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## Hydrodynamic instabilities and mix studies on NIF: predictions, observations, and a path forward

B. A. Remington,<sup>1</sup> L. J. Atherton,<sup>1</sup> L. R. Benedetti,<sup>1</sup> L. Berzak-Hopkins,<sup>1</sup> D. K. Bradley,<sup>1</sup> D. A. Callahan,<sup>1</sup> D.T. Casey,<sup>1</sup> P. M. Celliers,<sup>1</sup> C. J. Cerjan,<sup>1</sup> D. S. Clark,<sup>1</sup> E. L. Dewald,<sup>1</sup> T. R. Dittrich,<sup>1</sup> S. N. Dixit,<sup>1</sup> T. Döppner,<sup>1</sup> D. H. Edgell,<sup>1</sup> M. J. Edwards,<sup>1</sup> R. Epstein,<sup>2</sup> J. Frenje,<sup>3</sup> M. Gatu-Johnson,<sup>3</sup> S. Glenn,<sup>1</sup> S. H. Glenzer,<sup>4</sup> G. Grim,<sup>5</sup> S. W. Haan,<sup>1</sup> B. A. Hammel,<sup>1</sup> A. Hamza,<sup>1</sup> D. Hicks,<sup>1</sup> W. W. Hsing,<sup>1</sup> O. Hurricane,<sup>1</sup> N. Izumi,<sup>1</sup> O. S. Jones,<sup>1</sup> M. H. Key,<sup>1</sup> S. F. Khan,<sup>1</sup> J. D. Kilkenny,<sup>6</sup> J. L. Kline,<sup>5</sup> G. A. Kyrala,<sup>5</sup> O. L. Landen,<sup>1</sup> S. Le Pape,<sup>1</sup> J. D. Lindl,<sup>1</sup> T. Ma,<sup>1</sup> B. J. MacGowan,<sup>1</sup> A. J. Mackinnon,<sup>1</sup> A. G. MacPhee,<sup>1</sup> N. B. Meezan,<sup>1</sup> J. D. Moody,<sup>1</sup> E. I. Moses,<sup>1</sup> A. Nikroo,<sup>6</sup> A. Pak,<sup>1</sup> T. Parham,<sup>1</sup> H.-S. Park,<sup>1</sup> P. K. Patel,<sup>1</sup> R. Petrasso,<sup>3</sup> J. Pino,<sup>1</sup> J.E. Ralph,<sup>1</sup> K. Raman,<sup>1</sup> S. P. Regan,<sup>2</sup> H. F. Robey,<sup>1</sup> J. S. Ross,<sup>1</sup> B. K. Spears,<sup>1</sup> V. A. Smalyuk,<sup>1</sup> P. T. Springer,<sup>1</sup> L. J. Suter,<sup>1</sup> R. Tipton,<sup>1</sup> R. Tommasini,<sup>1</sup> R. P. Town,<sup>1</sup> S. V. Weber<sup>1</sup>

<sup>1</sup>Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550 USA

<sup>2</sup>Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

<sup>3</sup>Massachusetts Institute of Technology, Cambridge, MA, USA

<sup>4</sup>SLAC National Accelerator Laboratory, 2575 Sand Hill Rd. Menlo Park, CA 94025, USA

<sup>5</sup>Los Alamos National Laboratory, Los Alamos, NM 87545, USA

<sup>6</sup>General Atomics, 3550 General Atomics Court, San Diego, CA, 29186, USA

