LIQUID DT LAYER APPROACH TO INERTIAL CONFINEMENT FUSION

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Abstract

Recent experiments at the U. S. National Ignition Facility (NIF) demonstrated cryogenic liquid DT layer ICF implosions. Unlike DT ice layer implosions, DT liquid layer designs can operate with low-to-moderate convergence ratio (12 < CR < 25), with a hot spot formed mostly or entirely from DT mass originating within the central, spherical volume of DT vapor. With reduced CR, hot spot formation is expected to have improved robustness to instabilities and asymmetries. In addition, the hot spot pressure required for self-heating is reduced if the hot spot radius is increased. With a reduction in the hot spot pressure requirement, the implosion velocity and fuel adiabat requirements are relaxed. On the other hand, with larger hot spot size, the hot spot energy requirement for self-heating is increased, and the required capsule-absorbed energy is increased. The paper will summarize recent liquid layer experiments at the NIF and will discuss the hot spot energy, hot spot pressure, cold fuel adiabat, and capsule-absorbed energy requirements for achieving self-heating and propagating burn using liquid layer capsules with hot spot CR<20.

1. INTRODUCTION

The approach to Inertial Confinement Fusion (ICF) ignition at the U. S. National Ignition Facility (NIF) during the 2009–2012 National Ignition Campaign (NIC) employed high convergence ratio (CR > 30), low adiabat implosions using capsules containing a layer of DT ice [1]. DT ice layers require a high convergence ratio (CR > 30) implosion, with a hot spot that is dynamically created from DT mass originally residing in a thin layer at the inner DT ice surface. Although high CR is desirable in an idealized 1D sense, the high-CR, low-adiabat ice layer implosions failed to achieve ignition at the NIF due to the deleterious effects of asymmetries, instability-driven mix, capsule defects, and the capsule fill tube and support hardware [2].

An alternative ICF concept uses liquid layers [3], which are either formed spherically using an applied temperature gradient [4] or by wicking the liquid into a supporting foam [5-7]. A DT liquid layer allows for a much higher vapor density than is possible with a DT ice layer. As shown in Figure 1, the wide range of vapor densities that are possible with liquid layers having initial temperatures in the range of 20–26 °K provides flexibility in hot-spot CR (12 < CR < 25), which, in turn, will provide a reduced sensitivity to asymmetries and instability growth [8]. Given enough vapor mass, the hot spot can be formed by sending a strong shock through the vapor, with the imploding cold, dense fuel layer further heating the hot plasma via a compression work (PdV) process. In this manner, the formation of the hot spot and the formation of the dense fuel layer are separated, and the hot-spot formation is simplified and more efficient compared to a traditional DT ice layer implosion.

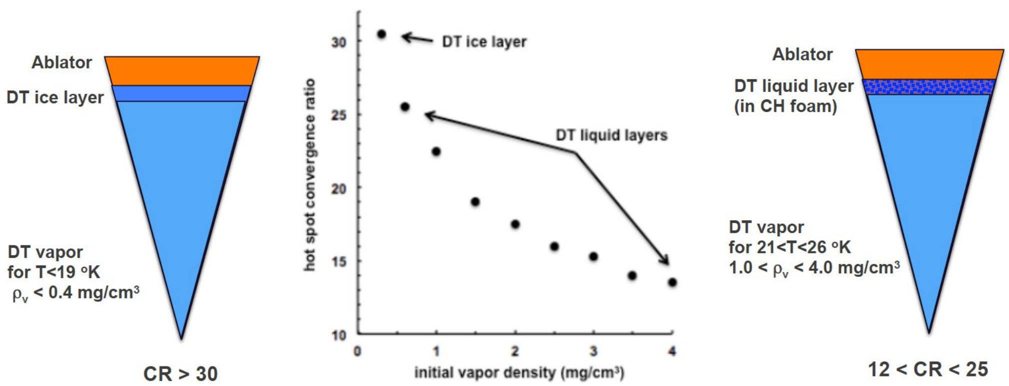

FIG. 1. A liquid DT layer allows for selecting a convergence ratio (CR) by adjusting the cryogenic fielding temperature and, hence the central vapor density.

