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GENERAL ATOMICS

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ABSTRACT

The High Average Power Laser (HAPL) Program, directed by the Naval Research Laboratory (NRL) in Washington, D.C., is pursuing an all-systems approach to Inertial Fusion Energy (IFE) with lasers. Systems that will be needed for an IFE power plant, such as the laser drivers, cryogenic targets, target factory, target injection, target tracking and engagement, chamber design, and chamber materials to name a few, are all being developed in parallel at various laboratories, universities, and companies across the U.S. While all such systems in an IFE power plant are essential, at the heart of the energy production is the fuel, the cryogenic target. The emphasis at General Atomics is the development of cryogenic targets within physics specifications, the economical mass production of targets, and the delivery of the targets to the center of the chamber within tight tolerances.

1. INTRODUCTION

In 1999, the HAPL program was initiated at NRL with the investigation of two different laser drivers to be used in an IFE power plant – a krypton-fluoride (KrF) laser system and a diode-pumped solid state laser (DPSSL) [1]. Within two years, this program expanded to include research and development into almost all of the major components of an IFE power plant: the laser drivers, fuel (target) design, target fabrication, target tracking and engagement systems, the chamber (reaction vessel with first wall materials and tritium breeder) to house the thermonuclear events, and the optics (to simultaneously aim the lasers onto the targets to cause the thermonuclear events). Each of these areas has progressed in parallel, with design criteria or operating requirements defined within each area then studied as the criteria affect other IFE systems. One example of this is the target physics research. Hydrodynamic code simulations are performed by target designers. Based on the results of these codes, target design criteria are established and disseminated to the HAPL target design community.

2. TARGET DEVELOPMENT

The direct-laser drive IFE target, which has either KrF or DPSSL lasers focused directly onto the target, is a highly symmetric sphere composed of three concentric material layers to hold the deuterium-tritium (DT) fuel. The DT fuel is cooled to 17.3 K, which has most of the fuel in solid (ice) form (Fig. 1). The methods used to produce the cryogenic fuel in mass quantities of 500,000 targets per day (6 targets per second) within design specifications must result in producing a smooth, uniform inner DT ice layer. The design specifications are listed in the following sections.

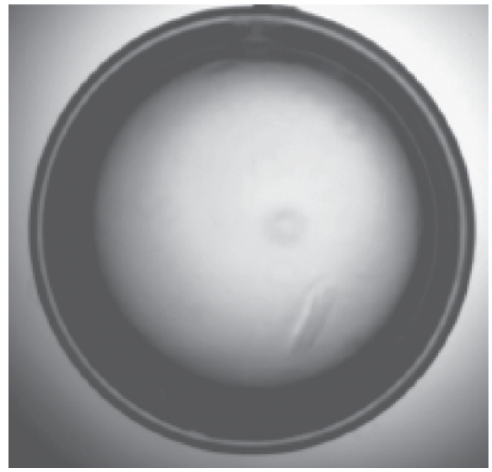

Fig. 1. Example of DT-filled capsule, courtesy of LLNL.

2.1. TARGET CHEMISTRY — PRODUCTION OF THE TARGET'S CONTAINER, THE CAPSULE

The DT fuel forms an ice layer within a container. The container, called the capsule, is made up of three layers as shown in Fig. 2 [2]. The first is a divinylbenzene (DVB) foam. This plastic, closed-pore, 10% dense foam could be considered a super-styrene which serves as an ablator in the thermonuclear fuel [3]. The DVB foam fills with the fuel between its closed pores. The DVB foam capsule is first mass-produced by microencapsulation, a production method that was perfected in the Inertial Confinement Fusion (ICF) program. After several chemical processing steps, then characterized for non-concentricity of its wall thickness (Fig. 3), the dry DVB capsule is conformally coated with polyvinyl phenol (PVP), a thermoplastic coating, followed by a thin layer of glow discharge polymer (GDP). The PVP/GDP together make a plastic CH seal coat that contains the DT fuel within the capsule. Last, a gold/palladium (Au/Pd) overcoat is applied by physical vapor deposition process using a sputter coater. This overcoat is used, in part, for infrared (IR) reflection. The chamber first wall produces blackbody radiation, and the Au/Pd overcoat helps to reflect that heat off the target outer surfaces, especially as the capsule passes through the hot chamber. The design criteria for these three layers are listed in Table 1.

