CHARGED PARTICLE LABORATORY REPORT NO. 3-79

FABRICATION AND CHARACTERIZATION OF CRYOGENIC TARGETS FOR INERTIAL CONFINEMENT FUSION

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ABSTRACT

A new technique has been developed which is capable of fabricating uniform cryogenic targets for use in inertial confinement fusion. The essence of the technique is to directly wet a target with a cold helium gas jet, which results in freezing of the DT mixture (fusion fuel material) contained in the target. A controlled amount of current is pulsed through a heater wire surrounding the target, giving rise to fast evaporation and refreezing of the DT-condensate into a uniform layer. The current technique is unique in that, unlike other existing techniques, it does not require troublesome cryogenic shields, that it is capable of retaining the integrity of the cryogenic targets for as long as required, and that it is directly implementable with the room-temperature target chambers. This technique, therefore, opens up a new avenue in developing practical power-producing fusion reactors. Experiments, which have been performed with D_2 -filled glass microshells, successfully produce uniform layers of both liquid and solid D_2 inside the glass shells. A set of data illustrating the technique is presented and analyzed.

TABLE OF CONTENTS

Chapter	Page
1. Introduction	1
2. Apparatus for Freezing Targets	6
3. Inspection, Selection, and Mounting of Targets at Room Temperature	15
4. Diagnostics for Inspecting Cryogenic Targets	20
5. Target Freezing Experiments - Results and Discussions	29
6. Conclusions and Suggestions for Future Experiments	40
Appendix I. Computer Printout of the Calculated Fringe Patterns	46
Appendix II. Theoretical Calculation of the Amount of D_2 - Condensate Inside a Target	53
References	57

FIGURE CAPTIONS

Figure	Page
1. Sequence in target implosions	3
2. Target-freezing apparatus	8
3. Schematic of cold jets-cold chamber apparatus	10
4. Schematic of cold jet apparatus	12
5. Flow control of the helium gas jet	13
6. Mach-Zehnder interference microscope for target selection	16
7. A typical batch of D_2 -filled glass microshells	17
8. Target mounting apparatus	19
9. The diagnostic system for analyzing the target	21
10. Ray tracing of Mach-Zehnder interferometer	22
11. Room temperature target	22
12. Ray tracing of room temperature target	24
13. Ray tracing of cryogenic target	24
14. Surface tension of hydrogen	31
15. Picture of a target mounted on a glass stalk placed in front of the cold helium gas jet nozzle	34
16. The target with no condensate	34
17. The beginning of condensation	35
18. The effects of different positioning	35
19. Droplet moved toward the nozzle opening	36
20. A thick layer of liquid	38
21. The optical setup using holography	43
22. The optical setup for obtaining Fourier transformation	45

CHAPTER 1

INTRODUCTION

One of the useful energy sources for the future is the fusion reaction that occurs in hydrogen isotopes, like deuterium (D) and tritium (T). This fusion reaction releases a substantial amount of energy⁽¹⁾:

Reaction (4) uses neutrons to breed tritium which is required for reaction (3).

The hydrogen isotopes can not fuse together unless their kinetic energies are sufficiently high⁽²⁾. For reaction (3), the required kinetic energy for ignition is in the order of 5 keV (cf. $1\text{ev} = 11,600\text{ K}$). To sustain fusion reactions, the probability for fusion events to occur has to exceed a certain level. This probability depends upon the density of ions, their confinement time, and their collision cross-section at a given temperature. To be more specific, a convenient criterion for unceasing fusion reaction is that the product of n and τ take on certain threshold values for each fusion reaction:

$$n \cdot \tau > 10^{16} (\text{sec}/\text{cm}^3) \text{ for D - D} \quad (5)$$

$$n \cdot \tau > 10^{14} (\text{sec}/\text{cm}^3) \text{ for D - T} \quad (6)$$

where n is the density of ions (cm^{-3}) and τ is the appropriate fuel ion confinement time. The above requirement is known as the Lawson Criterion. Since the ignition temperature for fusion is so high ($\sim 10^8\text{ K}$), it is necessary to find a way to confine the highly energetic ions. There are two major ways of doing so:

the magnetic confinement and the inertial confinement. One of the most convenient ways of achieving inertial confinement is the laser fusion.

The laser technology is advancing very rapidly, and high power lasers are currently available for a variety of applications. But the efficiency of these lasers is usually too low to be a good power source for fusion ignition. For laser fusion, several beams coming from different directions are focused onto a small target of DT in a spherically symmetric manner (Fig. 1).

The Lawson Criterion, when translated into a requirement for laser fusion, is

$$\rho R > 1 \text{ gr/cm}^2 \quad (7)$$

because the atoms' lifetime

$$\tau \approx R/V_s \quad (8)$$

where ρ is the mass density of the pellet (gr/cm^3), R is the radius of the pellet, and V_s is the velocity of the compression wave propagating toward the center of the pellet.

A laser pulse that can provide 10^{12} Watts in a period of a nanosecond can yield an implosion pellet density as high as 10,000 times that of liquid. The pressure at the pellet surface can go as high as 10^8 atm.⁽³⁾ The pulse length of the laser has to be short so that the plasma at the surface of the target, due to the high energy absorbed, may not reflect the incoming laser beams. The energy absorbed at the surface produces fast ablation, which, in turn, compresses the target. When the target reaches high enough density, fusion reaction occurs, and energy is released through emission of radiation.

Compression of solid fuel pellets is not considered to be efficient due to the back pressure built up inside the pellet. A more efficient way of achieving high compression is by using hollow targets.

A concentric hollow sphere of solid or liquid DT can be compressed more

Fig. 1 - Sequence in target implosion; (a) pulsed laser beams hitting the target; (b) target implosion due to the rocket-like effect of ablation; (c) radiation released by fusion reaction.

efficiently. In compressing a hollow sphere, the shell gets accelerated toward the center without building up much counter pressure inside the shell. Therefore, the momentum added to the shell yields higher fuel density. The uniformity in shell thickness of a hollow sphere is essential for achieving high density. The implosion force acting on the surface of the sphere is uniform assuming even intensity of the laser light incident on the surface. The mass per unit area of the surface, therefore, has to be uniform in order to achieve symmetric compression of fuel material toward the center point. A nonuniform thickness will result in lower fuel density for this reason.

A promising technique to fabricate hollow targets is to use a glass microshell filled with highly pressurized DT gas. Since a high percentage of input energy is desired to be delivered to the fuel mass, the size of this DT-filled glass microshell has to be very small (50 μm to 300 μm in diameter). The thickness of the target is a few micrometers, and the DT-fill pressure at 300 K is anywhere from 50 atm to 300 atm. Selecting targets with uniform glass shells requires advanced interferometric observation. Steady positioning of a target also involves some fine-control mechanism before it can be mounted on a glass stalk. To freeze the DT contained in a glass microshell target, the target has to be cooled down to a temperature below 20 K. This, of course, requires one to be equipped with high vacuum technology and cryogenic capabilities. Detailed observation at different temperatures of a target being frozen requires an accurate diagnostic system. To fabricate highly efficient targets, a perfectly uniform layer of DT has to be obtained (a few hundred angstroms in thickness variation).

