FUSION · TECHNOLOGY · INSTITUTE · WISCONSIN

Radiological Impacts of IFE Target and RTL Recycling Option: A Comparative Study

L. El-Guebaly, P. Wilson, M. Sawan, D. Henderson,
A. Varuttamaseni and the ARIES and Z-Pinch Teams

July 2004

UWFDM-1227

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Radiological Impacts of IFE Target and RTL Recycling Option: A Comparative Study

L. El-Guebaly, P. Wilson, M. Sawan,
D. Henderson, A. Varuttamaseni and the ARIES and
Z-Pinch Teams

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

http://fti.neep.wisc.edu

July 2004

UWFDM-1227

Abstract

Designers of heavy ion (HI) and Z-pinch inertial fusion power plants have explored the potential of recycling the target and recyclable transmission line (RTL) materials as an alternate option to disposal in a geological repository. Although the physics basis of the HI and Z-pinch concepts is widely different, many of the recycling issues facing both designs are quite similar. This work represents the first time a comprehensive recycling assessment was performed on both machines with an exact pulse history. We examined two extreme irradiation approaches and assessed their impact on multi-disciplinary design requirements, such as the waste level, economics, and design complexity. The first open-cycle, once-through approach irradiates the materials a single time and then disposes of them in a repository. In the second closed-cycle recycling approach, the materials are remanufactured, spending up to 10 days outside the chamber in an on-site factory, and reused for the entire life of the plant. Our results offer two divergent conclusions on the target/RTL recycling issue. For the HI concept, target recycling is not a “must” requirement and the preferred option is the one-shot use scenario as target materials represent a small waste stream, less than 1% of the total nuclear island waste. We recommend using low-cost hohlraum materials once-through and then disposing of them instead of recycling expensive materials such as Au and Gd. On the contrary, RTL recycling is a “must” requirement for the Z-pinch concept in order to minimize the RTL inventory and enhance the economics. The RTLs meet the low level waste and recycling dose requirements with a wide margin when recycled for the entire plant life even without a cooling period. While recycling offers advantages to the Z-pinch system, it adds complexity and cost to the HI designs.

1. Introduction

One of the dominant questions the national ARIES-IFE [1] and Z-pinch [2] power plant studies set out to answer is the technical, environmental, and economic feasibility of recycling the HI targets and Z-pinch transmission lines. The choice between recycling and disposal primarily depends on the volume of the target/RTL waste relative to the nuclear island waste and the added complexity and cost of the recycling process. The irradiation history begins with inserting the target/RTL into the chamber at a design-specific repetition rate and generating x-rays of sufficient energy and intensity to indirectly heat the DT capsule to ignition and burn. After burn, the target/RTL materials get irradiated by the energetic source neutrons, then the debris is pumped out of the chamber for recycling or disposal. The main goal of the recycling approach is to lower the target/RTL inventory and minimize the waste stream at the expense of more radioactive end products and a more severe radiation environment at the target/RTL fabrication facility.

In this study, we estimated the target inventory relative to the nuclear island waste, developed a comprehensive recycling approach for selected hohlraum wall and RTL materials, explored the radiological issues of the recycled materials, evaluated the gamma dose to the sensitive recycling equipment, and compared the pros and cons of the once-through and recycling scenarios. For the latter, we examined the design configuration and the details of the fabrication process to determine the applicable steps that control the residence time outside the chamber. Table 1 highlights the key configuration parameters for the ARIES-IFE-HI and Z-pinch power plants.

This paper is organized as follows. We begin with a brief description of the ARIES-IFE and Z-pinch recycling processes. The next section compares the in-chamber radiation environment and the role of the neutron flux intensity in the activation of the hohlraum walls and RTLs. Section 5 addresses the radiological criteria that have been proposed by the ARIES team over the past decade and applied to this analysis. At the end, we summarize the results and discuss the similarities and differences.

2. ARIES-IFE Overview

The ARIES-IFE study aimed at identifying tradeoffs and design windows for laser and HI concepts rather than developing a point design [1]. Here, we were concerned with the feasibility of recycling the HI targets, in particular the hohlraum wall that represents about 60% of the target mass. The choice of the hohlraum materials is a feasibility issue under debate in the fusion community. A careful material choice for the hohlraum wall could potentially reduce the beam energy losses, offering an incentive for more economical drivers. These materials affect many aspects of the IFE systems, such as:

Table 1. Key design parameters for ARIES-IFE-HI and Z-pinch studies.

Au/Gd Hohlraum Wall or RTL Thickness	15 µm	0.635 mm
Yield	458.7 MJ	3000 MJ
Rep Rate	4 Hz	0.1 Hz
# of Units per Plant	1	12
# of Shots per FPY	126 million	38 million
Volume of Single Hohlraum Wall or RTL	0.008 cm^3	6000 cm^3
Mass of Single Hohlraum Wall or RTL	0.12 g	50 kg
Plant Lifetime	40 FPY (47 y)	40 FPY (47 y)
Availability	85%	85%

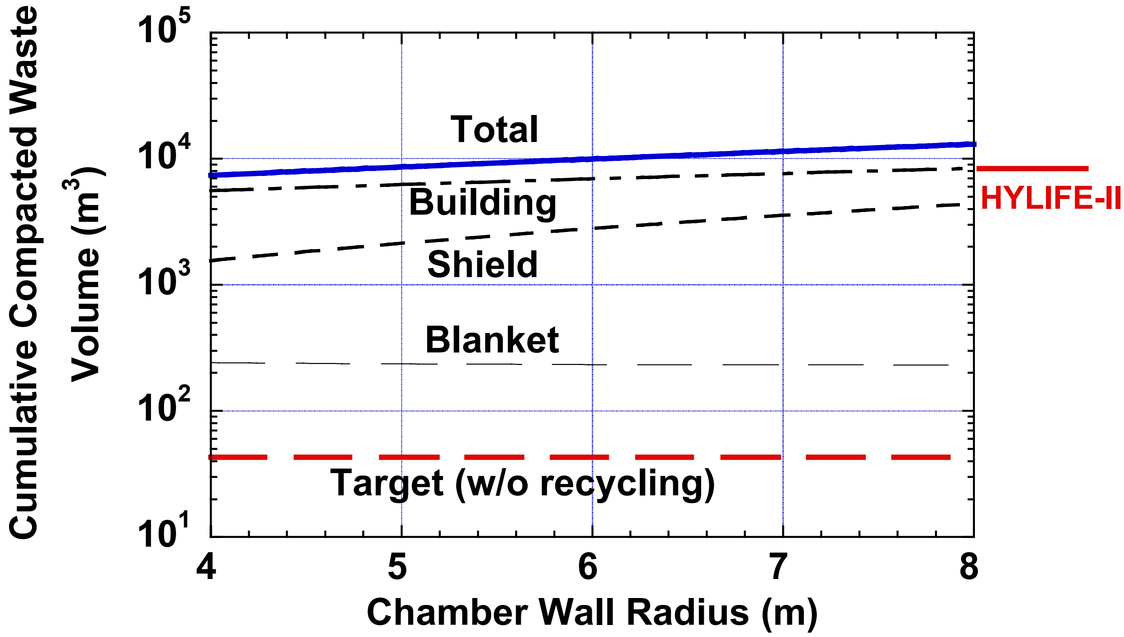

Figure 1. Inventory of HI target materials relative to other components.

