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COST-EFFECTIVE TARGET FABRICATION 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 IFE target fabrication programs are focusing on methods that will scale to mass production, and working closely with target designers to make material selections that will satisfy a wide range of required and desirable characteristics. Targets produced for current inertial confinement fusion experiments are estimated to cost about \$2500 each. Design studies of cost-effective power production from laser and heavy-ion driven IFE have found a cost requirement of about \$0.25–0.30 each. While four orders of magnitude cost reduction may seem at first to be nearly impossible, there are many factors that suggest this is achievable. This paper summarizes the paradigm shifts in target fabrication methodologies that will be needed to economically supply targets and presents the results of “nth-of-a-kind” plant layouts and concepts for IFE power plant fueling. Our engineering studies estimate the cost of the target supply in a fusion economy, and show that costs are within the range of commercial feasibility for laser-driven and for heavy ion driven IFE.

I. INTRODUCTION AND REQUIREMENTS

A central feature of an Inertial Fusion Energy (IFE) power plant is a target (Fig. 1) 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, energy is applied directly to the surface of a spherical capsule² containing the deuterium-tritium (DT) fusion fuel at approximately 18 K. For indirect drive,³ 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. The target must be accurately delivered to the target chamber center at a rate of about 5–10 Hz, with a precisely predicted target location.⁴ The relatively fragile cryogenic targets must survive injection into the target chamber without damage. The Target Fabrication Facility (TFF) of an 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 10⁴ less than current costs) is a critical issue for inertial fusion. The top-level requirement is the ability to provide targets filled with DT ice at ~18.5 K, and meeting the geometric requirements, and deliver them accurately and repeatedly to the center of a high-temperature target chamber at a high rate.

II. MANUFACTURING APPROACHES

There are tremendous differences in the criteria and requirements for current-day experimental targets and those anticipated for high-volume manufacturing of IFE targets. Consequently, major new “paradigms” must be incorporated into the manufacturing approaches for Inertial Fusion Energy. The first major step is to think in terms of continuing process improvement, but with a constant product line. This eliminates the highly significant development (first-of-a-kind) costs for experimental targets. Secondly, statistical process control will be employed along with rapid “quick-check” methods to ensure the validity of each target prior to injection. This eliminates the major costs due to individual characterization of current day targets. Thirdly, ongoing target technology development programs will result in

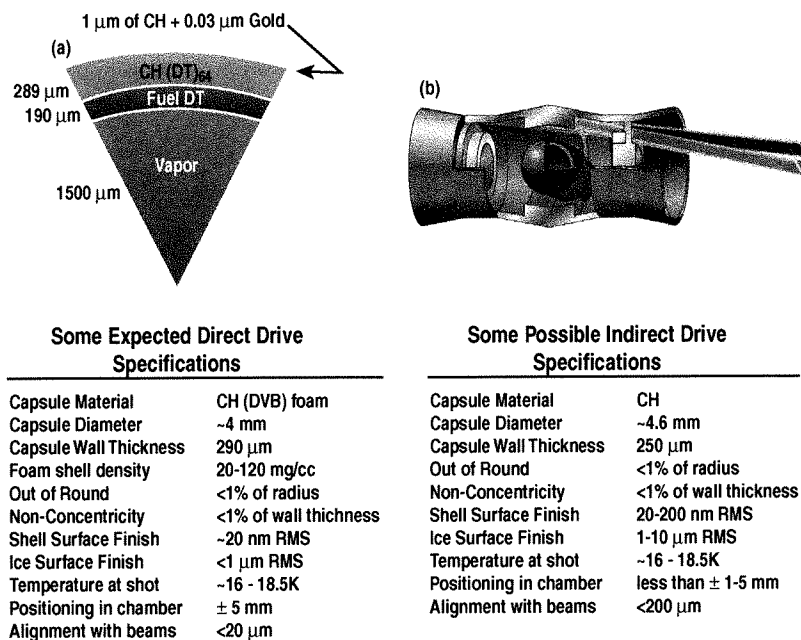


Fig. 1. Reference target designs have been identified.

increased product yields and, finally, nth-of-a-kind plants will naturally operate with larger batch sizes. These factors will all contribute to major cost reductions for mass-production of targets.

