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L. El-Guebaly, P. Wilson, D. Henderson, A. Varuttamaseni, and the ARIES Team

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

http://fti.neep.wisc.edu

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ABSTRACT

The issue of waste management has been studied simultaneously along with the development of the ARIES heavy ion driven inertial fusion energy (IFE) concept. Options for waste management include disposal in repositories, recycling, or clearance from regulatory control, following a reasonable cooling period. Here, we are concerned with the feasibility of recycling the heavy ion beam targets, in particular the hohlraum wall materials that include, for example, Au/Gd, Au, W, Pb, Hg, Ta, Pb/Ta/Cs/, Hg/W/Cs, Pb/Hf, Hf, solid Kr, and solid Xe. The choice between target material disposal and recycling depends on the amount of waste generated relative to the nuclear island, strategy to solve the recycling problem, and the impact of the additional cost and complexity of the recycling process on the overall machine. A detailed flow diagram for the elements of the recycling process was developed to analyze two extreme activation cases: (1) one-shot use, then disposal in a repository and (2) recycling continuously during plant life without removal of transmutation products. Metrics for comparing the two scenarios included waste level, dose to recycling equipment, additional cost, and design complexity. Comparing the two approaches indicated a preference for the one-shot scenario as it generates one cubic meter per year of extremely low-level waste (Class A) and offers attractive design and economic features. Recycling reduces the target waste stream by a factor of 10 or more, but introduces additional issues. It may produce high-level waste, requires remote handling, adds radioactive storage facilities, and increases the cost and complexity of the plant. The inventory analysis indicated that the heavy ion beam (HIB) target materials represent a very small waste stream compared to that of the nuclear island (less than 1% of the total waste). This means recycling is not a "must" requirement for IFE-HIB power plants unless the target materials have cost and/or resource problems (e.g., Au and Gd). In this case, the additional cost and complexity of the recycling process should be factored in the economics of IFE power plants.

I. INTRODUCTION

The indirect drive targets with heavy ion drivers belong to a class of devices known as the IFE plants where multiple beams focus on the deuterium-tritium (DT) targets that are repetitively injected into a nearly spherical chamber at 4-6 times per second. Such IFE devices may some day be capable of maintaining high performance and producing up to thousands of megawatts of electric power. The low-density foam inside the ultrathin hohlraum wall surrounding the DT capsule absorbs the ion beam energy and emits intense x-rays that compress the DT capsule, causing fusion to occur. It is widely recognized that liquid walls provide an attractive solution to the challenging material issues facing HIB applications. Thin or thick liquid walls could protect the solid walls against the highly energetic target x-rays and debris and therefore improve the reliability of the structural components. For this study, we considered the close-coupled Lawrence Livermore National Laboratory (LLNL) target (1) shown in Fig. 1 for the baseline design. The capsule diameter is ~5 mm and all dimensions are carefully chosen to ensure the stability of the target during burn. The hohlraum wall is of intrinsic interest in this study as it represents about 60% of the target mass and its material choice offers an incentive for more economical drivers for IFE-HIB power plants.

The selection of hohlraum materials is a feasibility issue under debate in the IFE-HIB fusion community. The hohlraum materials affect several critical aspects of the IFE system and must satisfy many multi-disciplinary requirements. The hohlraum has a direct impact on:

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

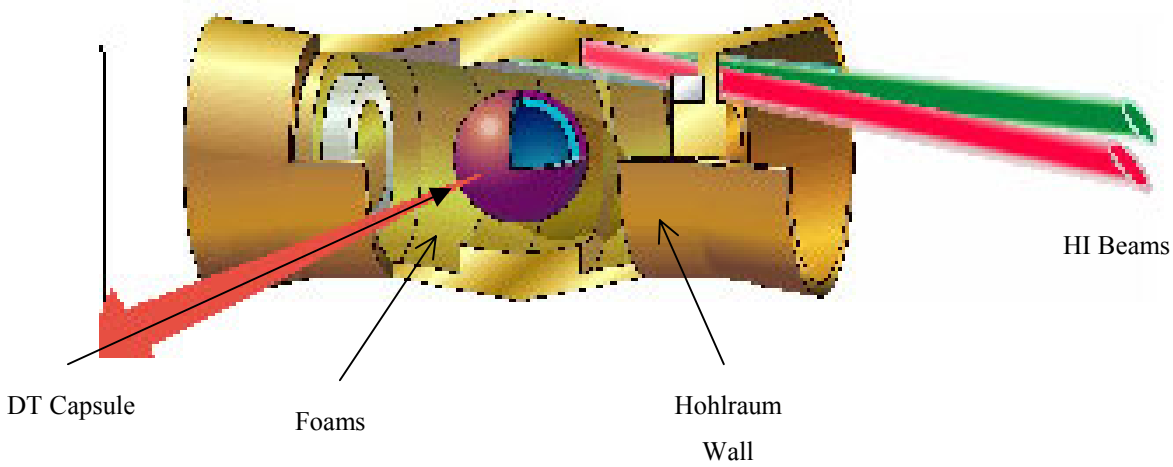

Fig. 1. LLNL close-coupled target design (1).

Ideally, an integrated design would address all these issues and optimize the hohlraum material selection process from the viewpoint of a viable power plant system. However, the goal of the ARIES-IFE study during this two-year period of the IFE research is to define the design space rather than developing a point design. The specific goal of our task is to evaluate the safety issues and identify the pros and cons of recycling versus disposal after one-shot use. Recycling has the advantage of reducing the volume of waste going to the disposal site but the disadvantages of manufacturing targets with radioactive materials and the smaller amount of material going to the waste disposal site would be highly radioactive. Fission critics have been advising fusion designers to avoid generating high-level waste from fusion. Others claim that high-level waste from fusion should be small compared to fission to retain a strong rationale for fusion over fission, but a small amount of high level waste is acceptable. The ARIES position is that a deliberate effort to produce high-level waste should be avoided. Hence, low-level waste production was adopted as a top-level requirement for all ARIES designs to demonstrate the environmental potential of fusion power plants (2). In general, the public is likely to accept the nuclear industry if the radwaste is minimized and the high-level waste issue in particular is resolved.

This study will address the following questions:

- How much waste would the HIB targets generate?
- Should the hohlraum wall materials be sent to a repository after being slightly activated during a one-shot use or should they all be recycled?
- What are the pros and cons of the once-through and recycling options?
- Should any candidate material be recommended for exclusion for failing to meet the recycling criteria?

To answer these questions, we estimated the target inventory relative to the nuclear island waste (Section II), developed a comprehensive recycling approach for all hohlraum materials using ARIES-IFE-HIB design rules (Section III), explored the safety features of the recycled materials (Section IV-VII), and compared the pros and cons of the two scenarios (Section X).

