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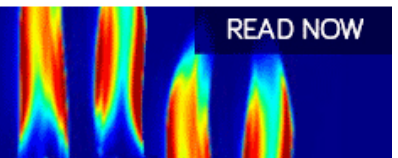
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C. A. Thomas,[1,a] E. M. Campbell,[1] K. L. Baker,[2] D. T. Casey,[2] M. Hohenberger,[2] A. L. Kritcher,[2]
B. K. Spears,[2] S. F. Khan,[2] R. Nora,[2] D. T. Woods,[2] J. L. Milovich,[2] R. L. Berger,[2] D. Strozzi,[2] D. D. Ho,[2]
D. Clark,[2] B. Bachmann,[2] L. R. Benedetti,[2] R. Bionta,[2] P. M. Celliers,[2] D. N. Fittinghoff,[2] G. Grim,[2]
R. Hatarik,[2] N. Izumi,[2] G. Kyrala,[2] T. Ma,[2] M. Millot,[2] S. R. Nagel,[2] P. K. Patel,[2] C. Yeamans,[2] A. Nikroo,[2]
M. Tabak,[2] M. Gatu Johnson,[3] P. L. Volegov,[4] and S. M. Finnegan[4]

AFFILIATIONS

[1] Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
[2] Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[3] Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[4] Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

[a] Author to whom correspondence should be addressed: cliff.thomas@stanfordalumni.org

ABSTRACT

Progress in inertial confinement fusion depends on the accurate interpretation of experiments that are complex and difficult to explain with simulations. Results could depend on small changes in the laser pulse or target or physics that are not fully understood or characterized. In this paper, we discuss an x-ray-driven platform [Baker *et al.*, Phys. Rev. Lett. **121**, 135001 (2018)] with fewer sources of degradation and find the fusion yield can be described as a physically motivated function of laser energy, target scale, and implosion symmetry. This platform and analysis could enable a more experimental approach to the study and optimization of implosion physics.

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I. INTRODUCTION

Experiments at the National Ignition Facility (NIF) are underway to test the physics and engineering limitations of thermonuclear burn at laboratory scale(s).[1] For an indirect drive experiment, this begins by heating a high-Z cavity/*Hohlraum* with a shaped laser pulse and by ablating a low-Z pusher/capsule at ≈ 300 eV.[2,3] This process generates the pressures (≥ 100 Mbar) needed to implode a thin deuterium tritium (DT) shell to high velocities (350–450 km/s) and make a central hot spot that self-heats. The primary goal of this work is to determine the characteristics of the laser and target that are needed for ignition. As documented elsewhere,[4–8] many advances have been made, but challenges remain. For example, it is still not possible to reliably relate performance to laser energy or implosion symmetry and account and correct for common variations in either. These sensitivities could suggest that one or more aspects of implosion physics are not understood or reproducible. In addition, it is still uncertain if all data can be taken at face value, as multiple measurements of a given quantity can disagree, as shown in Fig. 1. Observations of the hot spot can be related to stagnation properties (and the proximity of ignition) but only if the state of the system is well-defined. These issues complicate interpretation and present obstacles to predicting future data. Discrepancies could be due to errors in physics (theory or simulation) or variabilities in the target and facility that do not apply equally to all implosions.

