Recycling issues facing target and RTL materials of inertial fusion designs

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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. This work represents the first time a comprehensive recycling assessment was performed on both machines with an exact pulse history. Our results offer two divergent conclusions on the 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.

Keywords: recycling, recyclable transmission lines, inertial fusion, target activation, Z-pinch, hohlraum materials.

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. Table 1 highlights the key configuration parameters for the ARIES-IFE-HI and Z-pinch power plants. 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.

This paper is organized as follows. We begin with a brief description of the ARIES-IFE and Z-pinch recycling processes. The next section addresses the radiological criteria that have been proposed by the ARIES team and applied to this analysis. At the end, we summarize the results and discuss the similarities and differences.

2. ARIES-IFE Overview

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. 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 highly pure materials for this study: Au/Gd (50/50 wt%), W, and Pb. The former offers the lowest driver energy [3] while W and Pb can be easily 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. The annual throughput of the 15 micron thick Au/Gd hohlraum wall amounts to 1.1 m^3 per full power year (FPY) or 43 m^3 for 40 FPY. 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.

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. Reference 5 identifies the essential elements of the recycling process. 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 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), 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.

Reference 6 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 RTL manufacturing process developed by SNL [6] indicates the RTL fabrication and inspection processes could consume ~14 hr. Parallel fabrication of the target capsules, foam, etc. is anticipated. Before insertion into the chamber, a one-day storage is required [6]. The final assembly process is 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 [7]. Our analysis will determine the severity of the radiation environment in the RTL fabrication facility and the feasibility of personnel access.

Carbon steel, mild steel, low activation ferritic steel, and pure iron have been proposed for the RTLs. 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. For a yield of 3 GJ per shot and a 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 ~10,000 tons of steel will be recycled every couple of days, calling for a state-of-the-art RTL manufacturing facility [2].

4. Design Criteria and Codes

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). We report the highest Class C waste disposal rating (WDR) at 100 y after shutdown. A WDR $\leq$ 1 means LLW that qualifies for a shallow land burial and WDR > 1 means HLW that qualifies for a deep geological burial.

For the recycling dose, we adopted an approximate but conservative method based on the contact gamma dose rate. Hands-on recycling is permitted for materials that exhibit a recycling dose of 10 μSv/hr or less. 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. We recommend the 3000 Sv/hr limit for advanced remote recycling equipment [7], recognizing that the old 10 mSv/hr value is arbitrary and very conservative.

Clearance is the unconditional release of materials from radiologically controlled areas to the commercial market at the end of an interim storage period. After plant decommissioning, individual materials could be stored for 50-100 years, and be released to the commercial market if the clearance index (CI) falls below one.

For more elaborate discussion of the design criteria, the reader is referred to References 5 and 7 and the references therein. The results reported herein were computed using the ALARA pulsed activation code [8] and DANTSYS [9] discrete ordinates transport code with the FENDL-2 175 neutron 42-gamma group coupled cross section library. The ALARA code models all pulses (~10,000) and explicitly includes the effect of the projected 85% availability.

5. Results and General Remarks

5.1 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 cumulative 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, generating 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 product removal. Figure 1 shows the drop of WDR with cooling period. 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. 2, 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 ~70 mills/kWh cost of electricity (COE). The Au/Gd materials require an additional annual supply of $80M/y with an increment of ~3 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.

5.2 RTLs of Z-Pinch

The less intense neutron flux and softer spectrum at the RTL compared to the HI target [7] 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 very 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.

As Fig. 3 illustrates, the CI reaches the limit of one at 50 y after shutdown. 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.

The recycling dose peaks at 160 Sv/hr at shutdown and drops to ~1 Sv/hr after one day (refer to Fig. 4). The dominant radionuclides for the dose at shutdown are Mn^{56} from Fe^{56}, B^{13} from C^{12}, Al^{28} from P^{31}, and Mn^{58} from Fe^{58}. At one day following shutdown, Mn^{54} is the dominant radionulide. 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. Online removal of the nasty elements for dose could allow hands-on recycling unless these elements are difficult to separate because their chemical properties are very similar to the original materials of carbon steel.

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 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.

6. 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 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 to the RTL fabrication facility.

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.

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References

[1] F. Najmabadi, ARIES-IFE assessment of operational windows for IFE power plants, to be pubilshed.

[2] C. Olson, Progress on Z-Pinch IFE and HIF target work on Z, this issue.

[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, this issue.

