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The effects of pre-mix on burn in ICF capsules

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Abstract. Directly driven implosions at the Omega laser have tested the effects of pre-mix of Ar, Kr, and Xe in D_2 + ^{3}He filled glass micro-balloons. Diagnostics included: D+D and D+T neutron yields, D+^{3}He proton yields and spectra, Doppler broadened ion temperatures, time dependent neutron and proton burn rates, and time gated, high energy filtered, X-ray images. Yields are better calculated by XSN LTE than by non-LTE. Yields with a small amount of pre-mix, atom fractions of ~5e-3 for Ar, 2e-3 Kr, and Xe for 5e-4, are more degraded than calculated, while the measured ion temperatures are the same as without pre-mix. There is also a decrease in fuel ρr. The neutron burn histories suggest that the early yield coming before the reflected shock strikes the incoming shell is un-degraded, with yield degradation occurring afterwards. Adding 20 atm % ^{3}He to pure D fuel seems to produce a similar degradation. Calculated gated X-ray images agree with observed when the reflected shock strikes the incoming shell, but are smaller than observed afterward. This partially explains yield degradation and both the low fuel and whole capsule ρr's observed in secondary T+D neutrons and slowing of the D+^{3}He protons. Neither LTE on non-LTE captures the degradation by ^{3}He or at low pre-mix levels, nor matches the large shell radii after impact of the reflected shock.

1. Introduction

Mix between the outer shell of an ICF ignition capsule and its DT fuel can lead to degradation and ignition failure. We have designed and executed experiments designed to study our understanding not of the mixing process itself, but of fusion burn in the presence of known pre-imposed mix. Previous experiments have used argon [1] and krypton [2] trace gases to provide spectroscopic diagnostics of fuel temperatures and densities. Directly driven implosions at the Omega [3] laser using 1.0 ns square pulses with 23kJ of laser energy have tested the effects of pre-mix of Ar, Kr, and Xe in D_2 + ^{3}He filled glass micro-balloons ~4.5 μm thick and 900 μm diameter. Pre-mix gas pressures ranged from 0 to 0.8 atm in a ~6.7 atm D_2, 3.3 atm ^{3}He mixture. In most implosions ~0.01 atm of Kr was added to allow electron temperature measurement from the ratio of Li-like satellites to the He β line [4]. Standard diagnostics measured D-D primary and D-T secondary neutron yields. Neutron burn history was measured with the neutron temporal diagnostic (NTD) [5] while D-^{3}He proton yields and spectra were measured with the PTD and wedge range filters[6].

For diagnostic purposes a detailed atomic physics model is needed for the line emission details of Ar, Kr, or Xe. But for an integrated model implosion and burn local thermal equilibrium (LTE) is most frequently used, with the possibility of the XSN non-LTE model [7]. These models differ only in the ionization equilibrium and electron bound state populations, and hence radiation emission and absorption. Unfortunately we have to model the full problem as either LTE or non-LTE. LTE causes the shell to emit about 0.4kJ more radiation during implosion. This causes the neutron yield rate to be delayed by about 0.2ns. To test the LTE effects only during the stagnation and burn, we have adjusted the electron conduction flux limiter from 0.057 and 0.065 (0.06 is a nominal value often used) to have an equal amount of energy in the shell before final stagnation. This increases the energy absorbed by the shell in an LTE implosion by 0.4kJ, just enough to compensate for the extra radiation loss, leaving the same amount of energy in the shell, and making the neutron yield rates coincide for a capsule without pre-mix. Shock pressures within the shell are identical to within a few percent.

Our 1-dimensional radiation hydrodynamic simulations included mixing using the Scannapieco and Cheng [8] model with its one adjustable parameter α=0.09 or 0 (no mix). Although our mix model is 1D, it attempts to represent turbulent high mode mixing that occurs in 3-D through atomic mix. The observed X-ray images of the implosions were quite, but not perfectly spherically symmetric. There was no clear indication of consistent 2D or 3D asymmetries. For these reasons we do not think that the capsule performance degradations found here represent 2- or 3-D effects not included in the calculations.

2. Ar, Kr, and Xe Dopants

Figures 1, 2, and 3 compare the observed D-D neutron yields with calculations using both LTE and non-LTE models as Ar, Kr, and Xe pre-mix is added to 6.7 atm D_2 and 3.3 atm ^{3}He. . Zero pre-mix is plotted at 0.0001. All these calculations included mix, but the conclusions without mix are similar. Figure 1 shows that even with mix, we cannot explain a factor of 2 yield decrease between calculated and observed. For fully ionized Ar in the 3-6 keV fuel, there is no calculated difference between LTE and non-LTE. For Kr this agreement persists to an atom fraction of 0.003, and in Xe to 0.0005. With more pre-mix both the LTE and non-LTE yields decrease, but the LTE yield decreases more rapidly, better approaching the data. The non-LTE calculation obtains its higher yield from a small central hot spot that retains an ion temperature greater than the electron temperature. This results in a simulated