In this paper, we focus our analyses on experiments using the so-called "BigFoot" platform (see Fig. 3) as described in Ref. 9. These experiments are designed to reduce complex interactions in the laser, *Hohlraum*, and capsule with the goal of simplifying the integrated system. They use features in design (discussed below) that are conservative and do not try to maximize performance. This strategy has resulted in experimental data that are more predictable and self-consistent. Performance is found to compare favorably with theory and, as we show, is a simple function of laser energy per unit target mass (E/M), target scale (S), and low-mode implosion symmetry (hot-spot P_2). Neutron yield Y (measured at 13–15 MeV) scales as $(E/M)^{7.6}(S)^4(1 - 0.05|P_2/S|)$ to $\pm 8.7\%$. This analysis suggests small target flaws and imperfections do not determine the yield, and we can account for small/inadvertent changes in E/M, P_2, etc., while testing other aspects of inertial confinement fusion (ICF). (Typically, yield can be explained only by detailed calculations in 3D including features
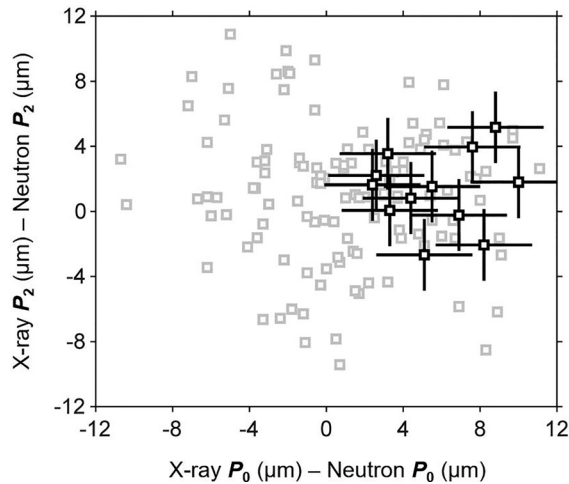
FIG. 1. The size and shape of the hot spot (Legendre P_0 and P_2) can differ in independent measurements of x-ray and neutron emission. Inconsistency can be quantified by the scatter in both, as shown here. The inability to correlate hot-spot properties to yield could suggest these data do not resolve or characterize all possible sources of degradation. (For example, if a hot-spot is highly 3D or subject to high-mode mix.) The expected deviation in the abscissa (ordinate) is 2.5 (2.2) μm although data at the NIF (open gray squares) vary by 5.2 (4.6) μm. Recent data using the BigFoot platform (open black squares) vary by 2.6 (2.4) μm and have an average abscissa (ordinate) that agrees with simulations.

unique to each target.[10,11]). These results provide a new perspective on data at NIF and a useful baseline for testing the physics of indirect drive.

II. EXPERIMENTAL DATA

We begin by summarizing the BigFoot design and experimental campaign.[9] The primary features and rationale are as follows: (1) a high-density carbon (HDC) ablator to substantially shorten the laser pulse; (2) a low-gas-fill (LGF) density *Hohlraum* (0.3 mg/cm^3) to reduce laser–plasma instabilities at high power, tamp *Hohlraum*-wall motion, and provide a well-understood radiation source; and (3) a $\geq$12-Mbar first shock to reduce phase coexistence in the ablator (liquid and solid)[12–14] and increase hydrodynamic stability. This work also introduced changes in laser pointing, the geometry of the *Hohlraum*, and the laser pulse that are complementary to (1) through (3). While the laser pulse in most NIF experiments is designed to launch a series of shocks that coalesce at the inner radius of the DT ice, the BigFoot pulse is unique, in that three shocks put the DT shell and pusher at relatively different adiabats (internal pressures) as defined in Ref. 9. This shock-timing scheme was characteristic of early experiments in the National Ignition Campaign that gave high yield (e.g., shot 110212) and could reduce perturbations at the fuel-ablator interface. This hypothesis is otherwise untested. With these choices, the radiation-hydrodynamic code LASNEX[15] is able to predict key aspects of *Hohlraum* performance, such as the time of peak capsule emission ($\pm$100 ps) with the measured laser pulse. We expect simulations to be more accurate when data can be matched without multipliers.[16,17] This has resulted in symmetric implosions near the power and energy limits of the NIF that do not rely on cross-beam energy transfer (Ref. 18). As a consequence, we have been able to

collect data over a large range in laser energy (0.8–1.8 MJ) and primary yield (1.7×10^{14} to 1.7×10^{16}) and quantify the main factors in performance.

The first experiments used HDC capsules with an inner radius R of 844 μm and a total thickness of 64 μm that we define as target scale $S = R/844 = 1$. The equimolar DT layer was 40 μm thick to enable high implosion velocities and accurate characterization(s). The *Hohlraum* was made of Au to avoid concerns with reproducibility (other materials can oxidize) and simplify fabrication. The diameter of the *Hohlraum* was 5400 μm and its length was 10130 μm [see Fig. 3(a)] to maintain continuity with prior work.[4,5] Since the *Hohlraum* is relatively small, it also has the potential to reach high radiation temperature(s) ($\geq$330 eV) without using maximum energy. This should limit the damage to laser optics and is important to maximizing the shot rate. Backscatter has been limited for all experiments ($\leq$1%), and the yield has been found to increase monotonically with hot-spot energy E_h. The latter is inferred from the burn-averaged ion temperature, neutron yield, neutron burn-width, and the time-integrated neutron hot-spot radius (defined by the 17% intensity contour) as explained in Cerjan *et al.*[19] We expect $Y \sim n^2 \langle \sigma v \rangle V \tau$ or roughly E_h^2 for NIF-scale experiments at 4–5 keV (Ref. 20). Data are self-consistent, as shown in Fig. 2, and suggest yield is a function of the underlaying physics. The remainder of this paper will consider data vs theory in greater detail.