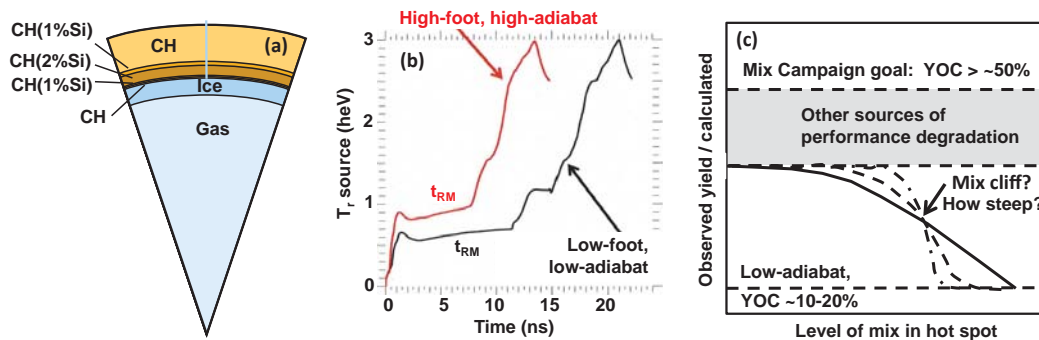
**Abstract.** The goals of the Mix Campaign are to determine how mix affects performance, locate the “mix cliff”, locate the source of the mix, and develop mitigation methods that allow performance to be increased. We have used several different drive pulse shapes and capsule designs in the Mix Campaign, to understand sensitivity to drive peak power, level of coast, rise time to peak power, adiabat, and dopant level in the capsule. Ablator material mixing into the hot spot has been shown conclusively with x-ray spectroscopy. The observed neutron yield drops steeply when the hot spot mix mass becomes too large. The mix appears to be driven by ablation-front Rayleigh-Taylor instabilities. A high foot, higher adiabat drive has a more stable ablation front and has allowed the mix mass in the hot spot to be reduced significantly. Two recent high foot shots achieved neutron yields  $> 10^{15}$  and measured neutron yield over clean 1D simulation (YOC)  $> 50\%$ , which was one of the central goals of the Mix Campaign.

### 1 Introduction

The goal of inertial confinement fusion (ICF) is to compress deuterium (D) and tritium (T) to the densities and temperatures required to achieve a burst of  $D+T \rightarrow {}^4\text{He}+n+17.6\text{ MeV}$  fusion reactions of sufficient intensity that the energy output exceeds the energy input. The indirect-drive approach pursued at the National Ignition Facility (NIF) uses a high power pulsed laser focused into a radiation cavity (hohlraum) to convert to soft x-rays which ablatively drive the implosion of a hollow spherical capsule at the center of the hohlraum. The capsule has a multi-layered ablator (Fig. 1a) and the radiation drive is shaped to launch 3-4 staged shocks to control the adiabat and achieve high compression of the fuel (Fig. 1b). [1-3] It has been known for decades, based on theory [4-11], 2D and 3D simulations, [12-18] and experiments on high power lasers [19-27] that the capsule ablation front in ICF is unstable to the Rayleigh-Taylor (RT) instability and that the ablation process reduces RT growth rates. What is not known sufficiently are the detailed effects RT has on NIF capsule



performance. This RT growth, if unchecked, can become large enough to perturb the ablator-fuel and fuel-hot spot interfaces and ultimately leads to ablator material contaminating the hot spot and quenching the burn by radiative cooling. This mix failure mode is often referred to loosely as the “mix cliff”, as suggested by the sketch in Fig. 1c. The goals of the Mix Campaign on NIF are to determine if such a mix cliff exists, locate it, determine how steep it is, and find ways to mitigate this mix failure mode. Once effective mitigation methods are found, the plan is to push the more robust capsules harder to test the limits of performance, and find the new mix cliff. This cycle of locating the mix cliff, finding new or more refined mix mitigation methods, then pushing these capsules to their new performance limits will be repeated, as we attempt to enter into the alpha heating (“boot strapping”) regime, and push closer to ignition. The remainder of this article describes our progress in this endeavour; recent results are encouraging.