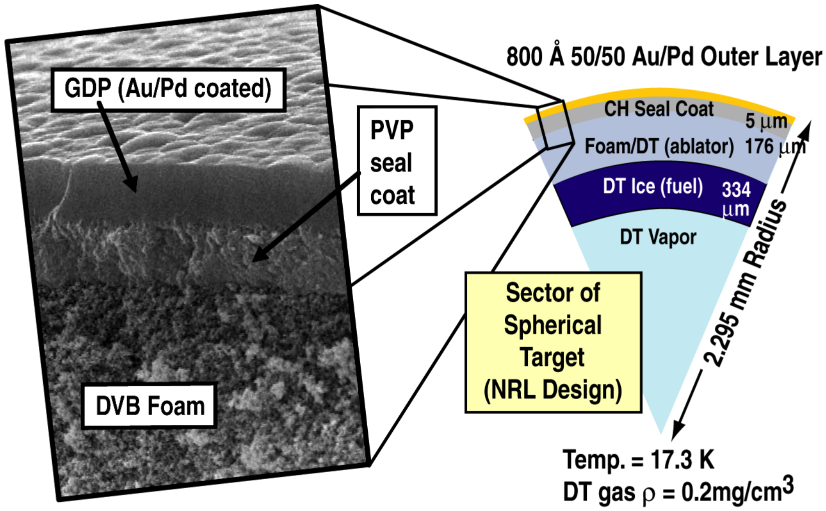

Fig. 2. This high-gain IFE target design has a yield of 350 MJ.

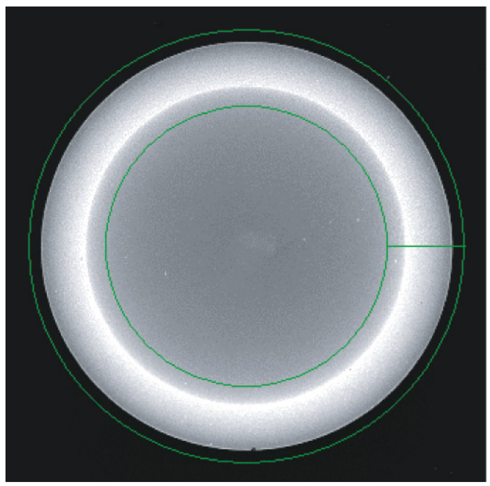

Fig. 3. Characterizing the non-concentricity of dry DVB foam shell.

Table 1
IFE Capsule Criteria [4]

Description	Criteria
DVB foam outer diameter	4.750 mm o.d.
DVB foam wall thickness	176 µm
DVB foam density	100 mg/cc
DVB foam pore size	< 3 µm
DVB foam non-concentricity	1%-3% of wall thickness
PVP seal coat thickness	<5 µm
Au+Pd overcoat	800 Å
GDP seal coat surface finish	<12 nm rms

2.2. TARGET FUELING — ADDING THE DT FUEL AND FORMING THE FUEL LAYER

The capsules are filled with DT fuel by diffusion through the continuous DVD foam, sealcoat, and top-coat layers. This is done in a high-pressure (117 MPa, 17 ksi) environment with careful attention paid to the buckling pressure limits of the capsules. The pressurization process is stepped such that the pressure differential across the capsule wall will not exceed capsule buckling strength limits. The estimated fill and subsequent cool time for the capsules is 8 hours [5].

Once the capsules are each filled with DT fuel and cooled, they are moved to a layering device where the solid DT fuel is made into a spherical ice layer within the capsule. The outermost extent of the ice is formed within the DVB foam. The innermost surface of the ice, which extends inward beyond the inner surface of the DVB foam, must be almost perfectly smooth (Table 2). It is proposed to perform this layering in a fluidized bed with gaseous helium at approximately 18.5 K as the fluidizing medium (Fig. 4). The fluidized bed is expected to provide a time-averaged highly-uniform temperature environment. The random motion within the fluidized bed is expected to induce the capsules to spin such that a uniform ice layer will be produced. Layering times have been calculated to be 13 hours [5].

