The Use of Tritium Rich Capsules with 25-35% Deuterium to Achieve Ignition at the National Ignition Facility

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Abstract. Diagnostics such as neutron yield, ion temperature, image size and shape, and bang time in capsules with >~25 % deuterium fuel show changes due to burn product heating. The comparison of performance between a THD(2%) and THD(35%) can help predict ignition in a TD(50%) capsule. Surrogacy of THD capsules to TD(50%) is incomplete due to variations in fuel molecular vapour pressures. TD(25-35%) capsules might be preferred to study hot spot heating, but at the risk of increased fuel/ablator mixing.

1. Introduction

The path to ignition at the National Ignition Facility (NIF) [1] relies upon using experimental information to tune target conditions. Hohlraum radiation drive, shock timing, symmetry, and mass ablation will all be tuned using surrogate capsules without a cryogenic fuel layer. THD (tritium, hydrogen, deuterium) capsules that include a fuel layer were proposed to perform final adjustments [2], [3]. By maintaining the fuel atomic weight these capsules can be made hydro-dynamically equivalent to T(50% D) capsules, up to the time when burn product heating becomes significant. Capsules with ~ 2% deuterium are now included in ignition tuning. Above ~ 10% alpha particle heating becomes significant. As ignition is approached ion temperature increases, both X-ray and neutron images become larger and more symmetric, and peak yield rate is delayed. Target parameters crucial to hot spot formation, such as central gas density, ice mass, and ice roughness, can be tuned to optimize ignition. Trade-offs that affect burn, such as between un-ablated mass and fuel/ablator mix can be finalized.

A data set of ~ 700 THD capsule implosions with a variety of initial conditions was created based on the 285 eV 1.3MJ Rev 2 beryllium ignition capsule (very similar to the Rev 3 reported in [4]). Spears et al. [2] described how ~ 40 initial parameters affecting the drive were varied in a Latin Hypercube design to represent variation that might occur in a tuned ignition capsule. 2D static hohlraum drive asymmetries up to mode 10 were included. 2D roughness perturbations on all surfaces were taken as multiples of the capsule roughness specification. Mix between the beryllium shell and the layered fuel was simulated. The total variations are more than we expect from a tuned ignition capsule. The complete set of ~700 capsules was simulated with 0.3, 2, 25, 35, and 50% deuterium to simulate THD and TD(50%) implosions. Of these TD implosions only 20% achieve a yield > 1 MJ.
Other smaller sets used intermediate deuterium fractions. Spears et al. [3] reported on results from the 0.3% set. We have since chosen 2% as our nominal deuterium fraction to increase the neutron yield to \( \sim 2 \times 10^{14} \) and still be able to use X-ray diagnostics. Here we focus on the higher deuterium fractions.

2. Changes as ignition is approached

One objective in using THD capsules is to be able to predict the yield of the equivalent TD(50%) ignition capsule. Ignition has been defined as a yield of 1.0 MJ, equivalent to 3.5\( \times \)10\( ^{17} \) DT reactions, or \( \sim 3\times10^{17} \) neutrons between 12 and 17 MeV. Expected experimental errors in yield measurements are ±10% and in ion temperature ±0.1 keV. Figures 1, 2 and 3 plot the THD capsule neutron yield on the horizontal axis vs the energy yield (MJ) from the equivalent TD(50%) capsule. In figures 1 and 2 the horizontal span is a factor of 10. In figure 3 it is 1000. As the deuterium fraction is increased from 2% to 25 and 35%, the THD yield increases. At the same time the range of the Doppler broadened ion temperature also increases, allowing better discrimination among capsules whose TD(50%) equivalent would ignite. 2% of the 35% D capsules ignite with yields > 1MJ. These are not shown in figure 6 since their ion temperatures reach up to 25 keV.

![Figure 1](image1.png)

**Figure 1.** The energy (MJ) produced by a TD(50%) capsule compared to the neutron yield (12-17 MeV) from a THD(2%) capsule.

![Figure 2](image2.png)

**Figure 2.** The energy (MJ) produced by a TD(50%) capsule compared to the neutron yield (12-17 MeV) from a THD(25%) capsule.