– Target performance (gain, stability)
– Target fabrication (feasibility, cost, complexity)
– Target injection (strength of materials, acceleration limits)
– Liquid wall cleanup system (separability, compatibility, cost)
– Safety (radwaste inventory, toxicity, recycling, disposal, high- or low-level waste)
– Economics (unit cost, fabrication cost, driver cost)
– Design complexity (hands-on or remote handling, radioactive storage system, cooling period).

Among the wide range of candidate hohlraum wall materials (Au/Gd, Au, W, Pb, Hg, Ta, Pb/Ta/Cs/, Hg/W/Cs, Pb/Hf, Hf, solid Kr, and solid Xe), we selected three materials for this comparative study: Au/Gd (50/50 wt%), W, and Pb. The former offers the lowest driver energy [3] while W and Pb can easily be recovered from Flibe [4], a candidate breeder for the liquid-protected chamber. The reader is directed to Reference 5 for a comprehensive study of all hohlraum wall candidates. We considered the close-coupled Lawrence Livermore National Laboratory (LLNL) target [3] where the hohlraum wall is 15 micron thick and the dimensions of all other components are carefully chosen to ensure the stability of the target during burn. The targets are repetitively injected into a nearly spherical chamber at four times per second, producing thousands of megawatts of fusion power. The annual throughput of the 15 microns thick Au/Gd hohlraum wall amounts to 1.1 m^3 per full power year (FPY) or 43 m^3 for 40 FPY (15 tonnes/FPY or 600 tonnes for 40 FPY). Switching from Au/Gd to other materials, the hohlraum wall should retain an equal mass by adjusting the thickness to make up for the density changes. Variations in the reported parameters will not alter the conclusions of this study. For instance, a higher rep rate (e.g., 5-6 Hz) and/or doubling the thickness of the hohlraum wall would still represent a small radwaste stream. The cumulative waste over the 40 FPY plant life is plotted in Fig. 1 as a function of the radius of a representative thin liquid wall chamber. The HYLIFE-II thick liquid wall design [6] is marked on the figure for comparison. The target materials represent a small waste stream (< 1%) compared to the nuclear island waste. This means recycling of target materials should not be a "must" requirement for IFE-HI except for materials exhibiting cost and resource problems, such as Au and Gd. All other spent target materials could be disposed of and fresh target materials would be supplied anew without representing a waste burden to IFE-HI power plants.

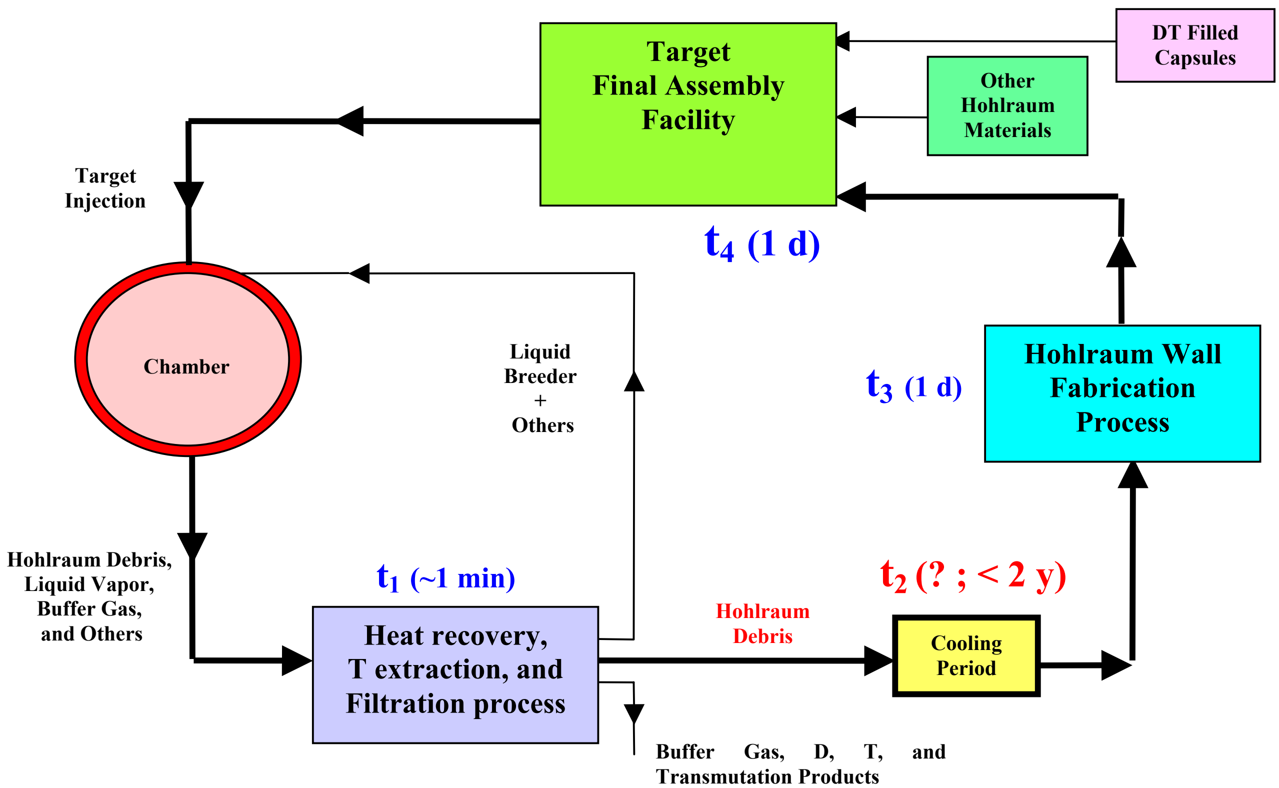

Figure 2. HI target recycling processes and proposed timeline.

It is generally accepted among the ARIES team members that the target materials should not be recycled unless recycling is imposed as a top-level program requirement for all fusion wastes. This is not the case at the present time. However, one might expect that as fusion develops and joins the commercial market in 2050, power plant designs would mandate recycling of all components, including targets, to reduce the waste volume and enhance the repository capacity. Therefore, we decided to develop a recycling approach for the target materials to understand the magnitude of the issue, highlight the economic and design impacts, and propose solutions for potential problems that may emerge during the recycling process.

The integration of the recycling process in fusion power plants and its financial impact are still to a large extent unknown. Figure 2 depicts the essential elements of the target recycling process. After each shot, the target debris is pumped out of the chamber for either disposal or recycling. A storage space for the hot, radioactive materials is needed in the target fabrication facility (TFF). The hohlraum wall materials spend approximately two days outside the chamber for re-fabrication and assembly. The main steps and processing time (quoted between parentheses) could be envisioned as:

1) Separation of hohlraum elements from liquid breeder and target debris (~ 60 s),
2) Storage of hohlraum elements for a specific cooling period (to be determined),
3) Fabrication of hohlraum wall (~one day) and other target components (DT capsules, organic and metal foams, washers, rings, etc.), and
4) Assembly of all components into a new target under a cryogenic environment (~one day).

