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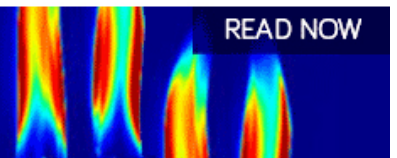
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Experiments to explore the influence of pulse shaping at the National Ignition Facility

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

The shaping of the drive pulse in time is a key tool in the design of fusion experiments that use inertia to confine burning plasmas. It is directly related to the adiabat and compressibility of the DT fuel and the characteristics of the laser and target that are needed to ignite. With this in mind, we have performed experiments at the National Ignition Facility that test small changes in the shape of the pulse. In contrast to theory, we find implosions at lower adiabats can have reduced yield and areal density. We discuss implications to performance and the mechanism(s) that could be responsible.

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I. INTRODUCTION

A primary goal of the National Ignition Facility (NIF) is to determine the laser and target requirements needed to achieve thermonuclear ignition and propagating burn.[1] In detailed calculations, performance is predicted to depend on the shape of the laser pulse and the design adiabat, α_v, of the DT fusion fuel.[2,3] By convention, the adiabat is defined by the pressure in the cold fuel relative to Fermi-degenerate DT at the maximum velocity of the implosion.[4] In the absence of mechanisms that disturb the fuel such as preheat, the shape of the laser pulse should determine the compressibility of the shell and the terms "pulse shaping" and adiabat are interchangeable. So far, experiments on the NIF have primarily reported tests at $\alpha_v = 1.5$[5,6] and $\alpha_v = 2$ to 2.5[7–9] using indirect drive. The integrated performance has improved as issues with hot-spot mix[10] and target engineering features[11,12] have been identified and corrected. Changes in the shape of the laser pulse have also played a role but have not proven as easy to study. In part, this is because uncertainties in hohlraum and capsule physics complicate the interpretation of simple tests.[13] Small and unpredictable changes in implosion velocity and symmetry confuse results. In addition, most experiments are subject to multiple sources of degradation, and sophisticated calculations are needed to unfold the importance of each. If aspects of these calculations are inaccurate, this would be expected to convolve changes in the pulse with other aspects of physics and make optimization difficult.

To provide new insight(s), this paper takes advantage of the "BigFoot" platform, which was developed to facilitate single-variable studies.[14] This design uses features that are conservative and reduces the number of mechanisms that impact data. As shown in prior work,[15] the yield is a simple and expected function of laser energy per unit target mass, target size/scale, and implosion symmetry. This relationship makes it possible to correct for variations in these quantities shot to shot and study other aspects of physics such as pulse shape. As a consequence, we have used this platform to perform implosions at two design adiabats ($\alpha_v = 4$ and 3 ± 0.1) and find that yield and areal density can decrease when the adiabat is reduced. These findings suggest the optimum design adiabat is above 3 (presently) and that one or more aspects of simulation are incomplete. We have not been able to explain these results in high-resolution calculations using

known details of the targets or facility. At the same time, these experiments provide the first direct evidence that performance can increase with compression and that further improvements could require non-intuitive changes to the drive.

For background, we briefly explain features of the BigFoot design that make it useful for this work [see Fig. 1(a)]. First, the length of the laser pulse is shorter (and the radius of the hohlraum entrance hole is larger) than conventional target designs.[5–9] This not only reduces the energy coupled to the target and the expected yield but also makes it considerably easier to control and maintain implosion symmetry. There is less time for high-Z plasma to move toward and impede the propagation of the laser. Second, BigFoot experiments have minimal laser–plasma instabilities and show no evidence of hot-electron pre-heat.[16] It is not necessary to account or correct for either when changes are made in the length, power, or energy of the laser pulse. Third, the first shock in the ablator is also considerably stronger (≥ 12-Mbar) than in prior studies. This should reduce the maximum possible compression of the DT fuel but, more importantly, should also reduce the instabilities seeded by target flaws and imperfections that can vary shot to shot (e.g., the capsule support, fill tube, and other debris). Fourth, calculations in LASNEX[17] are able to predict the time of peak emission (± 100 ps) and implosion symmetry ($\pm 5\,\mu$m in P_2) using the measured laser pulse.[18,19] Together, these features allow us to maintain implosion velocity and symmetry[20,21] while testing expectations vs pulse shape with fewer sources of uncertainty.

