Planar Cryogenic Target Handling Capability for the OMEGA Laser-Fusion Facility

Introduction

A high-performance "planar" Cryogenic Target Handling System has been added to LLE's OMEGA Laser-Fusion Facility.[1] Initially designed for equation of state measurements of liquefied D_2, it's versatility enables studies of Rayleigh–Taylor instabilities, shock timing, and cryogenic hohlraum performance. The system has demonstrated a shot-to-shot cycle interval of less than two hours and has fielded more than 125 experiments using several distinct target types. This article provides an overview of the cryogenic capabilities at LLE and compares the operational requirements of LLE's spherical and planar cryogenic systems. The unique features of the planar cryogenic system are described, and applications of this technology within the ICF community are discussed.

Direct-drive inertial confinement fusion (ICF)[2] implosion targets are susceptible to shell distortion because of Rayleigh–Taylor instability.[3] During the ablation phase, shock waves are launched into the capsule, resulting in compression of the fuel and gas core. Drive nonuniformities can be mitigated by rapidly heating the ablative surface of a fuel-containing capsule. Models used to predict how shock waves propagate in an ICF target and the resulting target performance depend on an accurate knowledge of the equation of state (EOS) of hydrogen isotopes at pressures exceeding 1000 GPa. Numerous experiments have been conducted in this regime using several different techniques with differing measured compressibility.[4]

LLE's planar Cryogenic Target Handling System [CTHS (Fig. 103.12)] is a versatile experimental platform used to study the EOS of D_2 using laser-driven shock waves. This apparatus was developed to obtain a better understanding of the discrepancies in prior experimental results. The planar CTHS leverages the technical expertise and infrastructure developed for direct-drive spherical cryogenic target experiments at LLE.[5–8] This system produces very repeatable experimental conditions with a short (~2 h) cycle time between target experiments and has been adapted to many different target and diagnostic configurations. Because of its versatile design, it is well suited to other applications like testing cryogenic sensors and evaluating tube-filled spherical ICF targets.

This article presents an overview of LLE's cryogenic target capabilities followed by a discussion of the operational differences between spherical and planar cryogenic experiments. Details of the planar CTHS hardware implementation and target construction are presented. Finally, performance of the planar cryogenic system is discussed.

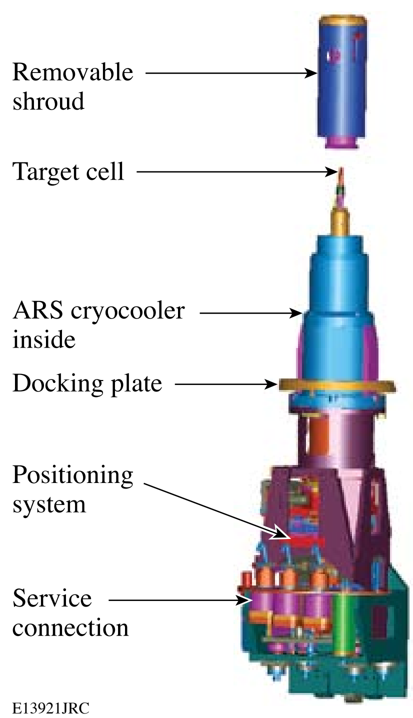

Figure 103.12
This moving cryostat (MC) was developed for cryogenic equation of state experiments. It occupies the same space envelope as a spherical MC. An MC module can be installed in approximately 4 h.

Overview

Since 1999, LLE has had the unique capability of diffusion-filling, freezing, layering, characterizing, and imploding thin-walled spherical cryogenic targets on the OMEGA Laser System.[5,6] This system requires an extensive infrastructure to support each stage of the process, as described in Refs. 7 and 8. The Planar and Spherical Cryogenic Target Handling Systems have much in common. In contrast, planar targets are filled through a tube from a self-contained reservoir, making the process much simpler than the diffusion-filling process used for spherical targets.

LLE's diffusion-filling apparatus for spherical ICF targets is located remotely from the OMEGA target chamber. Consequently, a self-contained transport system, known as the Moving Cryostat Transfer Cart (MCTC), was developed so that filled targets could be maintained at cryogenic temperatures indefinitely and transported between the filling and characterization stations and to the target chamber. The MCTC payload, known as the moving cryostat (MC), has several functions that include

- precisely controlling the thermal environment surrounding the target until moments before an implosion experiment,
- transporting targets ~6 m vertically into the target chamber, and
- providing fine-position control for the target once it is at target chamber center (TCC).