To start, we assume the mass forming the hot spot (1) has an initial energy $\sim v^2$ before compression by the cold fuel (it reaches the same implosion velocity as the shell prior to stagnation), (2) is compressed adiabatically with $\gamma = 5/3$ (losses relative to peak compression are small), and (3) achieves a radial compression ratio $\sim(v^2/\alpha_v)^{1/2}$, where the design adiabat α_v is a measure of compressibility (Ref. 21). This suggests the energy in the hot spot should increase as v^4 without accounting for alpha particle deposition. If self-heating is included, then we expect $E_h \sim v^{4f}$ with an internal feedback on energy $f \geq 1$. The yield $Y \sim v^{8f}$. Scaling(s) of this type are commonly used to explain performance in ICF,[2] but can be difficult to apply to data since the uncertainty in velocity can be 4%–5%. Alpha heating is not
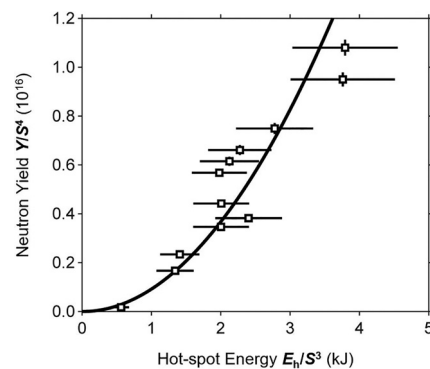
FIG. 2. The neutron yield in BigFoot data (open black squares) is shown as a function of hot-spot energy. To compare with expectations, we include a fit proportional to E_h^2 as the solid line. Uncertainties are primarily a function of hot-spot volume and can be directly related to the scatter in Fig. 1. To make the best comparison(s), the yield and hot-spot energy are divided by S^4 and S^3, respectively, to put all data on common axes. Performance as a function of hydrodynamic scale will be discussed.
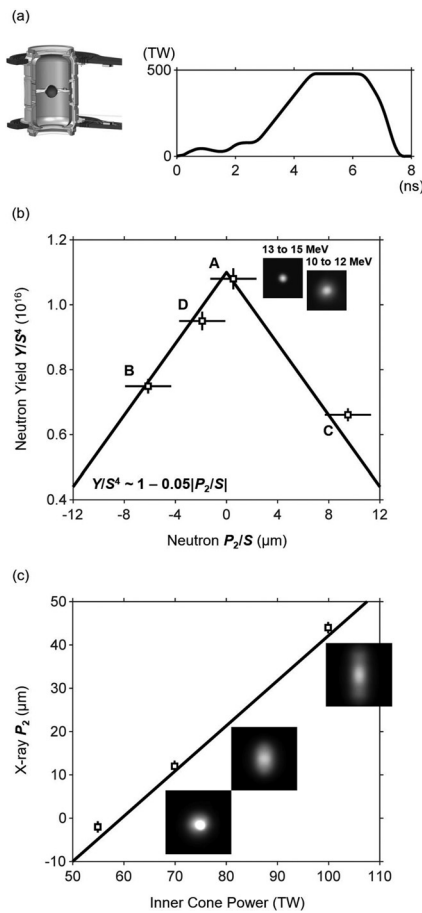
FIG. 3. (a) The BigFoot target and laser pulse from shot 180128 at $S = 1.125$. (b) Yield vs hot-spot symmetry for data (open black squares) and simulations (solid line). Yield has been divided by S^4 to simplify visualization. (c) The symmetry of the hot spot vs inner cone power at constant total power (inner plus outer).

measured and must be inferred. To make more precise comparisons, we find it useful to introduce a surrogate for velocity based on the laser energy E and the initial ablator mass M, which are both known to $< 1\%$. This makes it possible to make a "prediction" based on initial conditions. If the kinetic energy of the implosion is assumed to scale with laser energy E and its mass is proportional to M, then $v^2 \sim E/M$ and $Y \sim (E/M)^{4f}$. Calculations have been used to validate this approach and predict $f \sim 2$ for current experiments. Since data could be subject to mechanisms that are not included or are not known (such as alpha heating), we will assume $Y \sim (E/M)^N$ and use data to determine N.