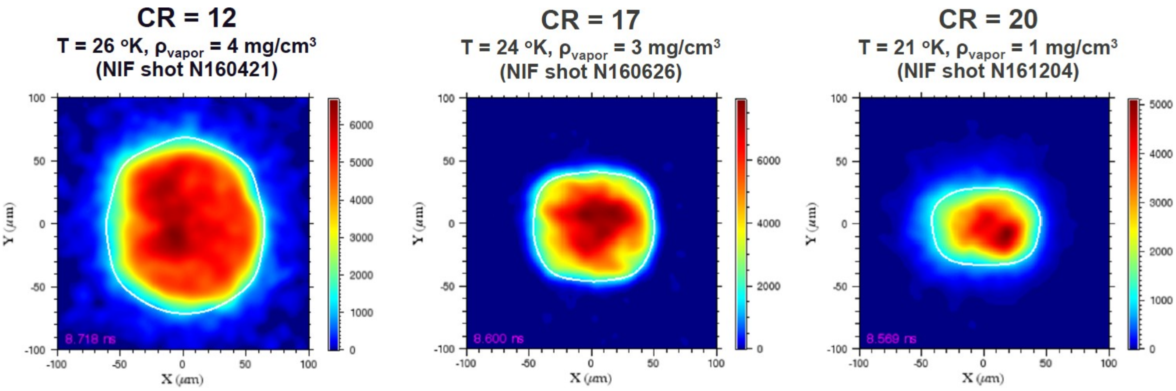

FIG. 2. The first liquid DT layer experiments at the NIF successfully demonstrated the ability to select a layered implosion convergence ratio (CR) in the range of 12<CR<20.

2. FIRST LIQUID LAYER ICF IMPLOSIONS AT THE NATIONAL IGNITION FACILITY

The DT ice layer and the DT liquid layer ICF concepts have been discussed for more than 25 years. After many years of research, the β-layering technique [9] used to form a DT ice layer has been developed to the point where it is routinely used in ICF implosion experiments [1,2]. During the past few years, a target fabrication process has been developed for lining the interior of a NIF ICF capsule with an ultra-low density CH foam that has the required uniformity and is robust enough to survive wetting with liquid hydrogen [6,7]. This new target fabrication innovation has led to the recent liquid D_2 and liquid DT wetted foam layer experiments at the NIF.

Detailed descriptions of the experimental setup, measurement techniques, and results of the NIF liquid layer experiments can found in References 10 and 11. Using the target fabrication process described in References 6 and 7, a thin (~30 μm) low density (~50 mg/cm^3) CH foam layer is created on the inner surface of a HDC capsule. The capsule is then placed into the hohlraum. After the target is cooled to a temperature in the range of 20^o K to 26^o K, liquid D_2 or liquid DT flows into the capsule through a fill tube, saturating the CH foam layer. Control of the target temperature allows for the initial vapor density in the central region of the capsule to be set in the range of 0.6 mg/cm^3 (at 20^o K) to 4.0 mg/cm^3 (at 26^o K). By comparison, typical DT ice layer capsules (which must be below the DT triple point temperature of 19^o K) have a central region vapor density in the range of 0.3 to 0.4 mg/cm^3 (the maximum possible vapor density being 0.46 mg/cm^3).

The NIF liquid layer experiments employed sub-scale CH foam-lined high density carbon (HDC) capsules and near-vacuum hohlraums. Our choice of laser pulse shape was based upon a preceding series of sub-scale experiments [12] employing a three-shock pulse shape with the type of gas-filled HDC capsules ("symcaps") routinely used to tune the symmetry of indirect-drive implosions. Experimental measurements included x-ray images and neutron images of the hot spot. Hot spot x-ray images from three of the experiments are shown in Figure 2. The images are from a CR-scan series of experiments at the NIF which successfully demonstrated the ability to select a layered implosion convergence ratio (CR) in the range of 12<CR<20. In this experimental series, it was also demonstrated that computational predictability of hot spot behavior improves as the CR is reduced. Details can be found in References 10 and 11.

3. TRADEOFFS IN DT LIQUID LAYER AND DT ICE LAYER REQUIREMENTS FOR IGNITION

There are tradeoffs involved in high CR ice layer and reduced CR liquid layer designs. With reduced CR, hot spot formation is expected to have improved robustness to instabilities, drive asymmetries, capsule defects, the capsule fill tube, and the support hardware. Results of 2D and 1D simulations employing variations on a full scale NIF wetted foam capsule design are shown in Figure 3. The 2D simulations include detailed and well-resolved models for the capsule fill tube, support tent, surface roughness, and predicted asymmetries in the x-ray drive. Details of the calculation techniques and simulation results can be found in Reference 8. As can be seen in the Figure 3 plot, the ratio of 2D/1D thermonuclear yield decreases dramatically as the hot spot CR increases from 17 to 35.