Cooling power for the MC is provided by a closed-cycle Gifford–McMahon helium refrigeration system.[9] A helium compressor is mounted on the MCTC, and a two-stage cryocooler is housed within the MC. The first stage of the cryocooler operates near 50 K, and the second stage operates between 10 and 20 K. Services for the MC, which include high-pressure helium lines, electrical conductors used for sensors and actuators, optical fibers, and exchange gas lines, are provided by an umbilical that extends and retracts with the MC.

Each MC assembly includes a multilayer removable shroud; its outer wall is at room temperature, whereas the inner walls are cooled. Once an MC is raised and secured at TCC, a four-axis positioner (X, Y, Z, rotation about Z) within the MC is used to position the target as it is viewed through windows in the shroud. A linear induction motor (LIM) then lowers a gripping mechanism that mates to the thermal shroud. Immediately before the laser is fired, the LIM rapidly pulls the shroud clear of all laser beams. The hardware supporting the target is designed so that it does not interfere with laser beam propagation.

The entire process is controlled by a combination of hardware and software interlocks, automated control systems, and operating procedures. Five MCTC's have been deployed. Currently, four are dedicated to spherical ICF experiments and one is configured for planar cryogenic target experiments. In all, more than two hundred cryogenic target experiments have been fielded on OMEGA.

Distinguishing Differences Between Spherical and Planar Moving Cryostats

The planar and spherical CTHS's are required to field (up to) 15 and 8 targets per 36-h shot week, respectively.[(a)] A major distinction between these systems is that a single planar MC can satisfy this requirement, whereas four spherical MC's are required. In addition, planar targets are hand-loaded into a warm MC, while spherical targets are transferred into a cold (~18 K) MC. The cycle time for planar targets includes cool down and warm up of the MC, whereas a spherical MC is not generally warmed between shots. As a result, the cycle time for planar targets is governed by the planar MC's thermal time constant and evacuation/vent times, while for spherical targets cycle times are dictated by the ice layering process.[8] Table 103.I summarizes some of the key requirements of, and differences between, the planar and spherical MC's.

The cooldown time (time to reach 18 K) for a spherical MC exceeds 3 h. Many MCTC's would have been required to satisfy the goal of 15 planar shots/week if the same MC were adapted for the planar experiments. Instead, a new planar MC having a short thermal time constant (τ_{th}) was developed. The required shot rate is satisfied using a single MCTC. The reduction of τ_{th} was possible because of the different operating requirements of the two systems, as discussed below.

Spherical cryogenic targets are cooled indirectly using helium "exchange" gas to conduct heat from the target to the surrounding cold copper "layering" sphere [Fig. 103.13(a)].[8] This design minimizes thermal gradients surrounding the capsule so that uniformly smooth ice layers form on the interior of the target shell. Exchange gas also allows the target support hardware to be mechanically decoupled from the cryocooler. The layering sphere is contained in the upper half

[(a)]Eight spherical target implosions have been carried out in a single week, but campaigns are currently planned assuming ≤4 shots/week to allow sufficient time to develop an ice layer and characterize it.

Table 103.I: Key differences and requirements for planar and spherical moving cryostats.

	Planar MC	Spherical MC
Target cooling method	Conduction through copper	Conduction through ~80 mTorr He exchange gas
Target temperature	13 to 30 K±50 mK (achieves <±10 mK)	17 to 21 K±10 mK
Target filling method	"Cryopumping" from integral reservoir through fill tube while target is in the MC	Diffusion filled in dedicated filling station, then frozen before transferring to the MC
Target installation method	Loaded by hand into the warm MC (open to atmosphere)	Mechanical manipulator transfers target at cryogenic temperature
Required shot rate	Up to 15 shots/week using ≤2 MCTC's	Up to 8 shots/week using 4 MCTC's
Laser beams required for target shots	Selected from all beams with $\theta < 155°$ (55 possible)*	All 60 beams
Target rotation	±5°	360°, continuous
Target heat source	Resistance heater	OPO IR laser, $\lambda = 3.16\ \mu$m

*θ is the angle measured relative to the vertical axis of the chamber. $\theta = 0°$ = top of chamber.