Implosions have also been done with HDC capsules having an inner radius of $950\,\mu m$ at target scale $S = 950/844 = 1.125$. All dimensions of the capsule and *Hohlraum* (and laser pulse) were increased by the same ratio. Peak laser power was increased by S^2 and laser energy by S^3. The first data of this type (shot number 170524) were compared to experiments at $S = 1$, and the yield was found to increase with hot-spot volume $V \sim S^3$ and confinement time $\tau \sim S$ as expected (Refs. 22 and 23). Small changes in target size are not

expected to change reactivity, and we can account for hydrodynamic scale by assuming $Y \sim (E/M)^N (S)^4$.

The data can also be used to address low-mode implosion symmetry, i.e., hot-spot P_2. This is the primary asymmetry on the NIF (laser irradiation geometry) and two-sided cylindrical *Hohlraums*. Calculations expect the primary loss mechanism in most implosions to be conduction, and a small P_2 suggests a hot spot with more surface area to volume. The time-average number density and temperature should be reduced relative to 1D. If we assume a Taylor expansion for yield in $|P_2/P_0|$, then $Y_{2-D} \approx Y_{1-D}(1 - C_2|P_2/S|)$, where $|P_2/S| \sim |P_2/P_0|$. To first order, this term can be viewed as a stand-in for $\delta n/n$, and $\delta T/T$, etc., in the case of a distorted hot spot. As we will show, it is not necessary to include higher order terms. The implosions reported here are nearly symmetric, and the changes in stagnation properties are small. Variations in the laser and target can cause a P_2 (shot to shot) even for implosions that are designed to be symmetric. In Fig. 3(b), we report the primary neutron yield vs hot-spot P_2, in micrometers, for four experiments that can be compared directly. Except for small changes in symmetry, shot to shot, these experiments were intended to repeat in the order shown: A through D. The range is $\pm 8\,\mu m$ in P_2 and a factor of 1.6 in yield. The typical radius of the hot spot is 25–$30\,\mu m$, and the maximum asymmetry can be expressed as a $|P_2/P_0|$ of 30%. Small changes in the laser, target fabrication, and target alignment could cause this variation. Data and simulation are consistent, and both suggest $Y_{2D} \approx Y_{1D}(1 - 0.05|P_2/S|)$. We would not expect to observe this correlation if performance were a function of uncontrolled variations in hot-spot shape (in 3D). To show the laser pulse can be adjusted to improve symmetry, we provide Fig. 3(c) in which $\pm 8\,\mu m$ in P_2 is shown to be equivalent to $\pm 10\%$ on the inner cone energy (64 beams) or $\mp 5\%$ on the outer cone (128 beams). As a consequence, we expect the neutron yield $Y \sim (E/M)^N (S)^4 (1 - 0.05|P_2/S|)$ and use the latter term to account and correct for small changes in hot-spot symmetry.

III. NUMERICAL ANALYSIS

We now determine N with a least-squares fit to all data accounting for changes in laser energy, ablator mass, target scale, and implosion symmetry. This analysis can use the x-ray or neutron P_2 since they are correlated (see Fig. 1) but uses the latter since it relates to the DT hot spot more directly. In Fig. 4(a), we assume $Y \sim (E/M)^N (S)^4 (1 - 0.05|P_2/S|)$ and find $N = 7.6 \pm 0.3$ with a $\chi_\nu^2 = 1.2$ normalized per degree of freedom. Given the measurement uncertainty in laser energy is $\pm 0.5\%$ and neutron P_2 is $\pm 1.8\,\mu m$, we should only fit data to $\pm 8.9\%$. The error in the fit is consistent (8.7%). We have also fit data with subsets of this model as a test of significance. For example, we provide Fig. 4(b), where we assume $Y \sim (E/M)^N (S)^4$ and find $N = 6.7 \pm 0.3$. In this case, the residual in the fit is increased by a factor of 3 (26.9% vs 8.7%) and $\chi_\nu^2 = 13.5$. Data are consistent with high levels of alpha heating ($E^{7.6} > E^4$) and require all terms for a good fit. Two experiments are excluded from this process due to known problems with each target: E and F. In one of these experiments, the capsule was found to have a defect/hole that would normally disqualify it from use, and in the other, it was found to be displaced from the target chamber center by approximately $200\,\mu m$ (from one perspective). Most targets are centered to $20\,\mu m$. These issues were identified