We examined two extreme irradiation approaches and assessed their impact on multi-disciplinary design requirements, such as the waste level, economics, and design complexity. The first open-cycle, once-through approach irradiates the materials a single time and then disposes of them in a repository. In the

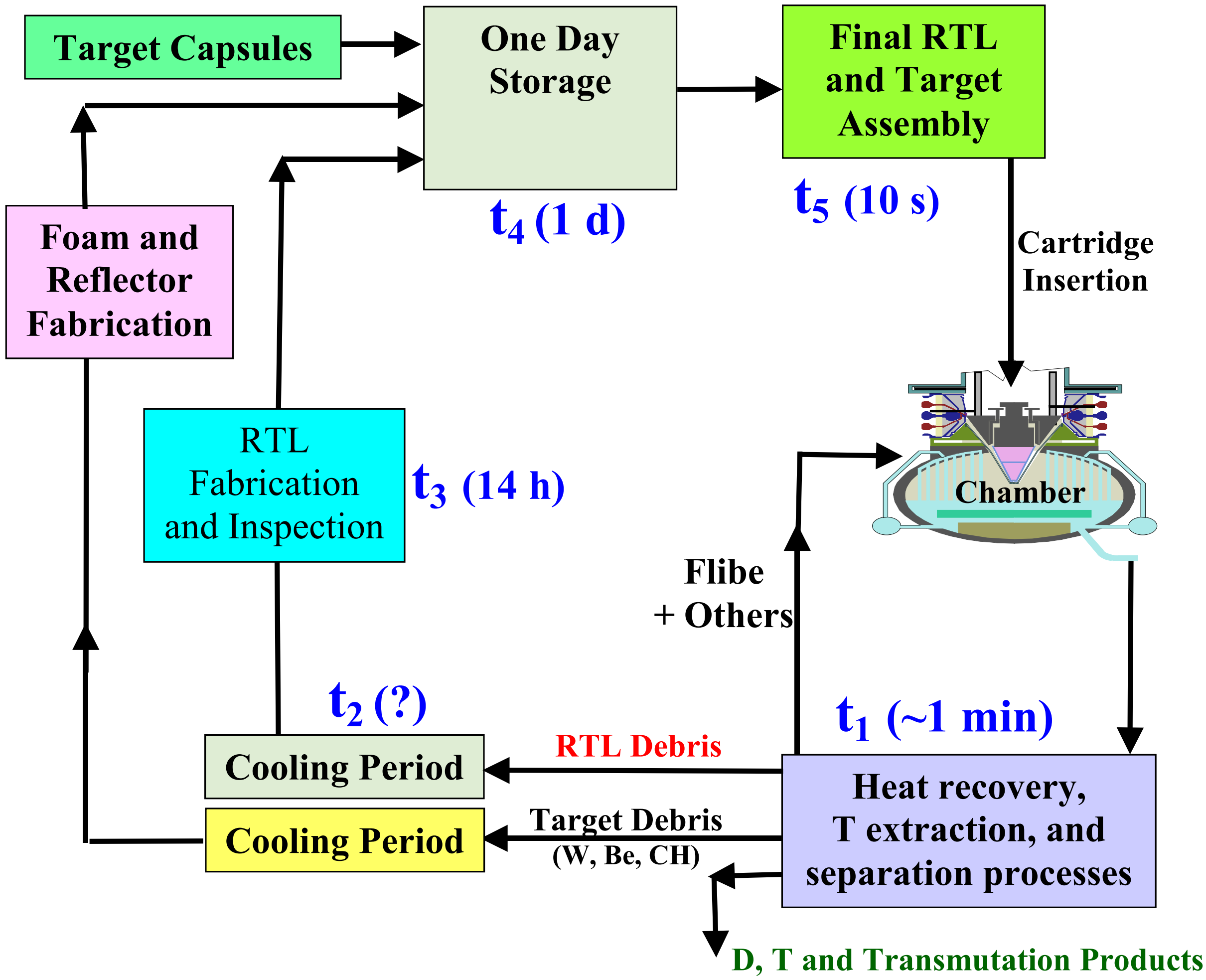

Figure 3. Flow sheet for RTL manufacturing processes and times.

second closed-cycle recycling approach, the materials are remanufactured, spending at least two days outside the chamber in an on-site factory, and reused for the entire life of the plant.

3. Z-Pinch Overview

The RTLs of the Z-pinch are worth consideration because of possible recycling advantages. The ongoing project, initiated by Sandia National Laboratory (SNL), investigates the scientific principle of a power generation system using the Z accelerator in a 1000 MW_e power plant application. The study will integrate the liquid-protected chamber, RTL recycling and manufacturing, and cartridge replacement mechanism. The present strategy is to use high yield (3 GJ per shot), a low rep rate per chamber (0.1 Hz), and a replaceable cartridge that is manufactured on-site. Since the inception of the Z-study, recycling of the RTLs has been recognized as a “must” requirement to control the radwaste stream and limit the RTL inventory to less than ten thousand tons. Equally important is the economic impact as a significant saving in materials cost has been identified.

Every 10 seconds, the RTL connects the repetitive pulsed power driver to the target, driving 50-100 MA in 150 nanoseconds. Each pulse destroys the in-chamber portion of the cartridge. Remote operation using robots to pick up the ignited cartridge and insert a new one into the chamber seems feasible. Figure 3 illustrates the basic sequence of the recycling process that is designed to operate in an automated fashion.

An online separation of the elements leaving the chamber would sort out the breeding material and target debris from the RTL shrapnel. The latter could be stored, then recycled using low technology manufacturing techniques. Prior to manufacturing, a cooling period might be needed to control the activity of the RTL debris. It is likely that the RTL fabrication and inspection processes could consume ~14 hr [7]. Parallel fabrication of the target capsules, foam, etc. is anticipated. Before insertion into the chamber, a one-day storage is required. The final assembly process must be fairly rapid and should not take more than 10 s in a cryogenic environment. On this basis, the RTL materials spend 38 hr outside the chamber. Even though the process is highly automated, personnel may still be required for some processes. Our analysis will determine the severity of the radiation environment in the RTL fabrication facility and the feasibility of personnel access.

The RTL materials affect many aspects of the design and must satisfy several requirements. They have a direct effect on:

- Economics
- Refabrication and machinability
- Structural integrity
- Joule losses
- Post shot shrapnel formation
- Disruption to Flibe jets
- Separability from liquid Flibe
- Vacuum and electrical connections to power feed
- Activation level and waste stream.