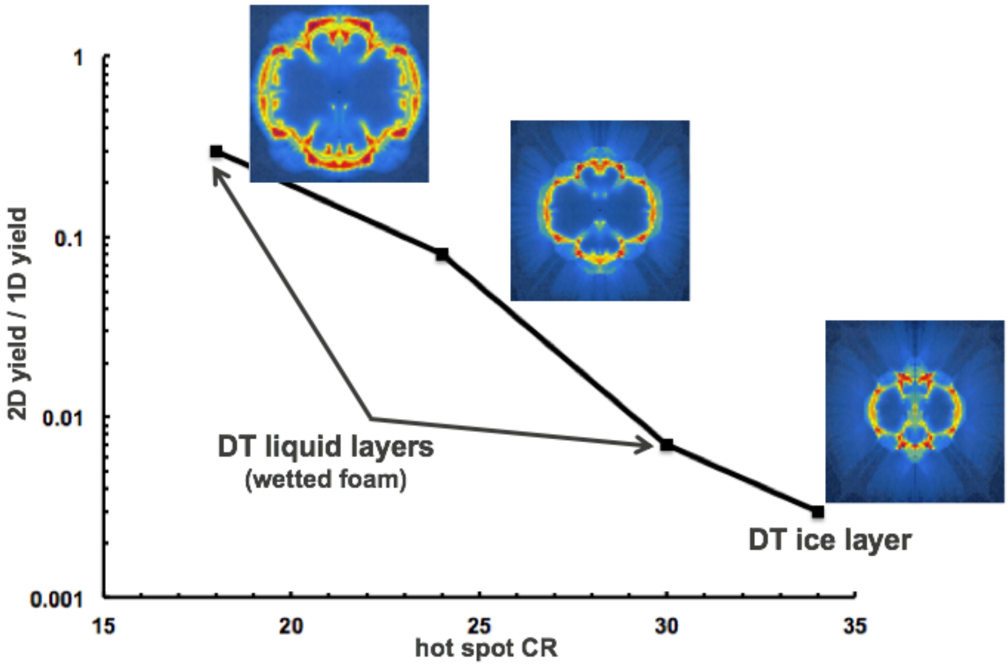

FIG. 3. DT layer implosions with reduced CR will have improved robustness to instability growth and distortions related to engineering features.

The hot spot pressure (Pr_{hs}) required for self-heating and ignition is reduced if the hot spot radius is increased. The hot spot pressure, Pr_{hs} α ρT, where ρ is the hot spot density and T is the hot spot temperature. If we require that the areal density of the hot spot, ρR_{hs}, is sufficient to stop the alpha particle fusion products ($\rho R_{hs} > 0.3$ g/cm^3) and that the hot spot temperature exceeds the bremsstrahlung ideal ignition temperature (T > 4.5 keV), then it follows that Pr α R_{hs}^{-1}. This dependence is shown quantitatively in the plot of Figure 4. In units of Gbar and μm, the dependence is $Pr_{hs} > 9000/ R_{hs}$.

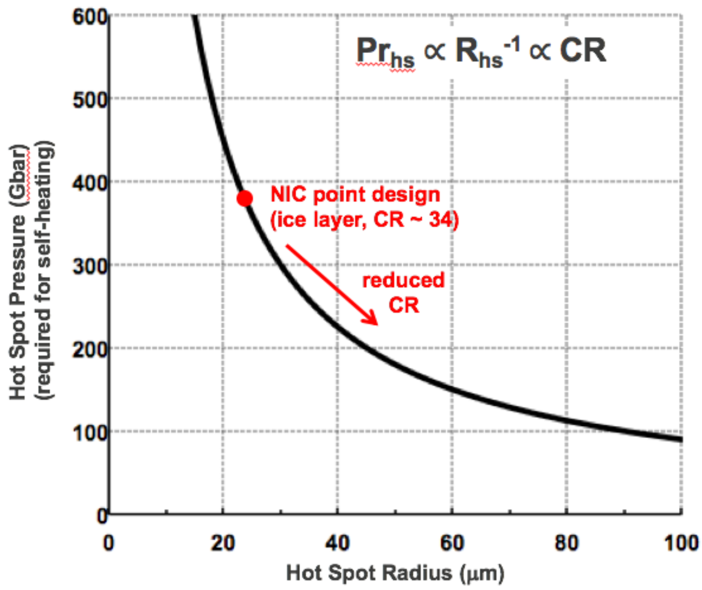

FIG. 4. The hot spot pressure required for self-heating is reduced if the CR is reduced and hot spot radius is increased.

