

# Target Technologies for Ignition on the NIF

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# Target Technologies for Indirect Drive Ignition on the NIF

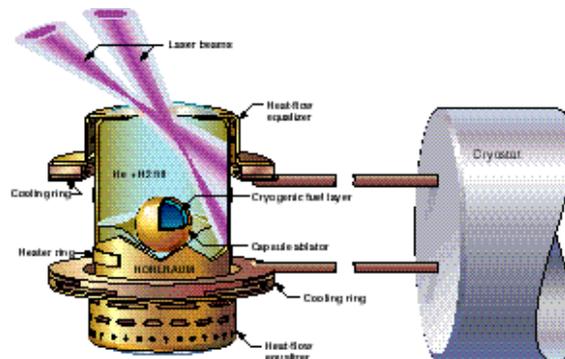
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## Abstract

X-ray driven ignition targets for the NIF will include fuel capsule materials different from those used up to now in ICF experiments. They will contain cryogenic fuel layers, and will be enclosed in cryogenic hohlraums. These hohlraums must provide the thermal environment required to shape the fuel layers, and must be supported by cryogenic equipment in the NIF target chamber. The methods for filling and delivering the targets to the NIF chamber will combine high-temperature diffusion with cryogenic transport. A program is in place in the U.S. to design and develop the ignition targets, and the cryogenic support and fill systems needed to field them. This program includes participation from Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and General Atomics.

## 1. Introduction

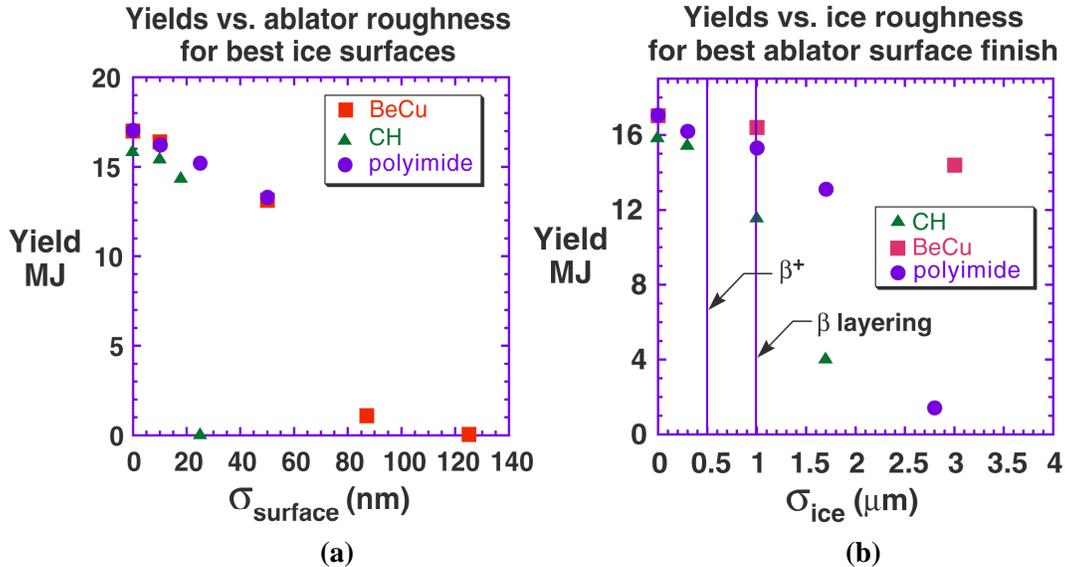
The first attempts to achieve ignition on the U.S. Department of Energy's National Ignition Facility will be by indirectly driven (sometimes called x-ray driven) implosions. An indirect-drive ignition target is shown in *figure 1*. The laser light is converted to the drive x-rays in a hohlraum made from a high-atomic-number material or mixture of materials to maximize the conversion efficiency. The symmetry and time-dependent x-ray drive intensity and spectrum are determined by the placement of the NIF laser beams on the hohlraum wall, and the time-dependence of their intensities. The material composition of the capsule contained in the hohlraum must be matched to the drive temporal profile and spectrum. For all current ignition designs, the D-T fuel in the capsule is a smooth, cryogenic, solid layer, with an interior vapor density that is a design parameter. The uniform thickness fuel layer requires that the hohlraum be a cryogenic enclosure, and that the isotherms at the capsule surface be extremely spherical. Especially for capsules with walls that are poor thermal conductors, sufficiently spherical isotherms require that the hohlraum wall must have a tailored temperature profile, requiring special heating and cooling rings as indicated. Almost all capsule materials are too weak to safely contain the fill pressure at room temperature, so that the target must be maintained at cryogenic temperatures from its filling until its insertion and implosion in the NIF target chamber. The filling and cryogenic transport and target-chamber support systems will be highly specialized to achieve ignition.