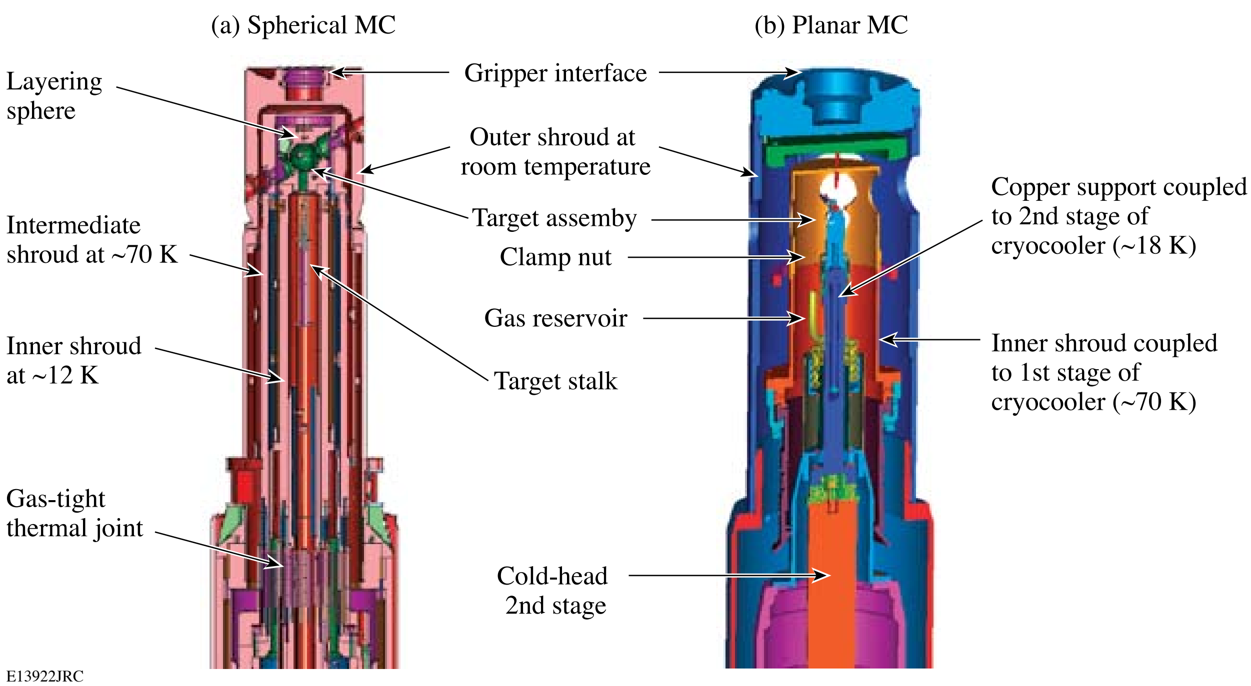

Figure 103.13
Exploded views of (a) a spherical MC and (b) a planar MC. The spherical system cools targets using a helium exchange gas; the planar system uses direct conduction through copper. These cross sections do not show the four-axis target positioners or the cold heads. The planar cold head is attached directly to the positioner; the spherical cold head is mechanically and thermally decoupled from the positioner.

of the shroud and is thermally connected to the second stage of the cryocooler.

The entire MC is inside the target chamber (maintained below 1×10^{-5} Torr); therefore, exchange-gas leakage from the spherical MC must be minimized. This constraint is satisfied by enclosing the (room temperature) fine-motion target positioner in a sealed box that mates to the upper shroud using complex, gas-tight, thermal joints. The room-temperature positioner is mechanically coupled to, but thermally isolated from, the target by means of a long slender "stalk." This stalk is supported near its midpoint by a compliant joint that provides the necessary degrees of freedom to position a target, including the full 360° rotation needed to characterize the ice layer.[10,11] The design chosen to satisfy these requirements separates the layering sphere from the cryocooler's second stage by nearly 0.6 m. Approximately 8 kg of material must be cooled to an average temperature of 14 K in order to freeze the D_2 fuel in a spherical target.

