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ABSTRACT

The target for an Inertial Fusion Energy (IFE) power plant introduces the fusion fuel to the chamber, where it is compressed and heated to fusion conditions by the driver beams. The "Target Fabrication Facility" (TFF) of an IFE power plant must supply over 500,000 targets per day. The target is then injected into the target chamber at a rate of 5–10 Hz and tracked precisely so the driver beams can be directed to the target. The feasibility of developing successful fabrication and injection methodologies at the low cost required for energy production (about \$0.25/target, about 10^4 less than current costs) is a critical issue for inertial fusion.

The technologies for producing Heavy Ion Fusion (HIF) targets have significant overlaps and synergisms with current day inertial fusion experimental targets and with laser fusion (direct drive) IFE targets. Capsule formation and characterization, permeation filling, and layering of the DT using a cryogenic fluidized bed are common methodologies shared between laser fusion and HIF. Specific to HIF targets are the techniques for fabricating and assembling the hohlraum components. We will report on experimental progress with the Laser-assisted Chemical Vapor Deposition (LCVD) technique to produce "micro-engineered" low density metallic foams for the hohlraum, and calculations of hohlraums materials performance during handling. Fiber growth by LCVD in arrays has been demonstrated for the first time, important to achieve the volume production needed for IFE. We have also evaluated a variety of hohlraum material selections, with consideration of target physics, cost, ES&H, activation, and compatibility with the molten salt coolant. These materials include selections for once-through and for re-cycle scenarios. We have performed a cost analysis for an "nth-of-a-kind" Target Fabrication Facility using our current assumptions about the production processes. Some of these scenarios result in future target manufacturing costs consistent with economical electricity production.

Keywords: fusion, inertial, heavy-ions, targets, fabrication

1. INTRODUCTION

IFE power plant conceptual designs have been published over the past three decades [1,2]. A variety of target designs have been analyzed for heavy ion fusion (HIF), including the "distributed radiator" design illustrated in Fig. 1 [3], which is the current focus of development interest. This target utilizes illumination by a number of beams from two sides, focused in an annular ring on the ends of the target. The ion beams deposit their energy all along the nearly cylindrical hohlraum materials, thus the term distributed radiator. The distribution of radiation is accomplished by tailoring the density of radiator materials in the target; which means that fabrication of a number of special high-Z doped CH foams and high-Z (metal) foams are required. These hohlraum materials are the subject of materials development tasks unique to the HIF target. Other manufacturing aspects of the HIF target are similar to laser-driven direct-drive IFE targets and to current experimental inertial confinement fusion targets (e.g., spherical shells, permeation filling). The selection of materials (element and composition) for the hohlraum areas indicated in Fig. 1 remains the subject of evaluations and studies [4].

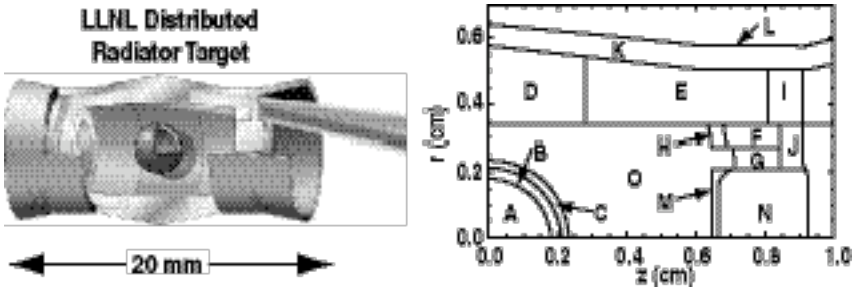

Fig.1. Distributed radiator target design for heavy ion fusion (material composition of labeled areas are being evaluated) [4].

In a previous paper [5], we described an outline for the entire pathway, from beginning to end, for fabrication of a high-gain, distributed radiator target for energy production. We believe that defining applicable process methodologies for mass-production of this target was a significant advance in showing feasibility of energy production from Heavy Ion Fusion. In this paper, we provide an update on that "pathway" with:

1. Streamlining of the mass-production pathway with improved process steps addressing issues of low-density foam handling and assembly,
2. Preliminary estimates of the per-target cost for a number of processing options, and
3. Evaluation of hohlraum material selections and their impact on cost of targets.

