DEMONSTRATING A TARGET SUPPLY FOR INERTIAL FUSION ENERGY

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A central feature of an Inertial Fusion Energy (IFE) power plant is a target that has been compressed and heated to fusion conditions by the energy input of the driver. The technology to economically manufacture and then position cryogenic targets at chamber center is at the heart of futureIFE power plants. For direct drive IFE (laser fusion) energy is applied directly to the surface of a spherical CH polymer capsule containing the deuterium-tritium (DT) fusion fuel at approximately 18 K. For indirect drive (heavy ion fusion, HIF) the target consists of a similar fuel capsule within a cylindrical metal container or "hohlraum" which converts the incident driver energy into x-rays to implode the capsule. For either target, it must be accurately delivered to the target chamber center at a rate of about 5–10 Hz, with a precisely predicted target location. Future successful fabrication and injection systems must operate at the low cost required for energy production (about \$0.25/target, about 10⁴ less than current costs).

Z-pinch driven IFE (ZFE) utilizes high current pulses to compress plasma to produce x-rays that indirectly heat a fusion capsule. ZFE target technologies utilize a repetition rate of about 0.1 Hz with a higher yield

This paper provides an overview of the proposed target methodologies for laser fusion, HIF, and ZFE, and summarizes advances in the unique materials science and technology development programs

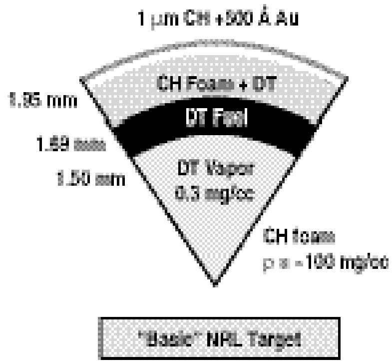
I. INTRODUCTION

A central feature of an Inertial Fusion Energy (IFE) power plant is a target (Fig. 1, for example, shows a laser fusion target) that has been compressed and heated to fusion conditions by the energy input of the driver beams. A target development program is underway to demonstrate successful target technologies for IFE applications.[1]

For direct drive IFE,[2] energy is applied directly to the surface of a spherical CH polymer capsule[3] containing the deuterium-tritium (DT) fusion fuel at approximately 18 K. For indirect drive.[4] (heavy ion fusion, HIF) the target consists of a similar fuel capsule within a cylindrical metal container or "hohlraum" which converts the incident driver energy into x-rays to implode the capsule. For either target, it must be accurately delivered to the target chamber center at a rate of about 5–10 Hz, with a precisely predicted target location.[5,6] The relatively fragile cryogenic targets must survive injection into the target chamber without damage. [7]

The Target Fabrication Facility (TFF) of a laser or heavy ion IFE power plant must supply about 500,000 targets per day. 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.[8,9]

Z-pinch driven IFE (ZFE)[10] utilizes high current pulses to compress plasma to produce x-rays which indirectly heat a fusion capsule. ZFE target technologies differ somewhat from the other IFE concepts in that the repetition rate is only about 0.1 Hz and the target yield is significantly higher (about 3000 MJ per target compared



Some Expected Direct Drive Specifications	
Capsule Material	CH (DVB) foam
Capsule Diameter	~4 mm
Capsule Wall Thickness	290 µm
Foam shell density	20-120 mg/cc
Out of Round	<1% of radius
Non-Concentricity	<1% of wall thickness
Shell Surface Finish	~20 nm RMS
Ice Surface Finish	<1 µm RMS
Temperature at shot	~15 - 18.5K
Positioning in chamber	± 5 mm
Alignment with beams	<20 µm

Fig. 1. Laser fusion baseline high-gain target and expected target specifications.

to about 400 MJ for laser and HIF).[a] In addition to these features, the (baseline) ZFE capsule is made of Be, which leads to some different requirements for Z-pinch driven systems.

