Wetted foam liquid fuel ICF target experiments

R E Olson^1, R J Leeper^1, S A Yi^1, J L Kline^1, A B Zylstra^1, R R Peterson^1, R Shah^1, T Braun^2, J Biener^2, B J Kozioziemski^2, J D Sater^2, M M Biener^2, A V Hamza^2, A Nikroo^2, L Berzak Hopkins^2, D Ho^2, S LePape^2 and N B Meezan^2

^1Los Alamos National Laboratory, Los Alamos, New Mexico, USA
^2Lawrence Livermore National Laboratory, Livermore, California, USA

E-mail: reolson@lanl.gov

Abstract. We are developing a new NIF experimental platform that employs wetted foam liquid fuel layer ICF capsules. We will use the liquid fuel layer capsules in a NIF sub-scale experimental campaign to explore the relationship between hot spot convergence ratio (CR) and the predictability of hot spot formation. DT liquid layer ICF capsules allow for flexibility in hot spot CR via the adjustment of the initial cryogenic capsule temperature and, hence, DT vapor density. Our hypothesis is that the predictive capability of hot spot formation is robust and 1D-like for a relatively low CR hot spot (CR~15), but will become less reliable as hot spot CR is increased to CR>20. Simulations indicate that backing off on hot spot CR is an excellent way to reduce capsule instability growth and to improve robustness to low-mode x-ray flux asymmetries. In the initial experiments, we will test our hypothesis by measuring hot spot size, neutron yield, ion temperature, and burn width to infer hot spot pressure and compare to predictions for implosions with hot spot CR's in the range of 12 to 25. Larger scale experiments are also being designed, and we will advance from sub-scale to full-scale NIF experiments to determine if 1D-like behavior at low CR is retained as the scale-size is increased. The long-term objective is to develop a liquid fuel layer ICF capsule platform with robust thermonuclear burn, modest CR, and significant α-heating with burn propagation.

1. Background and motivation

The hot spot formation processes in DT ice layer and DT liquid layer ICF capsules are quite different. The National Ignition Campaign (NIC) baseline DT ice layer ICF ignition capsule design \cite{1} requires a hot spot convergence ratio (CR) of 35 with a hot spot that is dynamically formed from DT mass originally residing in a very thin layer (a few microns) at the inner DT ice surface. In contrast, DT liquid layer capsules can have the hot spot formed from mass originating within a spherical volume of DT vapor. Liquid DT (or D2) layer capsule designs allow for flexibility in hot spot CR through the adjustment of the initial cryogenic temperature with significant hot spot energy gain occurring at relatively large radius. Additional benefits of the liquid layer approach include potentially improved robustness to low-mode x-ray flux asymmetry and ablator surface roughness. A detailed comparison of the performance of DT liquid and DT ice layer capsules can be found in Reference 2.

We are developing a new NIF experimental platform that employs wetted foam liquid fuel layer ICF capsules. We plan to use the liquid fuel layer capsules in a NIF experimental campaign to explore the relationship between hot spot CR and the predictability and robustness of hot spot formation. Our hypothesis is that hot spot formation will be robust and 1D-like for a relatively low convergence ratio hot spot (CR~15) in which the hot spot is formed largely from the vapor, but will deviate from 1D-like
behavior as vapor pressure is reduced and hot spot CR is increased to CR>20. We will begin with NIF sub-scale experiments to determine a CR limit at which burn truncation begins to occur due to 3D effects. When we discover a CR threshold for 1D-like behavior in the NIF sub-scale experiments, we will advance from sub-scale to full-scale NIF experiments to determine if the good predictive capability is retained as the scale-size is increased. The wetted foam liquid layer platform would then be used for hot spot diagnostic applications (eg., perhaps via dopants in the foam) to understand and repair departures from 1D-like behavior as CR is gradually increased.

2. Liquid fuel layer NIF sub-scale experimental platform

The NIF sub-scale liquid layer platform builds upon some recent innovations – 1) a new approach to lining the interior of HDC capsules with an ultra-low density CH foam that can survive wetting with liquid hydrogen [3,4]; and 2) NIF near-vacuum hohlraums (NVH) for driving implosions with HDC ablators [5]. Our initial NIF experiments will use sub-scale HDC capsules with liquid DT (or D2) layers fielded in a scale 575 NVH (5.75 mm diameter, 10.13 mm length, 3.375 mm diameter LEH’s, and 0.032 mg/cm³ He gas fill) [5,6]. The detailed sub-scale HDC wetted foam capsule dimensions and densities are shown in Fig. 1.

In the initial DT liquid layer sub-scale experimental series, we will use a 900 kJ NIF laser pulse of ~ 7 ns duration with peak power of 300 TW to produce a capsule drive with peak Tr ~ 285 eV. The laser pulse shape is a slight variation on a 3-shock pulse shape that has previously been used to achieve a symmetric implosion of a HDC sub-scale “symcap” capsule in a 575 NVH [5,6]. As shown in the plot in Fig. 2, DT liquid layer capsules can provide flexibility in hot spot CR via the adjustment of the initial vapor density. The initial goal of the experiments will be to measure hot spot size, neutron yield, ion temperature, and burn width to infer hot spot pressure [7] for liquid layer implosions. We will begin with a CR ~ 15 (initial vapor density of 3 mg/cm³) experiment, and then gradually increase the hot spot CR (by decreasing the initial vapor density) in succeeding experiments. Our hypothesis is that the hot spot pressure will be predictable and 1D-like for a relatively low CR hot spot in which the hot spot is created largely from the vapor, but will deviate from 1D-like behavior as vapor pressure is reduced and hot spot CR is increased. Simulations indicate that sensitivity to capsule instability growth and low-mode x-ray flux asymmetries will increase as CR is increased. An example of this effect is shown in Fig. 3, in which 2D simulations of liquid layer capsules with initial vapor density of 3.0 mg/cm³ are compared to ice layer capsules with initial vapor density of 0.3 mg/cm³. One caveat here is that the presence of the foam matrix in the fuel layer might introduce perturbations that are not currently included in the simulations.