2. DEVELOPMENT OF THE TARGET PRODUCTION PROCESS

The basic requirement for the TFF of an IFE power plant is to provide about 500,000 targets per day (at ~6 Hz) with precision geometry, and with precision cryogenic layered DT fuel. Target fabrication for inertial fusion is being investigated by a number of institutions throughout the world, including Russia [6], Japan [7], China [8], France, and the USA [9]. Targets for HIF include a CH polymer spherical shell (capsule) to contain the DT fusion fuel and to fix the fuel geometry. Density matched microencapsulation has been used in the laboratory to produce similar capsules from polystyrene [10]. This fabrication step is relatively well-understood and demonstrated, although significant work remains to scale the process to larger batches and to increase product yields for IFE. The principal technical issues are meeting non-concentricity and out-of-round requirements when fabricating the CH shells at large diameter and with thick walls, as well as scaling the equipment to high-volume production. Some expected HIF target specifications are given in Table 1.

Table 1. Listing of some expected HIF target specifications and requirements

Some Possible Indirect Drive Specifications	
Capsule Material	CH or Be
Capsule Diameter	4.6 mm
Capsule Wall Thickness	250 μm
Out of Round	<1% of radius
Non-Concentricity	<1% of wall thickness
Shell Surface finish	20–200 nm RMS
Ice Surface Finish	1–10 μm RMS
Temperature at Shot	~15–18.5 K
Positioning in Chamber	± 1–5 mm
Alignment with Beams	<200 μm

Filling of polymer capsules with hydrogen isotopes by permeation through the wall, removal of the excess DT after cooling to cryogenic temperatures (to reduce the capsule internal pressure and prevent rupture), and transport under cryogenic conditions have been demonstrated in the

laboratory [11,12]. Estimates of the DT filling (and layering) time and models to predict its effect on tritium inventory in the Target Fabrication Facility have been prepared [13]. The principal issue regarding permeation filling with DT is minimizing the tritium inventory "at risk", and thus maximizing the attractiveness of the power plant. Since void space within the hohlraum results in up to 30 times more tritium required during filling[1], a final cryogenic assembly step will be required (after permeation filling of the capsule). Using cryogenic assembly, the inventory models indicate that operating with less than ~1 kg tritium in the TFF will be feasible. Layering [14,15], is the process of redistributing the cryogenic DT fuel into a smooth uniform layer inside the ablator. Layering requires establishing an extremely precise (within 250 μK), uniformly spherical temperature distribution at the surface of the capsule. A cryogenic fluidized bed experiment with hydrogen isotopes has been designed to demonstrate this process. The basic concept is for the fluidized bed to rapidly randomize the movements of the targets, yielding a very uniform time-averaged surface temperature. Layering in a fluidized bed requires very rapid (a few seconds or less) removal of the layered capsule from the bed, assembly into the hohlraum, and injection.

The challenge of the HIF target that is unique for fabrication is its distributed radiators. To fabricate these materials, a new process, high-pressure laser chemical vapor deposition (LCVD), is being experimentally demonstrated. LCVD utilizes a laser to catalyze a chemical vapor deposition in a controlled manner. A precursor molecule containing the high Z element of interest is laser-decomposed to form lattices of high Z low density material. Diffractive optics are used to generate an array of focused hot spots on an initial substrate, and the fibers are grown normal to the substrate by thermal decomposition of the precursor mixture. As the entire array is grown under computer control, the overall shape of the material can be varied at will, and (axial and radial) material gradients can be built into the lattice – simplifying the design and assembly of target hohlraums. Thus, LCVD can "grow" fibers and interlink fibers on the scale of a few microns to produce a "microengineered" foam structure to meet the needs of material density,

[1] As compared to filling an array of bare capsules.

pore size, strength, rigidity, and geometric shape. This process is rapid and thus amenable to production scaleup. LCVD opens the door for more flexible hohlraum designs, as it is capable of creating functionally-graded materials that vary in both density and elemental composition. In addition, to some degree, the physical, mechanical, and thermal properties of the metal foams can be controlled to meet the target functional requirements (by controlling the microstructure of the matrix created).