As a first step, the capability of freezing DT gas inside a target is to be achieved. In the present investigation, a combination of cold helium gas jets and cold chamber will first be employed to freeze the target. After studying the behavior of liquid and solid DT on the formation of a uniform layer, a new system is then designed which uses the cold helium jet only, and which, therefore, can

operate inside a laser firing target chamber. As a result, a uniform layer of DT will be formed inside a chamber at room temperature.

The advantages of these new target fabrication techniques are:

- (1) The target can be cooled down, and the entire surface of the target can be exposed to the laser beams.
- (2) By keeping the cold gas jet on, the frozen layer of DT is in steady state, i.e., the retention time for the DT layer is infinite. This means that there is no time limitation required for the target to be fired. In conjunction with this, we note that in other target freezing techniques⁽⁴⁾ the DT layer retention time is on the order of 100 msec.
- (3) Different relative positioning of the target and the jet, combined with different jet flows, gives a control over the thickness of the uniform liquid layer.

Chapter 2 presents a detailed description of the systems used for fabricating hollow targets. Chapter 3 describes a method by which the targets are selected and mounted on a glass stalk. Chapter 4 gives the diagnostics used for inspecting the targets being frozen. Chapter 5 presents a discussion of the experiments, data collection, and their interpretation. The final chapter (Chapter 6) gives concluding remarks and suggestions for future investigations.

CHAPTER 2

APPARATUS FOR FREEZING TARGETS

Fabrication of cryogenic targets requires some special means. A key element for an apparatus which will do such fabrication is liquid helium, which has a boiling temperature of 4.2 K at atmospheric pressure. Maintaining such a low temperature inevitably requires thermal insulation.

This chapter describes the working components and the reasoning behind the design of two different target freezing apparatus. The first apparatus uses cold helium jets, which are thermally shielded by a cold chamber. The second one employs a single cold helium jet, and the freezing cell walls are maintained at room temperature.

2.1 - Apparatus Requirements

In order to solidify the contents of the glass microshell, namely, the D_2 gas in the current experiment, one must cool down the microshell to a temperature below 18.7 K, the triple-point temperature of D_2 . This requires that the temperature of the cooling gas jets be below 18.7 K. Also, if a uniform liquid layer of D_2 is required, the flow rate as well as the temperature of the jets need to be adjusted to create the appropriate thermal environment around the target.

Maintaining a low pressure in the surrounding area of the target is essential if one wants to achieve the most efficient coupling in the target chamber between the target and the incident laser beams focused onto it.

2.2 - The Liquid-Helium-Cooled Heat Exchanger

The boiling point of liquid helium at atmospheric pressure is 4.2 K, which makes it effective as a coolant in producing the required cold gas jets. Since

it is important in the current investigation to have the capability to control the jet temperature, a liquid-helium-cooled heat exchanger was used to cool down ultra-high purity helium gas, the gas employed to produce the cold jets. A schematic of this is contained in Fig. 2.

The heat exchanger is fabricated out of an OFHC copper block and its cylindrical bores are filled with copper beads for efficient heat transfer. The helium gas flows through the center portion of the heat exchanger. This section was kept cool by the surrounding section that contains liquid helium. The liquid helium is transferred from a pressurized liquid helium dewar and forced through the heat exchanger. By choking this at the exhaust end, one then achieves a convenient control of the temperature of the heat exchanger. A tubing with a dead end, which is filled with hydrogen gas, is in thermal contact with the heat exchanger at the exit end. By measuring the vapor pressure of the hydrogen gas in the tubing, one can measure the temperature of the heat exchanger at the exit end.

It is essential to minimize the heat transfer from the room temperature outside wall to the heat exchanger. To eliminate the conductive heat transfer, the heat exchanger was shielded by a thermal jacket that holds a high vacuum ($\sim 10^{-7}$ Torr). To minimize the radiative heat transfer, the heat exchanger was gold plated resulting in high reflectivity.

2.3 - Target Freezing Cell Featuring Cold Jets-Cold Wall Combination

The first system designed to fabricate a uniform DT-layer was a cold chamber equipped with cold jets. The main considerations in choosing this particular design were: first, to eliminate possible heat conduction from the chamber wall to the target; and second, to have the capability of cooling evenly the entire surrounding area of the target.

Fig. 2 - Target-freezing apparatus

Figure 3 shows a schematic of the apparatus. The chamber that houses the target was made out of copper and attached directly to the heat exchanger to obtain as low a temperature as possible. Indium was used to seal the cold chamber to the heat exchanger. Two stainless steel tubes inside the cold chamber bring the cold helium gas from the heat exchanger to the vicinity of the target. The suspension of the cryogenic parts in the vacuum chamber was made possible by using thin-walled stainless steel tubing and bellows to minimize the heat conduction.

Quartz windows (1/16" thick) were used to view the target, which gave rise to low aberration. To overcome the differences in expansion and contraction between the copper and the quartz, small windows ($\sim 1/4$ " in diameter) were used, which were epoxied to the chamber wall using Armstrong A-12 brand. This particular epoxy was chosen among many different brands because of its effectiveness at cryogenic temperatures.

Studying the optimal conditions for obtaining uniform cryogenic targets requires very accurate temperature and pressure diagnostics. A thermocouple pressure gauge was used at the exhaust port of the cold chamber to measure the pressure. For temperature measurements, a copper-constantan thermocouple was employed. This junction was placed ~ 0.5 mm from the glass microshell to obtain the temperature reading of the target as accurately as possible. The use of a compensating junction with an amplifier allowed us to measure the temperature within accuracy of 1 K.

A heater wire was mounted next to the ball to allow for temporary vaporization of the F_2 -condensate inside the target. The current and the duration of the current pulse through the heater wire were made variable and could be preselected.

Fig. 3 - Schematic of cold jets-cold chamber apparatus

2.4 - Cold Jet Apparatus

The purpose of fabricating cryogenic targets is to study their efficiency and characteristics as laser fusion targets in the target chamber during laser-induced implosion. In using the cold jets-cold chamber combination apparatus, one faces the difficulty of having to expose the cryogenic target to the laser beams without impairing its integrity. It is without a doubt a formidable task to remove the cold chamber and fire the target, all within the lifetime of the cryogenic target (~ 100 ms). Therefore, a second apparatus was proposed, which is designed to use a cold jet only without having recourse to an intermediate cold chamber for thermal shielding.