II. CHANGES TO THE PULSE

As an example, this paper reports the result of two experiments where the length of the laser foot (the low power section of the pulse) is increased by approximately 400 ps, as shown in Fig. 1(a). This change could appear to be small but is exceedingly important to the calculated yield and areal density. A shock is launched by each rise in the pulse (labeled p1–p3), and the adiabat of the fuel at peak velocity is a function of their relative timing. For the experiments described here, the adiabat of the fuel should decrease (increase) when the delay between p1 and p2 is lengthened (reduced). In the limit the second shock catches the first at the inner radius of the DT shell (an additional 400 ps delay) these implosions are calculated to ignite. The rise to peak laser power is slow (~ 2 ns) to minimize the impact of p3 on the calculated adiabat. We seek to study and optimize p1 and p2 first. According to integrated calculations in LASNEX (in 2-D), the change in Fig. 1(a) should lower the mass-average design adiabat from 4 to 3 ± 0.1 and increase the neutron yield and DT areal density by a factor of 2.9 and 1.3, respectively. The target and laser pulse are otherwise identical, modulo a small increase in the laser cone fraction (the power on the inner laser cones of the NIF divided by the total) of 3%. The time of peak emission is delayed by 400 ps (as expected), and x-ray measurements confirm that the velocity and symmetry of these implosions are otherwise unchanged.[21] This makes it possible to isolate the influence of the pulse shape at a given laser energy, E. In Fig. 1(b), we show the primary neutron yield Y measured at 13–15 MeV, and in Fig. 1(c), the neutron down scatter ratio (DSR) averaged across multiple measurements. The DSR is a function of neutron emission at 10–12 MeV and is related to the burn-average DT areal density (in g/cm^2) by $\rho R_b = 20$ DSR.[6] (We average the DSR since most implosions are symmetric, and because diagnostics with a common line of sight can vary by more than the uncertainty in each.) In contrast to
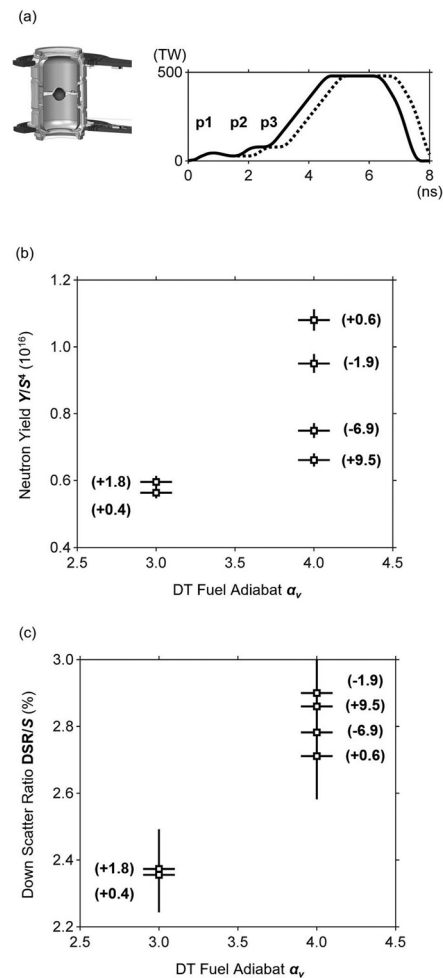
FIG. 1. (a) The BigFoot target and laser pulse at $\alpha_v = 4$ (3) are shown by the solid (dashed) line. We also show (b) yield and (c) neutron down scatter ratio (DSR) normalized for small changes in target size/scale S for six experiments that can be directly compared. The implosion velocity for each is 430 ± 10 km/s, and the shape of the hot spot in Legendre P_2 is provided in micrometers (in parentheses). The yield is correlated with the amplitude of P_2; the DSR is not.