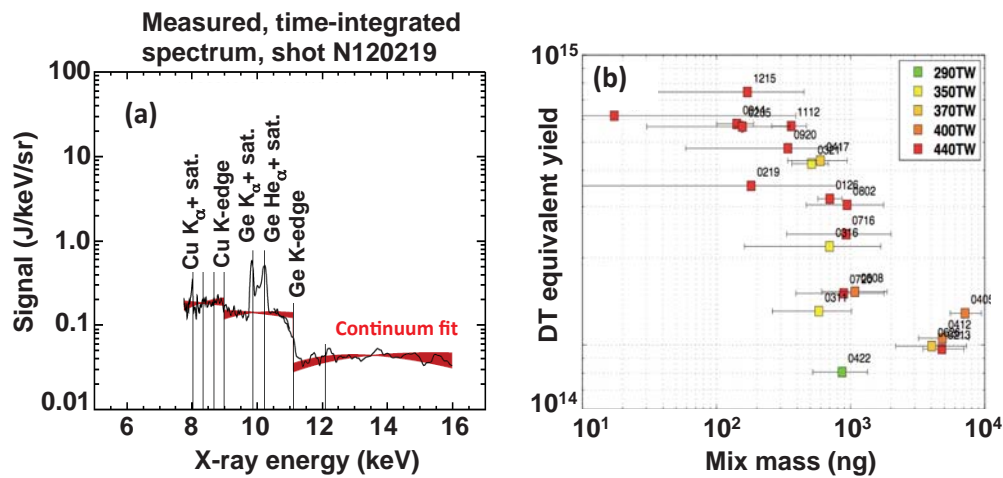


**Figure 1.** (a) Cut-out sketch of a typical capsule used in NIF ignition experiments, corresponding to an outer radius of 1.15 mm. The layers, from the outside in, correspond to 138  $\mu\text{m}$  of CH, 10  $\mu\text{m}$  of CH(1% Si), 35  $\mu\text{m}$  of CH(2% Si), 6  $\mu\text{m}$  of CH(1% Si), 6  $\mu\text{m}$  of CH, and 69  $\mu\text{m}$  of cryogenic DT ice. (b) Drive radiation pulse shapes used for the 4-shock low-foot, low-adiabat ( $\alpha \sim 1.5$ ) drive (black curve) and the 3-shock high-foot, higher-adiabat ( $\alpha \sim 2.3$ ) drive (red curve). (c) The basic plan for the Mix Campaign is illustrated in this qualitative sketch. Our expectation at the onset of the Mix Campaign was that as the level of ablator mixed into the hot spot increases, the experimentally observed neutron yield compared to clean 1D simulation (YOCC) would decrease. Depending on the steepness, we called this the “mix cliff”. To optimize implosions to approach ignition, we need YOCC > ~50% (in the absence of alpha heating) to have a tighter correlation between simulations and experiments to allow the wide parameter space to be more fully and efficiently explored.

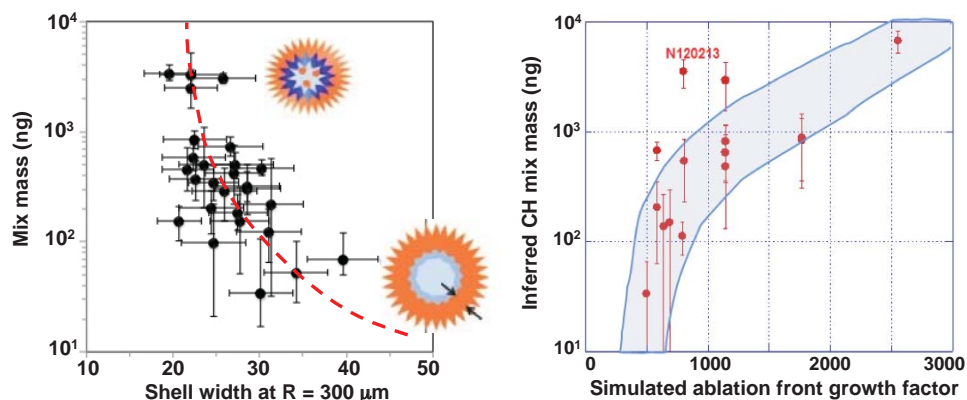
## 2 Experiments to probe the mix cliff

The first conclusive experimental evidence that there was ablator material penetrating into the DT hot spot came from x-ray emission spectroscopy. In one “tri-doped” DT layered implosion, the innermost 6  $\mu\text{m}$  layer in the ablator (adjacent to the DT layer) had 0.15% by number trace amount of Cu. And the next two layers moving back from the ice had 0.20% trace levels of Ge. In this implosion, Ge He- $\alpha$  emission from the hot spot was seen in the Supersnout-II spectrometer, but no Cu emission from the hot spot was observed, as shown in Fig. 2a. [28] Both the Ge and Cu cold K-edges were observed in the surrounding shell. These experimental observations are consistent with the predictions that ablation-front RT instability carries ablator material from the outside inward into the hot spot, [17] whereas instability growth at the ablator-fuel interface drives much less ablator into the hot spot. In parallel with these spectroscopy experiments, it was noticed that in poorly performing implosions, the neutron yield and ion temperature were low, but the hot spot x-ray emission was high. A very plausible way to explain this is that ablator material, in particular carbon, was mixed into the hot spot and radiatively cooled the hot spot, quenching the burn. This led to the development of the mix model; the carbon mass in the hot spot was inferred from the excess of radiation from the hot spot relative to that expected for clean DT, given the yield, hot spot volume