II. TARGET WASTE INVENTORY AND ANNUAL COST

To understand the magnitude of the inventory issue, the target parameters of Table I were considered to estimate the annual throughput of hohlraum wall materials. Historically, the Au/Gd mixture was the favorite hohlraum wall material for laboratory experiments, offering high target performance, low beam losses to hohlraum wall, and low driver cost. However, economic and resource considerations may limit its use in IFE power plants or mandate recycling as will be discussed later. Single or combination of other high-Z materials could be appropriate for HIB applications. A mixture of two or more elements is used to fill out holes in single element opacity and therefore, re-emit more radiation back into the hohlraum interior. Table II identifies the candidate materials taken from Callahan-Miller paper (1). To this list, we added more elements (Hf, solid Kr, and solid Xe) at Moir's request (3). Mercury is the only material in liquid form at room temperature and krypton and xenon are gases that solidify at 116 and 161 K, respectively. The cryogenic load for

Table I. HIB Target Parameters

DT Capsule Radius*	2.34 mm
Au/Gd Hohlraum Wall Thickness*	15 μm
Target Yield	458.7 MJ
Rep Rate	4 Hz
# of Shots	126 million shots / FPY
Plant Lifetime	40 FPY (47 y)
Availability	85%
Volume of Au/Gd Hohlraum Wall	0.0085 cm^3 / target 1.1 m^3 / FPY 43 m^3 / 40 FPY
Mass of Au/Gd Hohlraum Wall	15 tonnes / FPY 600 tonnes / 40 FPY

* Parameters obtained from Fig. 1 of Reference 1.

Table II. Candidate Hohlraum Wall Materials

		Composition (wt %)	Density (tonnes/m^3)
Gold/Gadolinium	$_{79}$Au/$_{64}$Gd	50/50	13.5
Gold	$_{79}$Au		19.3
Tungsten	$_{74}$W		19.4
Lead	$_{82}$Pb		11.3
Mercury	$_{80}$Hg		13.6
Tantalum	$_{73}$Ta		16.6
Lead/Tantalum/Cesium	Pb/Ta/$_{55}$Cs	45/20/35	9.1
Mercury/Tungsten/Cesium	Hg/W/Cs	45/20/35	10.6
Lead/Hafnium	Pb/$_{72}$Hf	70/30	11.9
Solid Krypton	$_{36}$Kr		2.826 @ 116 k
Solid Xenon	$_{54}$Xe		3.54 @ 161 k

Kr and Xe might not be prohibitive because a cryogenic system for the DT capsules is necessary to maintain the temperature below 20 K in the target fabrication facility. It is worth exploring these materials if their use offers advantages. Dealing with large amounts of radioactive gases at the end of operation may represent a challenging problem to the IFE fusion community. As part of this study, we explored various methods of disposing of radioactive gases and documented our findings in Reference 4. In the early 90's, Moir proposed the use of frozen Flibe for the relatively thick (~1 mm) hohlraum wall of the HYLIFE-CT design (5). He suggested encasing a thin high-Z hohlraum wall (~20 microns) with Flibe to minimize the throughput of heavy metals and to add strength for injection and handling. In the most recent close-coupled target design, combining high-Z and low-Z materials within the ultrathin (15-20 microns) hohlraum wall does not seem to be feasible.

The annual throughput of the 15 micron thick Au/Gd hohlraum wall amounts to 1.1 m^3/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

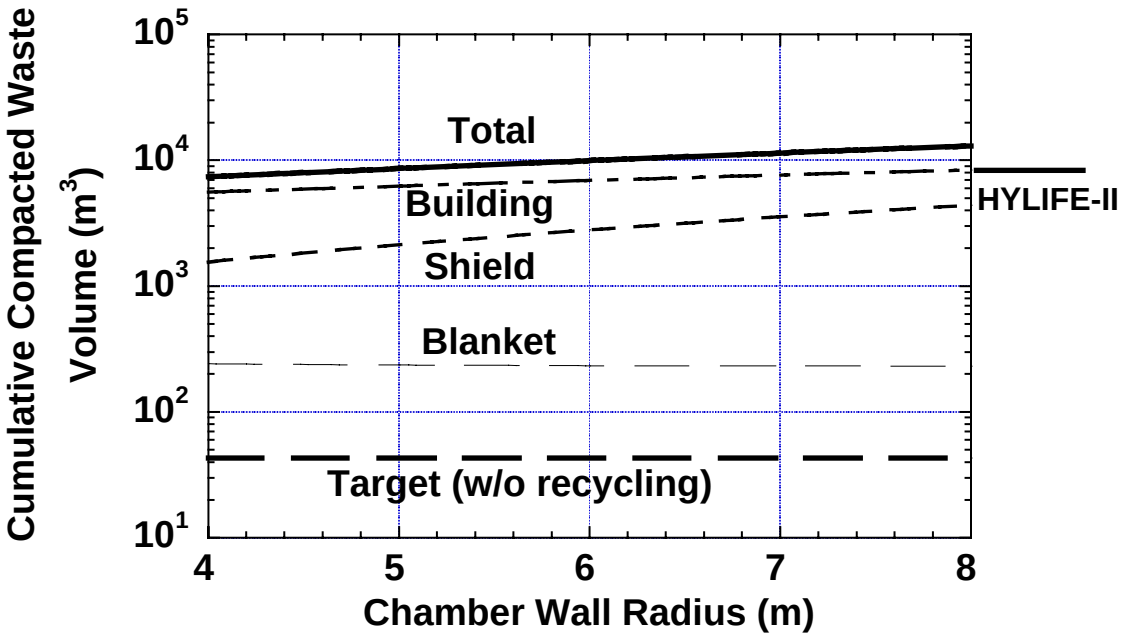

Fig. 2. Comparison of target inventory to nuclear island waste inventory.

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 waste stream as discussed below. Without a point design, the solid waste inventory of the nuclear island cannot be predicted with certainty. Preliminary estimates were used for the three essential components of liquid wall designs: blanket, shield, and building. The cumulative waste over the 40 FPY plant life is plotted in Fig. 2 as a function of the radius of a representative thin liquid wall chamber. The HYLIFE-II thick liquid wall design is marked on the figure for comparison. The target materials represent a small waste stream (< 1%) compared to the nuclear island. This means recycling of target materials should not be a "must" requirement for IFE-HIB 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-HIB power plants

It is generally accepted among the ARIES team members that the target materials would 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 all 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.

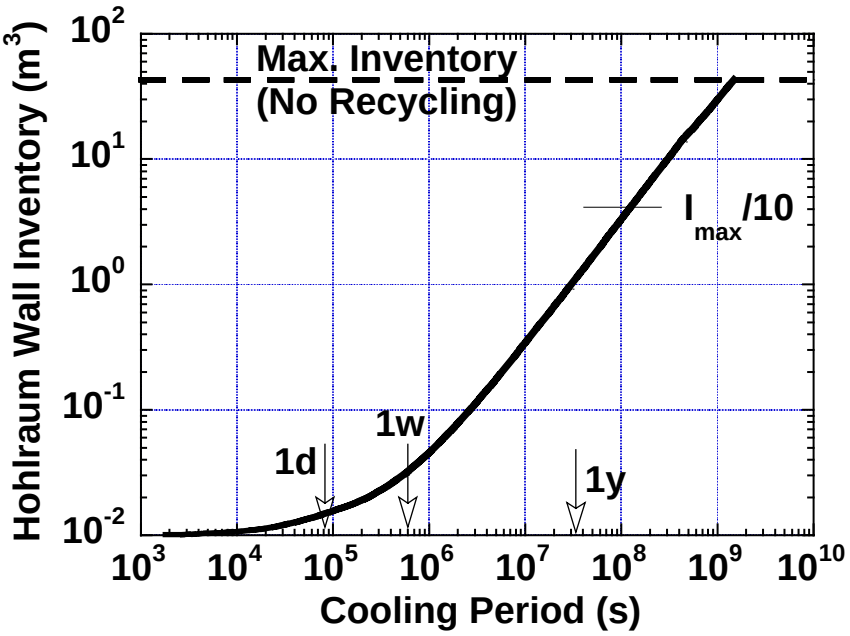

Fig. 3. Hohlraum wall inventory as a function of cooling period.