A schematic of this apparatus is shown in Fig. 4. The heat exchanger and the jet tubes are separated from the freezing cell and housed in a high vacuum jacket. In this way, one can maintain efficient cooling of the helium gas. The target is mounted in a chamber whose walls are maintained at room temperature. The x-, y-, and z-micrometer manipulators provide the flexibility in positioning the target.

In order to minimize heat conduction from the walls to the target, the chamber has to be evacuated at a high pumping rate. Using a wide exhaust port (~ 1.5 " in diameter) and a high capacity vacuum pump (~ 1000 l/min), a low enough pressure could be maintained.

The accompanying diagnostics for the measurement of pressure and temperature, and the heater wire unit were similar to the ones used in the previous section.

In order to operate this system on a pulsed basis, i.e., turning on the jet for a certain period of time that is required to freeze the D_2 , two solenoid valves with a time control were added (Fig. 5). The two solenoid valves are ac-

Fig. 4 - Schematic of cold jet apparatus.

Fig. 5 - Flow control of the helium gas jet.

tivated simultaneously either with a controlled time delay between them, or manually. An advantage of a system like this is that freezing of a D_2 -filled target and firing of the laser can be done without any interruption inside the laser firing target chamber.

The system is not complete without having the capability of observing the target while it is being frozen. Since the size of the target is so small, it has to be magnified optically, roughly by a factor of 1000 before it can be conveniently visualized and inspected. This means that a microscope objective has to be placed close enough to the target (~ 7 mm). For detailed observation of the frozen D_2 -layer, a Mach-Zehnder interference microscope was used (detailed description is given in Chapter 4).

CHAPTER 7

INSPECTION, SELECTION, AND MOUNTING OF TARGETS AT ROOM TEMPERATURE

To have a desired target mounted on a glass stalk, a side technology was developed out of the main experiment. A special and very delicate technique had to be developed for inspecting the glass microshells, selecting the one that meets the desired requirements, and mounting it on a very fine edge of a glass stalk. This chapter describes the special tools and techniques that were developed and used for the target mounting.

3.1 - Introduction

The technique used to manufacture the glass microshell⁽⁵⁾ does not produce good uniformity in the wall thickness. At random, some of the balls are uniform enough to have fluctuations in the wall thickness less than $3000 \text{ \AA}$. A reliable analysis of the frozen layer inside the D_2 -filled target requires one to select through inspection a uniform glass microshell to work with. The selected target is then mounted on a glass stalk ($\sim 10 \text{ }\mu\text{m}$ in diameter at the tip) so that the disturbances due to cooling can be minimized and the exposed portion of the target for analysis is maximized.

3.2 - Mach-Zehnder Interference Microscope Target Selector

The use of interferometry was incorporated into the inspection of targets, which proved to be very convenient, fast, and accurate. A Mach-Zehnder interferometer was used (Fig. 6). The beam splitters (B.S.) and mirrors (M) split up the laser beam into two. One beam was steered to go through a batch of glass microshells placed on a glass inspection plate, while the other was made to bypass it. The two beams were then recombined at the end of the interferometer to

Fig. 6 - Mach-Zehnder interference microscope for target selection.

give rise to fringes resulting from the optical path length differences (a complete analysis is given in Chapter 4).

Magnification of the glass microshells was achieved in the following manner. An objective lens (L2) and a microscope with a variable magnification were used on one arm of the Mach-Zehnder interferometer to obtain the required image size of the balls. Another identical objective lens (L3) was then positioned in a symmetric manner on the other arm of the interferometer to compensate for the distortion caused by L2. An attenuator and a lens (L1) were placed in front of the He-Ne laser to provide a wider beam, which is necessary to view simultaneously a large number of glass microshells and to provide low enough intensity for comfort in viewing.

Fig. 7 - A typical batch of D_2 -filled glass microshells.

Figure 7 shows a typical batch of glass microshells being inspected by using the Mach-Zehnder interference microscope. x- and y-micrometer man-

ipulators (Fig. 6) attached to the inspection plate, that holds the glass microshells, enable one to inspect a wide variety of balls.

3.3 - Target Mounting

Once a uniform glass microshell has been spotted, it has to be picked up. A vacuum chuck (Fig. 8) was constructed and employed to handle the ball. For ease as well as accuracy in the ball-maneuvering, x-, y-, and z-micrometer manipulators were used. The inside diameter of the vacuum chuck tube must be smaller than the diameter of the selected target. When a vacuum was applied to the vacuum chuck, the suction grabbed the ball as the open end of the chuck was moved next to the selected target. Applying a vacuum to a hollow glass stalk, and positioning a tiny amount of epoxy (Armstrong A-12) at the very tip of the stalk, the suction pulled some of the epoxy into the stalk. Using the micrometer manipulators of the glass stalk and the vacuum chuck, the tip of the glass stalk was positioned next to the target. By controlling the exhaust opening, and allowing a small flow of gas from the high pressure tank into the stalk, a controlled amount of epoxy was forced out of the glass stalk. Releasing the vacuum from the vacuum chuck leaves the target bound to the glass stalk.

Fig. 8 - Target mounting apparatus.

CHAPTER 4

DIAGNOSTICS FOR INSPECTING CRYOGENIC TARGETS

Inspection of the uniformity of a cryogenic target is very delicate because the target size and thickness are very small, the frozen layer of D_2 occurs inside the glass microshell, and the inspection must be done continuously as the experiment progresses. For these reasons, the use of an interferometric technique was an essential part of the diagnostics.

This chapter describes the interferometric technique used and some of the calculations upon which the technique is based.

4.1 - Mach-Zehnder Interference Microscope

The key apparatus used to analyze the uniformity of the frozen target was a Mach-Zehnder interference microscope similar to the one described in Chapter 3. A schematic of this is contained in Fig. 9. A He-Ne laser (in this setup, output power of 0.5 mw and $\lambda = 6328 \overset{0}{\text{\AA}}$) is used for a monochromatic light source. An iris is then placed in front of this to cut off the portion of the beam that has an uneven intensity. The two mirrors placed after the iris steer the laser beam onto the target. The two-mirror configuration gives rise to flexibility in illuminating the target from different angles, which enables one to direct the beam properly inside the interferometer. An increase in the illumination intensity on the target is achieved by a lens of long focal length placed in front of the interferometer.

By first splitting the coherent monochromatic beam into two, but later recombining them back together, the same intensity distribution would be obtained. However, if we insert the glass microshell into one of the beam paths (Fig. 10), the light going through the glass microshell will be slowed down. Slowing down

Fig. 9 - The diagnostic system for analyzing the target.

Fig. 10 - Ray tracing of Mach-Zehnder interferometer.

Fig. 11 - Room temperature target: (a) Shadow micrograph
(b) Interference micrograph.

has the same effect as propagation at the same speed for a longer distance. Since the laser light is coherent, an additional distance of $(N + 1/2)\lambda$ ($N = 0, 1, 2, \dots$) causes the light intensity to go to zero after the two beams have recombined. An additional distance of $N\lambda$, of course, results in the same intensity as the incoming beam.