Figure 1. HDC sub-scale capsule with a liquid DT wetted CH foam layer.

Figure 2. DT liquid layer capsules can be used to access hot spot CR’s in the range of 12 to 25.
Variations on 2D simulations of NIF sub-scale HDC wetted foam capsules. Roughness has been applied to inner and outer ablator surfaces, as well as to the DT vapor / liquid (or ice) surface.

3. Liquid fuel layer NIF full-scale experimental platform

When we discover a CR threshold with 1D-like behavior in the NIF sub-scale experiments, we will advance from sub-scale to full-scale NIF experiments to determine if the 1D-like predictive capability is retained as the scale-size is increased. An example full-scale HDC capsule with liquid DT wetted CH foam is shown in Fig. 4. We envision that a full-scale wetted foam capsule would be fielded in a NIF scale 672 NVH [6] and driven with a 1.7 MJ laser pulse of ~9 ns duration and 420 TW peak power. The resulting peak radiation drive is predicted to be ~300 eV. Of course, the 1D capsule performance will depend upon the initial vapor density and resulting hot spot CR as determined by the “threshold CR” for 1D-like behavior from the sub-scale campaign.

The red, green, and blue plots in Fig. 5 show the cumulative neutron yield as time progresses in a series of 1D simulations of the full-scale HDC wetted foam capsule design at different initial vapor densities of 1.0, 2.0, and 3.0 mg/cm$^3$. The result for a comparable DT ice layer simulation with vapor density of 0.3 mg/cm$^3$ is plotted in black. In all cases, as the capsule implodes a hot spot radius is defined, beginning at shock flash, as the radius of the zone at which TN burn is 10% of the peak value. Then, as the implosion progresses, the maximum hot spot CR increases to a value that is relatively low (15 < CR < 20) for the liquid layer simulations compared to the simulation employing an ice layer. In all cases, after achieving peak CR, the cumulative neutron yield continues to increase as the hot spot disassembles. Looking at times prior to peak CR, it can be seen that, for a given CR, the liquid layer implosions have achieved a larger 1D neutron yield than the ice layer implosion. This is important, since, for high CR implosions, we expect experimental measurements to show that the 1D-like burn will be truncated, and that the achievable yield will be set by a limiting CR caused by 3D effects. If, for example, 1D-like behavior is limited to CR’s of < 20, the black plot (ice layer) will have achieved a yield of $\sim 10^{14}$-$10^{15}$ prior to the onset of burn truncation, while the liquid layer capsules will be able to achieve full 1D yields of up to $3 \times 10^{17}$. If our hypothesis is correct, we would expect that liquid layer capsules will have higher achievable yields at lower limiting CR’s.
4. Summary

We will use DT liquid layer capsule implosions to explore the relationship between CR and robustness of hot spot formation. We will begin by using sub-scale HDC capsules with wetted CH foam layers to implode capsules with vapor densities in the range of 0.6 to 4.0 mg/cm$^3$ and predicted hot spot CR’s in the range of 12 to 25. The HDC sub-scale wetted foam capsules will be fielded in 575 NVH’s. Our hypothesis is that hot spot formation will be robust and 1D-like for a relatively low convergence ratio hot spot in which the hot spot is formed largely from the vapor, but will deviate from 1D-like behavior as vapor pressure is reduced and hot spot CR is increased. A goal of the sub-scale experiments is to measure hot spot size, neutron yield, ion temperature, and thermonuclear burn width to infer hot spot pressure for liquid layer implosions and determine a CR limit at which burn truncation occurs due to 3D effects. When we discover a CR threshold with 1D-like behavior in the NIF sub-scale experiments, we will advance from sub-scale to full-scale NIF experiments to determine if the good predictive capability is retained as the scale-size is increased. The wetted foam liquid layer platform would then be used for hot spot diagnostic applications (eg., perhaps via dopants in the foam) to understand and repair departures from 1D-like behavior as CR is gradually increased. The long term objective is to develop a liquid fuel layer ICF capsule platform with robust thermonuclear burn, modest CR, and significant α-heating with burn propagation.

References
[1] S. W. Haan et al. 2011 Phys. Plasmas 18 051001.
[2] R. E. Olson and R. J. Leeper 2013 Phys. Plasmas 20 092705.
[3] J. Biener et al. 2012 Nucl. Fusion 52 062001.
[4] T. Braun et al. 2016 ACS Applied Materials and Interfaces 8 2600.
[5] L. Berzak Hopkins et al. 2015 Phys. Rev. Lett. 114 175001.
[6] S. LePape et al. 2016 Phys. Plasmas, to be published.
[7] C. Cerjan, P. T. Springer, S. M. Sepke 2013 Phys. Plasmas 20 056319.
[8] L. Berzak Hopkins et al. 2015 Phys. Plasmas 22 056318.