Before examining the recycling process, it is essential to estimate the impact of the cooling period on the hohlraum wall inventory. As will be discussed shortly, the time period between target injection and its re-injection consists of a cooling period and two days for fabrication and assembly. New targets are continuously injected during the cooling period and fabrication/assembly time. Our rough estimate for the steady state inventory is based on the following assumptions:

- A one-day startup inventory
- A two-day backup inventory to account for repairs to recycling equipment
- A two-day inventory for hohlraum fabrication/assembly
- A variable inventory depending on the cooling period.

Figure 3 illustrates the variation of the hohlraum wall inventory with the cooling period. Expectedly, longer cooling periods result in larger inventory, shorter irradiation time, and lower activation. Our goal is to reduce the end-of-life inventory by a factor of ten or more (i.e., from 43 m^3 to ~4 m^3 or less). A more ambitious goal is not beneficial as the once-through target waste represents a small fraction (less than 1%) of the total waste stream. A cooling period of two years or less seems acceptable and would drop the hohlraum wall inventory below 10% of the one-shot use value.

III. RECYCLING PROCESS

The recycling process is not well understood in the nuclear sector and for fusion in particular. Several fusion recycling studies were launched over the past few years (6-10). Nevertheless, the integration of the recycling process in fusion power plants and its financial impact are still to a large extent unknown. Understanding the time line of the various steps of the recycling process is of particular interest to our study as it displays a host of interesting features.

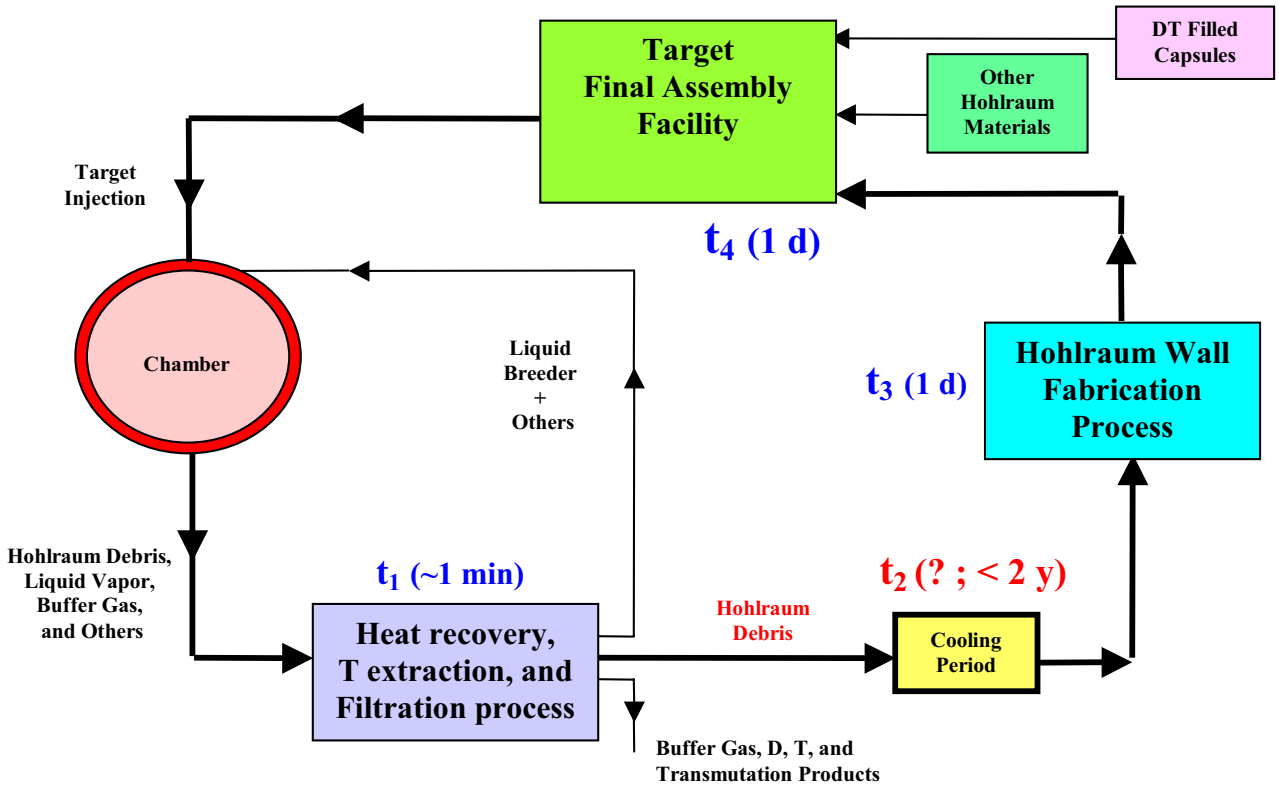

Fig. 4. Flow diagram and time line of the target recycling process in the target fabrication facility.

Figure 4 depicts the essential elements of the target recycling process. After each shot, the hohlraum becomes activated and the 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). A complete list of processes could be envisioned as:

- Separation processes:
  - Target debris separation from liquid wall vapor and chamber buffer gas
  - Separation of high-Z hohlraum elements from target debris (D, T, C, Fe, Al, Be, Br, etc.)
- Hohlraum wall elements sorted out, purified, and stored for a specific cooling period (to be determined)
- Highly pure elements to be recycled and sent in raw form to hohlraum fabrication facility in batches
- Parallel manufacturing of other target components (DT capsules, organic and metal foams, washers, rings, etc.)
- Assembly of all components into a new target under cryogenic environment.

