Effects of Fuel-Shell Mix upon Direct-Drive, Spherical Implosions on OMEGA

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Fuel-shell mix and implosion performance are studied for many capsule types in direct-drive experiments at OMEGA. The amount of mixing and the size of the mix region are inferred from charged-particle spectrometry data and confirmed with an experimentally constrained model. Measured yields and convergence ratios CR fall short of one-dimensional predictions, especially for low capsule fill pressures. CR is ~11 for pressures from 3 to 15 atm, in contrast to predictions of ~25 for 3 atm and ~12 for 15 atm. The performance shortfalls are likely to be caused by fuel-shell mix.

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High gain and ignition in inertial confinement fusion (ICF) require symmetric implosion of spherical targets to high temperature and density [1]. In the direct-drive approach, implosion occurs in response to energy deposited on a target capsule surface by a large number of high-power laser beams arranged for uniform illumination [1]. The OMEGA laser facility [2,3] is used to study many aspects of implosion physics and to explore concepts for high-gain, direct-drive capsule implosions on the National Ignition Facility (NIF) [4]. A critical issue is control of the Rayleigh-Taylor (RT) instability, which is seeded by laser beam nonuniformities, beam-to-beam power imbalance [5–7], and target imperfections (on the outer ablative surface and/or the shell-fuel interface). During the acceleration phase, the instability occurs at the ablation surface and feeds through to the fuel-shell interface, adding roughness to the inner shell. In the worst case, this process leads to shell breakup. During the deceleration phase, distortions at the fuel-shell interface grow and result in the mixing of fuel and shell materials, degrading target performance. Recent OMEGA experiments have shown that significant improvements in implosion performance are achieved with full single-beam smoothing; it has been suggested that this is due to an enhancement of shell integrity during the acceleration phase [5–7].

In this Letter, systematic experimental studies of fuel-shell mix are reported. For the first time, the relationship between mix and direct-drive spherical implosion performance is studied on OMEGA for a wide range of (theoretical) convergence conditions. We focus only on the presence and effects of mix, ignoring details of how it occurs (e.g., whether from low-mode or high-mode distortions, or with diffusive or turbulent processes), and we treat it as a radial redistribution of material, ignoring possible large-scale deviations from spherical symmetry. Earlier relevant work included studies of mix-enhanced particle slowing in a deuterium-deuterium (D_2) plasma [8]; inference of mix in direct-drive implosions of 15-atm capsules at OMEGA [6,9,10]; and aspects of mix for indirect-drive ICF [11,12].

Experiments were conducted on OMEGA, with 60 beams of frequency-tripled (0.35 μm) UV light in a 1-ns square pulse and total energy ~23 kJ. Full smoothing of individual laser beams was used, and beam-to-beam energy imbalance was typically $\leq 5\%$ rms. Nuclear diagnostics were used to measure parameters of imploded capsules: scintillators and neutron activations for primary neutron yields (Y_n); time-of-flight neutron Doppler widths (NTOF) [13] for ion temperatures (T_i); and a neutron temporal diagnostic (NTD) [14] for fusion burn history. Charged-particle spectra were obtained with two magnet-based (CPS1 and CPS2) and several "wedge-range-filter" (WRF) spectrometers [15,16].

The existence of fuel-shell mix in OMEGA direct-drive implosions is demonstrated by data from implosions of capsules filled with pure ^{3}He gas in a special shell, as depicted in Fig. 1. The plastic (CH) shells had a 1-μm

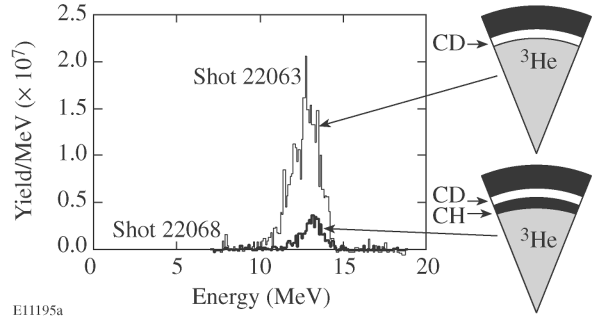

FIG. 1. The structures of two different capsules filled with 4 atm of pure ^{3}He gas, and measured spectra of primary D^{3}He protons from implosions at OMEGA. The ratio of number densities (D to C) is 1.56 in the CD layer.

