Status of cryogenic layering for NIF ignition targets

J. D. Moody, B. J. Kozioziemski, E. R. Mapoles, J. D. Sater, E. L. Dewald, J. A. Koch, N. Izumi, A. Chernov, J. Salmonson, R. C. Montesanti, L. J. Atherton, J. A. Burmann, J. W. Pipes, D. Stefanescu, K. Salari, T. Weisgrabber, J. Reynolds, C. Castro, J. Klingmann, B. Dzenitis

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551, USA
moody4@llnl.gov

Abstract. Recent advances in cryogenic layering include improved surface roughness characterization of many layers formed using “slow-cool” and “rapid-cool” protocols. At 0.25 K below the melt, slow-cooled layers meet the NIF smoothness requirement. However, at 1.5 K below the melt grain-boundary misalignments dominate the layer roughness and cause it to exceed the smoothness specification. Rapid-cool of the layer to 1.5 K below the melt shows promise for meeting the ignition requirements. Much of the current research effort is aimed at characterizing the onset of roughness during rapid cooling and determining the scale of the resulting roughness.

1. Introduction
The NIF indirect drive ignition target consists of a cryogenically cooled fuel capsule suspended in the center of a hohlraum[1]. The fuel capsule consists of an ablator shell (either Be or CH) with a layer of solid deuterium-tritium (D-T) on the inside. The hohlraum is filled with a mixture of He and H₂ gas at a density of 1 mg/cc. High intensity laser beams pass through the laser entrance holes (LEHs) and the He/H₂ gas and strike the hohlraum inner wall. The laser light is then converted to x-rays, which heat and compress the fuel capsule. The capsule implodes, compressing and heating the D-T to conditions sufficient for thermonuclear fusion. An essential requirement for significant fusion energy yield is that the starting D-T fuel layer be sufficiently smooth so as not to seed Rayleigh-Taylor instabilities that disrupt the implosion.

Solid D-T roughness is described as surface 2D power spectral density (PSD), bubble size and number, grain boundary size, and ablator gap size[2]. Hydrodynamic simulations have been used to set the requirements on these types of roughness. Experimentally, we have discovered that growing solid D-T layers with different cooling rates leads to different types of roughness. Controlling layer roughness and achieving a fuel layer meeting the requirements remains one of the challenges to making a successful ignition target. The D-T layer is formed by traditional crystal growth processes and is subject to growth instabilities, thermal stress, and possible anisotropic surface energy. The remainder of this paper will concentrate on the effect of different cool-down rates on controlling the roughness of the D-T layers.

2. Experimental setup
D-T layering studies were performed in a spherical hohlraum geometry [3]. A NIF ignition scale Be or CH shell is suspended from a fill tube in the center of a 1-inch sphere carved out of the center of an Al block. Helium gas at a pressure of several Torr fills the region between the shell and the Al block. The low gas pressure allows conduction but not convection. After filling the shell with the required volume of D-T liquid, the D-T is frozen by lowering the D-T temperature approximately 1 K below the melt temperature. Then, the temperature is raised slowly to melt the D-T until a small (100 to 200 μm size) seed crystal remains. The seed crystal is usually located opposite the D-T liquid near the fill tube since the heat generated by beta-decay in the tritium causes the lowest temperature to be opposite the D-T liquid. The temperature is then slowly ramped downward at a rate of about 1 mK every 1 to 4 minutes to grow the D-T layer.

3. DT layer diagnosis
Quantitative determination of the D-T surface roughness utilizes phase contrast x-ray imaging[4] or optical shadowgraphy[5]. Only x-ray phase contrast can diagnose the D-T layer in a Be shell, but both techniques can be used on a CH shell. An x-ray sensitive CCD detector with 13.5 μm pixel pitch is placed 800 mm from the shell. X-rays travel through the shell and are deflected only at the boundaries between materials, where there is a sharp change in the refractive indices. This refraction tends to accentuate the boundaries between materials in the image including the D-T solid—vapor interface.

Visible diffuse light is utilized to backlight the shell for optical shadowgraphy. An optic with f/number of about 4 images the shell on a CCD camera. This camera can be set to capture a series of images at 30 Hz (or less). Both diagnostic systems have a pixel size at the object plane of about 2.5 μm. An x-ray image requires about 120 sec. of exposure to ensure that the signal-to-noise is high enough to allow a meaningful measurement out to mode 100. On the other hand, an optical image requires only about 50 msec to achieve similar signal-to-noise.

Layer roughness analysis consists of first determining the 1D r(θ) position of the D-T solid—vapor surface from an image. This is then converted to a PSD and compared to the requirement. Both the x-ray and optical diagnostic techniques were validated using modeling, surrogate targets, and cross-comparison on D-T layers in CH shells. Simulations [5] show that the two methods agree when the layers have RMS roughness less than about 0.4 μm for modes 7-128. However, the optical method tends to give a higher roughness than the x-ray method for a rougher surface. Several spheres were created with roughness less than and greater than the NIF D-T roughness specification. These spheres were first characterized by atomic-force microscopy (AFM) and then characterized using the x-ray imaging. Figure 1 shows very good agreement between the x-ray imaging and the AFM results below mode 60. We are currently working to understand the difference between the AFM and x-ray measurements at the high modes.

