step plan in order to implement the recycling at the maximum extension possible, Studsvik report nr N-06/195, EFDA task TW5-TSW-001/D8a & D8b (2006).