II. LASER FUSION

The target supply process for laser fusion, heavy ion fusion, and even ZFE have significant elements in common. The various development programs take advantage of this commonality. The basic requirement for the TFF of a laser fusion power plant is to provide about 500,000 targets per day (at ~6 Hz) with precision geometry, and with precision cryogenic layered DT fuel. The targets include a divinylbenzene foam shell[11] to contain the DT fusion fuel. Density matched microencapsulation has been used in the laboratory to produce these shells. This fabrication step is relatively well-understood and demonstrated, although work remains to scale the process to larger batches and to increase product yields for IFE capsules. The principal technical issues are meeting non-concentricity and out-of-round requirements when fabricating the CH capsules at large diameter and with thick walls. 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 has been demonstrated in the laboratory.[12,13] 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.[14] The principal issue regarding permeation filling with DT is minimizing the tritium inventory "at risk", and thus maximizing the attractiveness of the power plant. Layering,[15,16] is the process of redistributing the cryogenic DT fuel into a smooth uniform layer inside the ablator. Layering requires establishing an extremely precise (~250 µK), uniformly spherical temperature distribution at the surface of the capsule. A cryogenic fluidized bed experiment has been designed to demonstrate this process with hydrogen isotopes in a batch-mode. This concept is for the fluidized bed to rapidly randomize the targets yielding a very uniform time-averaged surface temperature. Layering in a fluidized bed is followed by a very rapid (a few seconds or less) removal of the layered capsule from the bed, and assembly into a sabot for injection. The sabot protects the cryogenic target during injection, and springs apart and is deflected from the capsule trajectory prior to its entering the target chamber. The target in the back half of the sabot is supported by a thin membrane which distributes the load and prevents point-contact loading of the fragile capsule during the ~1000 g acceleration during injection.

A potential option for the laser fusion target that helps protect it from thermal radiation during its injection is a "foam-insulated" target which uses a relatively thin layer of foam to reduce the heat load to the cryogenic DT.[17] This target configuration also has other advantages in that it allows faster permeation filling with DT. The degree of heating of the target during injection is determined by the radiation heating from the first wall and by heating from the gas in the chamber. The pressure of the gas in the chamber for first wall protection is the subject of current trade studies for laser fusion. Modeling of cooling mechanisms for gas within the chamber, the temperature of the gas during target injection, recombination of the plasma after the shot, and the heat flux the target will experience has been initiated.[18] Preliminary results show that heat fluxes of 0.6 to 0.7 W/cm^2 can be obtained only with extremely low gas densities ($<10^{20} m^{-3}$), whereas thermally insulated targets could withstand modest gas densities ($\sim 10^{20}$–$10^{21} m^{-3}$). A large-scale convective motion induced within the chamber was found to be an effective way to speed up the

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[a]A proposed, large ZFE power plant has 12 chambers, with 10 chambers operating at any one time, each chamber at 0.1Hz to produce a total of about 1000 MW(e).

plasma cooling and recombination, by effectively bringing hot particles closer to the wall.

The cost of the target is also a key issue in the IFE target supply. Laser fusion targets have been the subject of the most extensive and well-documented analyses for future target manufacture of all the IFE concepts considered. We have prepared preliminary equipment layouts,[19] and determined floor space and facility requirements for nth-of-a-kind production of high-gain laser-driven IFE targets. The results for a 1000 MW(e) baseline plant indicate that the installed capital cost is about $100M and the annual operating costs will be about $19M (labor $9M; materials/utilities $4M; maintenance $6M), for a cost per target of slightly less than $0.17 each.