The cross-section of a glass microshell (Fig. 12) shows that the effective additional distance in the optical path length changes as we go from the center point to the edges. Therefore, for a spherical glass shell of uniform wall thickness, symmetrical circular rings result (Fig. 11).

4.2 - Analysis of Fringe Patterns⁽⁶⁾ for a Room Temperature Target

Since the Mach-Zehnder interference microscope target-sorter described in Chapter 3 enables us to select the uniform glass microshells, the analysis that follows will be for uniform glass microshells only.

Figure 12 shows the path of a ray incident on a target a distance d from the center. At room temperature, the D_2 gas inside the target has an index of refraction n_3 .⁽⁷⁾

$$\sin \alpha = \frac{d}{R} \quad , \quad (4.1)$$

where R is the radius of the glass microshell.

Using Snell's law

$$\frac{\sin \beta}{\sin \alpha} = \frac{1}{n_1} \quad , \quad (4.2)$$

where n_1 is the index of refraction of glass.

Fig. 12 - Ray tracing of room temperature target.

Fig. 13 - Ray tracing of cryogenic target.

Therefore,

$$\beta = \sin^{-1} \left(\frac{d}{Rn_1} \right) \quad (4.3)$$

For the targets we used, w_1 is the glass shell thickness; $w_1 \ll R$, so,

$$L = \frac{w_1}{\cos \beta} \quad (4.4)$$

Since $w_1 \ll R$ and $n_3 \approx 1$, we can assume that the ray propagate parallel to the optical axis.

The effective path length through the glass is

$$2Ln_1 = \frac{2w_1 n_1}{\cos \beta} \quad (4.5)$$

Without going through the glass, the path would have been 2ℓ .

$$\frac{\ell}{L} = \cos (\alpha - \beta) \quad (4.6)$$

Therefore,

$$2\ell = \frac{2w_1}{\cos \beta} \cos (\alpha - \beta) \quad (4.7)$$

The path length difference through the shell is ΔS_1

$$\Delta S_1 = 2Ln_1 - 2\ell = \frac{2w_1}{\cos \beta} \left[n_1 - \cos (\alpha - \beta) \right] \quad (4.8)$$

The path length inside the shell is

$$U = 2(R - w_1) \cos \alpha \quad (4.9)$$

The path length difference inside the shell is

$$\Delta S_3 = (n_3 - 1)U = (n_3 - 1) 2(R - w_1) \cos \alpha \quad (4.10)$$

Combining Eqs. (4.8) and (4.10) gives the desired optical path length difference ΔS .

$$\Delta S = \Delta S_1 + \Delta S_3 = \frac{2w_1}{\cos \beta} \left[n_1 - \cos(\lambda - \beta) \right] + 2(n_3 - 1)(R - w_1)\cos \alpha \quad (4.11)$$

For a given target, ΔS is a function of d only. When $\Delta S = N\lambda$, a bright ring is observed, and when $\Delta S = N\lambda + \lambda/2$, a dark ring results.

A computer program (see Appendix I), using the given values of R , n_1 , and n_3 as an input, calculates the fringe patterns across the target for different values of w_1 . By comparing the computer printout with the interference micrograph (Fig. 11(b)), the thickness of the target can then be determined, and used for the analysis of a frozen target.

4.3 - Analysis of Fringe Patterns for a Cryogenic Target

As the temperature of a DT-filled glass microshell target changes, as long as there is no liquefaction of DT, the fringe pattern should remain as it is at room temperature (n_3 is a function of density only). But, when a liquid or solid DT is formed, w_2 , n_3 , and n_2 (Fig. 13) all vary. The temperature of the target determines the vapor pressure inside the ball, of which n_3 is a function. The remainder of the gas has been liquefied and has a certain mass density⁽⁸⁾ corresponding to the temperature. n_2 and w_2 can therefore be calculated (Appendix II).

Figure 13 shows the ray tracing for a cryogenic target. Using the same approach that was used for the room temperature target

$$\frac{\sin \gamma}{\sin \beta} = \frac{n_1}{n_2} \quad (4.12)$$

Using Eqs. (4.2) and (4.12) results in

$$\gamma = \sin^{-1} \left[\frac{\sin \alpha}{n_2} \right] \quad (4.13)$$

Considering the case where $w_2 \ll R$

$$L_2 = \frac{w_2}{\cos \gamma} \quad (4.14)$$

The effective path length through the frozen layer is

$$2L_2 n_2 = \frac{2w_2 n_2}{\cos \gamma} \quad (4.15)$$

Without going through the frozen layer, the path length would have been $2\ell_2$,

$$2\ell_2 = 2L_2 \cos (\alpha - \gamma) = \frac{2w_2}{\cos \gamma} \cos (\alpha - \gamma) \quad (4.16)$$

The path length difference through the frozen layer is

$$\Delta S_2 = 2L_2 n_2 - 2\ell_2 = \frac{2w_2}{\cos \gamma} \left[n_2 - \cos (\alpha - \gamma) \right] \quad (4.17)$$

The modified path length difference inside the shell is

$$\Delta S_3 = (n_3 - 1) 2(R - w_1 - w_2) \cos \alpha \quad (4.18)$$

Combining Eqs. (4.8), (4.17), and (4.18) gives the desired optical path length dif-

$$\begin{aligned} \text{ference} \quad \Delta S = \Delta S_1 + \Delta S_2 + \Delta S_3 &= \frac{2w_1}{\cos \beta} \left[n_1 - \cos (\alpha - \beta) \right] \\ &+ \frac{2w_2}{\cos \gamma} \left[n_2 - \cos (\alpha - \gamma) \right] + 2(n_3 - 1)(R - w_1 - w_2) \cos \alpha. \end{aligned} \quad (4.19)$$

4.4 - Rotating Mirror-Pinhole-P.M.T. Combination

A quantitative analysis of the fringe pattern is desired to characterize the uniformity of the frozen layer. A rotating mirror was used to scan the center line of the target fringe pattern across a pinhole (Fig. 9). The light intensity after the pinhole was detected by a photomultiplier tube. The electrical signal out of the P.M.T. was displayed on a storage oscilloscope. By measuring the symmetry of the signal, the uniformity of the target could be inspected.

A drawback was that the noise level of the signal due to the light diffraction and the low light intensity was too high to give rise to the required resolution for inspection. Due to this difficulty, a new system was proposed which utilizes the analog signal out of a television camera.

4.5 - Minicomputer System

The video system used for observation and recording of the experimental events (Fig. 9) can also be used for a quantitative analysis of the fringe pattern. The analog signal out of the television camera can be picked up and displayed on an oscilloscope. But it can also be converted into digital codes, stored, plotted, and compared against the theoretical calculations. A minicomputer system has been designed and is under construction to serve all these functions.