The layering sphere in a spherical MC has an optical fiber to transmit radiation heat from an optical parametric oscillator (OPO) IR laser source ($\lambda = 3.16$ μm, matched to an absorption band of D_2) to heat the ice during the layering process.[8] This requires spherical shrouds to be equipped with optical fiber connectors as well as temperature sensors and a cryogenic photodetector to provide feedback for closed-loop control of the OPO. The planar system has no requirements for sensors in the shroud.

Vibration is a critical issue for the spherical MC.[6] Spherical target assemblies are delicate, supported by a slender stalk (and its compliant joint), and are susceptible to vibration sources that couple to the MC. Many hardware improvements have been made to mitigate vibration susceptibility, with more pending.

Planar Cryogenic Target Handling System

The planar MC was designed to be interchangeable with a spherical MC and to use a common control system. The planar MC module [Fig. 103.13(b)] can be interchanged with a spherical MC in approximately 4 h, giving a high degree of flexibility when planning experimental campaigns. Since its first use on OMEGA, one planar MCTC has been used for over 125 target shots with up to 5 shots per day. OMEGA typically has three shot days per week; one planar MC can meet the 15 shot per week requirement. Target fabrication, diagnostic setup, and personnel availability are often the rate-limiting factors in the shot cycle. Typically, ambient temperature shots are interleaved with planar cryo shots to take advantage of OMEGA's 1-h repetition rate.

The planar system was not required to use exchange gas and was required to have only ±5° of rotation, since coarse rotational alignment can be established by target design. These requirements were satisfied by mounting an ARS (Advanced Research Systems, Inc.)[12] cryocooler directly onto the planar MC's fine-motion positioner. The target is attached to the cryocooler's second stage using a high-thermal-conductivity copper support [Fig. 103.13(b)]. The resulting cold mass in the planar MC is less than 0.5 kg; therefore, the time constant τ_c is dramatically shorter than a spherical MC. This design is mechanically very stable and eliminates the exchange gas and complex thermal joints used on a spherical MC. Figure 103.14 shows the structure of the planar MC without a shroud.

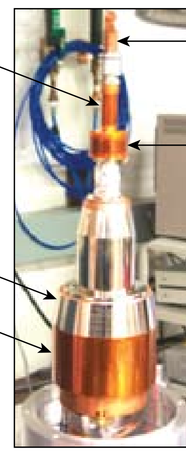

Figure 103.14
The internal structure of the planar MC (target is shown without reservoir).

Planar cryogenic experiments typically use a subset of OMEGA's 60 laser beams that are located no more than 65° below the equator, however, spherical targets with fill tubes could be fielded on the planar MC using all 60 beams.

1. Planar Cryogenic Target Design

The primary requirement for planar cryogenic targets is to contain liquid or solid D_2 in a cell having a 1-mm inside diameter and a 0.5-mm depth. Diffusion filling was deemed impractical; therefore, targets are filled through a tube from a local reservoir. Various options were considered, including supplying the fill gas through the umbilical and using valves and pressure sensors to meter the gas. This would have required a vent line in the umbilical to purge contaminants from the target cell and fill lines. A much simpler approach was adopted; a sealed gas reservoir is connected to each target cell by a stainless steel capillary fill tube (Fig. 103.15). The reservoir (approximately 4-cc capacity at STP) is an accurately formed spiral copper tubing coil that is filled to a known initial temperature and pressure.