To arrive at this cost, a number of process assumptions have been made, based on 1) preliminary requirements for the NRL high gain direct drive targets, 2) discussions with researchers in each of the enumerated process steps to reflect their latest findings, and 3) interactions with vendors of process equipment that is adaptable to this service ~such as critical point driers. The plant conceptual design includes a process flow diagram, mass and energy balances, equipment sizing and sketches, storage tanks, and facility views (plan, elevation, and perspective). The cost estimating process uses established cost-estimating methods and factors for the chemical process industry. Recycle and beneficial reuse of process effluents is designed into the facility. A detailed material and energy balance was prepared to provide information on flow rates and quantities of raw materials, finished products, and byproducts for the entire plant. All of the cost calculations for chemical, utilities, and waste disposal use mass quantities calculated in the material and energy balances. Statistical sampling of target batches will be performed at each process step to avoid unnecessary further processing of out-of-spec targets. Finished dry shells will be sampled at 100% quality assurance in a final flow through step and stockpiled, potentially at a central facility serving multiple power plants. The target would be DT-filled and layered onsite prior to injection. For these cost estimates we make an arbitrary assumption that the final product reject rate is 25%[b]. Plant capital costs are treated as an annual expense. Standard financial treatments result in a levelized charge rate corresponding to an annual expense. Here we assume a 12.5% fixed charge rate for a 30 year facility.

A generous operating staff has been allocated to the laser fusion target production plant. Maintenance expenses are calculated using a factored percentage, 6% per year of installed capital costs. Utilities, waste disposal and chemical costs are calculated based on current day vendor prices coupled with mass and energy balance data. 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. Further details of the laser fusion cost estimating process can be found in Ref. [20].

III. HEAVY ION FUSION

IFE power plant conceptual designs for heavy ion fusion (HIF) have been published over the past several decades.[21,22] A variety of target designs have been analyzed for heavy ion fusion, including the "distributed radiator" design illustrated in Fig. 1,[23] 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. 2 remains the subject of evaluations and studies.[24]

In a previous paper,[25] we described an outline for the entire pathway, from beginning to end, for fabrication of a high-gain, distributed radiator target for energy production. This pathway has been further detailed in Ref. [26]. The capsule[c] supply process is very similar to laser fusion, up to the point where the filled and layered capsule is placed within the sabot for injection – instead the HIF capsule is placed within the prepared, cryogenic hohlraum. A room temperature assembly of the capsule and hohlraum (followed by layering within the hohlraum) is not favored for IFE since void space within the hohlraum would result in up to 30 times more tritium inventory during filling as compared to filling of capsules alone.

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[b]Actual final product reject rates are of course expected to be much less than 25%, and the rejects will take place at various stages throughout the process.

[c]A full density CH capsule is used for HIF.

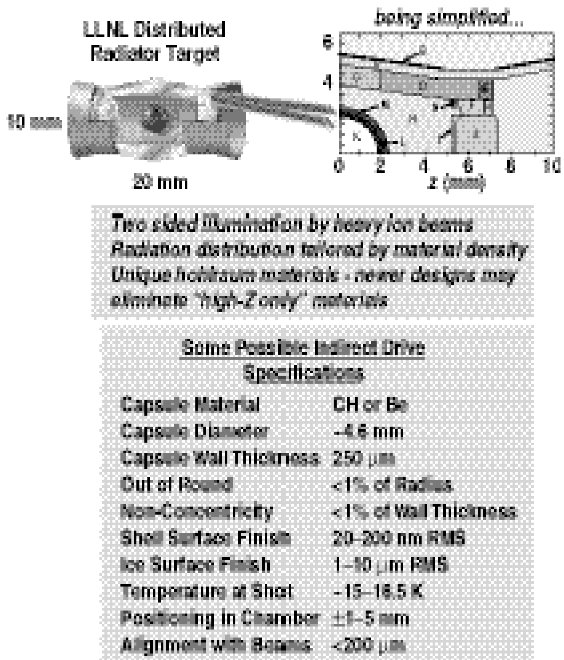

Fig. 2. LLNL distributed radiator target is driven by heavy ion beams.

Using cryogenic assembly, the HIF inventory models indicate that operating with less than ~[illegible]g tritium in the TFF will be feasible.[14]

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[27] 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 hot-foci 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, 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 hohlraum manufacture that minimizes handling and assembly steps with the hohlraum component 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 by maximizing use of the LCVD. A multiplexed laser array produces fibers of the desired material, precursor gas flows are controlled to allow changing materials, even allowing a gradual change of density and material content within the sample. 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 (such as flame spray or plasma spray) 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). A filled, layered capsule freshly taken from a 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.