calculations, the yield and DSR are found to decrease when the pulse is lengthened and α_v is reduced. The statistical significance of these results is addressed in Fig. 2. In Ref. 15, we have shown the outcome of BigFoot experiments at $\alpha_v = 4$ is a simple function of laser energy per unit ablator mass E/M, target size/scale S, and the time-integrated shape of the hot-spot P_2. S is defined by $R/844$ (where R is the radius of the capsule in μm), and Legendre P_2 characterizes the dominant asymmetry. This analysis lets us account for small changes in each, shot to shot, while comparing new results to the aggregate of prior findings. We find data at $\alpha_v = 3$ are below trend by 40–50%, or 4–5σ ($40\%/9\% \approx 4$), and are not explained by normal variations in target physics. Though not shown here, the yield and DSR at $\alpha_v = 3$ are even below prior implosion results at $\alpha_v = 4$ using smaller capsules at reduced laser energy.
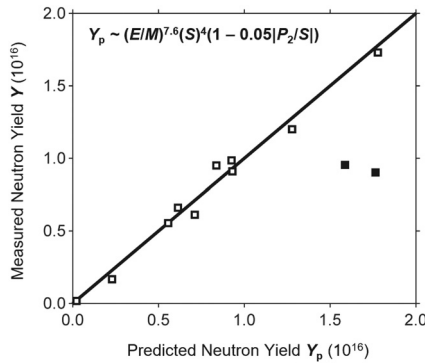
FIG. 2. The measured and predicted yield for BigFoot implosions using the analysis in Ref. 15. This model appears to predict data at a design adiabat of 4 (open black squares) but not 3 (solid black squares).

III. THEORY AND ANALYSIS

We can illustrate the principles involved with simple models. It is only necessary to assume the mass that forms 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 $C_p \sim (v^2/\alpha_v)^{1/2}$ (Ref. 22). If so, the energy in the hot spot E_h should increase as $v^2 C_p^2 \sim v^4 \alpha_v^{-1}$ without accounting for alpha deposition. If self-heating is included, then we assume $E_h \sim (v^4 \alpha_v^{-1})^f$ with a feedback $f \geq 1$. The neutron yield $Y \sim n^2 T^3 V\tau \sim E_h^2$ for NIF-scale experiments at 4–5 keV (Refs. 2 and 3). Since the kinetic energy of the shell is roughly proportional to laser energy E (when the coupling between the hohlraum and capsule is fixed), this is roughly comparable to $Y \sim (E/M)^{4f}(\alpha_v)^{-2f}$, where M is the initial mass of the ablator. This derivation clearly outlines the expected relationship between yield and adiabat and shows that self-heating should have multiple signatures in data. E/M is measured to $< 1\%$ and α_v is a function of design. Calculations have validated this relationship, and expect $f \sim 2$ in current experiments, i.e., $Y \sim (E/M)^8 (\alpha_v)^{-4}$. Since areal density $\sim C_p^2$, it follows that $DSR \sim (E/M)^1 (\alpha_v)^{-1}$. The yield and DSR should increase when adiabat is reduced, and it is imperative to study and quantify these behaviors in data.