It is almost impossible to state with certainty how long it will take to fabricate the hohlraum walls and assemble the target since the processes are not well defined. The minimum time that one can expect to receive a radioactive metal from the storage and fabricate it into hohlraum wall would be on the order of one day (11). Parallel processes could deliver other components prior to final target assembly. The assembly time could take at least one day (11). This means the residence time of the hohlraum materials outside the chamber could be on the order of two days or more, without cooling periods. The target assembly must be kept in a carefully controlled cryogenic environment at all times before injection into the chamber. This requires mechanization and full automation in order to meet the high throughput

demand. The fabrication and assembly of the radioactive target components must be done with remote handling equipment precluding personnel access to the TFF. The economic penalty could be severe as process automation with personnel access is faster, easier, and less expensive than fabrication with remote handling. The cost of operating and maintaining very precise assembly devices totally remote will be very high and should be reflected in the target cost. Each target costs 44 cents with hands-on fabrication (12), representing ~10 mills/kWh incremental increase to the cost of electricity (COE). With recycling, some preliminary estimates have suggested a factor of 2-3 higher cost for glove box operation and a factor of ten higher cost for totally remote operation, raising the unit cost to $3.15 per target (12) and the incremental change in COE to 72 mills/kWh. Clearly, doubling the COE to recycle the highly radioactive target materials is unacceptable. The target manufacturers would like to avoid dealing with recycled, activated hohlraum materials and would rather be able to work with non-radioactive materials to reduce the fabrication cost and complexity.

IV. RECYCLING CONCERNS

Recycling introduces its own set of problems as it produces high-level waste, increases activity and decay heat, requires remote handling, adds radioactive storage facilities, and increases the cost and complexity of the plant. Issues that may prematurely terminate the recycling process include:

- The waste disposal rating (WDR) of the hohlraum debris exceeds the Class C low-level waste limit (≤ 1), violating the ARIES waste requirement.
- The gamma dose rate to the remote handling equipment is excessive (> 3000 Sv/h).
- The transmutation products reach a limit set by target designers to minimize beam losses to hohlraum walls.
- The decay heat of radioactive hohlraum materials raises the cryogenic DT temperature by > 1.8 K before target injection.
- The dose at the site boundary exceeds the no evacuation limit of 1 rem following an accident in the chamber and/or in the TFF.
- The chemical toxicity of volatile materials in particular exceeds the exposure limit.

The WDR and recycling dose are the most stringent elements and will be addressed in detail in the remaining sections of this paper. At the time being, there is no data on the allowable concentration of the transmutation products that degrade the physics performance of the recycled hohlraum walls. Nevertheless, we assume the hohlraum debris could be sufficiently purified before fabrication into a new target. This is not an easy task and could be a significant feasibility issue for target recycling. A preliminary analysis (13) showed that the incremental change in the temperature of the DT capsule from the decay heat of the radioactive hohlraum wall is negligible compared to the allowable 1.8 K. The low-density foam (0.03 g/cm^3) surrounding the capsule acts as a perfect thermal insulator. The accident dose does not seem to be a significant issue as previous studies (10) identified low doses at the site boundary during accidents for segregated radioactive inventory within the plant boundary. The chemical toxicity would not represent a key issue when realistic assumptions are incorporated in the safety analysis (14). Even though volatility makes a particular hohlraum material easy to separate from liquid wall materials, it makes it unattractive for human exposure during routine operation and accidents. It would be desirable to enhance the safety rating of IFE devices by reducing the vulnerable materials at

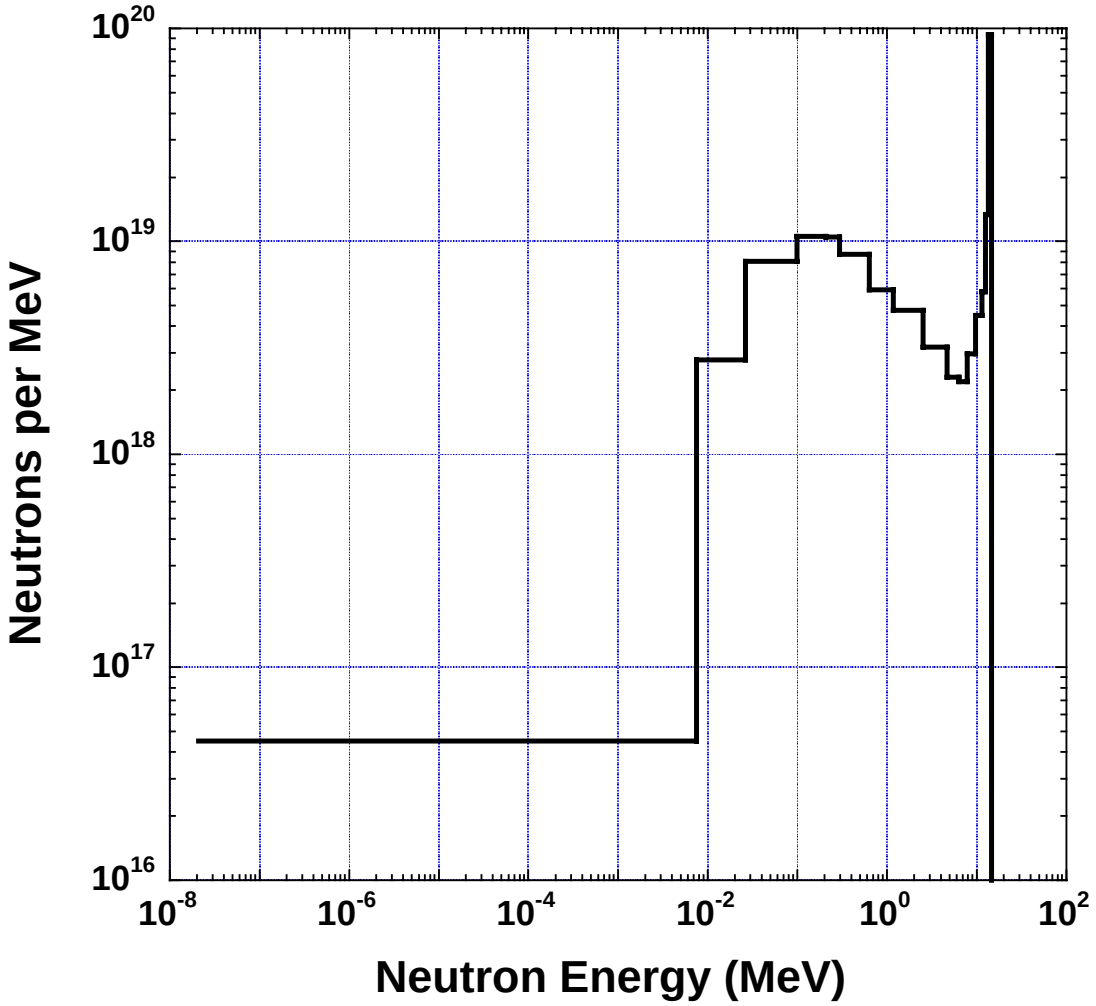

Fig. 5. Neutron spectrum for 458 MJ HIB target.

an incremental increase in the overall cost for installing a cleanup system to remove the majority of the hohlraum debris from the liquid wall materials.