**Figure 1** NIF indirect-drive ignition targets are complex assemblies with exacting tolerances.

## 1.2 Ignition Capsules

Three types of ignition capsules are under development and theoretical investigation: beryllium, polyimide, and CH polymers. A set of 3-dimensional implosion simulations<sup>[1]</sup> were recently completed for this set of NIF ignition designs. The simulations imposed capsule and D-T ice surface spectra, based upon measurements of polymer sphere capsules as well as cryogenic D-T layers which were observed in cylindrical cells. Variations to designs are still being studied. In general, though, as seen in *figure 2*, for the same ice roughness and capsule surface roughness, beryllium is superior to polyimide, which is superior to CH. However, while CH capsules have been used over the past decade in both direct and indirect drive experiments, beryllium and polyimide capsule development is not yet complete. We review their status below.

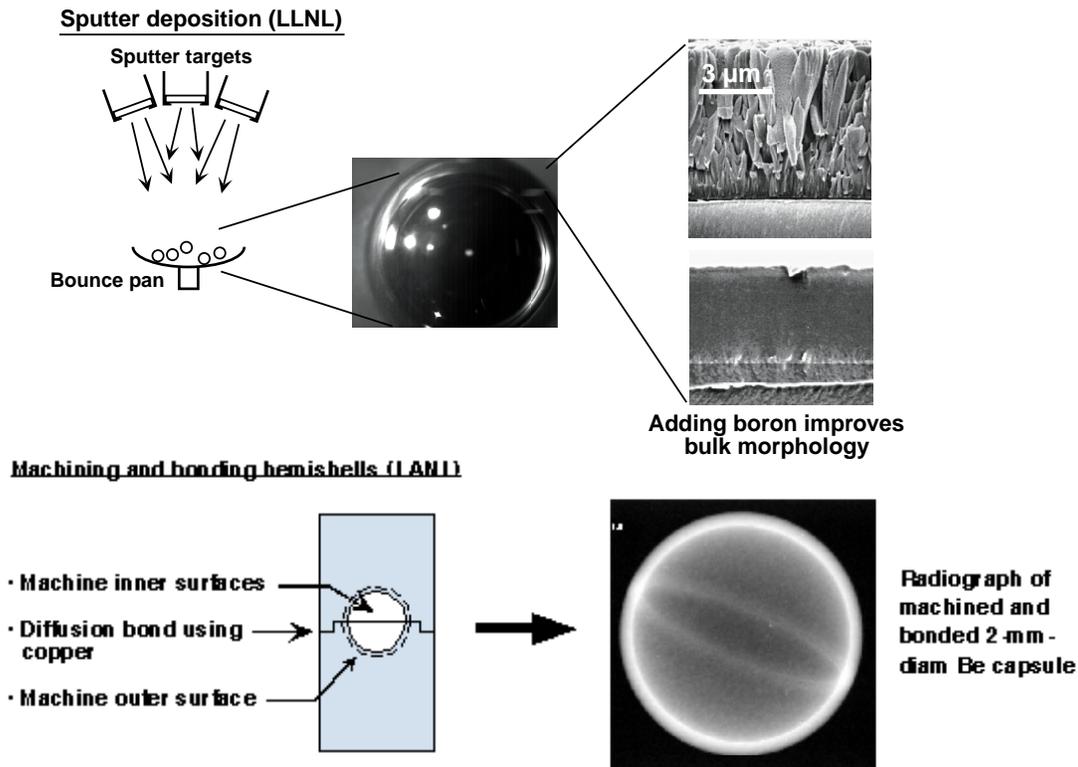


*Figure 2 (a) Yield vs. ablator rms surface roughness for the best ice surfaces obtainable (  $1 \mu\text{m}$  for beryllium,  $0.5 \mu\text{m}$  for polymers using auxiliary smoothing techniques). (b) Yield vs. ice roughness for the best rms outer surface roughness ( $10 \text{ nm}$ ).*