Carbon steel, mild steel, low activation ferritic steel, and pure iron have been proposed for the RTLs. Frozen Flibe has also been considered but we are using the baseline material (carbon steel) to examine the recycling issues. Carbon steel (99.51% Fe, 0.08% C, 0.32% Mn, 0.04% P, and 0.05% S) is the preferred material as it offers the lowest cost per unit mass of all forms of steel. Unlike Flibe, steel has a high electrical conductivity for a thin low-mass RTL, a property of great importance for Z-Pinch. Also, steel precipitates as solids and can be easily recovered through filtering from the liquid that protects the chamber vessel. The present RTL weighs 50 kg and operates in a 10-20 torr background chamber pressure. For a yield of 3 GJ per shot and 1000 MW electric power plant, the RTL must be manufactured at a high rate. A plant containing 12 units, each operating at 6 pulses per minute, requires 72 RTLs per minute. This means ten thousand tons of steel will be recycled every couple of days, calling for a state-of-the-art RTL manufacturing facility [2].

The RTL connects the pulsed power driver to the dynamic hohlraum (DH) that contains the cryogenic DT capsule. An essential function of the RTL is to carry the high current pulse to the DH, calling for materials with high electrical conductivity. The three elements (RTL, hohlraum, and capsule) are assembled into a cartridge that is repeatedly inserted every 10 s into a 5 m radius chamber. Figure 4 displays the conical RTL in the chamber. The liquid breeder jets and pool protect the vessel from the energetic neutrons, breed tritium, recover the fusion energy, and minimize the pressure impulse of the strong shock wave on the chamber wall. Assuming 45-50 years of planned operation with a reasonable duty cycle of 85%, approximately 40 cm thick Flibe would be needed to protect the chamber wall for 40 FPY.

Since the inception of the Z-study, recycling of the RTLs has been recognized as a "must" requirement to control the radwaste stream. We plotted the radwaste inventory with and without recycling in Fig. 5. Recycling limits the RTL inventory to less than ten thousand tons over the entire plant life. Equally important is the economic impact as a significant saving in materials cost has been identified.

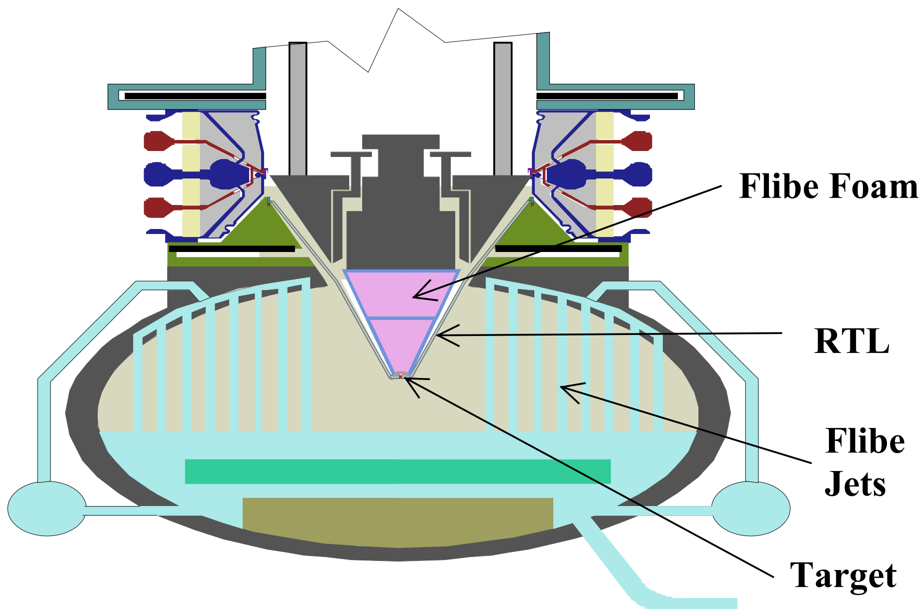

Figure 4. Z-pinch chamber and RTL connecting the target to the power supply.

4. Comparative Study

To understand the nature of the in-chamber radiation environment for the HI and Z chambers, we made a quantitative comparison between the neutron-induced activities using the same material for the hohlraum wall and RTL. We applied the physical operating parameters and the chamber arrangements of the ARIES-IFE-HI and Z-pinch studies and included the actual neutron source spectra. Pure iron has been selected for this comparison even though it does not represent a baseline material for either case. In both designs, the neutron source profile peaks at 14.1 MeV and has an average energy of 11.5-11.8 MeV. The uncollided 14.1 MeV neutrons comprise 65-70% of the total. The results plotted in Fig. 6 suggest that the hohlraum wall activity exceeds the RTLs by far due primarily to the higher rep rate and the more intense, harder neutron flux at the hohlraum wall (~2 x 10^{20} n/cm^{2}s). Figure 7 illustrates the differences in the flux level. The lower activity translates into lower waste disposal rating, recycling dose, and clearance index for the RTLs.

The activation results reported herein were computed using the ALARA pulsed activation code [8] and the FENDL-2 175 neutron group transmutation cross-section library. The neutron flux was calculated with the DANTSYS [9] discrete ordinates transport code with the FENDL-2 175 neutron 42-gamma group coupled cross section library. The activation model assumes the irradiation process continues for the entire plant life (~50 y) with 85% availability. The ALARA code models all pulses (~10,000) and explicitly includes the effect of the 85% availability. For the recycling dose, we adopted the FISPACT methodology [10] based on the contact gamma dose rate. It is an approximate but conservative method that evaluates the decay gamma dose at the surface of an unshielded semi-infinite slab using material-specific attenuation coefficients.

5. Design Criteria

5.1 Waste Disposal Rating

There are two categories of materials that are candidates for disposal according to the radiological criteria: high-level waste (HLW) and low-level waste (LLW). In both cases, the limits are set by the waste disposal rating (WDR) defined as the sum of the ratios of the specific activity for each radionuclide to its limit