CHAPTER 5

TARGET FREEZING EXPERIMENT - RESULTS AND DISCUSSIONS

The experiments were performed on two different systems. A system with cold jets-cold chamber combination was first employed to study the behavior of a D_2 -filled glass microshell at cryogenic temperatures. Behavior of a D_2 -filled glass microshell at cryogenic temperatures had not been previously studied in detail. How to go about fabricating uniform cryogenic targets was, therefore, something to be explored.

As the investigation progressed, a new system employing a cold helium jet only was designed, whose freezing cell was maintained at room temperature. The result was a very practical and simple system capable of fabricating uniform cryogenic targets. This system is directly adaptable to current laser fusion target chambers and, therefore, adds a new dimension to the present laser fusion technology.

5.1 - Cold Jets-Cold Chamber Combination

The cold jets-cold chamber combination system has the distinct feature of spraying fresh cold helium gas jets directly onto the D_2 -filled glass microshell (Fig. 3). The two jets wet the target in opposite directions, and a mechanical pump continuously evacuates the cold gas filling the chamber. Another important feature is that a heater wire surrounds the target for quick evaporation and re-freeze of the D_2 -condensate inside the target once it has been formed. This system was designed to study the behavior of a D_2 -filled glass microshell, with no practical applications for a laser fusion reactor.

A glass microshell $\sim 80 \mu m$ in diameter of $\sim 1 \mu m$ wall thickness and with D_2 gas at 50 atm was used for the first experiment. As the temperature dropped

below 18.7 K (triple point of D_2), a nonuniform layer of solid D_2 was seen. Pulsing current through the heater wire just enough to vaporize the D_2 -condensate and keeping the jets on for quick refreezing caused a uniform layer of solid D_2 to form.⁽⁹⁾ However, the thickness of the solid layer was less than 1 μm .

To achieve a thicker layer, a glass microshell filled with D_2 gas at 200 atm was used. However, since the wall thickness was greater than 5 μm , and the mass of D_2 gas was much higher than before, we could no longer achieve a uniform solid layer. This was mainly due to the fact that refreezing could not be made quickly enough. An interference pattern of the D_2 -filled glass microshell monitored on the television screen clearly exhibited that, when the temperature surrounding the target was above 36 K, no condensation took place. But as the temperature was lowered below 36 K, a uniform liquid layer was formed. As the jet flowrate was raised and the temperature lowered, the thickness of the uniform liquid layer increased. An abrupt change occurred as the temperature decreased further: the liquid suddenly moved downward and collected at the bottom in the form of a droplet. When the heater wire was used to vaporize the D_2 -condensate, or the heat exchanger temperature raised by lowering the liquid helium flowrate, the same behavior was observed over and over again.

In order to understand this unique behavior, one is reminded of the fact that the surface tension force of hydrogen and its isotopes, i.e., H_2 , D_2 , and T_2 , decreases as the temperature goes up, and vanishes at temperatures equal to or higher than the critical point^(10,11) (Fig. 14). Consequently, the uniformity of the liquid D_2 layer depends largely on the extent that the wetting of the glass surface by liquid D_2 overpowers the surface tension and gravitational force effects. Within the limit of the experimental error, it appears that the effect of gravitational force is almost entirely negligible.

Fig. 14 - Surface tension of hydrogen.

These experimental observations are very encouraging mainly for two reasons: First, when there is no temperature gradient along the surface of the D_2 -filled glass microshell, a uniform liquid layer is formed as long as the wetting of the glass surface by liquid D_2 overpowers the surface tension. The thickness of the liquid layer can then be varied by changing the temperature. Second, a liquid layer is formed even when the cell pressure is ~ 15 mTorr. Such a low pressure can give rise to sufficient thermal insulation, suppressing heat conduction from the outside world. Consequently, a successful operation of a target freezing apparatus having the chamber wall at room temperature becomes a realistic possibility.

5.2 - A Single Jet-Room Temperature Chamber-Combination

This target freezing system (Fig. 4) has extremely useful potential applications for laser fusion. The system itself is very simple to build. The target is mounted in a room temperature chamber. So, firing of the target with laser beams is direct and straightforward. Keeping the cold jet on allows the cryogenic target to retain its integrity as long as required for the laser illumination.

The jet nozzle has an inside diameter of 100 micrometers. By applying a low flow of cold helium gas, a pressure of less than 20 mTorr could be maintained inside the target freezing cell, with a 1000 liter per minute capacity mechanical pump simultaneously evacuating the cell. This means that the high vacuum required in the target chamber can be maintained while the cold jet is on.

The current system also has the capability of pulsing the cold jet for a predetermined time duration. This feature should allow one to achieve a very high vacuum in a big capacity chamber while the jet is off. Then by turning on the jet for a required duration only to achieve a uniform liquid layer, the pres-

sure inside the chamber would not increase by much.

In the present experiment, a D_2 -filled glass microshell ~ 200 micrometers in diameter, of ~ 7 micrometer wall thickness, and with D_2 -fill pressure of ~ 200 atm was used. Figure 15 shows the setup inside the freezing cell. The single nozzle of cold helium gas jet is facing the target from the other side of the glass stalk. The thermocouple junction is placed close to, but below the target.

From room temperature all the way down to 36 K, there was no formation of D_2 -condensate inside the target (Fig. 16). At 36 K the onset of the formation of liquid condensate was observed (Fig. 17). Since the system is equipped with an x-, y-, and z-positioner so that the target can be moved around, the relative position between the jet nozzle and the target could be adjusted to give an optimal ∇T distribution around the target, (Fig. 18 (a)), which is required to form a uniform layer of D_2 -condensate. The pressure maintained in the freezing cell was very low (~ 15 mTorr), but the thickness of the resulting liquid layer was less than 0.5 micrometer. The target position had to be lowered relative to the jet nozzle to compensate for the gravity effect. Figure 18 (b) shows a nonuniform layer resulting from gravity and enforced by the cold jet. In contrast to the cold chamber target freezing system described in the previous section, in this case, the narrow jet can not cool evenly the entire surface of the target. Therefore, the key parameter that determines the liquid layer uniformity is the gradient of the temperature (∇T) along the target surface. Figure 19 illustrates the effect of a large ∇T which was set up using a higher jet flow. The position of the droplet can be determined by the resulting ∇T , which depends on the relative position of the target with respect to the jet. Calculation of the fringe pattern observed at room temperature predicts a glass wall thickness of ~ 7 micrometers. On the other hand, calculation of the fringe pattern of an empty glass microshell (Appendix I) of 7 micrometer wall thickness gives the fringe

(a)

(b)

Fig. 15 - Picture of a target mounted on a glass stalk placed in front of the cold helium gas jet nozzle. The thermocouple is seen below the target.
(a) Shadow micrograph; (b) Interference micrograph.