## 1.3 Beryllium Capsules

There are several reasons for beryllium's superior implosion performance<sup>[2]</sup>. Beryllium has smaller x-ray albedo and heat capacity than polymers in the temperature range characteristic of implosions (one to several-hundred eV), with x-ray drive spectra characteristic of hohlraums. This makes it more efficient and less susceptible to Rayleigh-Taylor instabilities seeded by surface imperfections, as indicated in *figure 2*. Its higher density also makes it less susceptible to "feed out" instabilities resulting from roughness perturbations in the frozen DT fuel layer. Its opacity, which is matched to the drive temperature to minimize instability growth and fuel preheat, can be adjusted by adding higher Z dopants. Also, beryllium's strength allows the capsules to hold their fuel charge at room temperature for many, although not all, target designs, so cryogenic assembly and handling would not be required. Finally beryllium's high thermal conductivity implies that a uniform thickness cryogenic layer may be easier to make (see below). Two disadvantages of beryllium are that the technique discussed below for enhancing the surface finish of frozen DT layers cannot be applied, and layer characterization is a much larger problem.

Two methods of fabricating beryllium capsules are being pursued: bonding together micromachined hemishells, at Los Alamos National Laboratory; and coating the beryllium onto suitable mandrels by sputter deposition, at Livermore. These are indicated in *figure 3*.



**Figure 3** Two approaches to beryllium ignition capsules.

At Livermore<sup>[3]</sup>, beryllium doped with copper has been sputter deposited onto thin polymer mandrels, as shown in *figure 3*. Beryllium sputtered on mandrels displays a columnar structure, with individual columns up to 1  $\mu\text{m}$  in diameter. These coatings typically have much less strength than bulk Be, and the columnar structure leads to high-mode surface roughness. This roughness has been reduced from about 150 nm rms to about 50 nm rms (as measured by AFM over a 20- $\mu\text{m}$ -square patch) by applying a 120 V bias during deposition. Similar results have been obtained by depositing alternating layers of beryllium and boron in a 10-1 ratio. As with the films deposited using voltage bias, the grain size is less than a few hundred nm. The columnar structure of the bulk has been completely eliminated by continuous boron doping at concentrations of 10 to 15 at.%, as seen in *figure 3*. These and related alloys show much promise for producing smooth, homogeneous, low-Z films, but their potential for capsule fabrication is still under investigation. A particular strength of sputter deposition is the ease of changing dopant concentrations and types by codepositing using multiple sources or fabricating custom alloy targets. As demonstrated by the near-amorphous BeB, this provides the ability to produce even non-equilibrium material mixtures.

At Los Alamos, using a clever fixture<sup>[4]</sup> and operational sequence, cylindrical blanks with 2 mm hemispherical cavities have been machined with cubic boron nitride tools as in *figure 3*, then mechanically polished to a surface finish less than 10 nm rms, measured over a patch about 200  $\mu\text{m}$  square<sup>[5]</sup>. The hemishells were bonded together at 900 C using a submicron layer of copper as a braze, which diffuses into the beryllium and melds with the copper dopant. A residual opacity variation from the bond is seen in *figure 3*, which has been reduced by a combination of thinner copper braze layers and longer bonding times. Computer simulations have shown that these levels of residual copper at the equator should not spoil the sphericity of the implosion. These bonds have yield strengths comparable to the bulk beryllium.

The diffusion bonding process has been applied under a hydrogen atmosphere, so perhaps the capsule can be filled and bonded in a single operation. Los Alamos is pursuing this approach with a newly acquired high-temperature, high pressure brazing vessel. They are also looking at another slight variation on this approach in which they trap the DT gas at room temperature inside the spherical cavity and backfill the exterior with an inert, pressurized gas. This assembly is then brazed in that environment. Both of these methods, however, require that the bonded cylinder be machined extensively under undesirable radioactive handling conditions. Therefore, methods for bonding fully machined hemispheres, where machining operations that are post-tritium exposure would be kept to a minimum, are also being investigated.

An alternative and yet highly desirable filling method is diffusion filling. Literature values of permeability suggest that high-temperature permeation can provide a filling method for both machined and sputter deposited beryllium capsules. The advantage for this capsule fabrication method is that for both machined and sputter-deposited Be, the capsule fabrication is completed before the filling takes place, making the handling of a tritiated part much more limited and therefore easier. For this to work, it is essential that oxide layers on the interior or exterior surfaces be eliminated. A possible method of eliminating oxidation is *in-vacuo* ion etching followed by application of a layer of oxide-preventing but hydrogen-permeable material. This technique is being investigated to fill both sputtered and machined beryllium capsules. The effects of bulk additives (such as boron) on permeation are also being studied.