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deuterated plastic (CD) layer either at the fuel-shell interface or offset from the fuel-shell interface by 1 μm. These capsules had diameters ~920–960 μm and total shell thickness ~20 μm. No D^3He yield is expected for a one-dimensional (1D) implosion [17]. A D^3He fusion reaction [$D + {}^3He \rightarrow \alpha + p(14.7\ \text{MeV})$] will occur only when a deuteron from the CD layer meets a ^3He ion in the core, and significant yield requires atomic-level mixing (the yield at an interface without atomic-level mix, even with ripples from an instability, is negligible). Data from such implosions, illustrated in Fig. 1, show yields that are the direct signature of fuel-shell mix. With a 1-μm CD layer and zero offset, shot 22063 had a D^3He proton yield of $Y_p \sim 2.4 \times 10^7$. Indications of the spatial extent of mixing can be seen in data from shot 22068, which had a 1-μm offset for the CD layer and a much lower D^3He proton yield of about $Y_p \sim 4.3 \times 10^6$. The reduction in yield by a factor of 6 (relative to shot 22063) indicates that less CD material was mixed into the fuel because of the 1-μm CH offset.

The dependence of D^3He proton yield on ^3He gas-fill pressure in these implosions is illustrated in Fig. 2, where it can be seen that the yield increased as the fill pressure decreased. Using the fact that approximately the same T_i's have been measured for all these implosions, and the fact that the radial convergence is also independent of pressure (as shown below), we conclude from the yield variation that more CD is mixed into the core as the pressure is reduced.

Having demonstrated the existence of fuel-shell mix using ^3He-filled capsules, and having shown that deviations from 1D predictions for these capsules are strongly connected with mix, we turn to the effects of mix on implosions of room-temperature capsules with similar shell thicknesses and fill pressures but deuterium-tritium (DT) or D_2-fill gas (all which should have similar hydrodynamic behavior [6]). Fill pressures from 3 to 15 atm were used because the corresponding implosions belong to different regimes of predicted radial convergence (CR), defined as the ratio of the initial fuel radius to the final core radius, and are expected to have different stability properties [6]. Simulations with the 1D hydrodynamic code LILAC [18] predict that, under current experimental conditions, a 3-atm capsule should achieve high convergence (CR ~ 25) at bang time while a 15-atm capsule should achieve moderate convergence (CR ~ 12). Figure 2 suggests that 3-atm capsules are more unstable and susceptible to fuel-shell mix.

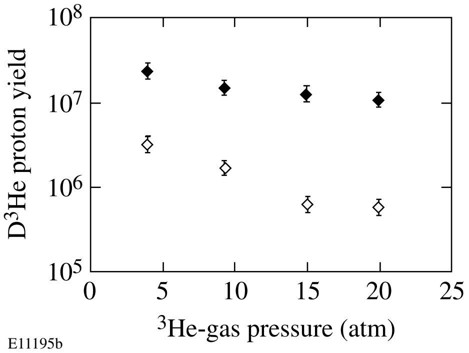

FIG. 2. D^3He proton yields plotted as a function of gas-fill pressures for implosions of capsules with ^3He fuel and zero-(closed dark diamond) and 1 μm-offset (open diamond) CD layer shells.

Fuel-shell mix and its relationship to implosion performance were characterized by comprehensive sets of measurements and comparisons to 1D predictions for a variety of types of capsules, based upon the strong connection between mix and deviations from 1D predictions established above. Mix should affect the dynamics of compression and the profiles of T_i and density (n_i) at burn time. Fuel convergence reduction can be caused by the mixing of fuel outward into the shell, which will also cause cooling of the outer part of the fuel and a reduction in nuclear yield. Reduction of convergence can also result from conversion of radial shell kinetic energy to lateral shell motion due to nonlinear growth of inner-surface perturbations during the deceleration phase. Both processes may lead to a truncation of nuclear burn; the intermixing of shell and fuel may cause the fuel T_i to drop earlier than predicted, while the reduction of inward motion of the shell may lead to a shortening of the interval in which conditions are conducive to burn. All of these processes appear to manifest themselves in the following data.

To study CR we measured fuel and shell areal densities (ρR_{fuel} and ρR_{shell}). For DT-filled capsules with CH shells, areal densities can be determined from measured yields of "knockon" particles elastically scattered by 14.1-MeV primary DT neutrons [7,19]; for the fuel we use knockon deuterons, and for the CH shell we use knockon protons.