(a)

(b)

Fig. 16 - The target with no condensate.
(a) Shadow micrograph; (b) Interference micrograph.

(a)

(b)

Fig. 17 - The beginning of condensation.
(a) Shadow micrograph; (b) Interference
micrograph.

(a)

(b)

Fig. 18 - The effects of different positioning. (a) Uniform D_2 -layer resulting from the ∇T along the target surface which compensates for gravity effect; (b) Nonuniform D_2 -layer resulting from nonuniform ∇T along the target surface and gravity effect.

(a)

(b)

(c)

(d)

Fig. 19 - Droplet moved toward the nozzle opening.
(a) The jet cooling the lower part of the target;
(b) The jet cooling the front end of the target;
(c) The jet cooling the upper part of the target;
(d) Interference micrograph of (c).

pattern shown in Fig. 19 (d) (excluding the droplet fringe pattern). This means that there is no condensate of D_2 other than the droplet inside the glass target.

Formation of the droplet occurred when the temperature of the target surface where the droplet is such that the higher surface tension of liquid D_2 overpowers the wetting force. As the target was moved away from the nozzle opening, two interesting effects took place. The target temperature was raised, so the tendency of the liquid was to spread out. The cross-sectional area of the cold jet hitting the target was much wider. This reduced the magnitude of the temperature gradient along the surface by a substantial amount. Figure 20 shows the target with a uniform liquid layer of 5 micrometer thickness. To maintain such a thick layer, the jet flow had to be increased. Consequently, the freezing cell pressure went up to 60 mTorr. Moving the target away from the nozzle opening also creates a desirable situation from the standpoint of practical application, that is, a complete exposure of the target surface to the incident laser beams.

This approach for fabricating a cryogenic target is very promising for the following reasons:

- (1) It is directly adaptable inside the existing room temperature target chamber, with absolutely no need for adding cryogenic shields.
- (2) Since the uniform liquid D_2 layer inside a target can be retained for as long as desired simply by maintaining the cold helium gas jet, the usual most troublesome constraint concerning the prolonged retention of the integrity of a cryogenic target for laser illumination no longer exists.
- (3) Since the pressure of the target freezing cell as measured during the experiment is in the range of 50 mTorr, the current target fab-

(a)

(b)

Fig. 20 - A thick layer of liquid D_2 which is uniform.
(a) Shadow micrograph; (b) Interference micrograph.

rication technique appears to be compatible as it is with the target chamber conceived for a future laser fusion power plant. Noting that the above pressure was affected by a modest size mechanical pump, it looks very promising that with a more adequate means of vacuum-pumping one can further lower the pressure in the freezing cell to make it more compatible with the existing target chamber. If necessary, one can always shut off the cold helium gas flow before the laser shot by activating the two electronic valves described in Chapter 2 (also Fig. 5). In this way, one can achieve very low pressure inside the target chamber if it is demanded for more accurate diagnostic measurements of laser target implosion.

CHAPTER 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE EXPERIMENTS

The experiment described in this report started with a system that was capable of freezing D_2 gas contained in a glass microshell. But only under certain conditions could a solid uniform layer be formed: the glass microshell wall thickness had to be small (~ 1 micrometer); the D_2 -fill gas pressure at room temperature had to be low (< 100 atm); and vaporizing of the non-uniform solid layer once it has been formed and refrozen had to be done fast. The observed behavior of the liquid layer, described in Chapter 5, has resulted in opening a new dimension in fabricating cryogenic targets. This technique of fabricating a uniform layer of liquid D_2 inside a glass microshell (which should be equally applicable to other isotopes of hydrogen, including DT) is easy to implement with any target chamber configuration, and therefore forms the highlight of the present work.

Some of the important conclusions derived from the current investigation concerning fabrication of cryogenic targets are summarized in the following.

The mass densities of liquid DT and solid DT are the same in the practical sense. This means that, for target implosion by laser beams, the effectiveness of imploding a mass of liquid or solid makes no difference. However, the vapor pressure of a liquid is much higher than that of a solid. This pressure produces a counter force to the implosion force. But when a target with a D_2 -fill gas pressure of 200 atm (at room temperature) is cooled down to ~ 36 K (the point where condensate starts to form), the pressure inside the target is reduced to only ~ 10 atm. As one lowers the temperature even further to form more liquid, the vapor pressure also drops substantially. Advanced laser systems will produce a pressure of $\sim 10^8$ atm on the surface of the target during implosion

event. Therefore, in a practical sense, it should not make much difference whether the cryogenic target contains solid DT or liquid DT.

The advantages of using liquid DT are:

- (1) The fabrication process is much simpler. The target temperature should be above 18.7 K (triple point of D_2 ; for fabrication of a solid layer the target temperature should be below 18.7 K, triple point). The uniformity of the liquid layer is guaranteed as long as the wetting of the glass surface by liquid D_2 overpowers the surface tension. No special means is needed to obtain a uniform liquid layer.
- (2) The thickness of the liquid layer can be controlled by controlling the target temperature. This feature is particularly appealing, because one can produce targets of varying aspect ratios to test their efficiencies in giving rise to fusion reactions. For a given power density of the laser beams incident on the surface of the target, the fusion energy released is expected to be a function of the thickness of the DT layer. The peak of the released energy should occur when the thickness of the DT layer is somewhere between zero (no condensate) and the radius of the target (solid target).
- (3) A perfect DT liquid layer can be obtained when the target is placed in an environment free from gravity. Such a condition can be easily achieved when the target is in free fall. Since future laser fusion reactors would have to operate on a continuous basis, refueling of such reactors could therefore be done by letting the cryogenic laser targets enter the reactors in free-fall fashion at a controlled injection speed.

- (4) The transport of cryogenic targets to the center of a fusion reactor in a power plant can face the difficulty of not having the desired target due to their short lifetime. By first cooling the targets to 4.2 K (boiling point of helium) to form a nonuniform solid layer, and then letting them fall into the reactor, one could, however, resolve this difficulty, because on the way down the targets would heat up resulting in liquefaction of the initially frozen nonuniform DT-layer into a uniform liquid layer. Since a uniform liquid layer would be obtained at temperatures below 36 K, and if the target speed is pre-selected so that the target will reach the center of the reactor when it is at its optimal temperature (for formation of right liquid layer thickness), successful fueling of a laser fusion reactor will be achieved. Collection of data regarding free-fall of cryogenic targets at different temperatures and pressures would therefore be very useful.

Finally, some suggestions concerning future investigations are in order. Inspection of the fringe image of a target requires a more quantitative means of checking the symmetry. The proposed system that uses the analog signal out of a television camera (see Chapter 4, Section 5) is a promising one. There are some other techniques that can be used for the diagnostics of the interference fringe patterns of the target.