Figure 1. Comparison between x-ray analysis and atomic force microscope measurements shows good agreement out to mode 60 to 80.

In addition to the PSD, the x-ray and/or optical images are analyzed for evidence of bubbles and grain boundaries. Bubbles can result from accumulation of 3He as the tritium decays. Bubbles of size ≥ 2 – 4 μm are not observed in 75μm thick D-T layers formed by slow-cooling to 0.25 K below the melting temperature. We believe the reason for this is that the 3He diffusion rate through the D-T solid is high enough to prevent 3He from collecting into micrometer-sized bubbles. Furthermore, if the
bubble size were below 1 μm and the bubble density exceeded the limit (4%) we would observe significant light scattering from the solid D-T. At temperatures less than 18 K, where the ³He diffusion through the D-T solid is greatly reduced, bubble formation is observed.

4. DT layer growth
Beta decay of the tritium in the D-T produces 50 mW/cm³ of heat, which is conducted through the D-T solid, the shell, and the He gas to the Al block. Nonuniform D-T layer thickness produces temperature variations (and related vapor pressure variations) on the inner layer surface. The consequence of this is that the solid redistributes itself through beta-layering[6] which consists of D-T vaporization from hotter regions and condensation at colder regions. This process continues with a time constant of about 30 minutes until the inner D-T surface reaches constant vapor pressure.

NIF ignition designs require the D-T layer to be 1.5 K below its triple point temperature (19.79 K) to meet the vapor pressure requirement for ignition. Smooth D-T layers can be formed near the triple point but they roughen as the temperature is reduced. Figure 2 shows the RMS roughness for multiple D-T layers formed in several different shells at 19.5 K and then slowly cooled to 18.3 K. Nearly 85% of the layers meet the roughness specification at the higher temperature but only 15% do so at the lower temperature. Previous studies show that the roughness is minimized when the layer temperature is decreased at a rate of 1 mK/min, or slower. While this minimizes the overall roughness it creates a number of isolated grain boundary features.

The x-ray imaging can be used to characterize the shape of grain boundaries when they happen to intersect the center-plane of the shell. Figure 3 shows an x-ray image containing several examples of these features. The cusp-shape clearly discernable in two of these features is consistent with the cross-section of grain-boundary grooves. The cusp-shape is the groove that forms when the grain-boundary intersects the surface in order to minimize the energy. The x-ray imaging combined with modeling suggests a typical feature depth of 15 μm and width of 45 μm. This exceeds the maximum allowed defect cross-section of 200 μm². We have not observed any slow-cooling rates (within the practical range from 12 hours to 3 days) that produce defect-free layers at 1.5 K below the triple point.

Alternative rapid-cooling methods, investigated by Bittner[7] and proposed as a viable technique for ignition by Martin[8] show promise as a way of achieving smooth layers having cracks within spec at 1.5 K below the triple point. Rapid-cooling begins by following the same seed crystal formation and slow cool until the D-T layer is approximately 0.25 K below the triple point. As was shown in Fig.

Figure 2: RMS roughness for D-T layers in several different shells at 19.5K and 18.3K using the slow-cool method. Approximately 85% of these layers meet the D-T surface roughness specification of 0.8 μm for modes 7-128 at 19.5K. Approximately 15% of these layers meet the D-T surface roughness specification of 0.8 μm for modes 7-128.

Figure 3. X-ray phase contrast image shows evidence of grain boundaries on the inner D-T surface.
4, very smooth layers with few defects can be formed routinely at this temperature. Then the
temperature of the layering sphere is quickly lowered to 1.5 K below the triple point temperature on a
time scale of about 5-25 seconds. We find that the RMS roughness does not change significantly
during cooling. However, localized defects that appear to be ripples are observed in some cases.
Optical shadowgaphy can detect the presence of these defects but cannot quantify their size and shape.
Our current effort on forming ignition D-T layers is focused on determining the best rapid-cool
scheme for achieving the lowest layer temperature before the appearance of defects which exceed spec.
In order to better quantify the layer defects that appear during/after rapid cool we are constructing an
experimental platform which uses interferometry to measure the detailed surface shape of a D-T layer
formed inside of a hemi-shell.

Rapid cooling of ignition targets relies on a cryogenic target system and ignition hohlraum which
are capable of supporting the sudden temperature drop. Analysis shows that the cryo target system
can support this. In addition, dynamic thermal modeling of the ignition hohlraum shows that the solid
D-T temperature lags the hohlraum temperature by about 1 – 2 seconds. Reaching the required D-T
temperature will require waiting a specific time (several seconds) after the hohlraum reaches the set
temperature. This wait time will be experimentally verified in future studies.

5. Conclusions
Developments in target fabrication, D-T fuel layer characterization, and D-T layering studies have led
to considerable progress toward the capability of providing a smooth D-T fuel layer in a hohlraum for
NIF ignition experiments. Current and future experiments are devoted to precision characterization of
the D-T solid just before and just after rapidly cooling it to the required temperature.

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