Developing a commercial production process for 500 000 targets per day: A key challenge for inertial fusion energy[a)]

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As is true for current-day commercial power plants, a reliable and economic fuel supply is essential for the viability of future Inertial Fusion Energy (IFE) [*Energy From Inertial Fusion*, edited by W. J. Hogan (International Atomic Energy Agency, Vienna, 1995)] power plants. While IFE power plants will utilize deuterium-tritium (DT) bred in-house as the fusion fuel, the "target" is the vehicle by which the fuel is delivered to the reaction chamber. Thus the cost of the target becomes a critical issue in regard to fuel cost. Typically six targets per second, or about 500 000/day are required for a nominal 1000 MW(e) power plant. The electricity value within a typical target is about $3, allocating 10% for fuel cost gives only 30 cents per target as-delivered to the chamber center. Complicating this economic goal, the target supply has many significant technical challenges—fabricating the precision fuel-containing capsule, filling it with DT, cooling it to cryogenic temperatures, layering the DT into a uniform layer, characterizing the finished product, accelerating it to high velocity for injection into the chamber, and tracking the target to steer the driver beams to meet it with micron-precision at the chamber center.
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I. INTRODUCTION AND SUMMARY

Over the past 10–15 years the worldwide Inertial Confinement Fusion (ICF) programs have developed the technologies needed to fabricate the small quantities of targets needed for inertial fusion and high energy density physics experiments. These programs are directed towards providing the targets that will be needed in the next 5–10 years to achieve ignition on the National Ignition Facility (NIF) (Ref. 1) and Laser Megajoules (LMJ).[2] While fabricating an ignition-quality target (even in small numbers) is still under development today, this effort has provided methodologies for producing highly spherical capsules, filling capsules with deuterium-tritium (DT) and forming smooth DT ice layers. Inertial Fusion Energy (IFE) target development programs are leveraging the ICF technological base to address the target fabrication issues that are unique to IFE targets, and to develop the understanding needed to produce targets in large quantities and deliver them to the center of a target chamber. Using this leveraged approach, the IFE target fabrication programs are well along in their near-term goal of showing the fundamental feasibility of a mass-production target supply.

Overall, the processes needed for supplying targets to fuel an IFE power plant have been identified and the critical issues for development are understood. Foam capsule production methods for laser IFE targets have been developed, but further work is needed to improve capsule quality, yield, reproducibility, and large-scale production. Experiments with surrogate materials to demonstrate layering with multiple targets in a fluidized bed have shown promise and these proof-of-principle demonstrations are being extended to cryogenic temperatures and hydrogen isotopes in new experimental equipment. A new and versatile facility for studying target injection has been constructed and room temperature experiments have been conducted at 6 Hz demonstrating sabot separation under vacuum and the high velocities needed for injecting into high temperature IFE chambers.

II. TARGET DESCRIPTION AND SPECIFICATION

A central feature of an IFE power plant is a target (Fig. 1 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.[3] For direct drive IFE,[4] energy is applied directly to the surface of a spherical CH polymer capsule[5] containing the (DT) fusion fuel at approximately 18 K. 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.[6,7] The relatively fragile cryogenic targets must survive injection into the target chamber without damage.[8] The Target Fabrication Facility (TFF) of an IFE power plant must supply about 500 000 targets per day. The feasibility of devel-

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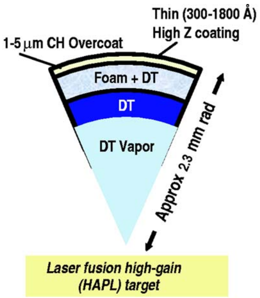

Some Expected Direct Drive Target Specifications	
Capsule Material	DVB foam
Wall Thickness	~ 175 μm
Foam shell density	~100 mg/cc
Non-Concentricity	<1% of wall
Shell Surface Finish	~20 nm RMS
Ice Surface Finish	~1 μm RMS

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

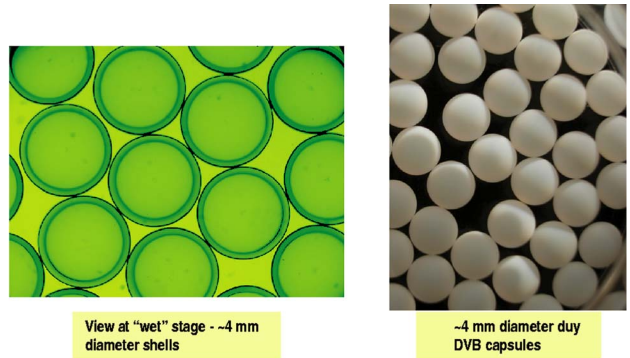

FIG. 2. Divinyl benzene foam capsules for laser fusion baseline target.