V. SEQUENCE OF EVENTS, IRRADIATION HISTORY, AND ACTIVATION MODEL

The sequence of the events would begin with the injection of the HIB target every 0.25 s into the chamber. Multiple HIBs focus on the target, generating energetic neutrons, x-rays, ions, and other species. The 14.1 MeV neutrons initially constitute ~ 80% of the fusion energy. During burn, the neutrons experience several collisions with the dense capsule materials. As a result, the neutrons moderate and lose a fraction of their original 14.1 MeV energy to the target materials. The computed neutron energy spectrum (15) for the 460 MJ yield HIB target is shown in Fig. 5, having an average neutron energy of 11.8 MeV. The x-rays reach the liquid wall first and evaporate about ten microns of the liquid surface. After interacting with the hohlraum wall, the neutrons travel through the cavity followed by the ions and hohlraum debris. The liquid wall (LW) vapor may slow down and stop the debris before reaching the wall. The chamber

clearing system will pump out most of the debris along with the LW vapor and recondition the chamber for the next shot. Some debris may reach the LW, embed in the liquid, and get re-irradiated with the lower and softer first wall (FW) flux during subsequent shots. For a 6 m radius chamber, the FW flux is approximately six orders of magnitude lower than the target flux. The in-chamber residence time of the energetic debris is unknown as it depends on the complex evaporation and condensation processes of the LW (16,17). Since the debris gets attenuated in the front ten microns of the LW surface, it seems likely that it will survive a few shots only before being pumped out of the chamber. The re-irradiation of the hohlraum debris with the much lower FW flux will not change the activation level greatly and can be ignored.

The irradiation history of the hohlraum wall materials can then be presented as a pulsed history with a single pulse using the target neutron flux. If recycled, the materials will spend at least two days outside the chamber for fabrication and assembly into a new target. Design solutions to recycling problems may call for additional cooling periods, extending the ex-chamber residence time beyond the nominal two-day fabrication period. This cooling period between the extraction of the hohlraum debris from the LW materials and re-fabrication as a new hohlraum wall is material dependent. To examine the recycling issues and the ultimate disposition of the hohlraum wall materials as radwaste, we evaluated two extreme cases with widely different activation characteristics:

- One-shot use and disposal of the lightly activated materials
- Recycle continuously during the plant life without removal of transmutation products.

The actual activation level of the recycled materials could be somewhere between the two extreme cases as some radionuclides could be filtered out online before fabrication. Because of code limitations, the actual case cannot be modeled at the present time. Depending on the efficiency of the purification system, the end product could be less radioactive than the second extreme case considered here unless the key transmutation products are difficult to separate because their chemical properties are very similar to the target material elements.

The WDR and recycling dose were computed using the ALARA pulsed activation code (18) and the FENDL-2 175 neutron group transmutation cross-section library (19). The target neutron flux was calculated with the DANTSYS (19) discrete ordinates transport code and the FENDL-2 175 neutron 42-gamma group coupled cross section library (21). A typical radial build based on the SiC/LiPb blanket design represented the chamber of a thin liquid wall HIB concept (16,17). Highly pure hohlraum wall materials were considered in this analysis and the model assumes the recycling process continues for the entire plant life (~50 y) with 85% availability. The code models all pulses (107 million/y) and explicitly includes the effect of the 85% availability.

VI. ARIES DESIGN LIMITS

VI.1 Waste Disposal Rating

Throughout all phases of the ARIES studies, we have assumed that 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 evaluated by either Fetter (22) or the Nuclear Regulatory Commission (NRC) (23). A computed volumetric average WDR $\leq$ 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. For Class C LLW, all radioactive materials should meet both Fetter's (22) and 10CFR61 NRC (23) limits. The NRC waste classification is based largely on radionuclides that are important to fission facilities. In fusion power plants, the isotopes are different because of the different materials being considered and the different transmutation products that are generated. In the early 90's, Fetter et al. 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 10CFR61. 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. 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 $\leq$ 1 means LLW and WDR > 1 means HLW.

VI.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. This was originally based on an annual limit of 20 mSv/year for a worker working 2000 hr/year. 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 such as cables, electrical connectors, coatings, detectors, insulators, cameras, sensors, etc. In most studies, a conservative limit for the dose rate that allows recycling of materials by remote-handling operations has been assumed to be 10 mSv/hr based on an arbitrary factor of 1000 above the hands-on limit. There has long been concern about the arbitrary nature of these limits, believing that modern control electronics can be designed for much higher radiation fields. In 1999, the UKAEA fusion division of the Culham Science Center (24) launched a study on various aspects of recycling by industrial contractors. In the course of the study, it was revealed that routine remote-handling operations of fission waste are done in a gamma dose rate of 3000 Sv/hr, i.e., more than five orders of magnitude higher than the 10 mSv/hr assumed limit. These operations, to a large extent, are different than expected fusion materials recycling operations, but it does indicate that the 10 mSv/hr is way too conservative. Another recycling study is currently underway at Culham by the same industrial group to better understand what is feasible for fusion materials recycling from all aspects, not only radiological (24). For the ARIES project, we recommend the 3000 Sv/hr limit for remote recycling, recognizing that the 10 mSv/hr value is arbitrary and very conservative.

Table III. Changes in WDR and CI 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}
Gold	0	0.04	645
Tungsten	2×10^{-6}	14.9	0.6
Lead	2×10^{-5}	5.6	31
Mercury	5×10^{-4}	0.22	31
Tantalum	0	0.013	0.5
Lead/Tantalum/Cesium	1×10^{-5}	3	13
Mercury/Tungsten/Cesium	2×10^{-4}	3.3	5
Lead/Hafnium	8×10^{-5}	2.2×10^{3}	24
Hafnium	3×10^{-4}	8×10^{3}	1.2
Solid Krypton	0.01	4×10^{5}	68
Solid Xenon	2×10^{-5}	5.3×10^{3}	0.2

*No cooling period. No transmutation product removal.

VI.3 Clearance Index

Clearance is the unconditional release of materials from radiologically controlled areas to the commercial market after an interim storage period of 100 years. At the writting of this paper, the NRC has not yet released the standards that guide the radiation protection program for clearance of solid materials. Currently, a commercial market for recycling radioactively contaminated materials does not exist in the U.S. It is possible that the national policy will change in the future. We therefore decided to monitor the clearance level for all ARIES designs and apply the NRC clearance standards when released. In addition to the U.S. activity, various organizations are working toward release standards for clearance. In conjunction with various international organizations, the International Atomic Energy Agency (IAEA) has developed clearance standards for 1650 radioisotopes of interest to nuclear applications (25). Due to the absence of official U.S. guidelines, we have temporarily adopted the IAEA nuclide-specific clearance limits and applied those limits for the hohlraum wall materials of ARIES-IFE-HIB. After irradiation, individual materials could be stored for 100 years, and be released to the commercial market if the clearance index (CI) is below one. By definition, the CI is the ratio of the activity (in Bq/kg) to the allowable IAEA limit summed over all radioisotopes. It is calculated in a manner similar to the WDR (26).