and hot spot temperature. [29] With this mix model in hand, a full ensemble of cryogenic layered implosions can be plotted in terms of DT neutron yield versus experimentally inferred hot spot mix mass, as shown in Fig. 2b. A similar trend between the neutron yield and the hot-spot mix mass was



**Fig. 2.** (a) Measured hot-spot x-ray spectrum for an ignition target with a tri-doped ablator (black curve), corresponding to NIF shot N120219. The x-ray continuum from the hot spot transmitted through the compressed shell is modeled (red curve) assuming the x-ray continuum and the shell optical thickness scale with photon energy ( $h\nu$ ) as  $\exp(-h\nu/kT)$  and  $(h\nu)^{-3}$ , respectively. [28] (b) Measured DT neutron yield versus inferred mix mass from the mix model for an ensemble of 21 cryogenic layered DT implosions on NIF. Points are color coded by peak laser power. [29] When the hot spot mix mass exceeds several hundred nanograms, the yield drops steeply, suggesting a "mix cliff".



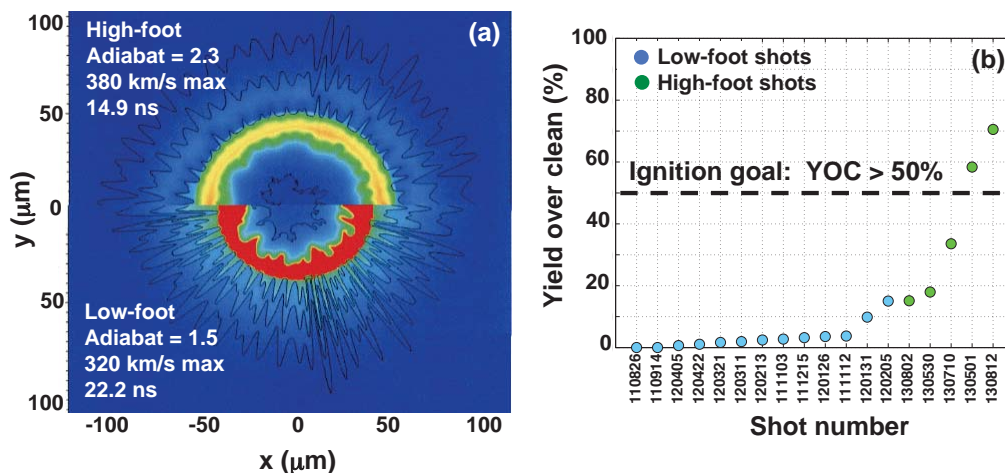
**Fig. 3.** (a) Experimentally inferred hot spot mix mass versus experimentally inferred shell thickness, based on in-flight backlit radiography. [30] (b) Inferred hot spot mix mass versus maximum ablation front growth factors from 2D simulations. [30] The smooth curves in (a) and (b) are only to guide the eye. [30]

observed with the x-ray spectroscopy [28]. It is quite clear from Fig. 2b that when the amount of ablator mixed into the hot spot exceeds several hundred nanograms, neutron yield plummets sharply. The results shown in Fig. 2 all stem from the low-foot, low-adiabat drive shown in Fig. 1b, albeit with some variation in the rise time to peak power (1 ns, 2 ns, and 3 ns). At this point in the Mix Campaign, it was clear that we had located the "mix cliff", and that ablator mix into the hot spot was

a strong failure mode that needed to be mitigated. The next section describes our initial work in mitigation.