III. PROCESS DESCRIPTION

There are many steps leading to a filled, layered target ready for injection. First, the highly spherical and concentric capsule must be manufactured. The direct drive target (foam capsule) is based on a divinyl benzene foam^{5,6} with a density of about 100 mg/cc. These foam capsules are made with a dibutyl phthalate foam solvent and a 2,2' azo-bis-iso-butyronitrile initiator for subsequent DVB cross-linking. Water is inside the foam capsules during a "microencapsulation" process utilizing a droplet generator, and water/polyvinyl alcohol is on the outside. The partially cross-linked capsules are heated for full polymerization, then isopropanol is transferred into the inner part (the alcohol is sufficiently miscible in both water and oil to facilitate a transition from inner water to inner oil (parachlorotoluene). The inner oil provides a medium for dissolution of Monomer A (isophthaloyl dichloride); then water/surfactant replaces the oil outside the targets to prevent sticking and provide an aqueous medium for Monomer B (poly 4-vinyl phenol). These two monomers form a thin (1-5 μm) "seal coat" at the oil/water interface on the target surface. Isopropanol is sufficiently miscible in both oil (parachlorotoluene) and CO₂ to facilitate the transition from inner oil/outer water to CO₂ both inside and outside the capsule. Liquid subcritical CO₂ (10°C, 800 psig) replaces the inner isopropanol by countercurrent stagewise dilution contacting. The resulting liquid CO₂

filled capsules are heated beyond the CO₂ critical point (31°C, 1070 psig) to reduce surface tension to zero and prevent fracturing during the final "drying" process.

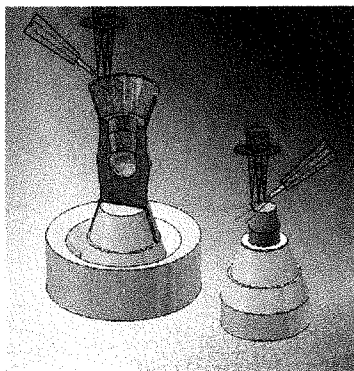
For direct drive targets, a thin gold and palladium coat is added to the capsule outer surface by a physical vapor deposition process. This Ag/Pd coating is about 30 to 100 nm thick; the addition of Pd to the coating has been shown to greatly increase its permeability (thus allowing rapid filling with DT). In addition, an outer "insulating" foam layer may be added to provide increased thermal robustness during the (later) injection into a target chamber. The capsule must be filled with a mixture of deuterium and tritium as the fusion fuel. The filling is done by permeating the DT through the capsule wall in a controlled manner (to prevent buckling) in a high pressure cell. Once the capsule internal density reaches the required value, the cell is cooled down to approximately 20 K to condense the fuel and reduce the internal pressure sufficient to allow removal of the excess DT outside the capsule. The filled capsules, which now must be handled cryogenically, are then placed in an extremely isothermal temperature environment to redistribute the DT into a highly uniform layer on the inner surface of the capsule (a process called "layering"). One method to achieve the required isothermal environment is a cryogenic fluidized bed,⁷ which provides a highly uniform time-averaged surface temperature for the capsule. Once layered, in the case of direct drive, the capsule is removed from the fluidized bed and quickly placed into a sabot to protect it during acceleration for injection into the target chamber. An electromagnetic accelerator or light gas gun is then used to bring the target up to injection velocity. The sabot is removed prior to entering the high temperature chamber.

In the case of indirect drive targets, the hohlraum components must also be provided and assembled.⁸ After manufacture, the target is injected into the target chamber. The DT layer must survive the exposure to the rapidly increasing heat flux, remain highly symmetric, and have a smooth inner ice surface finish. The final target design (e.g., the surface reflectivity, the heat capacity, amount of insulation, etc.) and injection conditions (e.g., velocity, initial temperature, chamber environment) must facilitate target survival. Target placement must be within a specified "box" at the chamber center (i.e., within the reach of beam steering). In addition to the placement, target tracking must be accurate enough to enable precise alignment of the driver beams with the actual target position. The accuracy requirement for indirect drive targets is alignment of the driver beams and the target to within approximately ± 0.1 mm perpendicular to the injection axis and about ± 0.3 mm along the injection axis. Direct drive targets will require alignment of the centerline of the driver beams with the centerline of the target to less than about ± 0.02 mm.

For indirect drive targets (Fig. 1), the polystyrene capsule is fabricated by a similar microencapsulation process, then the hohlraum components are prepared from the "inside out" using a Laser-Assisted Chemical Vapor Deposition (LCVD) process (Fig. 2). This allows precise control of the hohlraum component density and geometry, and avoids precision machining and assembly steps.

IV. TARGET FABRICATION FACILITY DESIGN AND COSTING ANALYSIS

Long-term R&D programs will be needed to develop production processes that can manufacture targets at low



Summary of Process Steps

- 1) Fabricating the spherical capsule
- 2) Fabricating the hohlraum case
- 3) Fabricating the radiators
- 4) Filling the capsule with fuel
- 5) Cooling the capsule to cryo
- 6) Layering the DT into shell
- 7) Assembling the cryo components
- 8) Accelerating for injection
- 9) Tracking the target's position
- 10) Providing steering/timing info

Fig. 2. Heavy ion fusion target fabrication process.

cost. Major paradigm shifts and 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. 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. To help identify major cost factors and technology development needs, we have utilized a classical chemical engineering approach to the TFF. 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 500,000 targets per day. We have prepared preliminary equipment layouts, and determined floor space and facility requirements. The purpose of this is not to provide a final plant design, rather to show that production of targets at the required throughput rates and at low cost is feasible. 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 doing these steps is not included in the TFF 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.