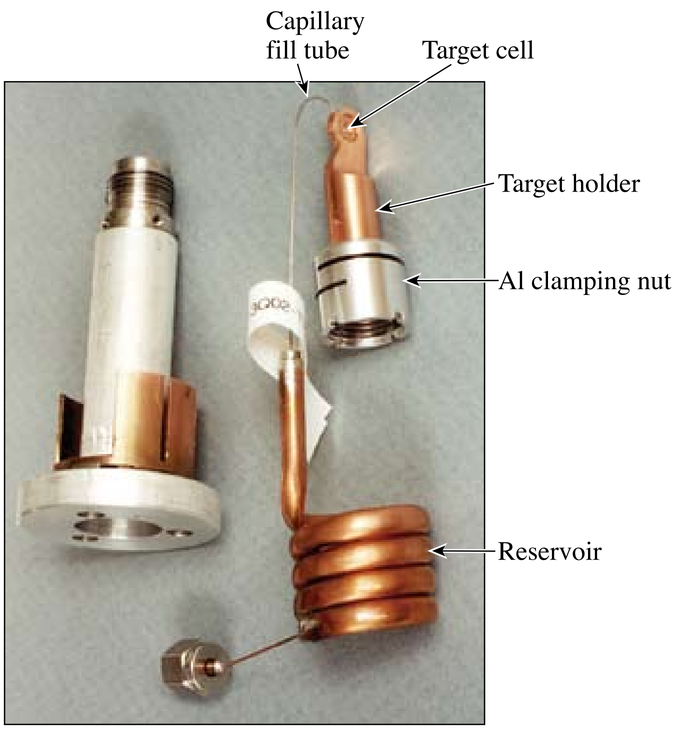

Figure 103.15
A typical planar cryogenic target assembly (right) is shown beside an assembly fixture (left). The split aluminum nut maintains joint preload when cooled. The gas reservoir is connected to the target cell by a capillary tube.

Planar targets are filled off-line at room temperature. Purge gas is circulated through the reservoir/cell assembly and exits through vent tube attached to the cell. Blocked tubes are detected if the purge gas is not discharged through the vent tube. After purging, the vent tube is crimped to form a gas-tight seal, and the assembly is filled to the desired pressure (typically <2 atm). After reaching the desired pressure, the valve on the fill source is closed, and the reservoir pressure is monitored.[b] If the pressure decay is within acceptable limits, the fill line is crimped and the target is ready for use.

This design allows great flexibility in the choice of fill gas with no chance of cross-contamination between experiments. It minimizes the volume of gas released into the target chamber and limits the total gas inventory for each target in the event that DT targets are fielded using this system.

When conducting equation of state experiments, the MC maintains the gas reservoir at about 250 K. Once the cell reaches 20 K, gas begins to condense in the cell, creating a pressure gradient between the cell and reservoir. Condensation is monitored with cameras that view the target through the shroud windows, and the process continues until the cell is full. Given that the fill volume of a target cell is approximately 0.2 mm^3, it is not practical to install sensors in the cell. Instead, a temperature sensor is permanently installed in the copper adapter, immediately below the target holder.

Liquid D_2 density decreases at a rate of –1.3%/K from 20 to 24 K (Ref. 13). Targets that can withstand ice formation are cooled through the triple point (18.63 K) during shot preparation. The temperature at which an operator first observes ice formation in the cell is recorded. This calibrates the sensor with the accuracy needed to determine the initial state. Variations in observed triple-point measurements give a clear indication of the quality of the thermal joint formed between the target and the copper support [Fig. 103.13(b)]. Targets that cannot withstand ice formation are equipped with temperature and pressure sensors on the gas reservoir. These sensors are connected to the umbilical for readout by signal conditioning hardware external to the MCTC.

Thermal joints require preload to maintain intimate contact between mating surfaces. The thermal conductivity of a joint degrades if this preload decreases when it is cooled. The planar MC overcomes this difficulty by using a novel aluminum nut to clamp the copper target to the copper cryocooler adapter (Fig. 103.15). Spiral grooves on the nut's perimeter form bending-beam spring elements. Joint preload increases in a deterministic manner as the target assembly is cooled because of differential contraction of the aluminum and copper components. An optimized nut design results from properly choosing the cross section and length of the bending element. When a small amount of thermal grease is applied between the mating copper surfaces that have roughness ≤16 μin rms, the temperature drop across the joint is less than 1 mK, even when the nut is initially only finger-tight.

The gas reservoir rests inside a copper cup that is weakly coupled to the first stage of the cryocooler. The perimeter of the cup is split axially, forming a series of spring "fingers" similar to the assembly fixture in Fig. 103.15. A resistive foil heater

[b]The pressure sensor is part of the filling apparatus, not the target.

on a Kapton substrate[14] is wrapped around the cup to heat the reservoir. This joint also employs differential contraction to increase preload between the cup and reservoir as the heater's Kapton substrate cools and contracts. It is possible to operate with a differential up to 250 K between the reservoir and cell and still freeze D_2 in the cell.