VII. RESULTS

Instead of excluding materials for violating the design limits, we utilized the cooling period (defined as the storage time between consecutive shots) to control both WDR and recycling dose for all the candidates listed in Table II. 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 (refer to Section II). The WDR and CI are summarized in Table III for both one-shot use and recycling scenarios. The once-through irradiation slightly activates the various materials. The

Table IV. Maximum Exposure Time and Minimum Cooling Period for Hohlraum Wall Materials Assuming No Transmutation Product Removal

	Maximum Exposure Time*		Minimum Cooling Period#	
		EOL Inventory (m^3)		EOL Inventory (m^3)
Au/Gd	10 shots	~ 43	>> 2 y	>> 4
Au	5.9 y	0.1	8.2 d	0.03
W	47 y	0.01	0	0.01
Pb	6 y	0.1	13 d	0.06
Hg	6 y	0.1	5 d	0.03
Ta	47 y	0.01	0	0.01
Pb/Ta/Cs	9.5 y	0.06	7.5 d	0.04
Hg/W/Cs	19 y	0.04	3 d	0.02
Pb/Hf	6.4 y	0.09	11.5 d	0.06
Hf	35 y	0.02	0.6 d	0.02
Solid Kr	0.7 y	0.8	250 d	0.8
Solid Xe	47 y	0.01	0	0.01

* No cooling period. No transmutation product removal.
\# 47 y of operation. No transmutation product removal.

Class C waste limit (WDR < 1) is met by a wide margin to the extent that all materials can easily qualify for the Class A near-surface burial (WDR < 0.1). A few materials (Au, Hg, and Ta) possess a CI less than one and can be released to the commercial market after a relatively short storage period of 35 years or less. Hg/W/Cs, W, and Au/Gd could be stored for a longer period (140-225 y) before release. All remaining materials have a CI much greater than one even with a much longer storage period (> 300 y).

For the recycling scenario, all materials except W, Ta, and Xe generate HLW in the absence of a cooling period and without online separation of transmutation products. Figures 6 and 7 illustrate the evolution of the WDR over the course of plant operational life. The combination of Au/Gd generates the highest WDR, followed by Au and Kr. As expected, extending the exposure time increases the WDR. Of interest, however, is the nonlinear variation of the WDR over part or the entire range of irradiation time. As Figure 7 indicates, cooling periods of 250 days or less help drop the WDR below one for all materials except Au/Gd. We summarized the maximum exposure time, minimum cooling period, and associated end-of-life (EOL) inventory in Table IV. We prefer the use of a cooling period to control the WDR for a more profound impact on the inventory.

As a measure for the recycling dose, we adopted the FISPACT methodology (27) based on the contact gamma dose rate. It simply evaluates the decay gamma dose at the surface of an unshielded semi-infinite slab using material-specific attenuation coefficients (28). It should be noted that this is an approximate but conservative method. The variation of the recycling dose with cooling period is plotted in Fig. 8, showing a strong material dependence. The analysis assumes continuous recycling during the plant life without transmutation product removal. 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 all

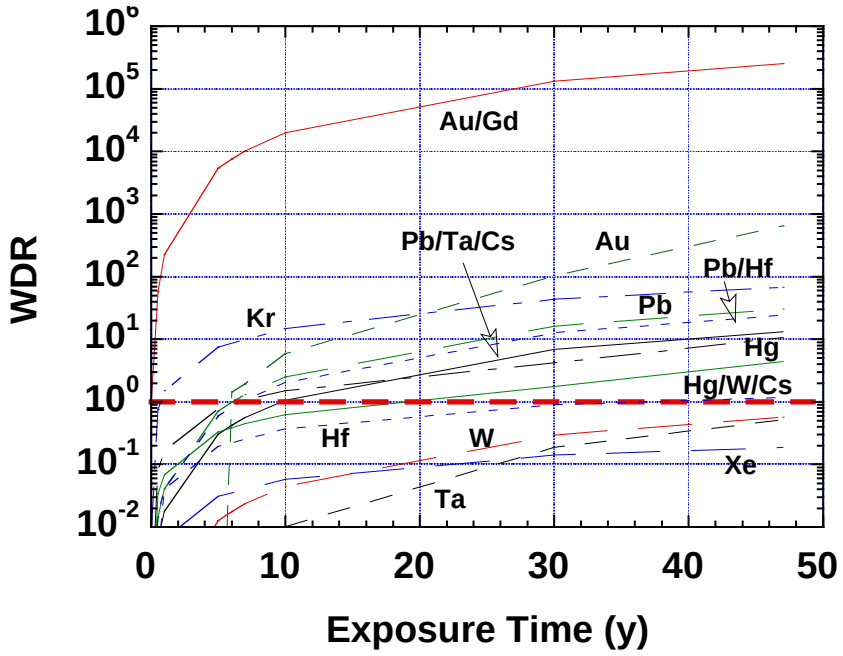

Fig. 6. WDR as a function of exposure time for no cooling period and without transmutation product removal. The Class C limit is marked at WDR of 1.

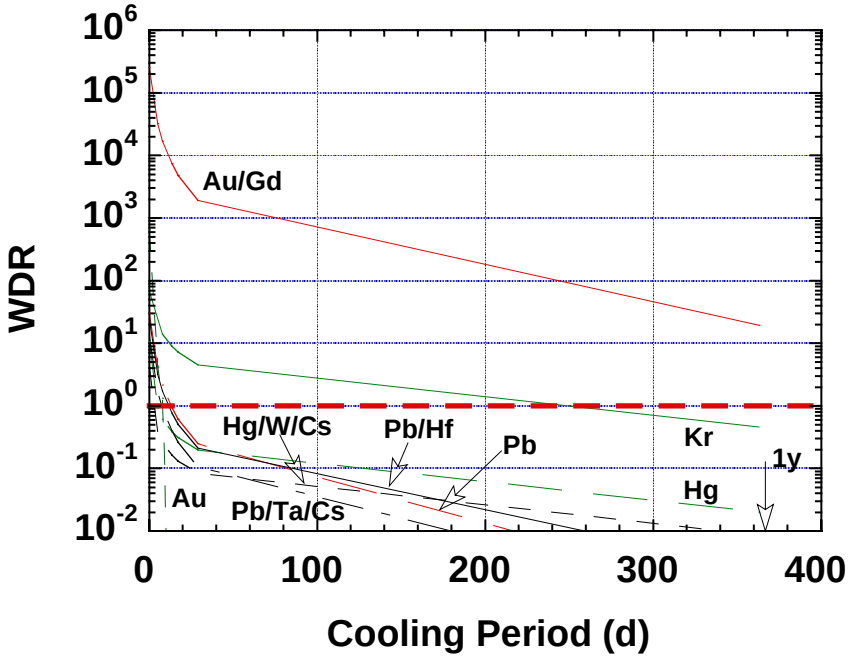

Fig. 7. WDR as a function of cooling period assuming continuous recycling over plant life without transmutation product removal. The Class C limit is marked at WDR of 1.