oping successful fabrication and injection methodologies at the low cost required for energy production (about \$0.25–0.30/target, about 10^4 less than current costs) is a critical issue for inertial fusion.[9,10]

The baseline high gain target design from the Naval Research Laboratory is made up of a low density foam capsule of about 4.6 mm outer diameter that has been overcoated with a "seal coat" of $\sim 5\ \mu$m of the CH polymer. A foam system of divinyl benzene is being developed for this foam shell; advantages include its relatively high strength and lack of oxygen in the chemical composition. The seal coat[11] has an additional few hundred angstroms layer of high-Z material applied which will increase the reflectivity of the cryogenic target in the infrared during injection into a high temperature chamber.[12] Figure 1 shows the baseline target geometry and expected specifications for this design. The geometric specifications of nonconcentricity, out-of-round, and surface smoothness are critical for meeting the requirements for implosion symmetry. After filling and layering of the DT (Process Description, Sec. III), the cryogenic foam capsule is placed into a sabot to allow acceleration for injection.

III. PRODUCTION PROCESS DESCRIPTION

Microencapsulation is used to produce the spherical capsule that is at the heart of laser fusion targets. It utilizes a multiple orifice droplet generator that can produce capsules at high rates and is thus highly suited to mass production for IFE. Microencapsulation is being extended to the divinyl benzene chemical system for the U.S. Naval Research Laboratory (NRL) high-gain direct drive target. This foam is of interest due to its chemical composition, only carbon and hydrogen, plus its potential to reach low densities ($10–100\ \mathrm{mg/cm^3}$) while maintaining relatively low cell sizes (a few microns). Divinyl benzene foam shells (Fig. 2) are made using dibutyl phthalate as the solvent and 2, 2′-azobisisobutyronitrile initiator for divinyl benzene cross-linking. The divinyl benzene is partially reacted, then microencapsulated with an interior water drop and an exterior polyvinyl alcohol aqueous stripping solution. The polymerization is completed by heating with rotation (to increase the shell uniformity). After a series of washes and fluid exchanges, supercritical CO_2 is used to finally dry the shells. A thin gold and/or palladium coat is added to the shell outer surface by a physical vapor deposition process (sputter coating). This Au/Pd coating is about 30–100 nm thick; the addition of Pd to the high-Z layer has been shown to greatly increase its permeability (thus allowing 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 (if chamber conditions require it).

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 well demonstrated in the laboratory.[13,14] Precise control of the pressure differential across the shell during filling is necessary to prevent "buckling" of the shell wall during the permeation process. Estimates of the DT filling (and layering) time and models to predict its effect on tritium inventory in a future Target Fabrication Facility have been prepared.[15] Layering,[16,17] the process of redistributing the cryogenic DT fuel into a smooth uniform layer inside the ablator has a critical effect on the performance (gain) of the target. Layering requires establishing an extremely precise ($\sim 250–500\ \mu$K), uniformly spherical temperature distribution at the surface of the capsule. A cryogenic fluidized bed (Fig. 3) is being evaluated experimentally for the capability to provide this temperature environment. The basic concept is for the fluidized bed to rapidly

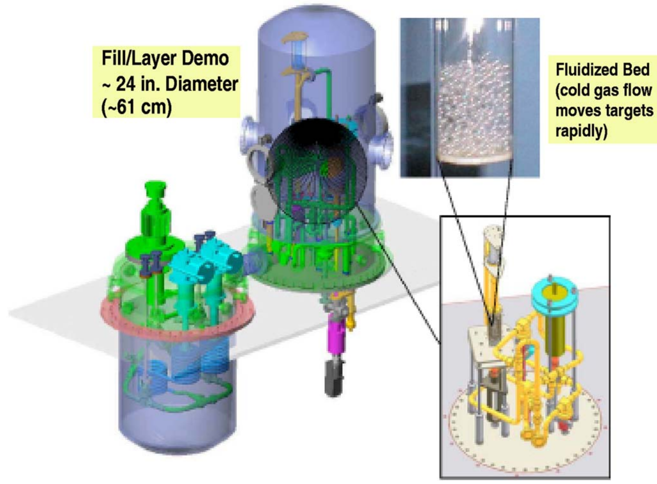

FIG. 3. Cryogenic fluidized bed experiment will show the basic feasibility of batch layering with hydrogen isotopes.