Controlling the thermal gradient between the reservoir and target has several benefits. It permits control of gas transfer into the cell, prevents ice from obstructing the fill tube, and provides a heat source that controls the rate of ice formation in the cell. Void-free ice layers have been produced. Heat transfer through the fill tube is very low because it is made of low thermal conductivity stainless steel. The thermal conductivity of this path can be altered as needed by adding a thermal shunt or by altering the tubing's cross section, length, or material.

2. Target Cell Construction

A typical target cell is shown in Fig. 103.16; it consists of stacked components that are bonded together and then inserted into a copper holder. This modular design allows users to select from various windows, "pushers," cell sizes, and radiographic windows without altering the basic geometry. Copper holders are reused 2 to 3 times or until laser-induced damage is too severe. Reservoirs can be reused many times after replacing the fill and vent tubes.

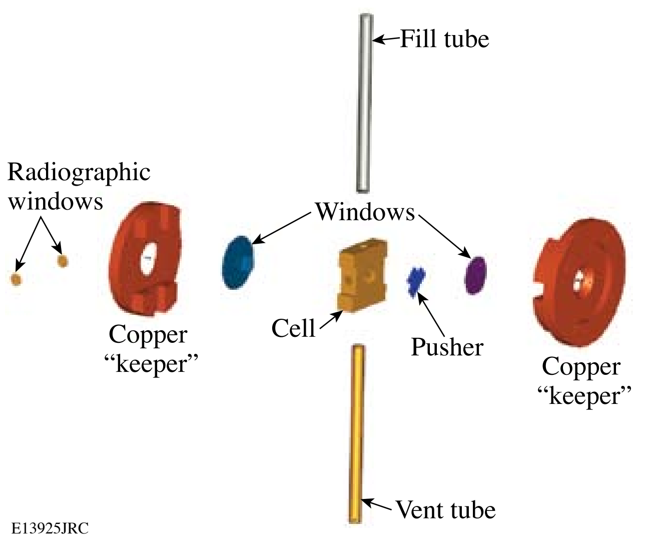

Figure 103.16
A target cell assembly consists of several elements that enclose a gas-tight volume of approximately 1-mm diameter and 500-μm deep. Fill and vent tubes are soldered to the cell. Some cells have radiographic windows (far left) that permit the driven shock to be imaged using an x-ray camera.

The outermost rings, referred to as "keepers," clamp the assembly into the holder. Safety wires are wrapped through holes in the keepers and holder to minimize debris ejection into the target chamber. The tension in these safety wires is critical to their effectiveness. Two opposing wires are tightly twisted, and the remaining two are relatively loose. The tight pair suffers from the initial impact and generally fail. The remaining pair of safety wires generally survive, allowing the entire assembly to be retrieved.

Although this modular target design is robust, fabrication is time consuming and requires highly skilled technicians to achieve satisfactory results. Some early targets failed because of gas leakage or blockage of the fill tube. These and other problems have been virtually eliminated with the processes that have been developed and the quality-control measures employed.

3. Shroud Construction

The spherical MC shrouds use a complex design, primarily because of the exchange-gas requirement. The heat capacity of the planar system allows it to be operated without a shroud and still freeze the fill gas. When practical, a shroud is used to minimize the possibility of condensate formation on the target and other cold components in the MC. The inner shield of the shroud [Fig. 103.17(a)] is cooled by the cryocooler's first stage to below 70 K. Thin-film Kapton windows permit the target to be observed while the shroud is in place using the OMEGA target viewing system and the video camera on the active shock breakout diagnostic.[15] The upper-shroud thermal joint consists of a set of spring-loaded fingers [Fig. 103.17(b)] that maintain thermal conductivity with the lower half of the MC while accommodating large radial positioning errors. The shroud can accommodate targets of up to 50 mm in diameter. The planar MC shroud weighs 70% less than the spherical shroud (3.6 kg versus 12.7 kg), is far less costly to manufacture, and is robust. These shrouds require no maintenance.