#### 1.4 Polyimide Capsules

The yield sensitivity of polyimide capsules to surface roughness is comparable to beryllium (*figure 3*), while its intermediate density (1.4-1.5 gm/cc compared with about 1 for CH and 1.85 for beryllium) makes it more susceptible to ice roughness than beryllium, but less than for CH. While the superior performance of polyimide ablators during implosions are reason enough for their pursuit, a polyimide capsule also potentially has higher strength than CH, comparable to beryllium for some formulations, allowing for room temperature transport with full DT fills<sup>[6]</sup>. However, since polyimide undergoes elastic and plastic deformation, and since it is also very permeable to hydrogen, room temperature transport is possible only if a co-yielding permeation barrier can be applied to the inner or outer surface.

Uniform thickness polyimide ablators are being formed on capsule mandrels by a vapor deposition technique<sup>[7]</sup>. In this approach the monomer precursors are independently heated under high vacuum in a nearly evacuated reactor to produce monomer vapor fluxes that are directed upon thin-walled capsule mandrels. The mandrels are kept in motion in a vibrating or rolling pan, so that the flux is uniform on the average. The coating pan is housed in the same reactor vessel as the monomer sources. The two monomers react on the surface of the mandrels to form a poly(amic acid), which upon further careful heating is converted to polyimide. The strength and surface properties of the resultant polyimide is quite dependent on proper stoichiometry. To obtain good, high strength coatings it is necessary to carefully balance the vapor fluxes by control of the temperatures of the monomer sources. The proper balance of vapor fluxes is different for different monomer pairs, as the chemical “sticking coefficients” of each of the monomers are not usually equal.

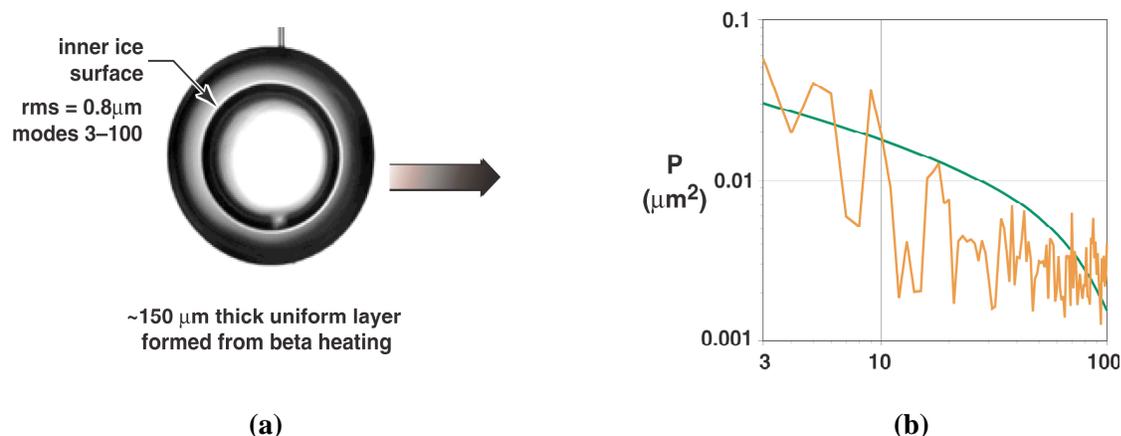
To date we have worked with monomers that produce a Kapton-like film<sup>[7]</sup>. Coating rates are typically 1-2  $\mu\text{m}/\text{h}$ . Initial work with deposition onto flat substrates produced very smooth films with no bulk structure. On spherical mandrels, coatings as thick as 160  $\mu\text{m}$  have been produced, and strengths as high as 100 MPa have been measured. For room temperature transport, strengths in excess of 120 MPa are necessary, and we plan to achieve

this goal by better control of stoichiometry and coating rate of the monomers, variations in heat treatments, and switching to monomer sources known to produce higher strength polymers, such as Upilex. However, the coatings on spheres have had disappointing surface smoothness, although the bulk morphology is extremely homogeneous, as in the earlier flat coatings. Localized coating defects usually appear that may be related to imperfect stoichiometry from self-shadowing, or to deposited debris that is created by the shell agitation. These are topics of current investigation in very recent preliminary work. We have been able to smooth out these localized defects by exposing a gas-levitated pre-imidized capsule to a solvent vapor. The solvent vapor is carried in the levitating gas. Imidizing after the solvent exposure reduced the surface roughness by more than an order of magnitude.