Measured and 1D-predicted values of ρR_{fuel} are plotted as a function of gas-fill pressure for DT-filled capsules in Fig. 3(a). Although 1D simulations predict $\rho R_{\text{fuel}} \sim$ 16–17 mg/cm^2 for all of these implosions, we find experimentally that ρR_{fuel} is lower by ~75%, ~55%, and ~15% for 3-atm, 7-atm, and 15-atm fill pressures, respectively. For ρR_{shell}, 1D calculations predict a range of ~70–110 mg/cm^2, while we obtained $\rho R_{\text{shell}} \sim$ 60 mg/cm^2 for all implosions [see Fig. 3(b)]; this indicates that shell compression was independent of capsule

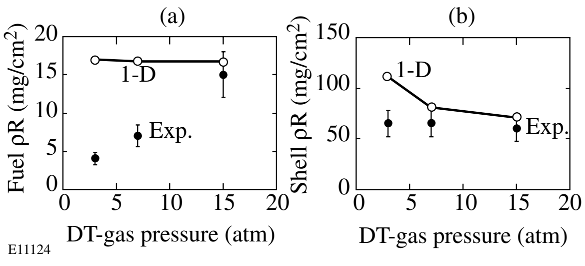

FIG. 3. Measured and 1D-predicted values of ρR_{fuel} (a) and ρR_{shell} (b) plotted as a function of DT gas-fill pressure.

gas-fill pressure. The corresponding neutron-burn-averaged values of CR are inferred from measured values of either ρR_{fuel} ($\mathrm{CR} \approx \sqrt{\rho R_{\mathrm{fuel}}/\rho R_{\mathrm{fuel0}}}$) or ρR_{shell} ($\mathrm{CR} \approx \sqrt{3\rho R_{\mathrm{shell}}/\rho R_{\mathrm{shell0}}}$), where the subscript 0 indicates a precompression value. In calculating these parameters, we assumed that the total mass of the fuel was conserved and that about 2/3 of the mass of the shell material was ablated off. The result is the same ($\mathrm{CR} \sim 11$) for all 3, 7, and 15-atm implosions, as shown in Fig. 4(a). The 15-atm implosions come close to 1D compression performance, while 3-atm implosions fall short of the 1D predictions. This trend is analogous to that seen above for ^{3}He- filled capsules, where increased mix was shown to be directly correlated with larger deviations from 1D performance in implosions of lower-pressure capsules.

To study how the relationship between measured primary neutron yield and 1D-predicted yield is affected by fuel-shell mix, we can use the fact that yield scales as

$$Y_n \approx \frac{4\pi}{3} R_b^3 n_i^2 \langle \sigma v \rangle t_b \propto \rho^2 R_b^3 T_i^m t_b \propto \left(\frac{R_b}{R}\right)^3 (\mathrm{CR})^3 T_i^m t_b, \tag{1}$$

where R_b is the radius of the region participating in the burn, $\langle \sigma v \rangle$ is the reaction rate coefficient (which scales roughly as T_i to the power m), t_b is the length of the burn, ρ is the compressed fuel mass density, and R is the total radius of the compressed fuel. This expression is approximate (since it relies on n_i and T_i being uniform in the burn region). Measured values of CR were shown above for DT fuel [Fig. 4(a)], and should be similar for capsules with D_2 at the same fill pressure because of their hydrodynamic similarity [6]. The ratio R_b/R can be less than 1, as we will see below, as a consequence of mix depressing the outer fuel T_i. Values of T_i for implosions of both DT- and D_2-filled capsules are shown in Fig. 5, and are generally higher than predicted for reasons that will be discussed below.