4. Performance Results

The planar MC has a cooldown time of 50 min. It is a very robust and stable mechanical platform that can support a wide variety of targets. Figure 103.18 shows a flow chart of the shot process, including approximate times, based on the most rapid shot cycles achieved to date. Several processes are performed concurrently, such as diagnostic alignment and cooling. During warm-up, all heaters in the MC are run at maximum output. Once the MC reaches 70 K and it is isolated from the target chamber, heated dry nitrogen is used to vent the MCTC to ambient pressure. This prevents moisture from condensing in the multilayer insulation used in the MC that, in turn, reduces the time required to achieve high vacuum for the next shot cycle. Variations in the shot cycle time are generally attributable to diagnostic preparation. Table 103.II summarizes performance achievements with planar and spherical MC's.

Figure 103.17
(a) The inner shroud of the planar MC operates at ~70 K during a target shot. Windows in the shroud permit the target to be imaged by the OMEGA target viewing system and the active shock breakout diagnostic. Window openings on the inner shroud are covered with Kapton film. (b) A compliant thermal joint connects the inner shroud to the cryocooler's first stage.

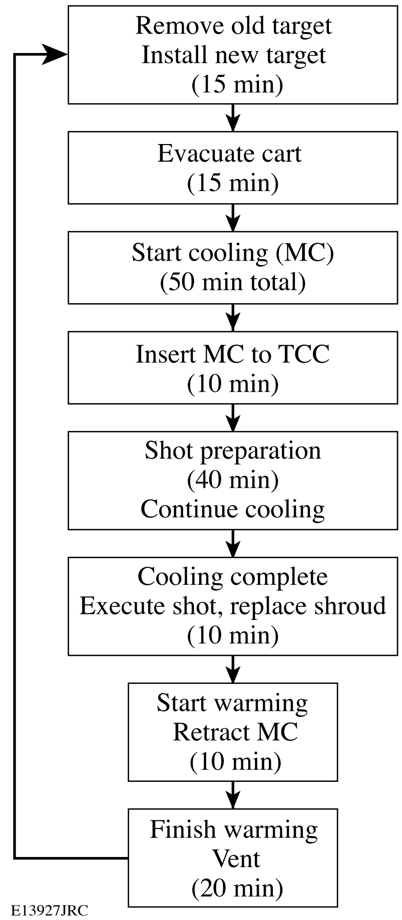

Figure 108.18
The shot cycle flow chart depicts how 2-h cycle times have been achieved.

Table 103.II: Cryocoolers used and resulting performance comparison between planar and spherical MC's.

	Planar MC	Spherical MC
Cryocooler model	ARS Displex DE204 60 Hz	Sumitomo RDK408S 60 Hz
Cryocooler load capacity	1 W at 10 K, 6 W at 16 K	1.8 W at 10 K, 9 W at 16 K
Target operating procedure	15 to 30 K	17 to 22 K
Mass cooled <50 K	<0.5 kg	8 kg
Maximum number of target shots/day	5, using single MCTC	4, using 4 MCTC's
Actual shot cycle using one MCTC (h)	<2	72 minimum
Cooldown time (min)	<50	>180

Future Applications

Many of the design features developed for, and proven on, LLE's planar Cryogenic Target Handling System are well-suited to other cryogenic applications within the ICF community and elsewhere. LLE may use the planar cryogenic system to evaluate the feasibility of filling spherical targets with a fill tube. Targets such as this may be used for cryogenic campaigns at the National Ignition Facility.[16]

The exceptional stability of the planar moving cryostat allows it to be used as a target chamber center alignment reference on OMEGA, both at vacuum and at ambient pressure. The planar MC serves as a "transfer standard" so that the target chamber center can be accurately established throughout the cryogenic system infrastructure, including the characterization stations used for layering spherical cryogenic targets.

Conclusion

This article has described a high-performance planar cryogenic target positioner for use on the OMEGA Laser System. Although initially designed for equation of state studies of cryogenic hydrogen isotopes, it is a versatile platform, readily adapted to suit a wide range of experimental designs. Through careful attention to experimental and operational requirements, this design has achieved shot-to-shot cycle times below two hours. Novel thermal joints employ differential contraction of dissimilar materials to maintain joint preload at all temperatures. The target has an integrated gas reservoir, permitting users wide latitude in designing experiments with different gasses. Modularity permits flexibility in designing each target. Many of these concepts are directly applicable to cryogenic devices being developed for the ICF community and elsewhere.

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