Recent work has identified a process flow for HIF hohlraum fabrication that builds upon that described in Ref. [5]. This new process minimizes handling and assembly steps with the hohlraum components and, basically, "grows" the hohlraum "from the inside out" in a single chamber. This method avoids precision machining steps, and eliminates issues of handling and assembly of the low density materials. A multiplexed laser array produces fibers of the desired material with controlled diameter and array spacing to give the desired foam density (Fig. 2). Precursor gas flows are controlled to allow changing materials, even allowing a gradual change of density and material content within the sample. The fabrication sequence is envisioned as starting with membranes (entrance windows) that are vacuum mounted to holding fixtures. Each hohlraum is grown in two parts, as shown in Fig. 3(a). The main body of the low-density material(s) is fabricated over one entrance window, while a hohlraum insert is manufactured on a separate window. These two components will later be assembled as shown in Fig. 3(c), once the DT-capsule is in place. Step two in the fabrication process is focus an array of laser beams through diffractive optics to create a pattern of high-intensity spots on the hohlraum window and injection mold surface. This operation is performed within a pressure vessel where gaseous chemical precursor(s) are present, and a laser-induced heterogeneous reaction occurs at the focal spots. Due to enhanced mass transport to/from each hot spot, an array of fibers grows rapidly outward from the spot pattern. By interlacing these fibers using two or more beams, a low-density interconnected lattice is formed — which will be a composite of the various precursors locally present in the gas phase. By modulating the gas composition though the use of nozzles

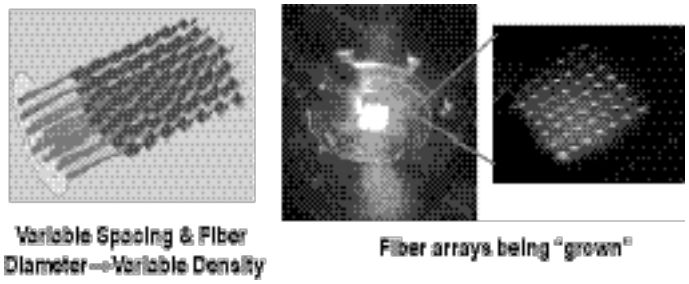

Fig.2. Laser assisted chemical vapor deposition uses diffractive optics to provide an array of hot spots to facilitate thermal decomposition of a precursor; the effect is to "grow" a micro-engineered structure with the desired properties

and directed gas flow, the composition of the lattice can be varied in real-time, creating a functionally-graded, low-density material with the "combined strength" of all the interconnected fibers. Junctions without distinct boundaries can be created within the lattice, so that the individual "pull-out strength" of each fiber approaches the yield strength of the fiber material itself.

After the foam components are produced, suitable processes are used to overcoat the foam wall and build a thick overlayer for support and containment. The hohlraum is then inserted into a casing with a cap to facilitate reactive injection molding of a polymer case (for handling and injection purposes), as in Fig. 3(b). A filled, layered capsule freshly taken from the cryogenic fluidized bed is then placed within the bottom hohlraum part, and the top part is placed over the capsule to provide an assembled HIF target for subsequent injection [Fig. 3(c)]. This concept assumes a higher than design density for foam nerar th capsule. If this is ultimately not allowed, a "standoff" between the foam and capsule could be achieved by incorporating a very thin support membrane for the capsule into the hohlraum structure.

The extreme localized growth rates afforded through LCVD make this method viable. Axial growth rates of individual carbon fibers, for example, often exceed 3 mm/s; the total volume of low-density material in each target is about 2100 mm^3. Assuming a spot array of 100 × 100 for each target, with 12 μm spacing, gives a cross sectional area of about 1.4 mm^2 for each spot. About 750 s would be needed to grow each hohlraum. We make the assumption that load-lock and transfer times are negligible compared to this. Each LCVD unit processor is designed to

grow 48 samples simultaneously, and 112 unit processors operate in parallel, so 5376 hohlraums are being made simultaneously and the total production rate would then be about 7 hohlraums per second. The estimated cost of this processing is discussed in the sections below.

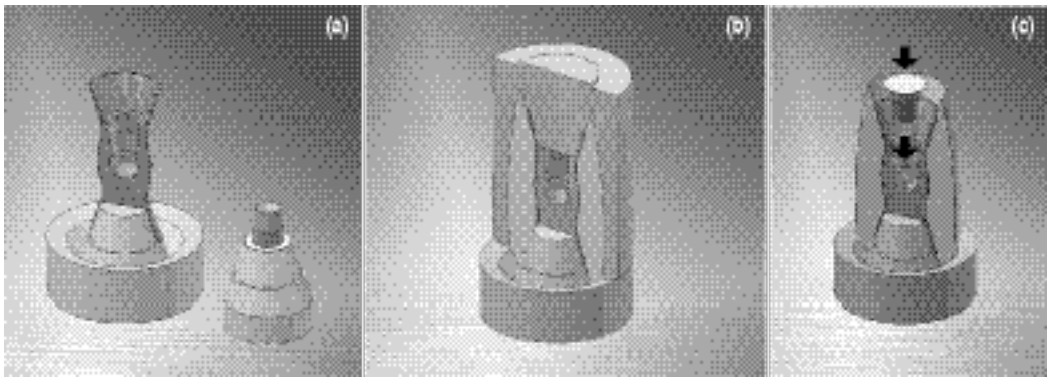

Fig. 3. Utilizing LCVD, the hohlraum manufacturing process can proceed without precision machining or delicate assembly steps for the low-density foams in the HIF hohlraum (see text for description of steps).