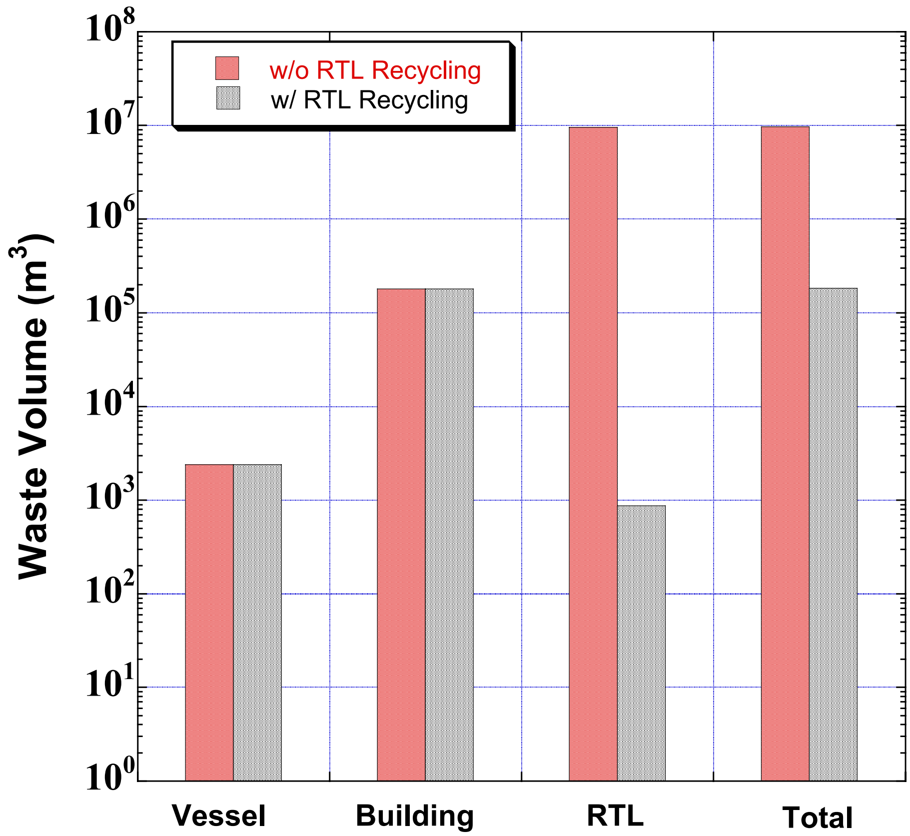

Figure 5. Comparison of RTL inventory to nuclear island waste inventory.

evaluated by either Fetter [11] or the Nuclear Regulatory Commission (NRC) [12]. A computed volumetric average WDR ≤ 1 at the end of the 100-year institutional control period at the disposal site means the component qualifies for shallow land burial as LLW. A WDR > 1 means the component is HLW requiring deep geological burial. The ARIES approach requires all components to meet both NRC and Fetter's limits until the NRC develops official guidelines for fusion waste. We take the following approach to report the WDR: we evaluate the WDR at 100 y after shutdown based on both Fetter's and NRC limits and report the highest value. A WDR ≤ 1 means LLW and WDR > 1 means HLW.

5.2 Recycling Dose

Hands-on recycling is permitted for materials that can be handled by workers without restrictions for any kind of recycling operations. The limit has generally been assumed to be 10 μSv/hr. A factor of ten lower limit should be considered by designers in consideration of the "As Low As Reasonably Achievable" principle, meaning a limit of 1 μSv/hr for hands-on recycling.

Radiation degrades optical, electric, mechanical, and physical properties of sensitive elements. Routine remote-handling operations of fission waste are done in a gamma dose rate of 3000 Sv/hr. A recycling study is currently underway at Culham to better understand what is feasible for fusion materials recycling from all aspects, not only radiological [13]. We recommend the 3000 Sv/hr limit for advanced remote recycling equipment, recognizing that the old 10 mSv/hr value is arbitrary and very conservative.

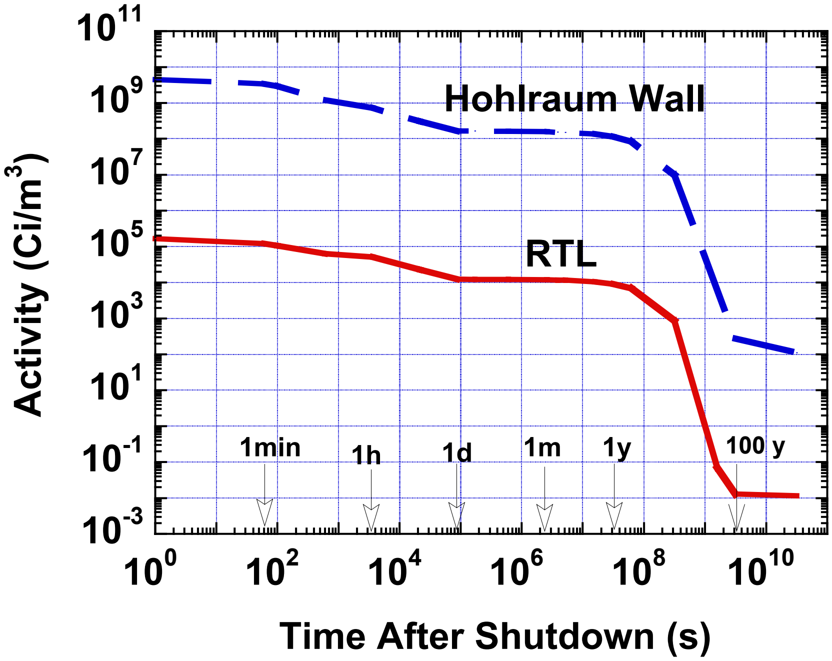

Figure 6. Comparison of activities of hohlraum wall and RTL made out of pure iron.

5.3 Clearance Index

Clearance is the unconditional release of materials from radiologically controlled areas to the commercial market at the end of an interim storage period of 100 years or less. By definition, the clearance index (CI) is the ratio of the activity (in Bq/kg) to the allowable limit summed over all radioisotopes. Currently, a commercial market for reusing slightly contaminated materials does not exist in the US. It is possible that the national policy will change in the future and therefore we decided to monitor the clearance level for the ARIES-IFE and Z-pinch designs. In conjunction with various international organizations, the International Atomic Energy Agency (IAEA) has developed clearance standards for 1650 radioisotopes of interest to nuclear applications [14]. After plant decommissioning, individual materials that are slightly radioactive could be stored for 50-100 years, and be released to the commercial market if the CI falls below one.

6. Results and General Remarks

6.1 Hohlraum Wall Materials of HI-IFE Targets

We utilized the cooling period (defined as the storage time between consecutive shots) to control the WDR and recycling dose for the highly pure Au/Gd, W, and Pb materials. Note that the longer the cooling period, the shorter the irradiation time, and the lower the activation. Cooling periods ranging between a few days and one year were considered for most materials presented here. This wide range meets our goal of a factor of ten or more reduction in the inventory [5]. The WDR and CI are summarized in Table 2 for both one-shot use and recycling scenarios. The once-through irradiation slightly activates the various materials and generates only low-level waste. The Class C limit (WDR < 1) is met by a wide margin to the extent that all materials can easily qualify for the Class A near-surface, shallow land burial (WDR < 0.1). However, none of the materials can be cleared or released to the commercial market after a single shot even at the end of the 100 y storage period (CI > 1).