It is our near-term 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 HIF target fabrication.

A key factor in the cost of the HIF target is the choice of hohlraum materials. A systematic review of available information for all high atomic number elements has been conducted to evaluate candidate hohlraum materials.[24] Effect of materials on target fabrication, energy cost, target gain, radioactivity, chemical toxicity, and potential for recycle were considered. Lead and tungsten are estimated to be the lowest cost acceptable materials. The combination of Pb and W provide better target gain than either material alone. However, precipitation of the W in the primary coolant is a concern (W growth can plug small openings in power plant components such as vacuum tritium disengagers; seeding the primary coolant with sub-micron sized W particles can minimize this but further experiments are needed to assure acceptable use of W). Thus we have prepared a preliminary cost analysis using a 70/30 mixture of lead and hafnium. We have also assumed a process of single use and discarding of the hohlraum materials. This is a key decision of course. Recycling would reduce the volume of radioactive waste streams from the facility, but requires a high level of material purification (for re-use in a hohlraum) and also requires remote (and/or contaminated) manufacturing process steps due to the high activation of the materials.[28] Our preliminary estimate of the cost to provide fully remote handling of the recycled 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.[d] The estimated cost for mass-production of Pb/Hf targets is about $0.41 each.[e] The installed capital cost is estimated at $304 million (38 million annualized cost). 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.

IV. Z-PINCH DRIVEN IFE

In contrast to "injecting" laser and HIF targets into a chamber, ZFE targets are "placed" in the chamber about once every 10 s.[10] The baseline target configuration for ZFE (Fig. 3, designed by Sandia National Laboratory) is centered on a "dynamic hohlraum". At the center of the target assembly is a DT filled beryllium capsule surrounding by low density foam. The foam is sealed and contains helium gas to aid in heat removal from the capsule (DT decay heat). Above and below this foam cylinder are reservoirs of liquid hydrogen. The reservoirs could be made of tungsten. The purpose of the liquid hydrogen is to absorb energy coming into the target assembly during handling. The added heat capacity of the liquid hydrogen allows a reasonable amount of time for insertion of the target assembly into the replaceable transmission line (RTL). A tungsten foil wall surrounds all these items. This wall provides the "First Strike Liner" as required by the target design. It also contains the helium gas and provides a low emissivity radiation heat boundary. A pedestal of low-density foam mechanically supports this assembly. In order to reduce heat leak, this foam has vacuum in its pores. The foam pedestal sits on the RTL sealing plate. This plate is attached to the RTL in order to maintain a vacuum between the RTL cathode and anode. More detailed specifications are still being defined for this target.

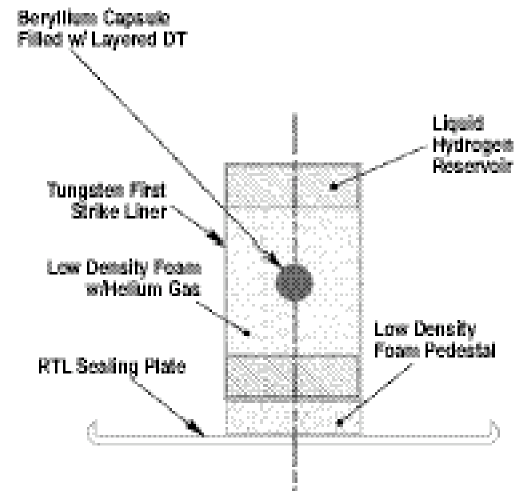

Fig. 3. Z-pinch target assembly from SNL is placed within a "dynamic hohlraum".