Experiments are currently being conducted to develop the methodologies and to verify the deposition rates for a variety of elements and alloys of interest. First the thermodynamics of decomposition are estimated as a function of temperature. The experimental data given in Fig. 4 is for a carbon fiber grown from ethylene; it shows the measured peak fiber temperature as a function of time. The thermodynamics prediction matched the measured temperature during fiber growth, showing that the desired fiber temperature for a particular reaction can be used to control the growth.

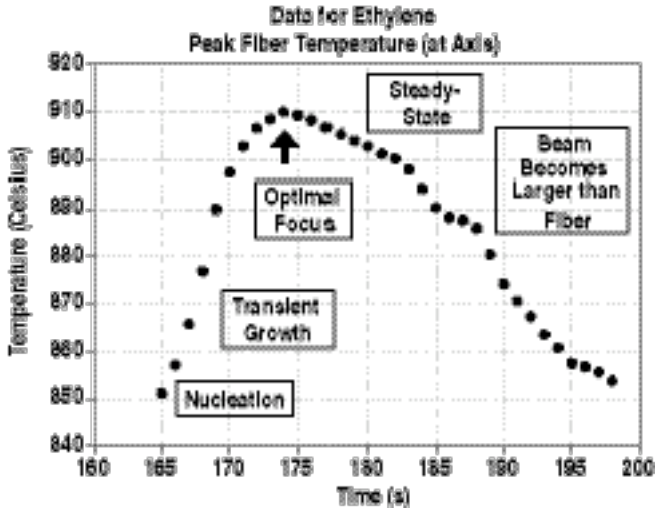

Fig. 4. Measured peak fiber temperature as a function of time during LCVD experiment; understanding the thermodynamics of fiber growth allows process control to be based on observed temperature peaks.

3. PRELIMINARY TARGET COST ESTIMATES

3.1. BASE-CASE AND ASSUMPTIONS

It is not our short-term goal to develop a "final" design of a facility to mass-produce HIF targets. However, it is our goal to show the viability of manufacturing targets at a cost that will allow economical generation of electricity. The electricity value in one target is approximately $3.00. While there is no fixed requirement for the "fueling" cost of a future IFE power plant, one can consider that spending about 10% of the electricity value on fuel would be a reasonable solution. This rough approximation results in the cost goal for IFE targets of about $0.30, which has been mentioned often. To evaluate whether such cost goals can be met, we have prepared preliminary layouts and cost estimates for future target fabrication. In this analysis, it is assumed that the long term R&D programs that are needed to develop production processes have been accomplished. We assume that our best understanding today of the technologies and controls required for target manufacture are valid. With time, evolution in manufacturing technology will continually reduce the costs of each target. Therefore, estimating the cost of targets requires one to select a single time frame in the evolution of target manufacturing. For this analysis, we define our "point of evolution" for cost estimating purposes to be the complete optimization (i.e., nth-of-a-kind plant) for the current-day understanding of target manufacturing processes. We have utilized a classical chemical engineering approach to the costing. We have identified potential manufacturing and handling processes for each step of production, and have evaluated the raw materials, labor force, cost of capital investment, and waste handling costs for providing approximately 500,000 HIF targets per day. We have prepared preliminary equipment layouts, and determined floor space and facility requirements. The analyses utilize standard industrial engineering cost factors. In these analyses, it is assumed that the power plant produces its own tritium which is extracted from the breeding material and purified — the cost of the tritium production, extraction, and purification steps are not included in the target production cost and

must be considered separately. The per-target cost basis is for current-year dollars; one can assume an escalation factor of 3% to 5% per year until plant construction takes place.