For the recycling scenario, W generates LLW while Au/Gd and Pb generate HLW in the absence of a cooling period. The analysis assumes continuous recycling during the plant life without transmutation

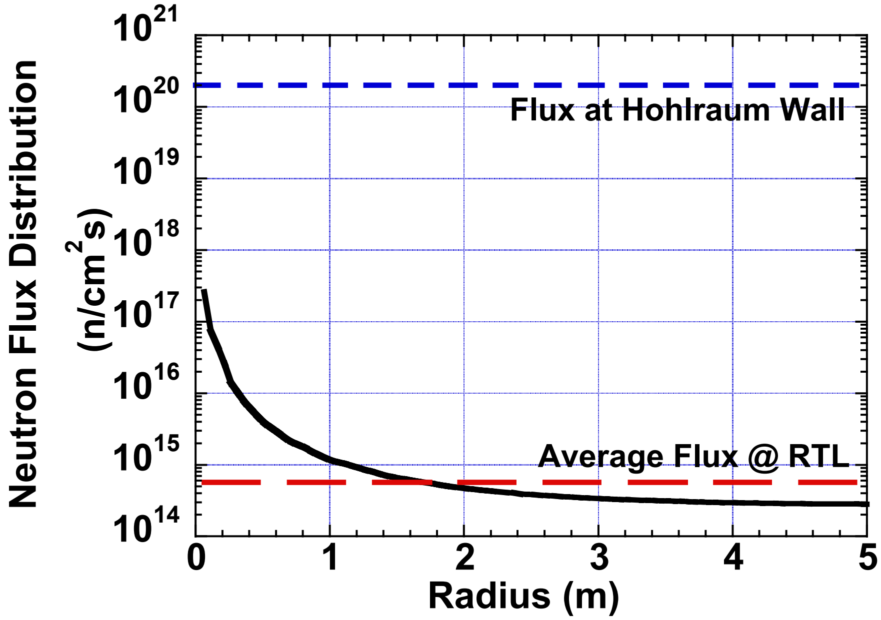

Figure 7. Radial distribution of the neutron flux in the 5 m Z-pinch chamber. The flux at the HI hohlraum wall is shown for comparison.

product removal. Figures 8 and 9 illustrate the evolution of the WDR over the course of plant operational life. As expected, extending the exposure time increases the WDR. Au/Gd generates HLW and the WDR does not drop below one even with a long cooling period of two years. The variation of the recycling dose with cooling period is plotted in Fig. 10, showing a strong material dependence. Only Pb can meet the hands-on limit (1 μSv/hr) with an extended cooling period of two years. Advanced remote handling equipment could recycle the Au/Gd and W providing that hohlraum debris can be stored for up to 10 days before fabrication. In Table 3, we give the recommended cooling period that satisfies both WDR and dose criteria and the main contributing radionuclides. When cooled for 1-10 days, Pb and W meet the waste and dose requirements. In this case, the cumulative waste is less than 0.1 m^3. Online removal of the highly radioactive elements will certainly shorten the cooling period but hands-on fabrication may still not be feasible.

One would expect the cost of fabrication of the hohlraum walls and the highly precise assembly processes using remote handling equipment to be very high. For the once-through scenario, a 41 cents fabrication cost per target has been estimated [4], representing ~10 mills/kWh out of the ~70 mills/kWh cost of electricity (COE). The Au/Gd materials require an additional annual supply of $80M/y with an increment of ~3

Table 2. WDR and CI of hohlraum wall materials for one-shot use and recycling scenarios.

	One-Shot Use Scenario		Recycling Scenario
	WDR	CI	WDR*
Gold/Gadolinium	2×10^{-8}	42	3×10^{5}
Tungsten	2×10^{-6}	14.9	0.6
Lead	2×10^{-5}	5.6	31

* No cooling period. No transmutation product removal.

Table 3. Recommended cooling period for hohlraum wall materials (main contributors shown in parentheses in descending order).

	Cooling Period for WDR < 1	Cooling Period for Dose < 3000 Sv/h	Recommended Cooling Period
Gold/Gadolinium	> 2 y* (^{158}Tb)	9.5 d (^{196}Au)	—*
Tungsten	0 (^{186m}Re, ^{178n}Hf)	6.2 d (^{184}Re)	6.2 d
Lead	13 d (^{208}Bi, ^{202}Pb)	< 1 d (^{203}Pb, ^{202}Tl)	13 d

* Insignificant inventory reduction for cooling period exceeding 2 y [5].

mills/kWh to the COE. Less expensive materials, such as W and Pb, have a negligible incremental change to the COE. Recycling would eliminate the incremental change of the materials cost to the COE but adds the cost of remote handling equipment and operations that offsets the savings in materials cost. Some preliminary estimates have suggested raising the target cost from \$0.41 to \$3.15 [4] and the corresponding change to the COE from 10 to 72 mills/kWh just to cover the cost of recycling the hohlraum wall materials. Clearly, doubling the COE to recycle materials that have no waste problems is totally unacceptable. The target manufacturers prefer dealing with non-radioactive materials to speed up the process, lower the fabrication cost, and reduce the complexity.

6.2 RTLs of Z-Pinch

The less intense neutron flux and softer spectrum at the RTL compared to the HI target (refer to Section 4) result in much less activity, WDR, CI, and recycling dose. Our results show that at the end of the projected plant life (40 FPY), the carbon steel of the RTLs qualifies as Class A low level waste, can be cleared from regulatory control at the end of 50 y storage period, and meets the 3000 Sv/hr RH limit for advanced recycling equipment even in the absence of a cooling period and without the removal of the transmutation products. The Class C and Class A WDRs are extremely low (10^{-7} and 10^{-3}, respectively) immediately after shutdown and drop by a factor of a few at 100 y. The CI reaches the limit of one at 50 y after shutdown. The recycling dose peaks at 160 Sv/hr at shutdown and drops to ~1 Sv/hr after one day. The dominant radionuclides for the dose are Mn^{56} from Fe^{56}, B^{13} from C^{12}, Al^{28} from P^{31}, and Mn^{58} from Fe^{58}. The dose exceeds the 1 μSv/hr hands-on limit by several orders of magnitude, meaning the entire recycling process should be done remotely with no personnel access to the RTL fabrication facility. The results are conservative as no credit is given to the removal of the slag that may contain some of the transmutation products.

Figures 11 and 12 illustrate the variation of CI and dose with time after operation. The results are conservative as no credit is given to the removal of the slag that may contain some of the transmutation products. Note the rapid drop in the CI on a time scale of a century. A CI < 1 means the RTL carbon steel contains traces of radioactive elements and represents no risk to the public health and safety. On this basis, the ~10,000 tons RTL radwaste can be cleared after 50 y and released to the nuclear industry or commercial market for reuse. This release saves a substantial disposal cost for such a large quantity, freeing ample space in the repositories for other higher-level wastes.