(a)

$$Y_p \sim (E/M)^{7.6}(S)^4(1 - 0.05|P_2/S|)$$

F

E

$X^2 = 1.2$

(b)

$$Y_p \sim (E/M)^{6.7}(S)^4$$

F

E

$X^2 = 13.5$
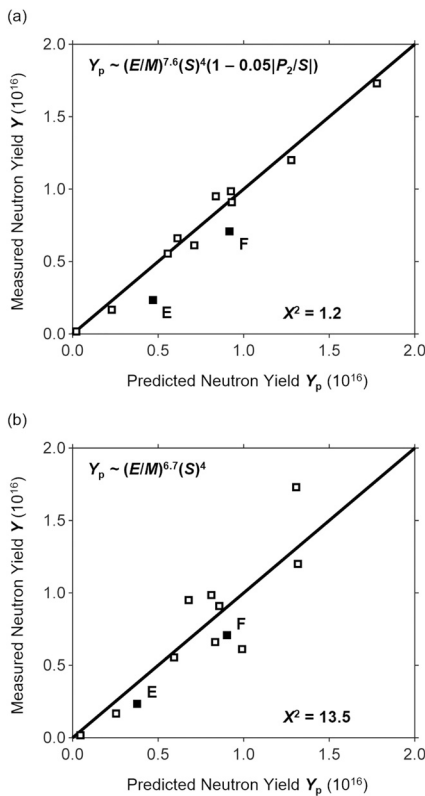
FIG. 4. The best fit to data assuming (a) yield is a function of laser energy per unit mass, target scale, and hot-spot symmetry and (b) the same, but no dependence on P_2. The residuals are 8.7% and 26.9%, respectively.

before each shot and could not be corrected. Both experiments are below trend and inconsistent with our analysis. They also show that we can identify outliers. All of the other targets met specifications and were not subject to selection effects. These targets used different capsule supports (30- and 45-nm plastic tents) and fill tubes (5- to 10-μm outer radius) as available. Since the data are fit with a simple formula that follows expected sensitivities, these data also provide constraints on other factors. Given the sensitivities in laser energy, target scale, and implosion symmetry have now been characterized, this platform can now be used to study other aspects of implosion physics with precision. [It is common for the laser energy (P_2) to miss expectations by 3%–4% (8 μm) or more, and variations of this type need to be taken into account.] We have started a scan in pulse length that will look at adiabat ($\alpha_v = 2$–6)[24] and other features in design (e.g., the timing and slope of the final rise to peak power). These tests will search for unexpected sensitivities and may help explain performance relative to prior data and expectations of ignition.[25]

To motivate additional work, we briefly discuss the term(s) in the fit and the physics mechanism(s) that could play a role. (1) The sensitivity of yield to laser energy reported here is fast relative to prior results[7] and simple theory with no alpha heating ($\sim E^4$). The accuracy of a power law (and its ability to extrapolate) should relate to the range over which it applies. If data are inconsistent with a single value of N

or data can only be fit for a small range in energy (for a few points), this could suggest results are a function of other factors (or stochastic). The sensitivity to E/M is a central aspect of performance and the interpretation of other physics. (2) Yield should increase with target scale. BigFoot experiments are intended to be robust and provide the requisite control (shot to shot) to study changes in target dimensions. This requires a high level of control, as our analysis shows 6% in E/M can change the yield by a factor of 1.6, similar to a 12% change in S (or $\pm 8\,\mu$m in P_2). Understanding could be improved by doing experiments with more capsule radii and by making the sensitivity to scale a free variable in the fit. (3) Performance should depend on low-mode symmetry and other observations of the hot spot. This is easy to demonstrate in BigFoot experiments since P_2 is linear in the inner cone power (at constant total power) as shown in Fig. 3(c). These experiments also reduce the impact of target flaws and imperfections, which could distort the apparent shape of the hot spot. Even a small amount of high-Z material (mix) can increase x-ray emission (locally), reduce neutron emission, and decorrelate these measurements from each other and the yield (Ref. 26). This would be expected to confuse interpretations of P_0 and P_2 as well as other integrated metrics, such as the burn-averaged pressure. Observations of the hot spot in BigFoot data are self-consistent (as shown in Figs. 1–3) and strongly correlate with yield. The uncertainty in subsequent inferences is reduced. Experiments that make (large) intentional changes in implosion symmetry or stability could be used to extend this work and further establish the experimental signature(s) for different failure modes.