IV.A. Direct Drive Target Cost Analysis Results

We have prepared preliminary equipment layouts (Fig. 3), 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.

IV.B. Indirect Drive Target Cost Analysis Results

Compared to the direct drive target, the heavy ion driven, distributed radiator design has additional hohlraum components — but has a simpler capsule design. Changes to the original target design to reduce manufacturing costs are underway. Final choices for the hohlraum materials are still being evaluated, and individual target materials may or may not be recycled. Recycling reduces the radioactive waste streams from the facility, but requires a higher level of material purification and also requires remote (and/or contaminated) manufacturing process steps. Assuming a polystyrene capsule and use of a Pb/Hf mixture for the hohlraum components (and no near-term recycling of hohlraum materials), the estimated cost for target mass-production is about \$0.41 each. 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.

- Chemical engineering approach to Target Fabrication Facility (TFF)
- Costing is done for an “nth-of-a-kind” plant
- Results guide process development

Major Parameters

- 500,000 targets per day
- 2-3 weeks on “assembly line”
- Installed capital of \$97M
- Annual operating cost of \$19M
- Cost per injected target estimated at 16.6 cents

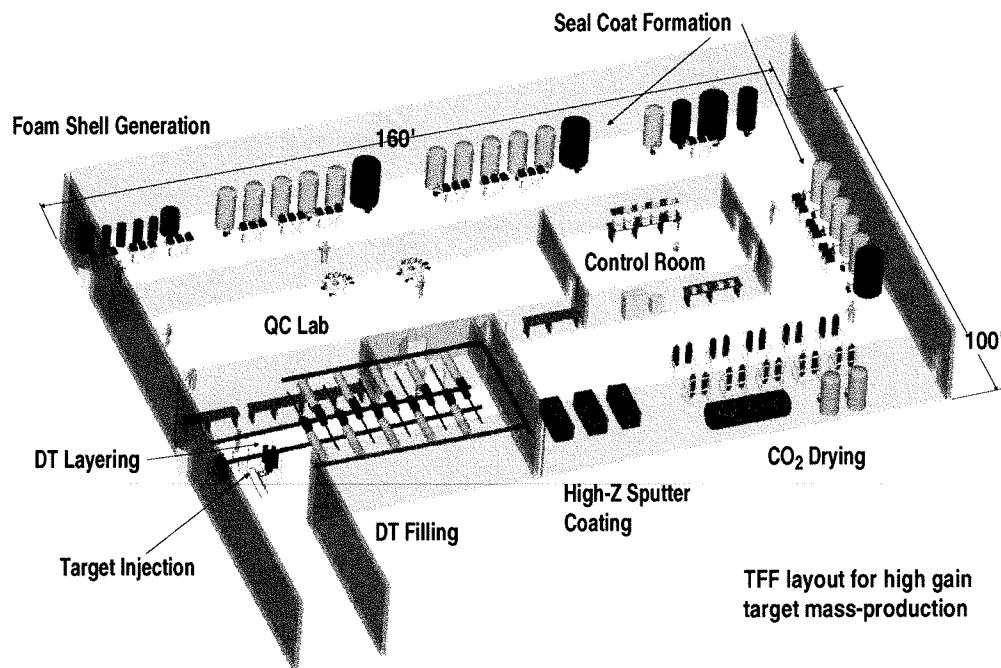


Fig. 3. Estimated cost of laser-driven high-gain target mass-production is less than \$0.17 each.

The Pb/Hf mixture entails an energy penalty in the gain of the target, and other materials may eventually be preferred.^a Pb/Hf allows once-through use then disposal of the materials. Other materials, with higher procurement or disposal costs may necessitate recycling. Requiring near-term recycling of hohlraum materials adds significantly to the per-target cost, due to the need for remote handling and maintenance in the facility.

V. CONCLUSIONS

An initial estimate for capital and operating costs for a Target Fabrication Facility to support Inertial Fusion Energy, both laser-driven and heavy ion driven, has been

prepared. The results show that targets are within the range of commercial feasibility for fusion energy.

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^aTungsten is another potential hohlraum material that would reduce the chemical toxicity concerns of using Pb/Hf. However, tungsten will precipitate as a solid from the molten salt coolant and removal systems must be provided in the primary coolant circuit. The energy penalty would also be greater for tungsten as compared to Pb/Hf.

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