Z-Pinch targets represent a variant of the "indirect drive" design. The target assembly (Fig. 3) is surrounded by a concentric wire array. The wire array consists of approximately 300 fine tungsten wires arranged vertically in a cylindrical shape. During the shot, a large current flows axially down the wires. The current creates a large circumferential magnetic field which implodes the wire array towards its center. The wires vaporize from the heating into a plasma, which continues to carry the current. The plasma is accelerated inward until it strikes the outer wall of the target assembly. The target assembly and wire array assembly are inserted into the RTL at a cyrogenic station. In this concept, pre-assembled wire arrays and filled/layered target assemblies are brought into the cryostat. The design allows the vacuum space between the RTL's anode and cathode to be maintained while the assembly process is performed. The RTL is mated with the cryostat in Fig. 4 through the use of an inflatable vacuum-tight seal. Once the gatevalve at the top of the cryostat is opened, the vacuum space between the RTL cups is continuous with the vacuum space inside the cryostat. Robots in the cryostat remove a temporary vacuum sealing plate from the RTL, then insert the wire array Assembly and target assembly into place. A vacuum

[d]The original published target design [22] utilized gold and gadolinium at various densities. The cost would require that these materials be recycled. We therefore evaluated lower cost hohlraum materials that could be used in a "once-through" cycle and then discarded as low level waste.

[e]The Pb/Hf mixture results in about a 2% plant energy loss (as compared to the original Au/Gd), 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.

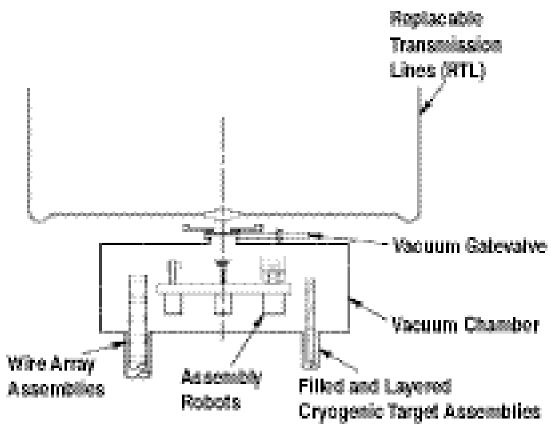

Fig. 4. Cryogenic station for assembly of wire arrays and targets for Z-pinch IFE.

seal is made by welding (or snap joints) at the lower RTL electrode where it contacts the target assembly, then the entire unit is removed from the cryostat and placed into the reactor chamber[f]. A simple thermal analysis of the cooling capacity of the hydrogen buffers (sized as shown in Fig. 3) show that the total time from when a target assembly is removed from the cryostat until it is shot, must be less than 38 s. This time is divided up into 34 s exposed to room temperature and 4 s exposed to a temperature of 900 K (i.e., when exposed to the hot chamber for final placement).

The mass-production of a beryllium capsule for the Z-Pinch target is a significant departure from previously developed technologies (or those under development), as compared to laser fusion and HIF. A possible process for mass-producing the Be capsule involves methodologies similar to those used to make aluminum soft drink cans. Rolled sheets of Be with a thickness slightly greater than the required capsule wall thickness is cut into circular disk shapes using a stamping process. The Be disks are hot forged at about 800°C to form hemispheres, and the edges of the hemispheres are trimmed to form a clean planar bonding surface. Holes of about 0.5 μm diameter are drilled into one half, and the edges are coated with about 0.025 μm of copper. The hemispheres are assembled together into a sphere, then pressed together and heated to about 900°C to bond them into a capsule (via diffusion of the copper into the beryllium). The capsules are batch-filled with DT in a pressure cell, and the holes are sealed by laser welding through a window in the cell. Use of the Be capsule for the Z-Pinch target simplifies the entire target assembly process since (a) the target can be filled and the Be can withstand the fill pressure at room temperature (i.e., avoids cryogenic transport after filling) and (b) the much higher thermal conductivity of the Be capsule wall greatly simplifies the requirement for uniform isothermal temperature control during the layering process (i.e., one can just cool an entire assembly and uniform temperature around the capsule will occur).