- (1) Using the advantage of holography to record amplitude and phase of a monochromatic light wave of an object, one can record the wave of the target on a holographic plate, develop it, and position it at the same place, so that the virtual image and actual target image will be overlapped with no fringes seen (Fig. 21). Then, by rotating the target, one should be able to detect the nonuniformity of a DT-layer thickness

Fig. 21 - The optical setup using holography.

by the amount of fringes that appear on the resulting image.

$$\Delta S = \Delta w \cdot (n - 1) \quad (6.1)$$

where Δw - change in thickness

n - index of refraction of a detected layer

ΔS - optical path length difference

(e.g., for $n = 1.5$ and $\Delta w = 1.2656$ micrometer, and with $\lambda = 6328 \text{ \AA}$ using a He-Ne laser, $\Delta S = 6328 \text{ \AA}$, which means a single fringe would appear).

This scheme enables one to inspect the entire target. The main drawback in implementing this scheme could be that it requires an extremely sensitive mechanism for rotating the target.

- (2) Since the geometry of the target is such that toward the edge the density of the fringes gets very high, which makes it difficult to obtain a quantitative analysis, the following method can be employed:

- (a) Recording the fringe pattern on a holographic plate (holographic plates have much higher resolution than regular film).
- (b) Obtaining optically the spatial Fourier transform of the fringe pattern. Figure 22 illustrates the optical setup.

The density of the fringe patterns toward the edge of the ball can first be presented at the highest spatial frequency on the input plane. Then, by taking the Fourier transformation of the input plane, the pattern on the output plane will represent the spectrum of the input spatial frequency. Fluctuations of the circular patterns on the output plane will therefore correspond to the nonuniformity along the edge of the target.

Fig. 22 - The optical setup for obtaining Fourier transformation.

APPENDIX I

COMPUTER PRINTOUT OF THE CALCULATED FRINGE PATTERNS

This appendix includes two computer programs and their printouts of the calculated fringe patterns.

The printout is of the fringe patterns along the radius of the target.

- (1) The first fringe pattern is of a glass microshell of 100 μm radius, with no gas inside. The glass thickness varies from 0.5 μm up to 15 μm .
- (2) The second printout is of the same glass microshell, but filled with 186 atm or 30 mg/cc of D_2 gas.