## 1.5 Cryogenic Fuel Layers

The beta-decay energy deposited in solid D-T drives a phenomenon called “beta layering in which an irregular formation of solid D-T inside an ICF capsule evolves into a spherically symmetric layer. For “clean” (no  $^3\text{He}$  present) D-T at the triple point (19.8 K), there is an exponential approach to perfect symmetry with a time constant of about 25 minutes.

As discussed for *figure 2*, the performance of an ignition target depends upon the modal spectrum of the inner D-T ice surface, although less sensitively than the capsule outer surfaces. This spectrum, and methods to control it, are currently being investigated. Beta-layered surfaces have been examined in spherical polymer capsules with a very small fill tube for introducing the D-T<sup>[8]</sup>. We have found that layers with surfaces smooth enough to ignite in 2 and 3 dimensional simulations in any of the capsule materials can be formed, as seen in *figure 4(a)*. In *figure 4(b)*, the surface spectrum taken from shadowgraphs is compared with the spectrum used in the simulations of *figure 2*. Those simulations used only the portion of the spectrum above mode 15. To obtain this layer quality, the initial layer must be carefully developed from a single nucleation point, which requires avoiding severe supercooling. Layers formed from a quick freeze, with many nucleation points, form a layer that is symmetric on average, but with roughness of many microns that doesn't decrease further. For the smoothest layers, the ice roughness actually goes through a minimum a few hundred minutes after freezing, which is thought to be related to the build-up of  $^3\text{He}$  in the solid. Similar behavior and layer smoothness have been observed in beta-layering experiments in cylindrical cavities, which offer better optical access<sup>[9]</sup>.



**Figure 4** (a) A shadowgram of a very smooth D-T layer formed by beta-layering in a very thin (approximately 10  $\mu\text{m}$ ) polymer shell; (b) the surface spectrum from (a) compared to that used in the simulations of Fig A.

While fuel layers smooth enough to ignite were achieved in spheres, they were formed just below the triple point (20.6 K for D-T). However, the design temperature, which sets the interior vapor density, is 18.3 K. Cooling the capsule to that temperature after forming the fuel layer results in a degrading of the layer smoothness. In spheres, even when cooled very slowly (a few millikelvin per second) the layer degrades below about 19.3 K.

The fuel layer smoothing by beta heating is halted by the surface energies of the multicrystalline surfaces. However, being able to form smoother surfaces would increase confidence in eventual ignition on the NIF by allowing for uncertainties in the simulations and variations in the surface features, and by allowing designs that ignite at lower drive energies.

Increasing the volumetric heating rate of the solid should give smoother surfaces. Absorbed radiation from an infrared laser provides this additional heating with the heating limit being set only by the available laser intensity. This bulk heating can be applied to D<sub>2</sub> or HD solids, making it possible to experiment without the complications of using tritium. The technique has been applied to HD layers in polymer spheres by centering them in a diffusely reflecting integrating sphere into which the infrared is injected and symmetrized. The layer smoothness achieved was comparable to that of beta layering in spheres, with a similar spectrum. To form layers by infrared absorption, the radiation wavelength has to be selected for the particular isotope or mixture, but is generally in the 2 to 3 micron range. There must also be a suitable transparency band in the capsule material. The plasma polymer ablator used for current Nova experiments has such a window, provided it is formed from fully deuterated organic monomers. Being applicable to non-tritiated fuel layers, such as D<sub>2</sub> or isotopic mixtures, this may be the only way to make sufficiently smooth layers of these materials, which could prove very useful in the pre-ignition phase of NIF experiments. Preliminary modeling has indicated that sufficiently uniform infrared intensity for a layer uniform in thickness to 99% can be achieved inside a diffusely reflecting hohlraum through a combination of a diffuse infrared source at the laser entrance hole aperture, plus a ring of infrared incident on the internal midline of the hohlraum. Experimental systems are currently in construction to develop this capability.