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

[7] L. El-Guebaly, P. Wilson, M. Sawan, D. Henderson, and A. Varuttamaseni, Radiological impacts of IFE target and RTL recycling option: a comparative study, University of Wisconsin Fusion Technology Institute, UWFDM-1227 (2004).

[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).

Figure Captions

1) Effect of cooling period on waste disposal rating of hohlraum wall materials assuming continuous recycling over plant life without transmutation product removal.
2) Effect of cooling period on recycling dose of hohlraum wall materials assuming continuous recycling over plant life without transmutation product removal.
3) Variation of RTL clearance index with time after shutdown for no cooling period and without transmutation product removal, using the International Atomic Energy Agency (IAEA) clearance limits.
4) Reduction of dose with time after shutdown for no cooling period and without transmutation product removal.

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

	ARIES-IFE-HI	Z-Pinch
Au/Gd Hohlraum Wall or RTL Thickness	15 μm	0.635 mm
Target 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	0.1 g	50 kg
Plant Lifetime	40 FPY (47 y)	40 FPY (47 y)
Availability	85%	85%

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

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

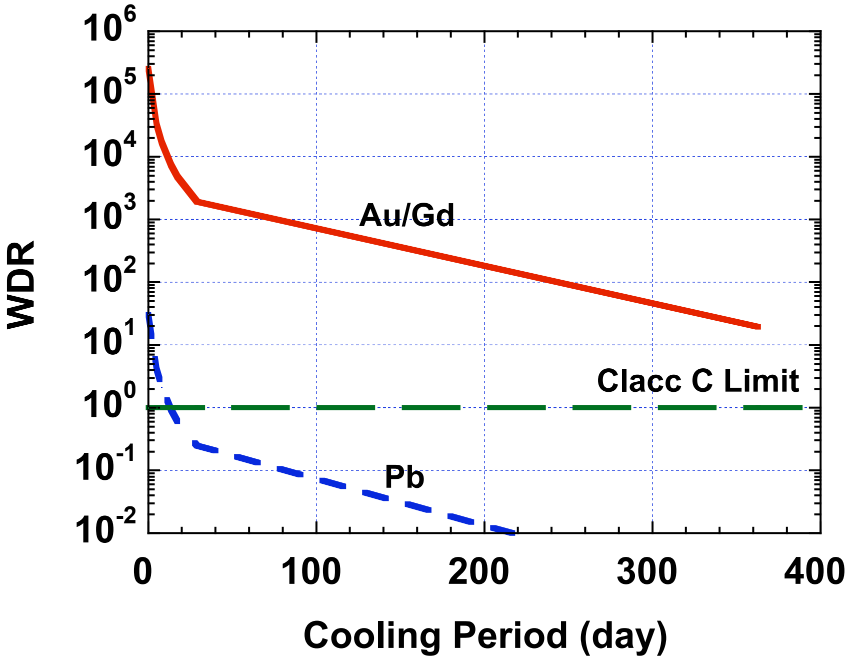
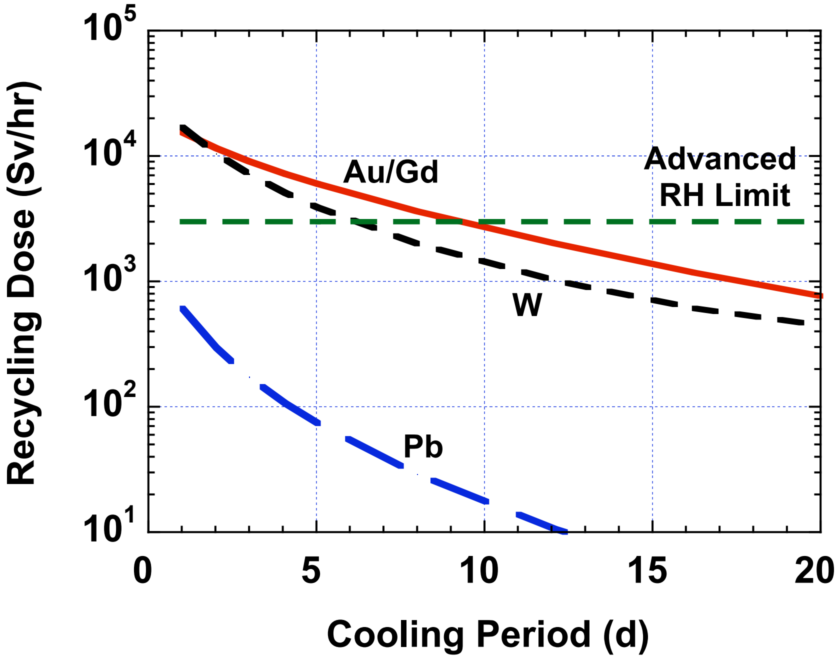
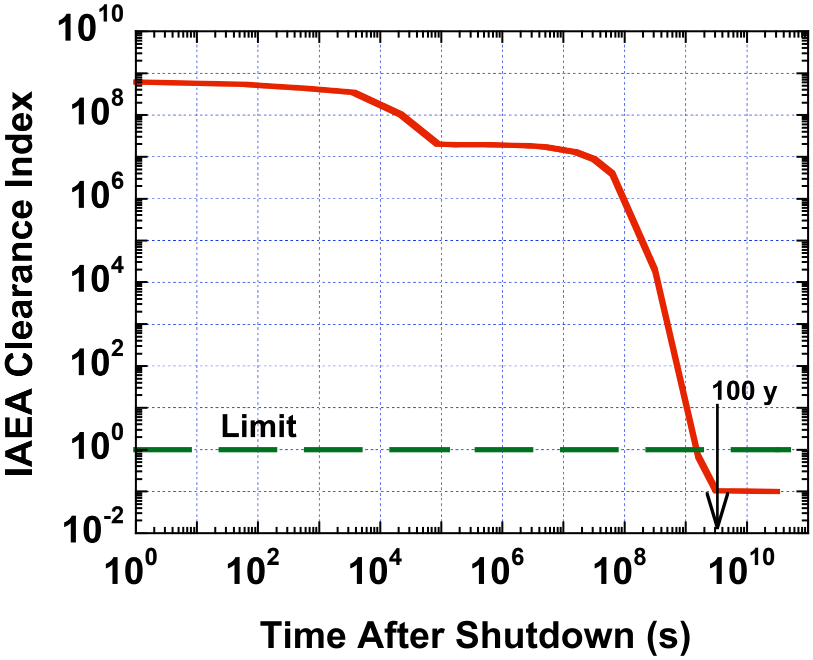