FIG. 4. Injection demonstration to simulate the full-length of a laser IFE fueling system, based on the Sombrero laser fusion power plant.

randomize the targets yielding a very uniform time-averaged surface temperature. Preliminary design calculations for a power plant target supply system shows that fluidized beds are of reasonable size.

The DT layering process is still under development at several institutions as part of the ICF program, and layering also has technical issues unique to IFE that must be addressed in the IFE technical programs. For example, it is desirable to cool the layered target as low as possible before injection to increase its strength (for acceleration) and to provide margin for heatup during its transit across a high temperature chamber. However, it is known that cooling to temperatures significantly below the triple point causes a roughening of the layered DT. This is a tradeoff that is currently being evaluated with DT layering experiments in the IFE program; it has been shown that a foam underlay (as in the IFE foam capsule target) can allow cooling to lower temperatures without significant roughening of the DT. Experiments in the program are continuing to determine the extent of this effect to a full-size IFE target. An additional issue with DT ice in foam capsules has been observed with small pore size foams; the contraction of DT from liquid to solid during cooling can leave voids in the foam pores (turning optically clear foam to opaque). Such voids are likely to be unacceptable from a physics viewpoint, and may require optimization of the foam pore size and sufficient time to allow ice redistribution to fill these voids.

Target injection must provide for repetitive placement of the filled, layered cyrogenic target at the chamber center to within ±5 mm of a specified point at a rate of approximately 5–10 Hz. Target tracking systems must allow alignment of all driver beams with the target centerline to within about ±20 μm. A system to study target injection and develop precise tracking methods has been constructed and tests are underway (Fig. 4). The system has been used to accelerate surrogate direct drive targets to appropriate velocities, begin tracking of these targets with highly accurate systems, and to demonstrate the concept of the separable sabot (under vacuum and at high speed). These tests have been done both in single-shot mode and in bursts of up to 5 shots at 5–6 Hz.

The ability to withstand the thermal transient and survive injection is a main issue associated with the target supply for a direct drive system.[8] Following injection in the chamber, the target is exposed to heating from energy-exchange with the chamber fill gas and from chamber wall radiation. The target must accommodate the resulting heat fluxes and maintain a high degree of spherical symmetry and surface smoothness to satisfy the physics requirements of implosion. The maximum heat flux that can be accommodated by the target (assuming it starts at ~16 K and the outside DT surface temperature cannot exceed the triple point) is about 0.6–0.7 W/cm^2 for a typical flight time of ~15 ms. This can be met if the outside of the target is highly reflecting (emissivity <0.05), the chamber wall is less than 1000 °C, and the density of the gas in the chamber is less than 10 mTorr (Xe at standard temperature). Currently, calculations of larger diameter chambers and magnetically protected walls are under way that can reduce the gas in the chamber to less than 1 mTorr, thus reducing substantially the convective heating of the target. If necessary for DT layer survival, the allowable heat flux can be increased by one of several methods. One is to inject the target at a lower initial DT temperature. Preliminary target design studies suggest that the target can be shot at 12 K or even less (i.e., no gas inside the DT shell) and still yield high gain. Another approach with higher leverage is to coat the outside of the target with a thermally insulating foam. Studies show the allowable heat flux can be increased by 20 times or more with this approach. The third approach is to evaluate the effect of allowing the outside of the target to go above the triple point. All of these are under study, and provide potential chamber operating windows compatible with target survival and that are useful for design of an attractive power plant.[18,19]

IV. 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 an IFE power plant must supply more than 500 000 targets per day, including manufacturing the spherical target capsule, filling the capsules with the DT fusion fuel, redistributing the frozen DT uniformly around the inside of the capsule, and injecting and tracking the targets into the chamber. 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 a summary overview of the proposed baseline target manufacturing methodologies for laser fusion, and the development programs associated with target technology for an IFE power system. We have prepared preliminary estimates of the costs associated with producing large quantities of targets,[20] 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.

The materials science development programs are highly leveraged from the technological database of ICF and other experimental programs, The target development efforts have made significant progress in recent years. In summary, all of the processes needed for supplying targets to fuel an IFE power plant have been identified and the critical issues are understood—as described in this paper. The target development plans have been established, and research teams are generating results in a focused and mission-oriented fashion. 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, the sabot separation needed for handling of direct drive targets has been demonstrated. Current work is focused on tracking experiments under representative conditions and demonstration of in-flight, real-time target engagement (integrated tracking and beam steering).

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 a challenge that can be achieved.

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