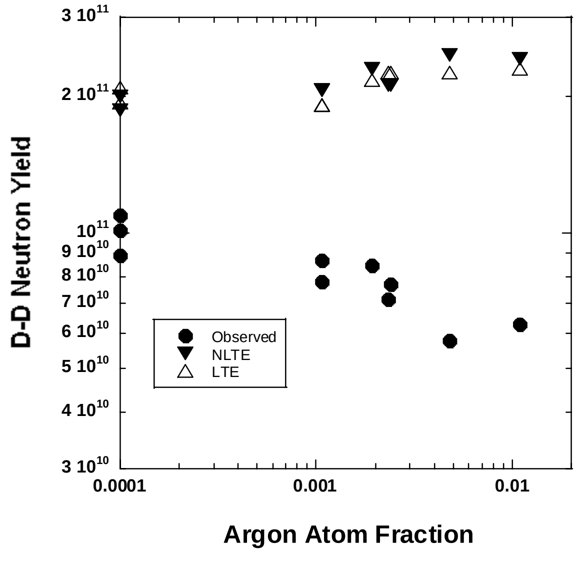

Figure 1. Neutron yield vs Ar atom fraction

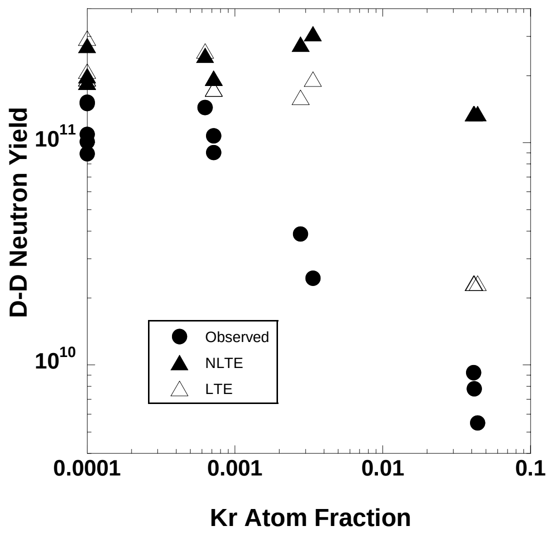

Figure 2. Neutron yield vs Kr atom fraction

neutron doppler broadened ion temperature that, with increasing pre-mix, becomes progressively higher than the measured. This unrealistic behavior is not seen with the LTE model.

The addition of premix decreases the measured yield by about a factor of 2 at an Ar atom fraction of ~5e-3, Kr of 2e-3, and Xe of 5e-4. Neither the LTE nor non-LTE calculations show such a decrease. Figure 4 compares the measured burn history of shot 47857 (0.085 atm of 3He and 0.009Kr) with others having less ^{3}He. The first shock reaches the capsule center at ~1.0ns, and is reflected to strike the incoming shell at ~1.15ns. For all the Ar pre-mixed capsules, the ratio of DT neutrons to DD neutrons, which is proportional to deuterium ρR, decreases with yield. This suggests the yield decrease may be connected with increased fuel size. For Kr at 0.005 there is also a decrease in rho-r by a factor of 1.5 to 2. With more pre-mix the yield decreases and the DTn/DDn ratio increases as expected and calculated.

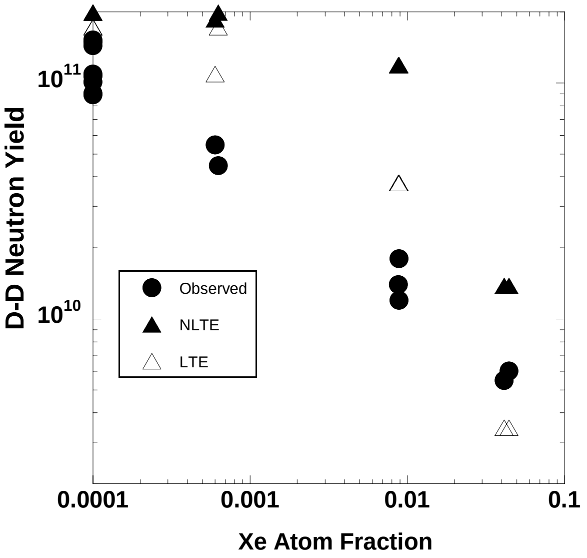

Figure 3. Neutron yield vs Xe atom fraction

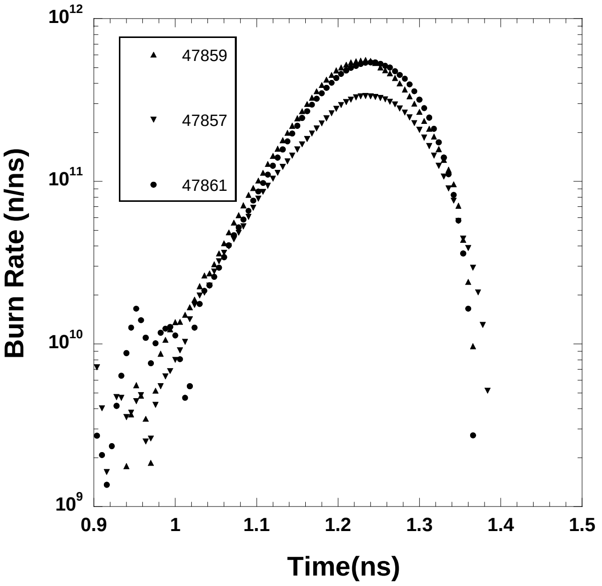

Figure 4. Burn history vs Ar fraction
(0.0019, shot 47859; 0.0034, 47861; 0.0085, 47857)