IV. IMPLICATIONS TO ALPHA HEATING

Our results can also be used to suggest methods for increasing the yield and alpha heating. As shown in Fig. 5, a straightforward approach would be to increase laser energy by 10%–20%. If we assume laser–plasma instabilities do not grow significantly, then this is expected to increase the temperature in the *Hohlraum*, the ablation pressure ($\sim T_r^{3.5}$), and the energy coupled to the capsule. Experiments at scale 1 (1.125) have been designed to use 1.5 MJ at 400 TW (2.0 MJ at 500 TW) with acceptable remaining mass. If we use the scaling(s) presented here, this could increase yield by as much as a factor of $(1.5/1.35)^{7.6} = (2.0/1.8)^{7.6} = 2.2$. We have also proposed targets that would use thicker capsules at higher power and energy.[9] To determine the expected change in alpha heating, we calculate χ_α (a common
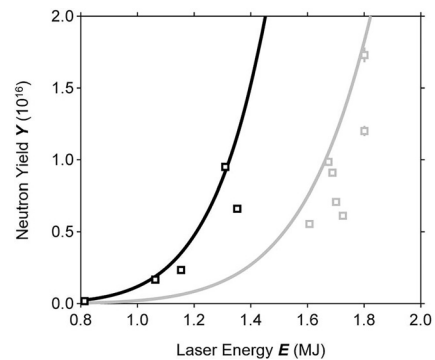
FIG. 5. Yield vs laser energy for BigFoot implosions at $S = 1$ and 1.125 are shown by the open black and gray squares, respectively. For context, we show the fit from Fig. 4(a) at each scale [the solid lines(s)] in the limit that $P_2 = 0$.

metric for ignition) and estimate yield amplification as $\exp(\chi_\alpha^{1.2})$. These formulas are described in Ref. 20 and have recently been confirmed by data.[27] For shot 180128 (the highest point overall), the measured areal density is 0.620 ± 0.030 g/cm^2 and primary yield is 1.7×10^{16}. We estimate a total yield of 2.0×10^{16}, $\chi_\alpha = 1.13 \pm 0.06$ and a yield amplification of 3.2 ± 0.2. Since $\chi_\alpha \sim Y^{0.34}$, a factor of 2.2 in yield would increase χ_α by 30%. This implies that existing targets could demonstrate yield amplification(s) as high as a factor of $\exp(1.47^{1.2}) = 4.9$. To put this estimate in perspective, the yield amplification in a burning plasma is commonly defined to be 3–3.5 (Ref. 20), and for ignition, a factor of 15–30. These implosions meet the criteria for an alpha-dominated plasma, but are still far from ignition. Nonetheless, we recommend caution with respect to both extrapolation(s). The measured yield and areal density are consistently below integrated 2D calculations by a factor of 4 and 1.2, respectively, for reasons that are still under investigation. Also, BigFoot implosions appear to have higher compression ratios than prior data despite having a higher design adiabat ($\alpha_v = 4$). This is inconsistent with theory and may indicate degradation mechanisms that are still unknown[28] that can be corrected.

V. CONCLUSION

In summary, we have analyzed implosions that simplify aspects of *Hohlraum* and capsule physics and find performance can be described by a simple function of laser energy per unit mass (E/M), target scale (S), and implosion symmetry (hot-spot P_2). Neutron yield Y is found to be expressible as $(E/M)^{7.6}(S)^4(1 - 0.05|P_2/S|)$ with a residual error that be accounted for by measurements of E/M and P_2. This analysis should improve the interpretation of future data and increase confidence in its extrapolation. To build on these results, we have started a scan in design adiabat that will use the same approach and make small changes in the pulse shape (only). We also propose experiments at greater energy per unit mass and will use both studies to address performance limits in indirect drive and criteria for ignition.

ACKNOWLEDGMENTS

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon request.

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