Table 2
IFE Target Fueling Design Values [4,5]

Description	Criteria
DT fuel inner surface finish	< 1 μm rms
DT fuel inner surface temperature uniformity	< 450 μK
Fuel fill time	8 hours
Fuel layering times	13 hours

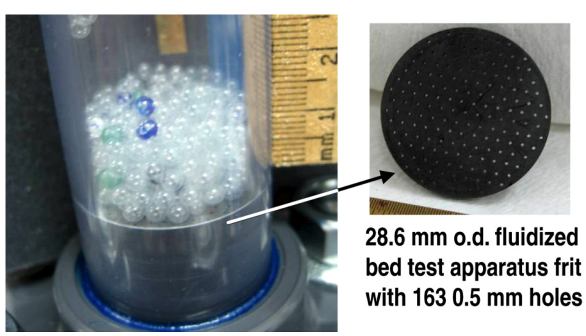

Fig. 4. Test apparatus is being used to verify fluidized bed performance for IFE capsules (some capsules marked for high-speed video tracking).

2.3. TARGET INJECTION AND TRACKING — GETTING THE TARGET INTO THE REACTION CHAMBER

Much progress has been made on demonstrating the feasibility of target injection and target tracking. A full-scale, 25 m gas-gun experiment was constructed at General Atomics to demonstrate high-speed (>400 m/s) injection with sabot (target protective casing) separation under vacuum and the required time "jitter" at chamber center (Fig. 5). The currently expected target injection velocity is 50-100 m/s and can be accomplished by simpler (mechanical or electromagnetic) injection. Other factors, such as maximum target acceleration, maximum surface heat flux, target spin rates, target structural strength, etc., were also evaluated to show the overall feasibility of injection for an IFE power plant.

Fig. 5. Full-scale IFE power plant target injection/tracking experiment.

Once the target is injected towards the target chamber center (TCC), it needs to be tracked along its trajectory so that its (x,y,z) location is precisely known at the TCC for the purpose of steering the lasers to that final location (Table 3). Poisson spot (x,y) illumination detection systems and Doppler fringe counting (z) detection systems have been tested on the optical table and continue to be improved with faster, more precise instrumentation and visualization hardware [6]. Proposed future experiments to improve the accuracy of target placement at TCC include in-flight target steering by the use of electrostatics.

Table 3
IFE Target Injection Criteria

Description	Criteria
Target travel velocity	50-100 m/s
Target placement accuracy	1-5 μm
Target injection distance	~10-15 m
Target engagement accuracy	<20 μm

3. DISCUSSION

To date, no IFE or inertial confinement fusion cryogenic targets have met all the design criteria such that any one target can be qualified as “ignition quality”. While fuel-filled targets have been made in several high-pressure target fill stations and shot with lasers [7], none of these high-pressure fills have involved mass production nor have the shots been ignition attempts. The target mass production work of the HAPL team is the first program to push for high-gain targets (i.e., suitable for energy production) that meet ignition-quality specifications in every way. A mass-production attempt for filled, cryogenic capsules is also being pursued by the Lebedev Physical Institute and Moscow State University, both in Russia [8,9]. Their method of mass production is very different from that in the USA.

All of the target development areas mentioned above are proceeding with experimental programs. In the areas of target fabrication, a recent focus has been on non-concentricity of the DVB foam capsules. Achieving a gas-tight seal coat with an outer surface meeting smoothness specifications is the next experimental emphasis; we are also constructing a cryogenic fluidized bed to demonstrate uniform ice layering of the hydrogen isotopes on a bench-scale. Analytical/computational solutions are also being pursued in parallel with the experimental programs.

4. CONCLUSIONS AND PERSPECTIVE

Some IFE target manufacturing methods, such at the DVB foam capsule formation by microencapsulation and high-pressure DT diffusion fuel fill, were derived from ICF program target production. The mass-production IFE layering process using a fluidized bed was derived from prior General Atomics experience in the production of TRISO fuel particles for commercial fission power plants. When looking at methods for target injection into the IFE reaction chamber, the methods used by magnetic fusion energy (MFE) pellet injectors were investigated. Years of developmental effort for fueling has been spent in the areas of ICF targets, TRISO fuel particles, and MFE pellet fuel injectors. Even though some of these production methods are being used for the IFE target fuel program, there is much work that remains within the IFE fuel development community to simultaneously obtain all of the IFE target specifications set forth by target physicists. While the IFE fuel development effort has much remaining work, all of the IFE fuel experimental and analytical development efforts thus far look promising.

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