3. Abnormal degradation by ^{3}He

Our data suggest that presence of ~20 atm % ^{3}He causes a yield degradation much like that observed by Rygg et al. [9] for CH capsules. This is not predicted. Nor is there any abnormal performance when D/T ratio is changed in DT filled capsules [10]. Figure 5 compares burn histories from shot 47857 with 7.2 atm D_2 and 3.3 atm 3He with two shots 47858 and 47863 designed to be hydrodynamically equivalent with 9.8 atm D_2 only. Our calculations show that except for a ~30ps shift earlier in time, and a yield scale factor of 0.52, the ^{3}He implosion should be identical in the time histories of neutron yield and radius. Figure 5 reflects these adjustments to 47858 and 47863. However we see that after about 1.18ns, when the reflected shock reaches the incoming shell, the capsule with ^{3}He shows a decrease in yield. This capsule also shows a reduced DTn/DDn ratio, suggesting a lower ρR at burn time. Correcting for the reduced deuterium, this suggests that the fuel radius at burn time is ~ 25% larger than the fuel without 3He. Measurements of the time dependent X-ray emission using DANTE [11] show no measurable difference with and without ^{3}He.

Gated X-ray imaging shows the capsule size during the burn. Figure 6 compares the observed capsule radius at 20% of peak brightness with that simulated by post-processing calculations with the instrument spectral response. Each image is averaged over ~60ps and filtered for X-ray energy greater than about 9 keV. This high energy filter permits seeing into the fuel through the shell. The sudden brightening of the image when the reflected shock strikes the shell allows us to tie the calculated and observed time scales at 1.18ns to within one frame. The calculated and observed radii agree at that time. Afterwards the observed radii are larger than the calculated. The observed peak neutron yield rate is at 1.27ns. Around that time the capsule with ^{3}He fill is 20-30% larger than the pure D_2 filled, agreeing with our estimate from DTn/DDn , but disagreeing with the calculations. The smaller calculated radius at ~2/3 of the observed may account for the previously unexplained factor of ~2 yield degradation without pre-mix, and for part of the factor of 3-4 lower ρr for the fuel from DTn/DDn ratios and for the capsule as a whole from proton spectroscopy.

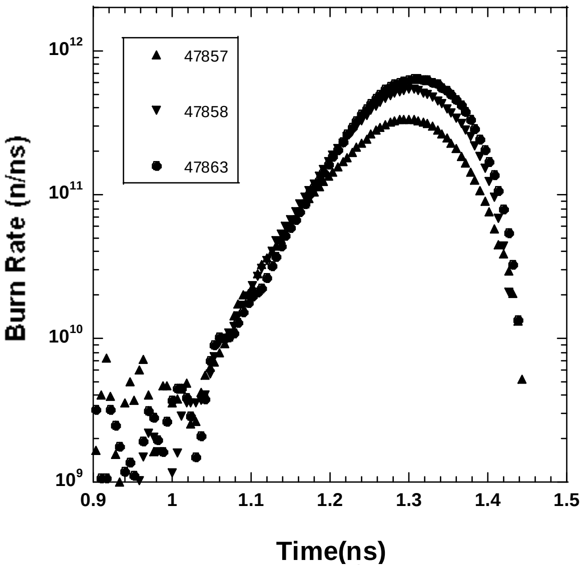

Figure 5. Burn history with ^{3}He (shot 47857) and without (47858 and 47863)

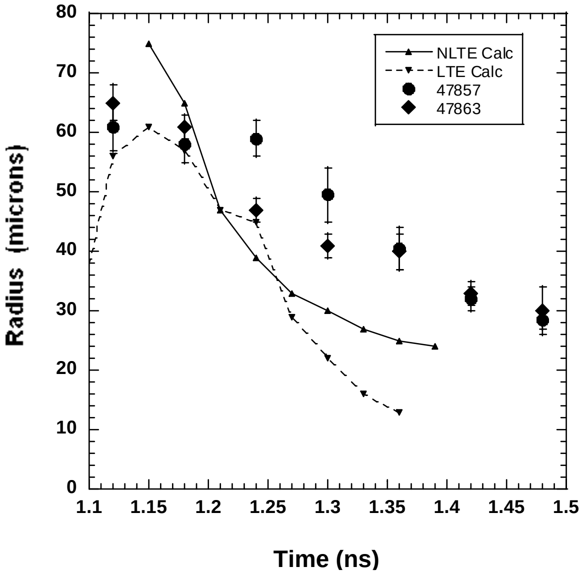

Figure 6. X-ray image radius with ^{3}He (47857) and without (47863) vs simulated using LTE and non-LTE.

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