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ABSTRACT

The "Target Fabrication Facility" (TFF) of an IFE power plant must supply about 500,000 targets per day. The targets are 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. To help identify major cost factors and technology development needs, we have utilized a classic chemical engineering approach to the TFF. The analyses assume an "nth-of-a-kind" TFF and utilize standard industrial engineering cost factors. The results indicate that the direct drive target can be produced for about $0.16 each. Iterations are still underway for the indirect drive target. These cost analyses assume that the process development is accomplished to allow scaling of current laboratory methods to larger sizes, while still meeting target specifications. A development program is underway at various laboratories to support this scale-up.

I. INTRODUCTION AND BACKGROUND

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. For direct drive IFE, energy is applied directly to the surface of a spherical capsule[1] containing the deuterium-tritium (DT) fusion fuel at approximately 18 K. For indirect drive,[2] 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.[3] 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 10^4 less than current costs) is a critical issue for inertial fusion.[4]

II. TECHNICAL ISSUES AND REQUIREMENTS

The top-level critical issue 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. First, the highly spherical and concentric capsule must be manufactured, then it 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 shell on the inner surface of the capsule (a process called "layering"). One method to achieve the required isothermal environment is a cryogenic fluidized bed,[5] which provides a highly uniform time-averaged surface temperature for the

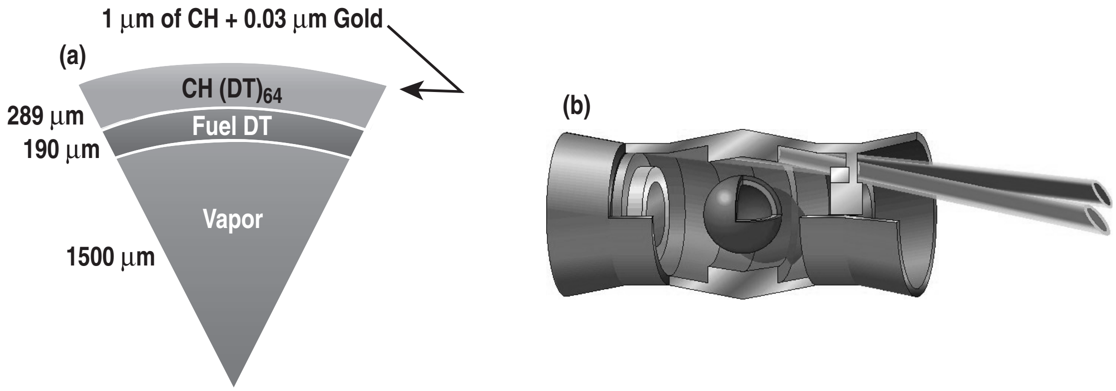

Fig. 1. (a) Laser driven direct drive high-gain target for IFE designed at NRL, (b) heavy-ion driven indirect drive target for IFE designed at LLNL.

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.[9]

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.[a] 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.

III. THE EVOLUTION OF TARGET MANUFACTURING METHODOLOGIES AND PROCESSES

As is the case for bringing most commercial products from initial concept through developmental and prototype stages to mass-production, IFE target fabrication must evolve from one-of-kind, highly characterized production to optimized and sustained high-volume manufacturing of an (essentially) unchanging product. The root cause behind Moore's Law, which predicts that micro-processor power doubles about every 18 months, is that significant and substantial new manufacturing processes, methodologies, and facilities are continually and rapidly being installed in the micro-processor industry. Target manufacturing processes must similarly undergo an evolution to new methodologies. Current production of targets for experiments, which is done at a cost that is estimated to be about four orders of magnitude greater than the IFE cost goal, focuses on unique and highly characterized individual products. To reduce costs to IFE goals, we have identified four major paradigm shifts that must be implemented to begin the evolution to mass-production. We elaborate below on these four major changes in production.

i. Paradigm Shifts Reducing the Costs of Target Production

There are tremendous differences in the criteria and requirements for current-day targets and those anticipated for high-volume manufacturing of IFE targets.[6] Given these differences, the major steps for cost reduction for IFE targets are summarized below:

1. Eliminating First-of-a-Kind (FOAK) Costs. Currently delivered targets for experiments are nearly always unique, with most of the labor going to development and trial runs. In contrast to this, the FOAK cost for IFE production will be almost non-existent (some small on-going process improvement cost can always be expected).

