Modelling the Effect of $^3$He in Direct Drive Capsule Implosions

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Abstract. $^3$He fuels are often used in ICF implosion experiments, either as a surrogate for DT to restrict the output neutron yield, or to produce protons for use in diagnosis of core conditions. Recent experiments have suggested that capsules filled with $^3$He do not behave as expected, but that both proton and neutron yields are anomalously degraded relative to the pure D$_2$ case. We have performed direct drive implosion experiments using the Omega laser to examine the effect of $^3$He on DT-filled glass capsules. The use of DT fuel allows reaction history measurements to be obtained using the Gas Cherenkov diagnostic (GCD). It was hoped that the detailed information provided by GCD measurements would complement existing measurements to constrain modelling. We present recent modelling and analysis of the experiments using radiation-hydrocode simulations, and explore some of the hypotheses proposed to explain the results.

1. Introduction
Recent experiments have suggested that ICF capsules filled with $^3$He do not behave as expected, with fusion yields being anomalously degraded relative to the pure D$_2$ case [1]. This result has consequences for experiments where $^3$He is used either as a surrogate for DT or where it is used to generate 14.7MeV protons as an additional diagnostic of core conditions.

To further explore the anomaly, direct drive implosion experiments have been performed at Omega which examine the effect of $^3$He on DT-filled glass capsules [2]. The use of DT fuel allows reaction history measurements to be obtained using the Gas Cherenkov diagnostic (GCD) [3]. This instrument measures reaction history without degradation by neutron time-of-flight, by observing gamma rays from a branch of the DT reaction. These experiments are amongst the first to demonstrate application of the GCD to elucidate implosion physics. GCD measurements complement existing observations to provide additional insight and help constrain capsule modelling. Modelling and analysis of the experiments is presented, with particular emphasis on the GCD and neutron yield data.

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2. Experiment
Two separate series of experiments were performed at the Omega laser using thin shell glass capsules (nominally 5\(\mu\)m thickness). Initial experiments used \(^3\)He mixed additively to 5atm of equimolar DT. More recently the targets have used a ‘hydrodynamically equivalent’ gas fill [1] in which \(^3\)He is substituted for D (with the tritium pressure held constant). Hydrodynamic equivalence minimises variation in the implosion dynamics as fuel composition is varied and is based on the assumption of fully ionised ideal gas. In practice simulations suggest that there is some deviation from perfect equivalence even when the pressure condition is met.

The GCD provides low noise, time resolved measurements of the fuel burn. Resolution in these experiments was \(~75\)ps following deconvolution of the instrument response. Two yield phases are apparent in all data; identified as being due to convergence of the initial shock at the centre of the fuel (shock phase) and subsequent compression of the fuel by the capsule shell (compression phase) (Figure 1). The signal evolves appreciably as the \(^3\)He fraction is increased, with the compression phase yield being clearly reduced. Excellent shot-to-shot reproducibility gives confidence that the observed features are real.

![Figure 1. DT burn histories measured using the GCD. The curves show distinct shock and compression phases (colour online).](image1)

![Figure 2. Comparison of GCD data with simulated reaction rates for 0% \(^3\)He case. Results are shown for clean calculations, Youngs’ mix model and the fall-line model (colour online).](image2)

![Figure 3. As figure 2 for 10% \(^3\)He case. The fall-line model now gives good agreement with experimental data (colour online).](image3)

![Figure 4. As figure 2 for 36% \(^3\)He case. In all cases simulated reaction histories are convolved with 75ps Gaussian response (colour online).](image4)
3. Modelling

Capsules were modelled in 1D spherical geometry using the radiation-hydrocode Nym [4]. Energetics were calibrated using the rise of the GCD signal. This part of the burn history was found to be insensitive to hydrodynamic mix and so provides an unambiguous calibration provided proper account is taken of the instrument response. This improves on bang-time calibration, which is subject to assumptions about mix.