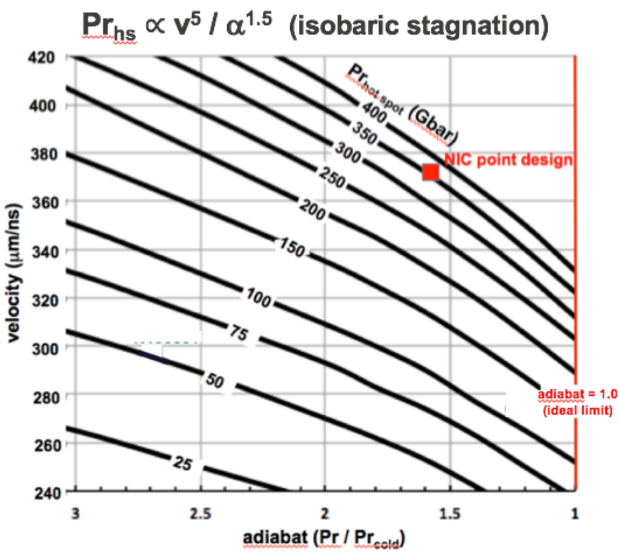

FIG. 5. If the hot spot pressure requirement for self-heating is reduced, the implosion velocity and cold fuel adiabat requirements are relaxed.

With a reduction in the hot spot pressure requirement, the implosion velocity and fuel adiabat requirements for ignition are relaxed. During the implosion, the cold fuel specific kinetic energy, ε_{KE}, will be proportional to the square of the implosion velocity, v_{imp}^2, and the cold fuel specific energy, ε_{cf}, will be proportional to the product of the cold fuel adiabat, α, and the cold fuel density, ρ_{cf}, to the 2/3 power ($\alpha\rho_{cf}^{2/3}$). Equating the cold fuel specific kinetic energy at peak implosion velocity with the cold fuel specific energy at stagnation results in a peak cold fuel density that is proportional to the implosion velocity cubed divided by the fuel adiabat to the 3/2 power ($v_{mp}^3/\alpha^{3/2}$) The cold fuel stagnation pressure will be proportional to the product of the fuel adiabat and the fuel density to the 5/3 power ($\alpha\rho_{cf}^{5/3}$). Assuming isobaric stagnation, it follows that the hot spot pressure will be proportional to the peak implosion velocity to the 5th power divided by the cold fuel adiabat to the 3/2 power ($v_{mp}^5/\alpha^{3/2}$). A quantitative version of these relationships is plotted in Figure 5. As indicated on the plot, the National Ignition Campaign (NIC) point design [1] has a cold fuel adiabat of 1.6, a peak implosion velocity of 370 μm/ns, and a no-burn hot spot pressure at stagnation of 350 Gbar. As can be seen in the plot, a reduction in the hot spot pressure requirement will result in a relaxation of the implosion velocity and fuel adiabat requirements.

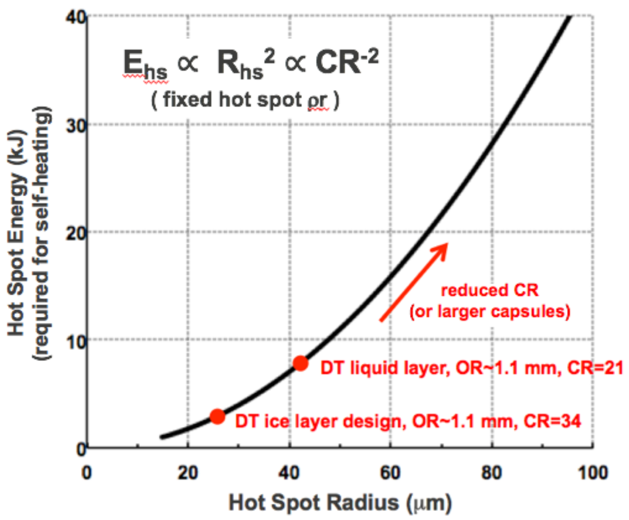

FIG. 6. With larger hot spot size, the hot spot energy requirement for self-heating is increased.