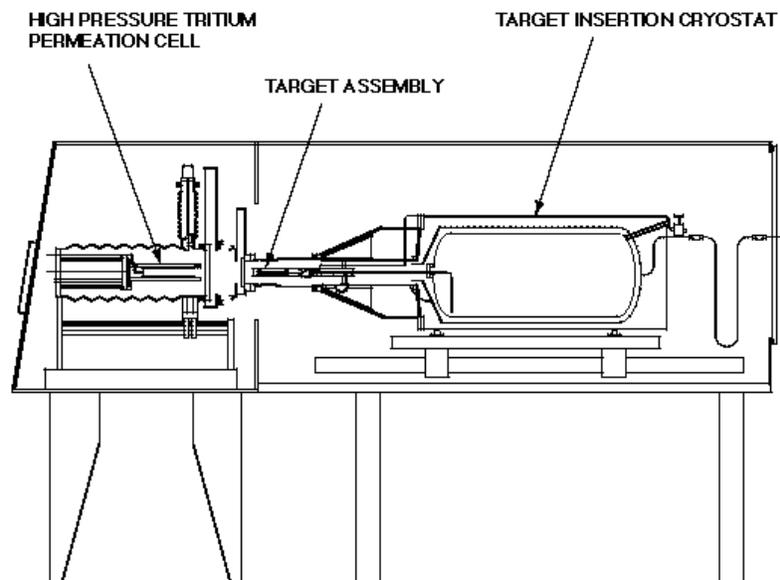
The cryogenic fuel layer must be uniformly thick to better than 1% to yield a sufficiently symmetric implosion. For this, the interface between the fuel layer and the spherical capsule must be isothermal to 15 K at an average temperature of 18.5 K. For indirect-drive, the hohlraum is a mini-cryostat, with the heat from the beta-decay conducted to the wall, but the isotherms in an isothermal cylindrical hohlraum are not spherical, and in fact can severely distort the layer. However, a high thermal conductivity capsule ameliorates this problem which gives another large advantage to beryllium. For plastics, the hohlraum boundary temperature must be tailored to provide spherical isotherms at the capsule. We are designing and testing hohlraums that will do this as in *figure 1*. Azimuthally symmetric cooling will require specially designed contacts, as indicated in *figure 1*. The axial temperature profile on the hohlraum wall will be maintained by microheaters on the hohlraum exterior. Thermal modeling shows that a uniform surface heating flux very nearly produces the required thermal profile if the cooling rings are attached at the hohlraum ends with partial shielding as shown.

## 1.6 Cryogenic Target Fill and Support Systems

Ignition capsules that are strong enough to hold their fills without bursting or distorting, such as beryllium or perhaps polyimide, and have sufficiently long permeation times at room temperature, can be filled at any location remote from the NIF. Typical room-temperature fill pressures are several hundred to one-thousand atmospheres. Strong, filled capsules can

easily be shipped to the NIF pre-assembled into complete targets, or assembled at the NIF site. Capsules that are not strong enough, or are too permeable, will have to be kept at cryogenic temperatures after filling to reduce the capsule pressure and permeability. Direct drive ignition capsules will assuredly require cryogenic transport after filling, since the capsules are very thin (a few microns) polymer, with more than a thousand atmospheres at room temperature. Both x-ray and directly driven targets will have to be layered and then maintained by a cryogenic system in the NIF target chamber. A collaboration between Los Alamos National Laboratory, Livermore National Laboratory, and General Atomics has developed several concepts for filling, cooling, transporting, and target-chamber support of x-ray driven ignition targets.

Of the many studied, the preferred concept is shown in *figure 5*. A target assembly such as in *figure 1*, which includes the hohlraum with its fuel capsule, sapphire cooling rods, and a support base, is inserted into a high-pressure tritium permeation cell to fill the capsule. While still in the fill cell, and under the high fill pressure, the target assembly is cooled to a low enough temperature that the outer D-T gas can be pumped away. With the tritium removed, the fill cell is opened and the target transferred to a cooled Target Insertion Cryostat (TIC). The attachment is made at the target assembly base. This attachment is critical since it provides thermal contact to the TIC, which will maintain the target from this point until it is imploded in the NIF target chamber. It also provides electrical contacts for temperature sensing and control on the hohlraum, and a gas-line seal for introducing approximately one atmosphere of a helium-hydrogen gas mixture into the hohlraum at 20 K. With the target attached to the TIC, a gate valve on the front of the vacuum shroud is closed, and the TIC is transported to the target chamber for insertion. The fuel layer is formed and checked prior to insertion. In the case of a capsule, such as beryllium, that is strong enough to hold the fill at room temperature, the capsules will be filled separately, then assembled into the hohlraum and attached to the TIC warm. Cooling the TIC will then cool the target, and layering and insertion will proceed as before.



**Figure 5** Ignition targets require a cryogenic fill system and target insertion cryostat for filling, layering, and supporting in the target chamber.

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