Matching the observed fringe pattern of the target at room temperature with printout number 2 gives the target glass thickness. Comparing the fringe pattern of the same target containing a droplet (excluding the droplet fringe pattern) against printout number 1 gives the same glass thickness that is obtained from printout number 2. This verifies that there is no liquid inside the target besides the droplet.

```

LIST
79.06/0H, 12.05.04.
PROGRAM FRINGS
00100 PROGRAM FRINGS(LRPU1,OUTPU1,TAPE6,OUTPU1)
00110 REAL RI,R3,LAMBDA,R
00120 INTEGER DRIGHT,DARK,STRI,ACT,CO
00130 RI=1.47
00140 R3=1.
00150 MAXJ=100
00160 LAMBDA=.5420
00170 R=100.
00180 DRIGHT=10.
00190 DARK=10X
00200 DO 10 RI=1,470
00210 DRIGHT=ACT/CO/2.
00220 WRITE(6,130)RI
00230 S0=2.*RI*(RI-1.)*DRIGHT+.01
00240 DO 20 R3=1,470
00250 Z=PI*RI*(R3)/L20.
00260 ALPHA=ASIN(Z)
00270 RE TA=ASIN(Z/R3)
00280 S1=2.*RI*(RI-1)*COS(ALPHA-RE TA)/COS(PI/6)
00290 S2=2.*RI*(RI-1)**(R-1)*RE TA/LAMBDA
00300 S=S1+S2
00310 S=S-S0
00320 DO 20 J=1,MAXJ
00330 IF (S,RI,LAMBDA) S=LAMBDA
00340 GO TO CONTINUE
00350 IF (S,RI,LAMBDA) DRIGHT=ACT/110) S
00360 IF (S,RI,LAMBDA) STRI=
00370 R=R3
00380 STOP DRIGHT
00390 IF (S,RI,LAMBDA/4.)) STOP. (S,1.63,41 DRIGHT/4.)) STRI DARK.
00400 ACT=S0+1
00410 GO TO CONTINUE
00420 WRITE (6,120) (ACT), 1,1,1,0)
00430 DO CONTINUE
00440 STOP "MORE"
00450 110 FORMAT (1X,F10.3)
00460 120 FORMAT (1X,F20.6)
00470 130 FORMAT (10H/1X,F10.6)
00480 END
11 END.

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1.00

20208201, 17.02.01.

THICKNESS

RADIUS

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1 CLASS THICKNESS= 7.500MICRONS, .....XXXXXXXXXXXXXXXXXXXX

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0.10Z 0033.
0L60C.
0L51
      79 06Z00L 12.00.25.
PROGRAM  FRTN05

00100  PROGRAM FRTN05(UNIT,OUTPUT,TAPE,6 OUTPUT)
00110  REAL N1,N2,N3,ABRDA,R
00120  INTEGER IRRIGHT,DARK,SPOT,AC(120)
00130  N1=1.47
00140  N2=1.0226
00150  MAXJ=100
00160  IABRDA=.6328
00170  L=100.
00180  MCFRHT=1H.
00190  DARK=1H
00200  DO DO K1 1,30
00210  M1=ELDAT(K1)/Z.
00220  M1=1/(6+.130)*M1
00230  S0=2.*(M1*(N1-1.)/(N3-1.)*(R-W1))
00240  W0=Z0*K3-1+.120
00250  Z=ELDAT(K3)/120.
00260  M1=M0-ASIN(Z)
00270  DFLA=ASIN(Z/N1)
00280  S1=3.481*(N1-COS(ALPHA-DETA))/COS(DETA)
00290  S2=2.*(N3-1.)*(R-W1)*COS(ALPHA)
00300  S=S1S2
00310  S=S-S0
00320  DO DO J 1,MAXJ
00330  F(S,61.1,ABRDA) S=S-ABRDA
00340  DO 1 CONTINUE
00350  F(S,61.1,ABRDA) WRITE(6,110) S
00360  F(S,61.1,ABRDA) STOP
00370  H K3
00380  SPOT=IRRIGHT
00390  F(C,4.0E-4,ABRDA/4.))AND,(S,1.1E-3,81,ABRDA/4.)) SPOT=DARK
00400  A=10-SPOT
00410  Z0=L/ABRDA
00420  MCFH=(6+120)/(6C1)+1-1+120)
00430  R6=CONTINUE
00440  STOP "NONE"
00450 110 FORMAT(1X,10.3)
00460 120 FORMAT(1X,1E04)
00470 130 FORMAT(11H//1X,6H ABSOLUTE FRTN05 4) 6.5,4,4,11,10,45,4)
00480 140
END
00130 05 1.

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1004

7906700. 11.56.24.
FIRMSM FRTG5

RADIUS

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GLASS THICKNESS= 7.500MICRONS	

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GLASS THICKNESS= 15.000MICRONS,
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END 40.600 BITS.

END COMPLETE
5000 MICRONS

APPENDIX II

THEORETICAL CALCULATION OF THE AMOUNT OF
D₂-CONDENSATION INSIDE A TARGET

This appendix contains calculations which, under simplifying assumptions, determine the following properties of a D₂-filled target at different cryogenic temperatures:

- (1) The D₂ gas pressure
- (2) The thickness of the D₂ liquid layer
- (3) The index of refraction of the D₂ gas and liquid.

A) Mass Density-to-Pressure-Conversion

$$\rho = \frac{M}{V} \quad (A.1)$$

where ρ is the mass density of D₂ in $\left[\text{kg/m}^3 \right]$

M is the total mass of D₂ in $\left[\text{kg} \right]$

and V is the volume of D₂ in $\left[\text{m}^3 \right]$.

For D₂ with atomic number 4:

$$M = (N) \cdot (4) \cdot (1.67 \times 10^{-27})$$

where N is the number of particles,

therefore,

$$\rho = \frac{N}{V} (6.68 \times 10^{-27}) \quad (A.2)$$

Using the ideal gas law

$$P = \frac{N}{V} kT \quad (A.3)$$

where k is Boltzmann's constant in $[J/K]$

T is the temperature in $[K]$

and P is the pressure in $[N/m^2]$.

Using the ratio $\frac{N}{V}$ from Eq. (A.2)

$$P = \left(\frac{\rho}{6.68 \times 10^{-27}} \right) \cdot \left(1.38 \times 10^{-23} \right) \cdot T = 2066 \rho T \quad (A.4)$$

(e.g., for $\rho = 30$ mg/cc the pressure at room temperature is $P = 186$ atm).

B) Mass Density-to-Molecular Density-Conversion

A different form of Eq. (A.2) is

$$\frac{N}{V} = \frac{\rho}{6.68 \times 10^{-27}} \quad (A.5)$$

$$Q = \frac{\rho / 6.68 \times 10^{-27}}{6.023 \times 10^{23}} = 249 \rho \quad (A.6)$$

where Q is the molecular density in $[mole/m^3]$,

e.g., for $\rho = 30$ mg/cc the molecular density is $Q = 7470$ mole/m³.

C) Density-Dependence of the Index of Refraction of D_2

A formula can be derived to approximate the index of refraction, n , from Fig. 1 of Reference 9.

$$n = 1 + \frac{0.0226}{7470} \cdot Q = 1 + 3.025 \times 10^{-6} Q \quad (A.7)$$

or

$$n = 1 + 0.753 \times 10^{-3} \rho \quad (A.8)$$

D) Temperature-Dependence of the Density of D_2

Temperature (K)	Density (Mol/Liter)	
	Vapor	Liquid
18.710	0.111221	43.1598
19.000	0.124876	43.0160
20.000	0.181841	42.5081
21.000	0.256456	41.9781
22.000	0.352051	41.4228
23.000	0.472322	40.8403
24.000	0.621418	40.2287
25.000	0.804045	39.5858
26.000	1.02561	38.9085
27.000	1.29242	38.1926
28.000	1.61194	37.4326
29.000	1.99316	36.6212
30.000	2.44712	35.7488
31.000	2.98769	34.8025
32.000	3.63281	33.7643
33.000	4.40669	32.6085
34.000	5.34403	31.2963
35.000	6.49920	29.7650
36.000	7.97036	27.9000
37.000	9.98197	25.4469
38.000	13.4367	21.4462
38.340	17.3280	17.3280

E) Thickness of the Liquid Layer

The total mass, M , of the D_2 contained inside a ball is

$$M = \rho_0 \cdot V = \rho_0 \cdot \frac{4}{3} \pi (R - w_1)^3 \quad (A.9)$$

where V is the volume of the ball occupied by the D_2 gas,

ρ_0 is the gas mass density with no condensate,

R is the radius of the ball,

and w_1 is the thickness of the glass shell.

Using the assumption that $w_2 \ll R$, with w_2 being the thickness of the liquid layer, the mass of the gaseous D_2 , M_g , can be approximated as

$$M_g \approx \rho_g \cdot V = \rho_g \cdot \frac{4}{3} \pi (R - w_1)^3 \quad (A.10)$$

where ρ_g is the D_2 -vapor mass density at a given temperature.

The mass of the liquid D_2 , M_L , is then

$$M_L = M - M_g \quad (A.11)$$

The mass density of liquid D_2 is ρ_L .

The volume of the liquid, V_L , using Eqs. (A.9), (A.10), and (A.11) is

$$V_L = \frac{M_L}{\rho_L} = \frac{(\rho_0 - \rho_g) \frac{4}{3} \pi (R - w_1)^3}{\rho_L} \quad (A.12)$$

The thickness of the liquid D_2 layer, w_2 , can therefore be estimated as

$$V_L = 4\pi (R - w_1)^2 \cdot w_2 = \frac{(\rho_0 - \rho_g) \frac{4}{3} \pi (R - w_1)^3}{\rho_L} \quad (A.13)$$

or

$$w_2 = \frac{(\rho_0 - \rho_g)(R - w_1)}{3\rho_L} \quad (A.14)$$

REFERENCES

- 1) F. Chen, Introduction to Plasma Physics, Plenum, N. Y. (1974).
- 2) Lectures From the Argonne Faculty Institute on Fusion Plasmas (1975) (Chapter 1).
- 3) J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, Nature 239, 139 (1972).
- 4) T. M. Henderson, R. B. Jacobs, D. E. Solomon, and G. H. Wuttke, Adv. in Cryo. Eng. 21, 455 (1975).
- 5) A. Rosencwaig, J. L. Dressler, J. C. Koo, and C. D. Hendricks, University of California report UCRL-81421 (1978).
- 6) B. W. Weinstein, and C. D. Hendricks, Interferometric Measurements of Laser Fusion Targets, University of California, Lawrence Livermore Laboratory, private communication (1977).
- 7) C. K. Briggs, R. T. Tsugawa, C. D. Hendricks, and P. C. Souers, University of California report UCRL-51921 (1975).
- 8) C. Souers, Cryogenic Properties of Heavy Hydrogen, Chemistry Department, Lawrence Livermore Laboratory, California, private communication (1973).
- 9) K. Kim, B. J. Smoot, R. L. Woerner, and C. D. Hendricks, Appl. Phys. Lett. 34, 282 (1979).
- 10) Yu. P. Blagoi, and V. V. Pashkov, Soviet Physics-JETP 22, 999 (1966).
- 11) V. N. Grigorev, and N. S. Rudenko, Soviet Physics-JETP 20, 63 (1965).