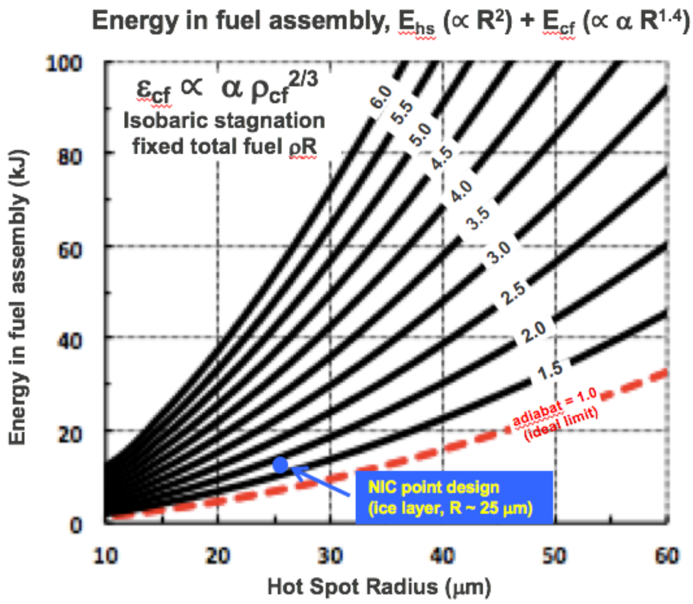

FIG. 7. The total energy required in the stagnated fuel assembly increases as hot spot radius increases and as cold fuel adiabat increases.

On the other hand, with larger hot spot size, the hot spot energy requirement for self-heating, E_{hs}, is increased. This dependence is shown in Figure 6 using the self-heating hot spot requirements of ion temperature > 4.5 keV and hot spot areal density, $\rho R_{hs} > 0.3$ g/cm^3. This analytic hot spot energy scaling is consistent with the results of 1D numerical simulations discussed in Reference 3. Although there is a penalty to be paid in energy investment for a larger hot spot, it should be noted that there is a significant benefit in the hot spot alpha particle energy production, which also increases with the square of the hot spot radius.

As previously discussed, and shown in Figure 6, the energy invested in the hot spot required for ignition is proportional to the hot spot radius squared. Similarly, as previously discussed and illustrated in Figure 5, the assumptions of isobaric stagnation and fixed total fuel ρR imply that the specific energy of the cold fuel will be

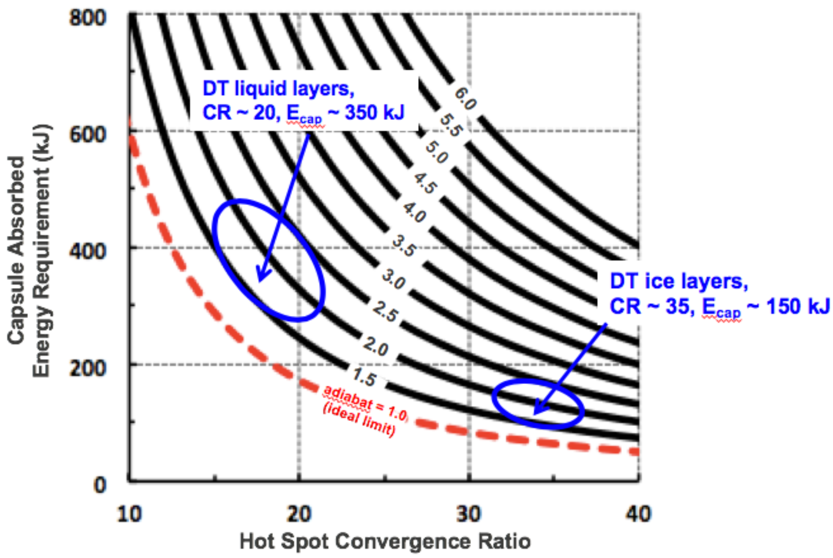

FIG. 8. Liquid DT layers offer a modest Convergence Ratio (CR) path to an ICF burning plasma. However, reduced CR requires more capsule absorbed energy.

proportional to the cold fuel adiabat and the cold fuel density to the 2/3 power ($\alpha\rho_{cf}^{2/3}$). The family of plots shown in Figure 7 assumes a fixed total fuel ρR of 2.0 g/cm^2 (comparable the NIC point design). Clearly, the total energy required in the stagnated fuel assembly will increase as the hot spot radius increases and as the cold fuel adiabat increases. Assuming an overall 10% hyro-coupling and a total ρR of 2.0 g/cm^2, the capsule absorbed energy required for ignition is illustrated by the family of plots shown in Figure 8. For reference, the NIC point design has a CR = 35, α = 1.6, and a capsule absorbed energy of 150 kJ. Using a liquid layer design to relax CR to 20 with a comparable low fuel adiabat would increase the required capsule absorbed energy to about 350 kJ. It can be seen that a more conservative design with increased adiabat and further reduced CR would require additional capsule absorbed energy as indicated in the series of plots of Figure 8.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by LANL under Contract No. DE-AC52-06NA25396.

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