Continual removal of the transmutation products during recycling would allow the RTL waste to meet the radiological limits with a wide margin, but generate a small amount of highly radioactive waste that violates the power plant top-level waste requirement developed by the ARIES team. Since the end products pose no radiological hazards and satisfy the remote recycling criteria, it is recommended not to remove the transmutation products to simplify the recycling process and reduce its cost. However, the transmutation

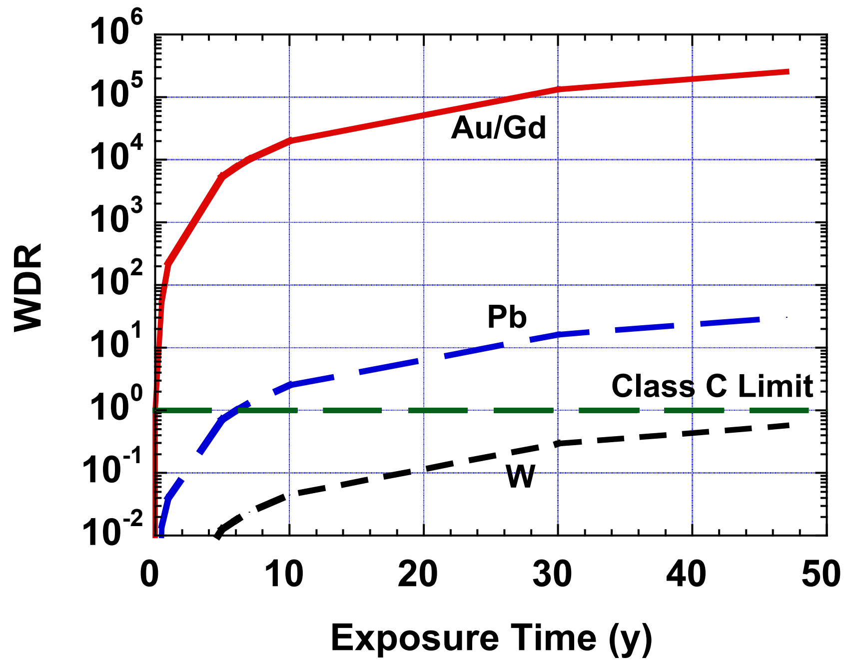

Figure 8. Increase of waste disposal rating of hohlraum wall materials with irradiation time for no cooling period and without transmutation product removal.

products could degrade the electrical property of the carbon steel. So, future studies should address the buildup of the transmutation products with time and monitor the changes in the electrical conductivity of the RTLs during plant operation.

7. Conclusions

The main justification for the recycling approach has been to improve the prospects for dealing with a large volume of fusion waste and the potential economic benefits of reusing materials that exhibit cost and resource problems, such as Au and Gd. The methodology discussed in this paper provides a simple means to estimate the recycling requirements for IFE fusion systems. If a specific component generates a substantial radwaste stream over the life cycle of the plant, recycling will improve the economy and offset the additional cost and complexity of the remote handling process.

Recycling the hohlraum wall materials of the HI targets will double the cost of electricity. Our preferred option is the one-shot use scenario as it satisfies the design requirements and has a positive impact on the radwaste level, economics, and design simplicity. The hohlraum walls represent a small waste stream for IFE-HI power plants, less than 1% of the total nuclear island waste. This means recycling is not a "must" requirement for IFE-HI. We recommend using low-cost materials once-through and then dispose of them instead of using materials with cost and resource problems such as Au and Gd. The one-shot use scenario offers attractive safety features, a radiation-free hohlraum fabrication facility, a less complex design, and lowest COE. The HI target factory designers would prefer dealing with non-radioactive hohlraum wall materials and this assessment supports the feasibility of a no-recycling approach.

Aside from the economic benefits, the high RTL inventory of the Z-pinch mandates recycling to minimize the radwaste stream. The RTL carbon steel will be slightly activated, containing traces of radioactive elements after recycling for the entire plant life without the removal of the transmutation products. The RTL waste management options include disposal in repositories as Class A low-level waste after plant

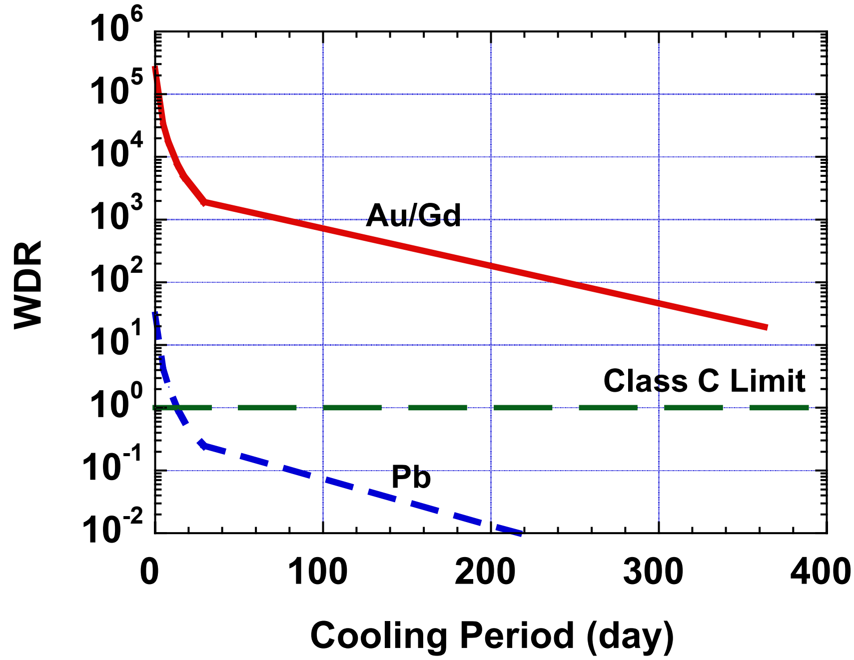

Figure 9. Effect of cooling period on waste disposal rating of hohlraum wall materials assuming continuous recycling over plant life without transmutation product removal.

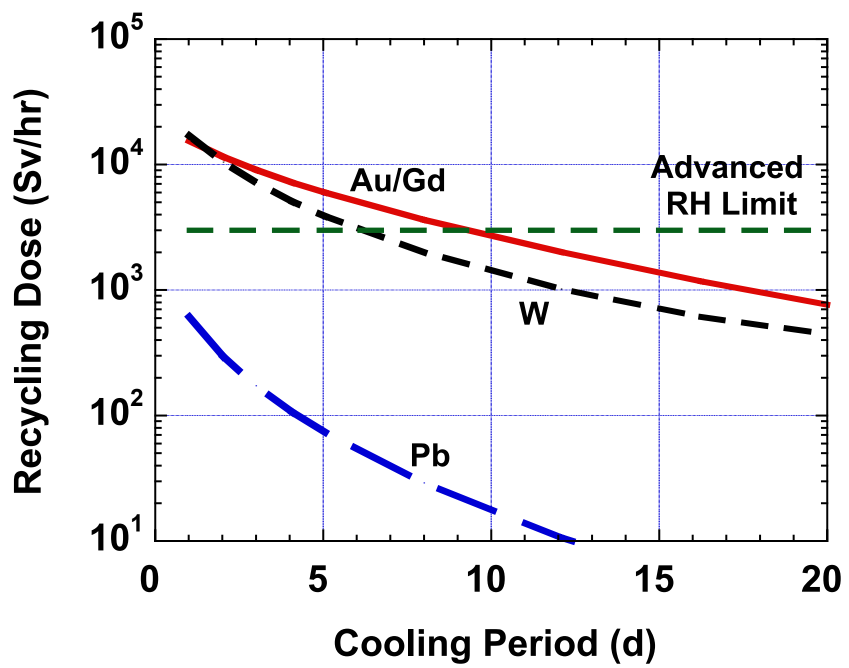

Figure 10. Effect of cooling period on recycling dose of hohlraum wall materials assuming continuous recycling over plant life without transmutation product removal.