Changes to the originally published target design to reduce manufacturing costs are being evaluated. Final choices for the hohlraum materials are still open, and individual target materials may or may not be recycled. For example, the original published target design utilized a number of hohlraum areas containing a mixture of gold and gadolinium at various densities. The cost of gold (and the scarcity of gadolinium) would require that these materials be recycled indefinitely in the plant fuel cycle. Recycling reduces the volume of radioactive waste streams from the facility, but it also requires a high level of material purification (for re-use in a hohlraum) and remote (and/or contaminated) manufacturing process steps. Our preliminary estimate of the cost to provide fully remote handling of the recycled (highly radioactive) hohlraum materials in this case (as well as fully remote maintenance of related target handling equipment) was more than the electricity value of the target (i.e. apoproximately $3.00 per target). We therefore evaluated lower cost hohlraum materials that could be used in a "once-through" cycle and then discarded as low level waste (i.e., removed from the coolant stream prior to building up high radioactivity). One potential solution is to use a mixture of lead and hafnium: ~ 70/30 wt% mixture results in ~ 2% plant energy loss (due to reduction in estimated target yield – as compared to the original Au/Gd mixture), and results in about $8000 per day worth of source material being discarded, which is small compared to the additional cost of utilizing highly radioactive material in the target production plant.

Assuming a polystyrene shell and use of a ~ 70/30 wt% Pb/Hf mixture for the hohlraum components (and no near-term recycling of hohlraum materials), the estimated cost for target mass-production is estimated to be about $0.41¢ each. The corresponding installed capital cost is estimated at $304 million ($38 million annualized cost over a 30 year plant life). Annual operating costs include materials and utilities ($11 million), maintenance ($18 million for labor & materials), and operating labor ($10 million). The single most significant factor in the cost per target is the capital cost associated with the LCVD system. While optimizing of the target design

and fabrication processes will certainly continue, this is a very encouraging result with respect to meeting target supply cost goals. The Pb/Hf mixture entails an energy penalty in the gain of the target, and other materials may eventually be preferred. Further discussion of potential hohlraum material selections is given in the sections below.

3.2. TARGET COST ESTIMATE SENSITIVITY ANALYSIS

Calculations were also performed to determine the sensitivity of the HIF target cost to changes in one or more of the assumptions. The results are summarized in Table 2. Note that these results all assume that no recycling or processing of radioactive material is done. A cost of about \$0.32¢ per injected target is calculated for a 3000 MW(e) plant. Additional cost savings are possible by fabricating the empty targets and hohlraums at a central facility and then filling/layering/injecting them at the power plant site. Each empty shell and hohlraum is estimated to cost only 12.8¢ per target when made in this large quantity (10,000 MW(e) equivalent). This economy-of-scale results in a savings of 12.7¢ per injected target at a 1000 MW(e) plant.

Table 2. Results of model sensitivity studies — HIF targets

Case	Description	Cost Per Injected Target (¢)
Single variable responses [1000 MW(e) plant]:		
1	Baseline (arbitrary 25% reject rate assumed)	40.8
2	Doubled staffing costs	46.0
3	Doubled capital costs	70.6
4	Doubled maintenance costs	50.5
5	Doubled utilities costs	43.1
Larger plant case:		
6	3000 MW(e)	31.9

Hybrid plant case (empty targets made at a 10,000 MW(e) equivalent central facility):

Case 7 — 1000 MW(e)	
Empty capsules/hohlraums (made off-site)	12.8¢/injected target
Fill/layer/inject (on-site)	15.3¢/injected target
Total:	28.1¢/injected target

4. HOHLRAUM MATERIALS SELECTIONS AND TRADEOFFS

The materials used in indirect-drive targets affect many aspects of an IFE power plant system and is a complex tradeoff. To choose a list of reasonable target materials, we considered the effect of the hohlraum materials on

- Cost and complexity (even feasibility) of target fabrication
- Target strength for injecting the targets
- Target physics for target gain
- Methods of extracting materials from the reaction chamber
- Radioactive inventory of materials
- Cost of target materials and
- Chemical toxicity

Using these selection criteria, we eliminated most elements from further consideration. We found a short list of reasonable material choices, each with distinct advantages and disadvantages. Tungsten is found to be a leading material choice and a method for removing tungsten from Flibe[2] in a liquid wall chamber was further investigated. Reference [16] considered the induced radioactivity in recycled materials that undergo radiation exposure from being part of a 500 MJ IFE target. For single-use, all materials could be disposed of as low-level waste [17]. Reference [2] considered all high atomic number elements for hohlraum walls and suggested many that could be eliminated. It's author also gave suggested methods of separating the elements from Flibe [18]. Taking into account this information, we down-selected to a smaller set of candidate materials for hohlraum walls.