10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
WDR
Au/Gd
Clacc C Limit
Pb
0
100
200
300
400
Cooling Period (day)

Figure 1



10^5
10^4
10^3
10^2
10^1
Recycling Dose (Sv/hr)
Au/Gd
Advanced RH Limit
W
Pb
0
5
10
15
20
Cooling Period (d)

Figure 2



10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
IAEA Clearance Index
Limit
100 y
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
Time After Shutdown (s)

Figure 3

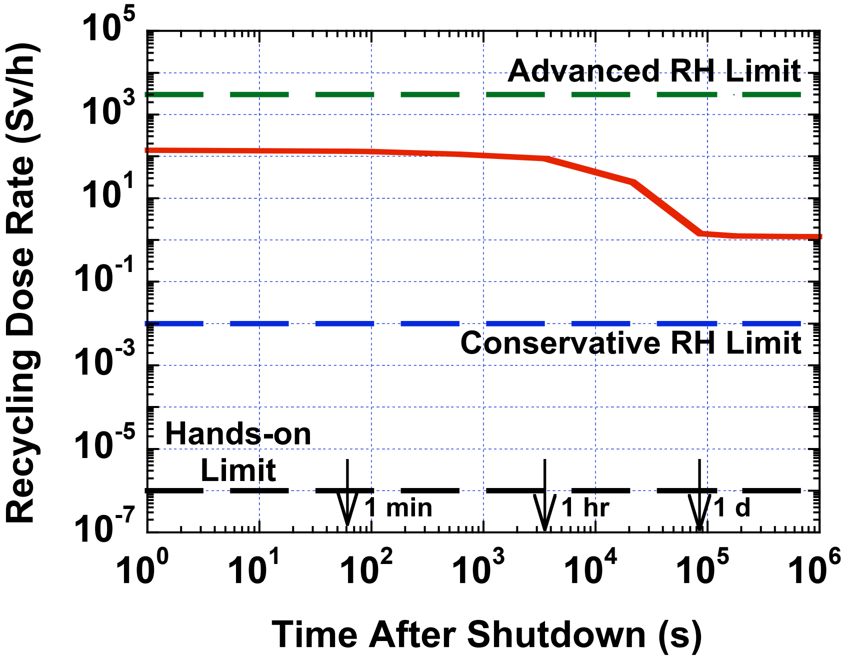

Recycling Dose Rate (Sv/h)
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
Advanced RH Limit
Conservative RH Limit
Hands-on
Limit
1 min
1 hr
1 d
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Time After Shutdown (s)

Figure 4