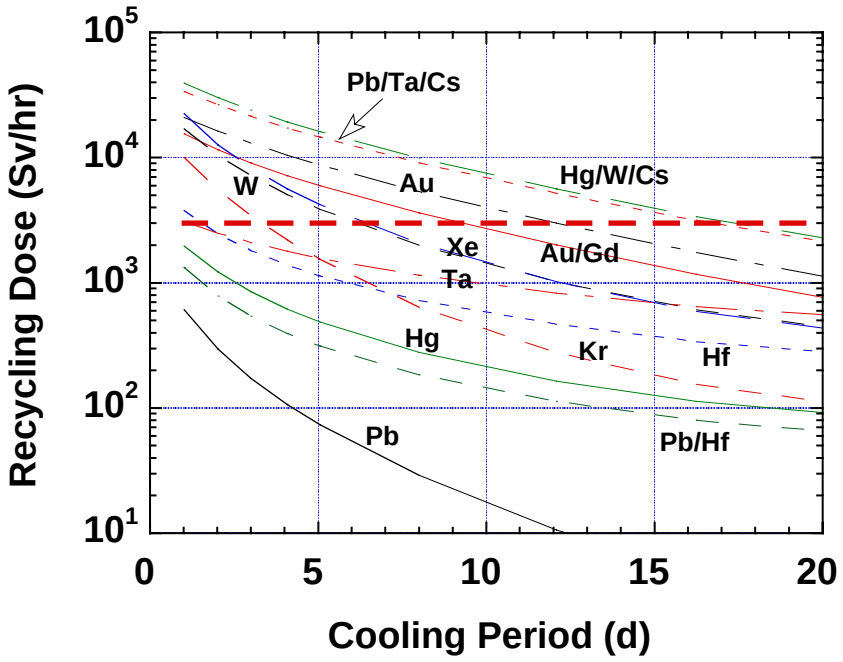

Fig. 8. Recycling dose as a function of cooling period assuming continuous recycling during plant life without transmutation product removal. The recycling dose limit is marked at 3000 Sv/hr.

materials providing that hohlraum debris can be stored for up to 18 days before fabrication. In Table V, we give the recommended cooling period that satisfies both WDR and dose criteria. When cooled for < 18 days, all materials except Au/Gd and Kr meet the waste and dose requirements. The cumulative waste is less than 0.1 m^3 for all materials except Kr. A one year cooling period would generate ~ 2 m^3 of waste, representing ~5% of the once-through inventory (43 m^3). Table VI identifies the main radionuclides contributing to the WDR and dose. Note that in some cases the same radioactive element contributes to both WDR and dose.

An acceptable, minimum cooling period of 18 days or less seems to solve the radiological waste and dose problems for all materials, except Gd and Kr, even with the conservative assumption of no transmutation product removal. Online removal of the highly radioactive elements will certainly shorten the cooling period considerably but remote handing during target fabrication may still be needed. Limiting the cooling period to 5-7 days (10) will cause problems and may force designers to exclude many materials from the list, filter out the transmutation products online, and/or isotopically tailor the materials to avoid making undesirable radioactive products.

VIII. POTENTIAL SOLUTION FOR HIGH-LEVEL WASTE AND REMOTE RECYCLING

Most of the recycled hohlraum wall materials generate 1-2 tonnes of high-level waste that violates the low-level waste requirement of ARIES fusion power plants. It seems possible that we can satisfy the waste requirement by separating online the small amount of highly radioactive elements (listed in Table VI) that are classified as HLW and dispose of the remainder as LLW. This process could represent a feasibility issue as some elements are difficult to separate from the bulk materials using current technology due to the nearly identical physical and chemical properties. A

Table V. Recommended Cooling Period for Individual Hohlraum Wall Materials

	Cooling Period[#] for WDR < 1	Cooling Period[#] for Dose < 3000 Sv/h	Recommended Cooling Period
Au/Gd	> 2 y*	9.5 d	—[*]
Au	8.2 d	12.2 d	12.2 d
W	0	6.2 d	6.2 d
Pb	13 d	< 1 d	13 d
Hg	5 d	< 1 d	5 d
Ta	0	1 d	1 d
Pb/Ta/Cs	7.5 d	17.2 d	17.2 d
Hg/W/Cs	3 d	17.5 d	17.5 d
Pb/Hf	11.5 d	< 1 d	11.5 d
Hf	0.6 d	1.5 d	1.5 d
Solid Kr	250 d	4.5 d	250 d
Solid Xe	0	6.5 d	6.5 d

47 y of operation. No transmutation product removal.
* Insignificant inventory reduction for cooling period exceeding 2 y.

Table VI. Main Contributors to WDR and Recycling Dose in Descending Order

	WDR[*]	Dose[#]
Au/Gd	^{158}Tb	^{196}Au
Au	^{192n}Ir, ^{194}Hg	^{196}Au
W	^{186m}Re, ^{178n}Hf	^{184}Re
Pb	^{208}Bi, ^{202}Pb	^{203}Pb, ^{202}Tl
Hg	^{192n}Ir, ^{194}Hg	^{202}Tl, ^{196}Au, ^{203}Hg
Ta	^{178n}Hf	^{182}Ta, ^{179n}Hf
Pb/Ta/Cs	^{208}Bi, ^{202}Pb	^{132}Cs
Hg/W/Cs	^{192n}Ir, ^{194}Hg	^{132}Cs, ^{203}Pb, ^{202}Tl
Pb/Hf	^{208}Bi, ^{202}Pb	^{175}Hf
Hf	^{178n}Hf**	^{175}Hf, ^{179n}Hf**, ^{179}Lu
Kr	^{81}Kr (gas)	^{84}Rb, ^{82}Br
Xe	^{129}I, ^{135}Cs, ^{137}Cs	^{134}Cs, ^{132}Cs, ^{127}Xe (gas)

*47 y of operation with no cooling period. No transmutation product removal.
#Contributors at recommended cooling period for dose. 47 y of operation. No transmutation product removal.
**Difficult to separate.

laser-based isotope separation process could be used to separate out the high-Z materials needed for hohlraum wall fabrication. One could therefore rely on advanced, extrapolated technology and hopefully the economical and technological limitations associated with such separation processes will be surmountable in 50 y before the commercialization of fusion power plants.

To recycle without the highly radioactive target processing, Peterson (29) and others (10) proposed the use of the isotopic tailoring approach to remove the high-Z materials that make any undesirable isotopes upon interaction with

neutrons. Combined with a highly efficient purification system that filters out the elements that are chemically different from the original high-Z target material, it can be postulated that the activation products are not recycled at all unless they are difficult to separate because their chemical properties are very similar to the original target materials. This approach requires installing online an isotopic tailoring system and an efficient transmutation product removal system to only recycle selective products with the same Z and exclude the troublesome elements for WDR and recycling dose. In this case, the feeding material to the hohlraum fabrication facility could theoretically be highly pure, as clean as the original material, and slightly radioactive (hopefully with a recycling dose < 1 μSv/hr), allowing hands-on recycling of the hohlraum materials and eliminating the excessive cost of the highly radioactive target fabrication process quoted in Section III. Therefore, the economic penalty of using slightly radioactive target materials would be acceptable as the incremental change to COE for HIB targets would be slightly higher than 10 mills/kWh, not 72 mills/kWh, depending on the cost of both isotopic tailoring and purification systems. However, the isotopic tailoring approach is not applicable to materials with a single isotope (such as Au, Ta, and Cs) and the credibility of the approach depends on the following feasibility issues:

- Could both systems be 100% efficient to allow hands-on fabrication of hohlraum walls?
- What radioactive elements will be difficult, or impossible, to separate from the hohlraum materials?
- What is the economic impact of installing both systems?
- Will the system generate any HLW that violates ARIES top-level requirements? Note that long-lived isotopes are not necessarily elements of concern for dose (see Table VI).