Figure 4(b) shows the ratio of measured to predicted neutron yield (YOC) as a function of gas-fill pressure for D_2 implosions. The 15-atm implosions are closest to 1D performance with $\mathrm{YOC} \sim 35\%$, while the 3-atm implosions result in a lower YOC of $\sim 20\%$. The shortfall of the 15-atm implosions cannot be explained by a shortening of t_b, because NTD data indicate that t_b tracks the 1D prediction well in terms of time dependence [6]. It cannot come from a lower T_i, because the measured yield-averaged T_i is higher than predicted [Fig. 5(a)] by $\sim 15\%$ (and the power m is ~ 3.5 at these temperatures). Similarly, it cannot come from the reduction in density due to decreased CR relative to 1D, because this would only lower the yield by $\sim 23\%$. According to Eq. (1) it must therefore be caused by a reduction in the volume participating in the burn ($R_b/R \sim 0.65$), which would result from a cooling of the outer portion of the fuel due to mix (and which could also raise the yield-averaged Ti even with the same central T_i). In the case of the 3-atm implosions, neutron measurements show that t_b is reduced by about 20% relative to 1D (Fig. 6) while the yield-averaged T_i is higher by $\sim 40\%$ [Fig. 5(a)] and CR is reduced by $\sim 55\%$ [Fig. 4(a)]. Matching the YOC of $\sim 20\%$ then requires $R_b/R \sim 1$. This indicates either no mix at all or uniform mix over the entire fuel volume, but we can rule out the no-mix possibility on the basis of the experiments with ^{3}He fuel at low fill pressure. The conclusion of uniform mix is not necessarily inconsistent with the fact that the measured T_i is higher than predicted, because T_i decreases toward the end of the burn period and truncation in time will cause the earlier, higher temperatures to dominate the yield-weighted average.

To confirm this overall picture of mix, a numerical model was constructed by varying assumed n_i and T_i profiles and attempting to match the neutron-burn-averaged experimental data, assuming the measured neutron-burn-averaged pressure (from time-resolved x-ray spectroscopy [20]) is isobaric in the core-mix region. It was found [21] that data from the 15-atm implosions are consistent with the assumption that ~ 0.5 μm of the original inner CH shell material mixes into the outer part of the fuel while the inner part of the core remains "clean"; the size of the mix region is not strongly constrained by the model, but is consistent with the conclusion above that the outer third of the fuel radius is mixed with shell material in the 15-atm D_2 implosions. Data from the 3-atm implosions are consistent with the assumption that ~ 0.8 μm of the original inner CH shell

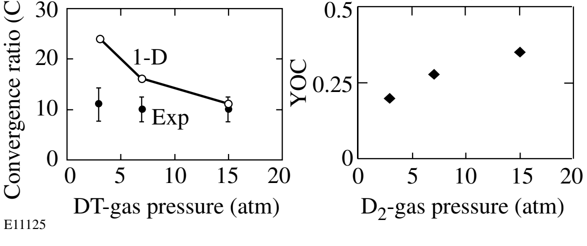

FIG. 4. (a) Measured and 1D-predicted values of the radial compression ratio CR, plotted as a function of DT gas-fill pressure. (b) Yield-over-clean (YOC) plotted as a function of D_2 gas-fill pressure.

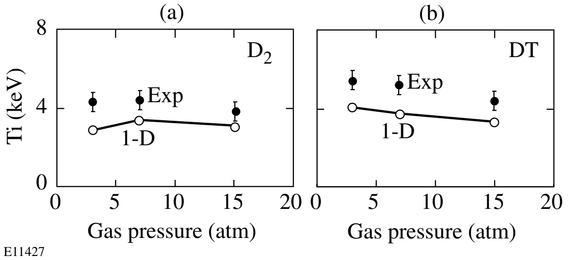

FIG. 5. Measured and 1D-predicted ion temperatures plotted as a function of gas-fill pressures for D_2-filled capsules (a) and DT-filled capsules (b).

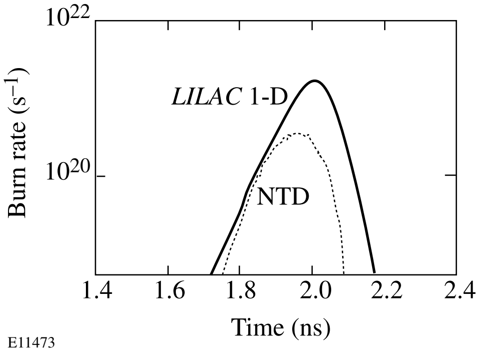

FIG. 6. Measured (dashed) and 1D-predicted (solid) neutron burn rates plotted as a function of time for shot 22864 (a 3-atm-D_2 fill in a 20-μm-thick CH shell).

was mixed into the entire core, with no clean region in the compressed core; this is consistent with the conclusion of uniform mix in the 3-atm D_2 data discussed above. (A different approach, which does not utilize the pressure constraint, has been applied to 15-atm implosions with the conclusion that ~1 μm of the initial shell material is mixed into the fuel [10].)