![Figure 3](image3.png)

**Figure 3.** The energy (MJ) produced by a TD(50%) capsule compared to the neutron yield (12-17 MeV) from a THD(35%) capsule.

![Figure 4](image4.png)

**Figure 4.** The 12-17 MeV yield vs. the ion temperature (keV) from a THD(2%) capsule.

![Figure 5](image5.png)

**Figure 5.** The 12-17 MeV yield vs. the ion temperature (keV) from a THD(25%) capsule.

![Figure 6](image6.png)

**Figure 6.** The 12-17 MeV yield vs. the ion temperature (keV) from a THD(35%) capsule.

The TD reaction rate from a capsule is proportional to the product of tritium fraction times deuterium fraction. Figure 7 compares the reaction rates, divided by this product, from 2% (A), 25%(B), 35%(C) and 50%(D). t=0 is the peak in the TD(50%) burn rate. Before ~ 150ps all scaled rates agree. Later when burn product energy deposition becomes important the rate grows, its peak
moves later. As a THD capsule approaches ignition conditions and as the fuel temperature increases as shown in figures 5 and 6, the size of the compressed fuel becomes larger than in a capsule with less yield. Figure 8 shows the radius of the down-scattered neutron (10-12 MeV) image and the down-scattered fraction (dsf) (6-12 MeV neutrons / 12-17 MeV). Spears et al. [3] found that the dsf$^2$*yield(12-17 MeV) of a THD(0.3%) was a good predictor of DT capsule performance. For capsules with > 25% D, the size increases and down-scattered fraction decreases as the yield increases. The dots shown in figure 8 contain 35% D. The other points include the 2 and 5% D capsules. The points with less than dsf < 0.05 have high yields > 1MJ. dsf is proportional to fuel $\rho r$. Thus the target radius $\propto$ dsf$^{-1/2}$, the scaling shown by the solid line.

Figure 7. Scaled neutron yield rate from THD(2%), 25%, 35% and 50% relative to the time of peak yield rate of TD(50%).

Figure 8. 10-12 MeV neutron image size vs down-scattered fraction.

3. Predicting Ignition
The performance of a capsule in which fusion product heating is significant, relative to a THD(2%) can help predict ignition of a TD(50%) capsule. Figure 9 shows the ratio of neutron yields, and figure 10 the increase in ion temperature. To predict a TD(50%) yield greater than 1 MJ (ignition) the yield ratio should be > 45 and the increase in ion temperature > 1.4 keV.
4. Remaining Surrogacy Errors

THD capsules are not complete hydrodynamic surrogates for TD(50%) capsules. Largely because hydrogen is added, the composition of the central gas differs from the ice due to the different vapor pressures of HH, DD, TT, HD, HT, and DT. In the filling process ice is formed near its triple point, allowed to symmetrize for many hours, then in a few seconds is cooled to produce the desired central gas density. For a TD(50%) capsule at 18.3 K, the 3e-4 g/cc central gas is 62% D and 38% T, with DT reactivity (0.62*0.38) essentially the same as the ice. To create a THD ice layer with roughness comparable to the DT layer, the capsule should be fielded at approximately the same 0.9 K below its triple point, or 17.4 K. The central gas then is 79%H 1%D and 20%T and has a molar density 1 ½ times the DT gas. Its reactivity is 14% that of the ice and it contributes very little to the hot spot burn. This halves the DT yield of a THD(2%) capsule, and has an even stronger effect on capsules with more deuterium. If a TD(25%) capsule is fielded at 18.7 K or TD(35%) at 18.5 K we can closely match both the reactivity of the gas and ice, and match both the molar pressure and the density of the gas to the TD(50%) capsule, but the ice density is too high. Hammel et al. [5] calculate this will change the aspect ratio at the ablator/ice interface, and cause more instability growth. To study ablator/ice mixing we might use a capsule with hydrogen, but to study hot spot ignition, a capsule without could be better.

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Acknowledgment

This work was supported by the US Department of Energy and performed at Los Alamos and Lawrence Livermore National Laboratories. LA-UR-09-07214