2. Reduction in Characterization Costs. Current experimental targets are supplied with what may be referred to as an individual "pedigree" (many pages of

[a]The relaxed requirement along the injection axis is due to the narrow angle from which the beams approach along this axis.

detailed characterization data that goes along with an individual target). Statistical process control will be employed in the TFF based on a defined sampling plan. And, likely, rapid "quick-check" methods will be employed to ensure the validity of each target prior to injection.

3. Increasing Yields. Consistent with the constantly changing specifications for experimental targets discussed above, current yields are quite low. The goal of the IFE target fabrication programs must be to provide sufficient development to achieve product yields in the vicinity of 95% or greater. This increase in yield is a quantitative criteria to define the development program.

4. Batch Size Increases. Similar to increases in yield, a requirement for the target technology development program is to provide processes that can operate at large batch sizes (or continuous processes) with minimal labor.

IV. TARGET FABRICATION FACILITY DESIGN AND COSTING ANALYSIS

We view the reduction in IFE target fabrication costs as analogous to "Moore's Law." That is, major paradigm shifts and evolution in manufacturing technology will continually reduce the costs of each target. As one set of manufacturing processes is optimized for minimal capital, labor, and materials costs, we expect that there will be breakthroughs – or major leaps – in technologies for production. This means, of course, that estimating the cost of targets requires one to select a single time frame in the larger picture of target manufacturing evolution. 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. As is expected for typical commercial processes, one can expect additional major shifts in future target manufacturing that could reduce costs even further.

i. Direct Drive Target Cost Analysis Results

We have prepared a chemical engineering analysis of all of the process steps needed to mass-produce direct drive targets having gains suitable for commercial fusion in a laser driven system.[7] 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 direct-drive high-gain targets per day. A number of process assumptions have been made, and are based on preliminary requirements for the direct drive high-gain target that have been derived in conjunction with the NRL target designers, discussions with researchers in each of the enumerated process steps to reflect their latest findings, and interactions with vendors of process equipment that is adaptable to this service (such as critical point driers). We have prepared preliminary equipment layouts (Fig. 2), 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 assume an "nth-of-a-kind" TFF and utilize standard industrial engineering cost factors. In short, 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 $20M, for a cost per target of slightly less than $0.17 each.

ii. Indirect Drive Target Cost Analysis Results

Compared to the direct drive target, the distributed radiator design has some components that will be lower cost to manufacture and some that will be higher. Changes to the original target design[2] to reduce manufacturing costs have been evaluated.[8] While final choices for the hohlraums materials are still being evaluated, selections must include consideration of (a) target design and physics, (b) target manufacturing costs, (c) ability – and costs – to remove the materials from the primary coolant circulating loops, (d) undesirable interactions of the materials with structural materials in the reactor, (e) activation and generation of high-level waste and (f) environmental safety and health. 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. Selections to date include the choice of polystyrene as the capsule material, which reduces the cost of manufacturing the beryllium/bromine capsule that was originally proposed.[9] Hohlraum material selections are still underway. Building on the work performed for the direct drive target, we have completed a partial analysis of the indirect drive target, estimating the cost of manufacturing the thick-walled polystyrene capsule, filling it with fusion fuel, and layering the DT. These steps are estimated to cost about $0.11 per target in a future commercial production basis. This result is also encouraging in that considerable cost margin remains for the manufacture of the hohlraum components and performing the hohlraum and capsule assembly steps. Future work will focus on evaluating these steps in conjunction with target designers, and arriving at cost-effective selections of materials and manufacturing processes.