In summary, novel diagnostics and a wide range of experiments and calculations were used to systematically study the relationship between fuel-shell mix and implosion characteristics for OMEGA direct-drive, spherical capsule experiments. Implosions of capsules filled with pure ^{3}He gas and with CD shell layers provided the clearest evidence to date of fuel-shell mix and its extent. Target performance degradations relative to 1D predictions were demonstrated to be strongly correlated with mix. Data show the relationships between mix and compression reduction, truncation of burn, and reduction of the effective volume of the fusion reaction. The dependence of target performance on gas-fill pressure was also established, with 3-atm capsules found to have performance further from 1D predictions than 15-atm capsules; fuel-shell mix is thus more severe for 3-atm implosions. 1D simulations predict that high convergence (CR ~ 25) should result for 3-atm capsules and moderate convergence (CR ~ 12) should result for 15 atm capsules, but we found CR ~ 11 irrespective of gas-fill pressure. This result that mix becomes more important as fill pressure is lowered is compatible with the fact that the physical gradients that favor Rayleigh-Taylor instabilities are worse for low pressures; the observations indicate the continuing importance of minimizing the seeding of Rayleigh-Taylor instabilities by minimizing imperfections in capsule structure and by maximizing laser illumination uniformity. Finally, we note that although mix compromises the performance of the targets under study here, the implications are less serious for cryogenic targets (including future ignition targets). The lowering of fuel temperature by mix should be less significant because the lower Z of the shell material (D_2 or DT instead of CH) means less cooling by bremsstrahlung, and there will be no dilution of fuel because the shell and fuel are actually the same material.

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[1] J. D. Lindl *et al.*, Phys. Today **45**, No. 9, 32 (1992).
[2] T. R. Boehly *et al.*, Opt. Commun. **133**, 495 (1997).
[3] J. M. Soures *et al.*, Phys. Plasmas **3**, 2108 (1996).
[4] S.W. Haan *et al.*, Phys. Plasmas **2**, 2480 (1995).
[5] R. L. McCrory *et al.*, Nucl. Fusion **41**, 1413 (2001).
[6] D. D. Meyerhofer *et al.*, Phys. Plasmas **8**, 2251 (2001).
[7] C. K. Li *et al.*, Phys. Plasmas **8**, 4902 (2001).
[8] H. Azechi *et al.*, Phys. Rev. Lett. **59**, 2635 (1987).
[9] D. D. Meyerhofer *et al.*, Plasma Phys. Controlled Fusion **43**, A277 (2001).
[10] P. B. Radha *et al.*, Phys. Plasmas **9**, 2208 (2002).
[11] M. D. Cable *et al.*, Phys. Rev. Lett. **73**, 2318 (1994).
[12] T. R. Dittrich *et al.*, Phys. Rev. Lett. **73**, 2324 (1994).
[13] M. A. Russotto *et al.*, Rev. Sci. Instrum. **61**, 3125 (1990).
[14] R. A. Lerche *et al.*, Rev. Sci. Instrum. **66**, 933 (1995).
[15] D. G. Hicks, Ph.D. thesis, MIT, 1999.
[16] F. H. Séguin *et al.*, Rev. Sci. Instrum. (to be published).
[17] One possibility for bringing ^{3}He and D ions together to generate protons without true 2D or 3D mix would be for some ^{3}He to diffuse through the inner CH shell layer and into the CD layer during the time interval between the fabrication and implosion of a capsule, but even if the ^{3}He density in the shell equals that in the core the resultant yields would be about 3 orders of magnitude smaller than what is measured. Another possibility is that the ^{3}He fill gas is contaminated with some D_2, but the capsule fabricators assure us that the ^{3}He is 99.9% pure. Another possibility is that either thermal ^{3}He ions from the compressed fuel plasma or thermal D ions from the CD layer travel through the intervening CH layer during the implosion, but it can be shown that the range in the compressed CH of the highest-energy thermal ^{3}He or D ions is more than 2 orders of magnitude smaller than required.
[18] E. B. Goldman, LLE Report No. 16, 1973.
[19] S. Skupsky *et al.*, J. Appl. Phys. **52**, 2608 (1981).
[20] S. P. Regan *et al.*, Phys. Rev. Lett. **89**, 085003 (2002).
[21] C. K. Li *et al.*, Bull. Am. Phys. Soc. **46**, 104 (2001).