Materials such as tungsten that are solid at plant operating temperatures if included in hohlraum materials will tend to plate out on the primary circuit surfaces wetted by the flibe coolant. This plating would tend to plug small orifices such as the 0.4 mm openings in the

vacuum disengagers for tritium removal from the Flibe (as described in Ref. [19]). Screens in the Flibe nozzles also have ~1□mm size orifices that could become clogged. One possible solution to this is to seed the Flibe with many very small tungsten particles that have a combined surface area that is much larger than the surface area of the internal plant components that are in contact with the Flibe. The tungsten atoms will adhere to the first surface that they contact. Most of the tungsten atoms will adhere to the fine tungsten particles, thereby greatly minimizing the growth rate of the tungsten on power plant surfaces. The tungsten particles will be filtered out of the Flibe in a small flow-rate slipstream to keep the quantity of particles at the desired level. The seed particles of tungsten can be uniformly mixed into the Flibe utilizing a high-shear mixer□[20]. Based on this study, we believe that it is feasible to seed tungsten particles into the Flibe to control plateout in the primary circuit. Further development and testing of the systems to accomplish this will be needed to verify this statement.

We proceeded to rank the small set of elements noted above for various characteristics, eliminating those that we judged unacceptable for each of the criteria. There are many tradeoffs to consider. Any single element (e.g., Pb, W, Hg) has an energy loss of at least 12%, thus evaluating mixtures of elements is highly desired. More technically challenging (and thus more costly) combinations such as Pb/Hf/Xe have essentially no significant energy loss compared to the original Ag/Gd target design. A mixture of Pb and Hf loses only 2% of the energy, while Pb/W loses 4%, and pure tungsten loses about 12%. The most expensive of these materials (and the only one with significant cost compared to the cost of the energy produced) is hafnium. Disposing of the required amounts of hafnium in a once-through cycle would cost about $8000 per day. For example, Pb alone has an energy loss of about 14% compared to Pb/Hf at 2%. The loss of 12% of the energy in a 1000 MW(e) plant is valued at about $150,000 per day, easily compensating for the $8000 per day to buy hafnium. However, additional operational costs for Hf processing, removal from the Flibe (probably requiring electrochemical separation) must be considered.

[2] Flibe is a mixture of LiF and BeF_2 that is the coolant in the HIF chamber.

An evaluation of these elements according to chemical toxicity ranged from literature comments of "entirely harmless" for Xe to "dreadful poison" for Hg. Lead has obvious toxicity issues, as well as the significant environmental disposal issue of creating "mixed waste" due to irradiation. Tungsten metal has low toxicity, but its compounds are considered toxic. In terms of separation from Flibe, high vapor pressure compounds such as Xe and Hg are most easy to separate of course, but they add complexity and cost in terms of handling (Xe requiring more cryogenic target manufacturing steps) or prohibitive toxicity concerns (Hg). As for compatibility with the Flibe loop, Xe, Pb, and Hg do not plate out on surfaces, but tungsten and hafnium are all solids at Flibe temperature. Plate out, as discussed earlier, is an issue that will need to be controlled. Separation from the Flibe, although not traditionally considered as a component of the target cost, nevertheless will add costs to the overall plant systems.

Ultimately, more extensive trade studies of systems costs based on actual plant designs will be needed, but this evaluation shows that a 70/30 wt % mixture of Pb/W is a very attractive hohlraum material from the viewpoint of low energy loss (4% compared to Ag/Gd), low cost of industrial materials and amenablility to LCVD. Of course the presence of lead is a mixed waste and toxicity issue. Disposal of about 250 pounds per day of slightly radioactive lead may devalue the environmental attractiveness of a fusion power plant. An alternate to this devaluation is to use pure tungsten as the hohlraum material. The penalty is an additional energy loss of about 8%. For a 1000 MW(e) plant this is a highly significant cost (about $100,000 per day), which may readily pay for the mixed waste handling of the Pb/W mixture. In short, there are tradeoffs between environmental effects and energy costs – as in all energy production methods. This preliminary study cannot make a final choice, but does show that a number of attractive options and choices do exist.

5. SUMMARY AND CONCLUSIONS

Supplying ~500,000 targets per day at a cost that allows economical energy production is a key issue for inertial fusion. Significant progress has been made in HIF target technology in the last few years, a pathway for production has been outlined, and now streamlined, taking advantage of the LCVD process to reduce material handling and assembly steps. Initial cost estimates for mass-production of HIF targets have been made and the results are reasonable for the current stage of technology development. Various hohlraum materials have been evaluated for use and offer good options for power from HIF.

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