A novel strategy to avoid the deep geological burial of the removed, highly concentrated HLW has been outlined in Reference 30. The concept requires fusion devices to burn their own HLW in a specially designed burning module, attempting to transmute the majority of the long-lived radionuclides into short-lived or preferably, stable isotopes. It remains to be seen if the added design requirements can be accommodated easily in fusion devices and if the cost of the proposed system can be much less than disposal in HLW repositories.

IX. TRADEOFFS BETWEEN TARGET PERFORMANCE AND DRIVER COST

To understand the tradeoff between the hohlraum wall materials and target performance, Meier and Callahan-Miller (31) examined the sensitivity of the close-coupled target parameters considering the energy loss to the ion beam, the driver energy/cost, and the incremental change in COE. Table VII shows the results for the potential candidates relative to Au/Gd that offer the lowest energy loss and driver cost. A combination of materials yields a 25% better performance than the use of a single material. A nominal cost of ~25 cents per target was considered in the original analysis (32) that ignored the actual cost of the hohlraum wall materials. An annual supply of Au and Au/Gd is estimated at $210M/y and $80M/y, respectively, and would increment the COE by 3-6 mills/kWh. Recycling would eliminate this incremental change in COE but adds the cost of remote handling equipment and operations. One would expect the fabrication of Au and Gd and the highly precise assembly processes using remote handling equipment to be very high. This tradeoff study shows that excessive recycling and material unit costs outweigh the benefits of Au/Gd. With or without recycling, the Au and Au/Gd hohlraums will result in the highest COE. From the physics standpoint, other combinations of materials can

Table VII. Energy Loss and Economic Impact of Hohlraum Wall Materials

Hohlraum Wall Materials	Relative Energy Loss to Hohlraum Wall	Driver Energy (MJ)	Driver Cost ($B)	Change in Direct Cost ($B)	Change in COE (mills/kWh)	
					w/o Recycling	w/ Au and Gd Recycling
Au/Gd	1	3.3	2.03	0	0 + Au/Gd Cost	0 + Recycling Cost
Pb/Ta/Cs	1.01	"	"	"	0	0
Hg/W/CS	1.04	3.4	2.06	0.03	0.4	0.4
Pb/Hf	1.04	"	"	"	"	"
Au	1.25	3.7	2.16	0.13	1.8 + Au Cost	1.8 + Recycling Cost
Ta	1.25	"	"	"	1.8	1.8
W	1.25	"	"	"	"	"
Hg	1.26	"	"	"	"	"
Pb	1.28	"	"	"	"	"

Table VIII. Qualitative Comparison Between Two Options for Hohlraum Wall Materials

	One-Shot Use Option	Recycling Option
Inventory @ EOL	40 m^{3*}	< 1 m^3
Material's cost	Higher#	Lower
Cleared metals	Some	No
High level waste	No	Yes
Hohlraum purification system	No	Yes
Cooling period	No	< 250 d
Radioactive storage facility	No	Yes
Remote handling in hohlraum facility	No	Yes
Hohlraum fabrication process	Fast	Slow
Overall cost	Lower	Higher

* < 1% of total waste.
\# < 1 mill/kWh for all except Au and Gd.

work nearly as well as Au/Gd and lead to a less expensive system. In particular, a combination of Pb/Ta/Cs has an energy loss and driver cost almost as low as the Au/Gd. Even though the Hg/W/Cs and Pb/Hf mixtures have 4% higher losses and the single materials offer 25-28% higher losses, the overall COE is lower compared to Au and Au/Gd.

X. QUALITATIVE COMPARISON BETWEEN RECYCLING AND ONE-SHOT USE SCENARIOS

In order to select the most attractive scenario, we made a qualitative comparison between the two options based on waste level, inventory, design requirements, handling operations, economics, and complexity. The economic impact of the storage requirements, operation and cost of the recycling process, and handling of radioactive materials in the target fabrication facility are all key issues that need further investigation and therefore a quantitative comparison cannot be made at the present time. Table VIII shows the relative judgment evaluation of the two options. As far as design

simplicity is concerned, the one-shot use option is superior for allowing hands-on fabrication of the hohlraums and eliminating the need for an onsite radioactive storage facility and hohlraum purification system. Overall, the recycling scenario results in a more expensive system due to the additional design requirements, slower operation process, and higher cost for remote handling equipment that offsets the savings in materials cost.

XI. CONCLUSIONS

We evaluated the activation issues associated with the radioactive hohlraum wall materials of the HIB target and recommended a scenario from the view of an integrated power plant system. An important part of this work was the development of a comprehensive recycling approach for ARIES-IFE-HIB, then comparing the pros and cons of two scenarios: one-shot use of the hohlraum wall materials and recycling during the entire course of plant operation. Our preferred option is the one-shot use scenario as it satisfies multi-disciplinary requirements and has a positive impact on the waste level, economics, and design simplicity. The hohlraums represent a small waste stream for IFE-HIB power plants, less than 1% of the total nuclear island waste. This means recycling is not a "must" requirement for IFE-HIB unless materials exhibit cost and resource problems (e.g., Au and Gd).

Even though a combination of Au and Gd is a favorite hohlraum wall material from the target physics viewpoint, cost considerations of the materials or recycling process will preclude its use in power plants. Recycling introduces additional design issues and problems. It generates high-level waste that violates the ARIES waste requirement, complicates the design, and calls for a totally remote hohlraum fabrication process. Potential design solutions to alleviate the recycling problems include removing the majority of the transmutation products online, isotopic tailoring, storing the materials for a specific cooling period, and/or limiting the exposure time and using fresh materials. An attractive recycling scheme would combine a controlled cooling period and efficient cleanup system to filter out and concentrate the HLW in a small volume. This HLW could then be burned in fusion devices to avoid the deep geological burial and meet the ARIES Class-C only waste requirement. It is true that recycling helps diminish the hohlraum inventory and material cost but the cost of the advanced purification system and the highly precise remote fabrication process will offset the material cost saving. With or without recycling, we would expect the Au/Gd and Au hohlraum walls to result in higher COE compared to other candidates.

We recommend using low-cost materials (such as W, Pb, Hg, Ta, Pb/Ta/Cs/, Hg/W/Cs, Pb/Hf, Hf, solid Kr, or solid Xe) once-through and then dispose of them instead of recycling expensive materials (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 target factory designers would prefer dealing with non-radioactive hohlraum materials and this assessment supports the feasibility of a no-recycling approach. As a final point, should the advanced target physics relax the high-Z requirement and permit hohlraum walls made of low-Z low-density materials, we suggest fabricating the hohlraum walls out of breeding or liquid wall materials (e.g., Pb, LiPb, Li, Sn, LiSn, Flibe, and Flinabe) to simplify the design further and eliminate the need for hohlraum separation and disposal processes.

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