### 3 Mitigating Rayleigh-Taylor induced hot spot mix

There are several indications that ablation-front RT instability is one of the dominant causes of ablator material being mixed into the hot spot. First, as shown in Fig. 2a, the spectroscopy measurement on the tri-doped capsule showed strong Ge emission from the hot spot, but no emission from Cu. Second, when experimental mix mass is plotted versus experimentally inferred shell width (Fig. 3a), there appears to be a trend that as shell width decreases, mix mass increases. [30] Third, the experimental mix masses tend to increase when plotted against simulated ablation front growth factors, as shown in Fig. 3b. [30] And finally, when mix masses are compared between the nominal capsules (Fig. 1a) and those with increased silicon concentrations, the latter had higher mix masses (not shown). The above four observations are all consistent with ablation front RT being a dominant source of ablator penetrating into the hot spot. Hence, our first mitigation strategy was aimed at a near-term modification that would reduce ablation-front RT growth. We used the same capsule shown in Fig. 1a, but switched to the high-foot, higher-adiabat drive, shown by the red curve in Fig. 1b. Examples of the 2D design simulations comparing the low-foot with high-foot capsule implosions are shown at peak compression in Fig. 4a. [3] The high-foot simulation converges slightly less, with convergence ratios (CR) of 25-30, as opposed to CR  $\sim$  35-40 for the low-foot implosions. The high foot drive creates a higher adiabat ( $\alpha \sim 2.3$  for the higher foot pulse versus  $\sim 1.5$  for lower foot pulse) starting in the very beginning of the drive. The net effect is a higher ablation velocity and larger density gradient scale length, both of which reduce the RT growth rates, and thereby reduce the overall ablator penetration into the hot spot. [5,6,8,9,11]



**Fig. 4.** (a) Two dimensional, 100-mode simulations with a spectrum of imposed surface roughness show, in density, the expected instability growth on the capsule. The bottom frame shows the low-foot capsule with adiabat  $\alpha = 1.5$  case and the top frame shows the high-foot, adiabat  $\alpha = 2.3$  case. The results are at the minimum implosion radius. The high foot simulation converges less and has a lower level of RT induced spikes penetrating into the hot spot. [3] (b) An ensemble of 18 cryogenic layered DT implosions plotted as experimental yield divided by clean 1D simulation. The blue symbols are for the low-foot, low-adiabat series and the green for the new high-foot, high-adiabat series. The low foot implosions have YOC  $\sim$  5-15%, whereas the high foot implosions have YOC  $\sim$  20-70%.

Accordingly, the high-foot simulation shows less RT growth and spikes penetrating into the hot spot

at this late stage of the implosion. The experimentally inferred mix masses for these high-foot implosions were low. When the ratio of experimental neutron yield over clean 1D simulation (YOC) is plotted, the high-foot implosions clearly demonstrate higher values, as shown in Fig. 4b. [31] Further, YOC for two of the high foot shots surpassed the 50% threshold, which was one of the central goals of the Mix Campaign, as indicated in Fig. 2b. The goal of achieving YOC > 50% is so that simulations and experiments are more closely correlated, allowing faster optimization of new, higher performance designs. Further, analysis and simulations (not shown) demonstrated that shot N130812 in Fig. 4b produced 50% enhanced nuclear yield due to alpha heating, meaning these high-foot implosions are entering into the regime where alpha heating is becoming significant. [3,31] Alpha dominated burn, in which the yield more than doubles due to the effects of alpha heating, is the next goal being pursued in these mix mitigated high-foot implosions.

## 4 Conclusion and future directions

In summary, the Mix Campaign conducted an extensive series of experiments. A steep mix cliff was found, using a number of diagnostic techniques. In particular, x-ray spectroscopy with tri-doped capsules, and the mix model based on comparing continuum x-ray yield to nuclear yield allowed the mix cliff to be mapped out, for the low-adiabat drives. Our mitigation strategy to date has focused on reducing ablation-front RT instability growth, using a higher adiabat design. This has allowed implosions with YOC > 50% and produced the first preliminary indications of the effects of alpha heating. This high YOC due to higher adiabat comes at the expense of reduced fuel areal density, however. Future work will test the limits of the high-foot design, and will also consider additional mitigation techniques such as alternate ablaters, [32,33] as we attempt to push performance further into alpha heating and start to approach the ignition regime.

## 5 Acknowledgements

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