V. RESEARCH AND DEVELOPMENT PROGRAM

These cost analyses assume that the process development is accomplished to allow scaling of current

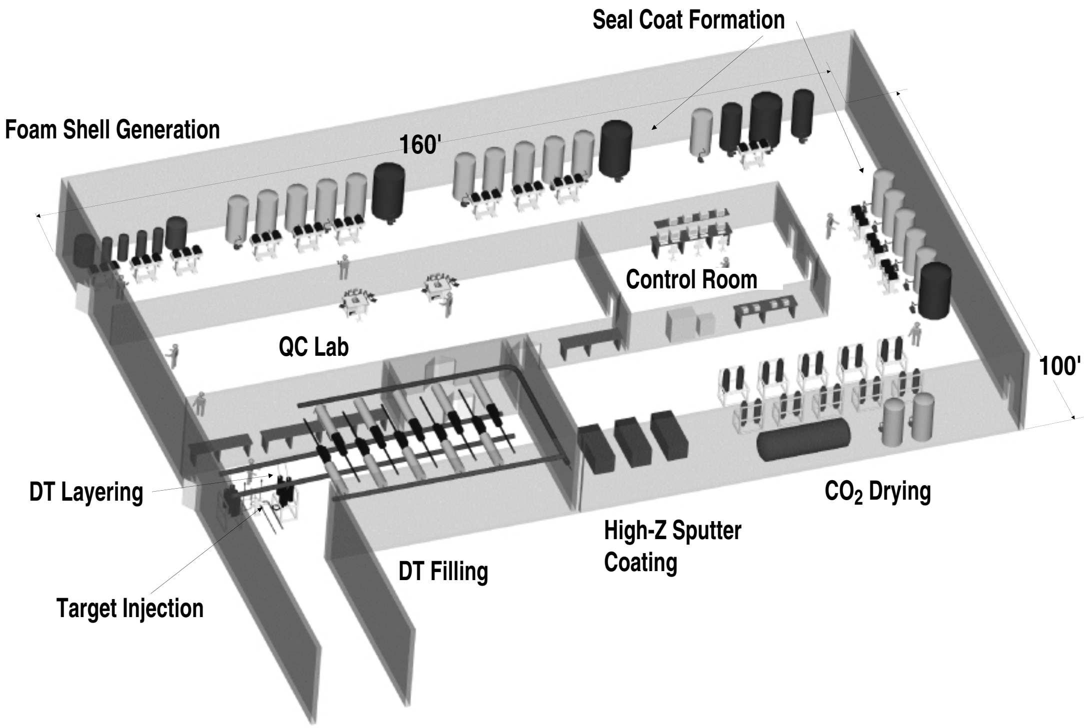

Fig. 2. Preliminary layout of direct drive target mass-production facility.

laboratory methods to larger sizes, while still meeting target specifications. A development program is underway at various laboratories to support this scale-up.[5,10,11]

The program includes development of methods to produce foam shells by microencapsulation, measurements and analyses of permeation filling of the shell with DT fusion fuel, studies of cryogenic fluidized beds for layering of the fuel, and construction of a precision injection and tracking system to demonstrate that proper placement of the final cryogenic target can be accomplished. While IFE power plant design studies have suggested potentially plausible overall scenarios for both direct drive and indirect drive target fabrication and injection, the purpose of the target development program is to provide the detailed scientific basis that will be necessary for fueling of future IFE power plants.

VI. SUMMARY AND CONCLUSIONS

The ability to economically manufacture and inject cryogenic targets is a significant feasibility issue for future inertial fusion energy power plants. A broad-based materials research and process development program is underway, both in the U.S. and internationally, to address this feasibility issue. The 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. Preliminary estimates of the costs to manufacture targets, in a future commercial power plant environment, indicate that cost goals for economical electricity production can be met. To help identify major cost factors and technology development needs, we have utilized a classic chemical engineering approach to the TFF.

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