Comparison of simulated and measured burn histories shows that clean simulations match the initial shock phase, but overestimate the compression phase (Figures 2-4). The effects of mix degradation were estimated using both Youngs’ model [5] and fall-line calculations [6]. Youngs’ model calculates the 1D spatial extent of mixing (mix width) assuming non-linear growth. The fall-line model assumes the extent of mixing into the fuel is limited by the trajectory the gas-shell interface would take if no deceleration occurs, and provides a worst-case estimate of degradation for a 1D model. Youngs’ model predicts little yield degradation. However the fall-line calculation predicts significantly greater yield degradation and gives surprisingly good agreement with the measured burn histories, particularly at 36% $^3$He.

Yield data and calculations from the initial (additive) experiments is shown in figure 5. Despite the poor match to GCD data, clean simulations are found to match the yield trend well; i.e. yield-over-clean is approximately constant. Fall-line calculations underestimate the relative yield degradation at higher $^3$He concentration. Thus if hydrodynamic mix is to account for the observed yields it is necessary to increase the extent of mix with increasing $^3$He. This is consistent with LANL calculations using the Scannapieco-Cheng mix model [2]. This finding is difficult to justify physically and suggests instead that mix alone cannot account for the observed performance. Other mechanisms must act to degrade the compression phase yield.

The data from the hydro-equivalent targets (figure 6) appears consistent with that from [1]. It is clear that the results do not match either analytic scaling or simulations. Simulations also show that the departure from hydrodynamic-equivalence cannot be attributed to non-ideal gas or non-equilibrium effects. The anomaly must arise from effects not captured by the 1D code model.

![Figure 5](image1.png)

**Figure 5.** Observed and calculated DT neutron yields for initial experiments with $^3$He mixed additively to DT. Yields are normalized to 0% $^3$He case (colour online).

![Figure 6](image2.png)

**Figure 6.** Scaled yields from hydro-equivalent targets. Yield scaling is detailed in [1] except that here values are normalized to the 0% $^3$He case. (colour online).
4. Discussion
The GCD data shows that the compression phase yield is not well modelled. This is consistent with other evidence from similar experiments [7] which also suggests that capsule compression is reduced compared to simulation. A number of hypotheses have been proposed to account for the reduced compression. These include fast electron preheat from resonant absorption and LPI, non-local electron transport, shell break-up following interaction with the outgoing reflected shock, and the effect of 2D asymmetries on fuel assembly.

In order to account for the $^3$He anomaly requires a differential effect as the gas composition is varied. One hypothesis that has been explored is uncertainty in the combination of the different equations of state (EoS) in the DT-$^3$He mixture. The experiments have been modelled using two different EoS mixing algorithms; the additive volume rule and the ideal mixing rule [8]. The capsules show little sensitivity to these algorithms, with yield variation of ~2% between the two cases. Theoretically the two methods should agree for ideal gases, for which they are exact. The lack of sensitivity thus implies that the individual EoS used are sufficiently close to ideal gases that the mixing algorithm is unimportant, and that other more sophisticated mixing rules will produce the same result.

It is also possible that the constituent EoS are in error. Although uncertainties in deuterium EoS are well documented [9], our results would require the EoS to be less compressible than the standard Sesame model, which is inconsistent with existing measurements. However, we admit the possibility of uncertainties in the derived tritium and $^3$He EoS, which have not been examined here.

5. Summary
A series of direct drive implosion experiments has been performed at the Omega laser to explore the effect of $^3$He on DT-filled glass capsules. Reaction histories measured using the Gas Cherenkov diagnostic (GCD) show two phases, attributed to the shock and compression. The shock phase is well matched by 1D simulation, but the compression yield is lower than calculated. The experiments are consistent with previous data, showing an anomalous effect with $^3$He. Mix alone cannot account for the observed behaviour. However, fall-line calculations, which represent an unrealistic extreme 1D mix limit, do reproduce the GCD data surprisingly well. A number of hypotheses have been proposed to explain the reduced compression and are being actively explored. We have shown that EoS mixing uncertainties are unlikely to have a significant effect due to the near-ideal constituent EoS.

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