While the Be capsule for ZFE offers significant advantages, the proposed process for mass-production has not been experimentally evaluated, and most steps of the process can be characterized as "conceptual". Another option is to utilize a CH polymer capsule similar to HIF. In this case, the capsule must be cooled to cryogenic temperatures prior to removal from the pressure (permeation filling) cell, it must be transported cryogenically, and the layering process must provide a highly isothermal environment. One sequence to allow use of CH capsules takes advantage of the synergism between ZFE and laser fusion development programs. The CH capsule is permeation filled and is then layered in a cyrogenic fluidized bed system. The filled, layered capsule is then "quickly" assembled into the dynamic hohlraum target assembly with the liquid hydrogen thermal buffer cans at each end for cooling. The foam is pre-formed to allow for positioning of the capsule within the target assembly. While each of the two approaches, Be or CH capsules, have uncertainties and require significant development, they represent promising design concepts that indicate the feasibility of utilizing a Z-Pinch system for producing energy.

On the same basis for costing as described above for laser fusion and HIF, we performed preliminary analyses of methods for the mass production of foam cylinder assemblies (foam plus capsule) to be used in the target assembly of a Z-Pinch driven power plant. Assumptions were made on the design of the target assemblies, their required production rate [1 Hz (equivalent for ten chambers, 1000 MW(e))], and their manufacturing process. Current foam production techniques were scaled up to mass production levels. Costs were calculated for ten categories of capital equipment. Operating costs were calculated for labor, consumable materials, electrical power, maintenance, and waste disposal. The results for a 1000 MW(e) baseline plant indicate that the installed capital cost is about $17.8M, and the annual operating cost is about $19.5M. The corresponding cost estimate per target is estimated at $1.83 each. Given the proposed target design of 3 GJ yield per target (about $22.50 worth of electricity), this preliminary result represents a little more than 8% of the energy value. Additional optimization of the mass-production process could be expected to further reduce this estimated cost. Of course, the additional components of the wire array and the RTL must be considered in a total fueling cost estimate.

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[f]The equipment to transport the RTL's into place has been referred to as "elevator technology".

V. SUMMARY AND CONCLUSIONS

At present, individual targets used in inertial confinement fusion experiments are produced with considerable time and expense. In contrast, the "Target Fabrication Facility" of a laser fusion or heavy ion driven IFE power plant must supply more than 500,000 targets per day, including manufacturing the spherical target capsule and other materials, filling the capsules with the DT fusion fuel, redistributing the frozen DT uniformly around the inside of the capsule, and assembling the hohlraum (for heavy ion fusion). Demonstrating a credible pathway to a reliable, consistent, and economical target supply is a major part of establishing that IFE is a viable energy source. We have presented here an overview of the proposed baseline target manufacturing methodologies that have been derived from the development programs associated with fueling of an IFE power system. These development programs focus on the unique materials science and chemistry for each target design. We have prepared preliminary estimates of the costs associated with producing large quantities of targets, and we found that these costs are within the range of commercial feasibility. This is a significant conclusion for the viability of future inertial fusion power plant concepts.

Over the next several years, we can expect to see target concepts further defined with detailed process scenarios, and we can expect to see targets meeting specifications that are produced using equipment and processes that are scalable to mass production. For target injection, a new and versatile facility for studying injection and tracking has been constructed and room-temperature target injection experiments have begun, both single shot and rep-rated. The system has successfully demonstrated the sabot separation needed for handling of direct drive targets. We have defined the characteristics and requirements of a next-phase project to validate the technology of full-scale components for direct drive[29] Elements of the facility include mass production (in batch mode) of cryogenic targets, injection into the chamber (under simulated background gas and wall temperature conditions), and steering of a low-energy pulsed laser onto the target in flight.

Overall, reference target designs, issues and R&D needs have been identified and a program of concept demonstration is well underway. Much progress has been made in defining mass production scenarios for laser, heavy ion, and Z-Pinch driven IFE and addressing the science and technology issues for target fabrication and injection. Although much work remains to be done, our initial results are promising and suggest that a credible pathway to a reliable, consistent and economical target supply is within reach.

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