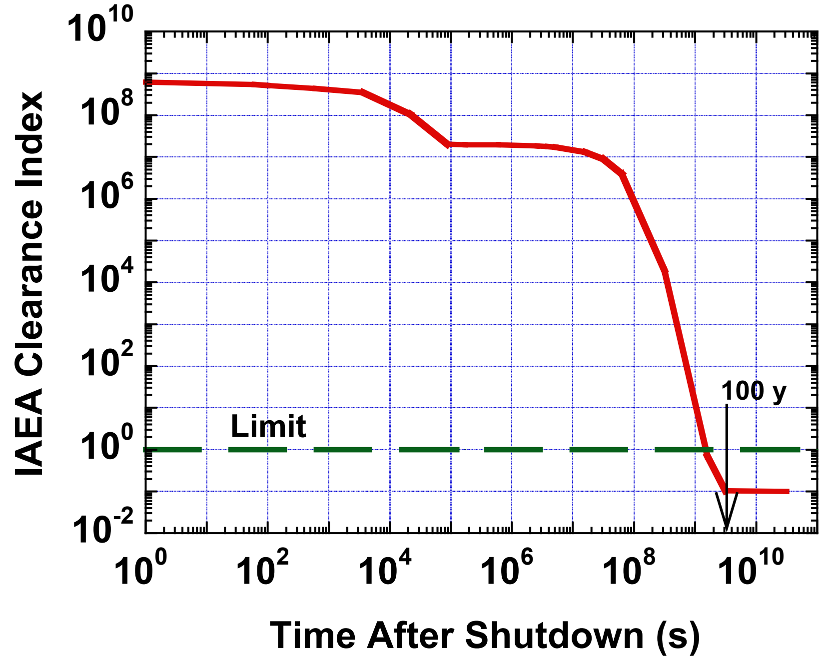

Figure 11. Variation of RTL clearance index with time after shutdown for no cooling period and without transmutation product removal.

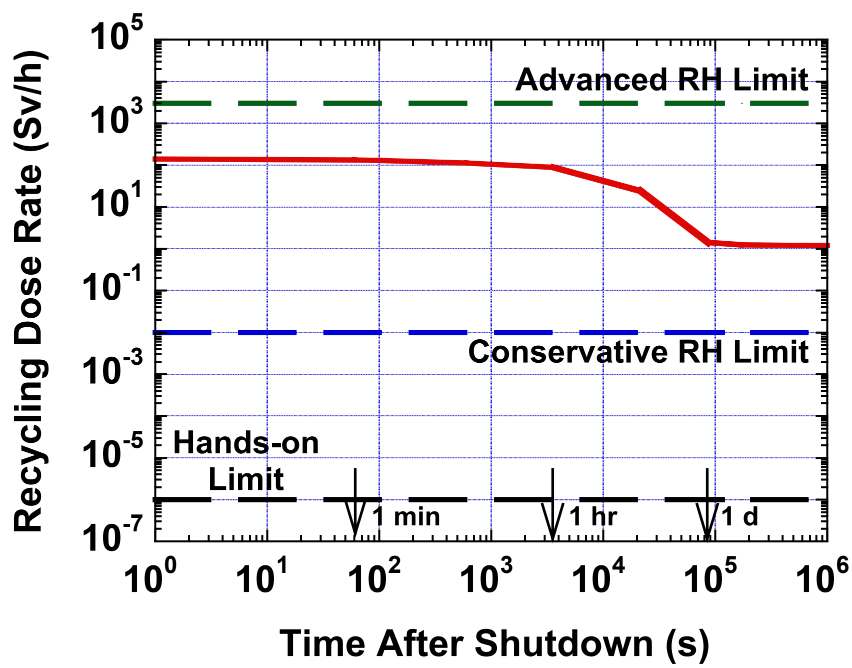

Figure 12. Reduction of dose with time after shutdown for no cooling period and without transmutation product removal.

decommissioning or, preferably, release to the nuclear industry after an interim storage period of 50 y. These conclusions are positive about the usefulness of recycling under certain conditions:

1) Advanced remote handling equipment should be developed to handle 200 Sv/hr,
2) The recycling process must be accomplished remotely in 1.5-day, and
3) The process must be economically feasible with no hands-on manufacturing and in the absence of personnel access.

The incremental cost associated with the RTL recycling scheme, the degradation of the RTL electrical conductivity due to neutron-induced transmutation products, and the timeline of the remanufacturing process using robotic or similar technology need to be investigated during the course of the Z-pinch power plant study.

Acknowledgement

The work was performed under the auspices of the US Department of Energy (contract # DE-FG02-98ER 54462) and Sandia National Laboratory (contract # 297000). The authors wish to thank I. Sviatoslavsky, G. Kulcinski, J. Santarius (UW), C. Olson, G. Rochau, C. Morrow (SNL), A. Nobile, A. Schwendt (LANL), D. Goodin, R. Petzoldt (GA), P. Peterson (UCB), and N. Taylor (UKAEA-England) for the helpful discussions and useful comments in preparing this manuscript.

References

[1] F. Najmabadi, ARIES-IFE assessment of operational windows for IFE power plants, to be published in Fusion Science & Technology.

[2] C. Olson, Progress on Z-Pinch IFE and HIF target work on Z, to be published in Nuclear Instruments and Methods in Physics Research.

[3] D. Callahan-Miller and M. Tabak, Progress in target physics and design for heavy ion fusion, Physics of Plasmas, 7, # 5 (2000) 2083.

[4] D. Goodin, A. Nobile, N. Alexander et al., Progress in heavy ion driven target fabrication and injection, to be published in Nuclear Instruments and Methods in Physics Research.

[5] L. El-Guebaly, P. Wilson, D. Henderson, and A. Varuttamaseni, Feasibility of target materials recycling as waste management alternative, to be published in Fusion Science & Technology.

[6] R.W. Moir et al., "HYLIFE-II: A Molten-Salt Inertial Fusion Energy Power Plant Design-Final Report," Fusion Technology, 25 (1994) 5.

[7] C. Morrow, Sandia National Laboratory, private communications (May 2003).

[8] P. Wilson and D. Henderson, ALARA: analytic and laplacian adaptive radioactivity analysis code technical manual, University of Wisconsin Fusion Technology Institute, UWFDM-1070 (1998).

[9] DANTSYS: A diffusion accelerated neutral particle transport code system, Los Alamos National Laboratory Report, LA-12969-M (1995).

[10] R. Forrest and J-Ch. Sublet, FISPACT 99: User Manual, United Kingdom Atomic Energy Authority, UKAEA-FUS-407 (1998).

[11] S. Fetter, E. T. Cheng, and F. M. Mann, Long term radioactive waste from fusion reactors: Part II, Fusion Engineering and Design, 13 (1990) 239.

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

[13] N. Taylor, Culham Science Centre, UK, private communications (January 2002).

[14] IAEA, Clearance levels for radionuclides in solid materials – application of exemption principles, International Atomic Energy Agency, IAEA-TECDOC-855 (1996).