If we assume the measured yield follows a power law in E/M and α_v (in the same way), then best-fit exponents can be found with a least-squares fit. In this manner, we can quantify the importance of each without relying on detailed calculations or theory. To account for other small changes shot to shot, we also include a correction for the target size/scale S and implosion symmetry (hot-spot P_2) as explained in Ref. 15. We then repeat this exercise for the DSR but include no dependence on P_2. (The data in Fig. 1(c) show little or no sensitivity.) In Fig. 3(a), we assume $Y \sim (E/M)^{N_1}(S)^4(1 - 0.05|P_2/S|)(\alpha_v)^{N_2}$ and find $N_1 = 7.5 \pm 0.3$ and $N_2 = 2.0 \pm 0.1$ with a $\chi_\nu^2 = 1.2$ (per degree of freedom). In Fig. 3(b), we assume $DSR \sim (E/M)^{N_3}(S)(\alpha_v)^{N_4}$ and find $N_3 = 0.9 \pm 0.2$ and $N_4 = 0.6 \pm 0.1$ with a $\chi_\nu^2 = 1.1$. These fits are a good representation of data and behave as expected with the exception of adiabat. Figures 4(a) and 4(b) demonstrate the significance of these results (again). In this case, we go through the same process but include no information with respect to α_v. For $Y \sim (E/M)^{N_1}$

FIG. 3. The best models for (a) yield and (b) areal density vs laser energy per unit mass, target scale, hot-spot symmetry, and design adiabat. The residuals are 8.6% and 3.9%, respectively. For reference, we differentiate data at $\alpha_v = 4$ (open black squares) and 3 (solid black squares).

$(S)^4(1 - 0.05|P_2/S|)$ and $DSR \sim (E/M)^{N_2}(S)$, then we find $N_1 = 5.1 \pm 0.2$ and $N_2 = 0.3 \pm 0.3$. Neither model is a good fit to data and $\chi_\nu^2 \gg 1$. (The residuals in the yield and DSR are increased by a factor of 2 or more.) It would appear that higher performance is possible at even higher adiabat. As a consequence, we have proposed to extend this work to $\alpha_v = 5$ and 6. We expect a more complicated relationship than shown here, with a local maximum in the yield and DSR at a design adiabat other than 4. Subsequent experiments would change other aspects of the pulse, such as the delay between p2 and p3.

BigFoot implosions have been designed to reduce the number of mechanisms that degrade performance. This should make it easier to perform and interpret experiments that test expectations. Here, a small change in the pulse shape is found to reduce the yield (DSR) by a factor of 0.56 (0.84) although both were expected to increase. The value of this approach is evident. Had we performed these experiments with changes in the pulse shape, laser energy, and/or implosion symmetry (at the same time), it is not guaranteed that calculations would arrive at the same interpretation(s). It would be even more difficult to reach these conclusions if experiments were sensitive to small changes in target quality. If calculations are unable to capture the primary sensitivities in data, then it is unclear how they can unfold combined effects. That said, it is possible to study the effect of the pulse shape in experiments with additional sources of degradation. If we assume the shot-
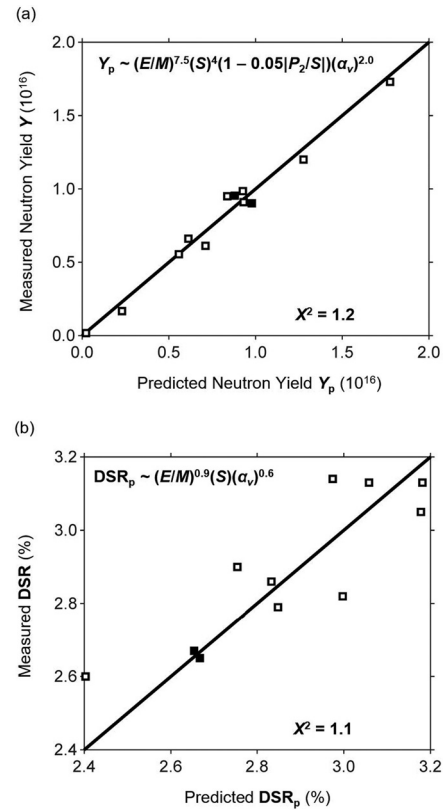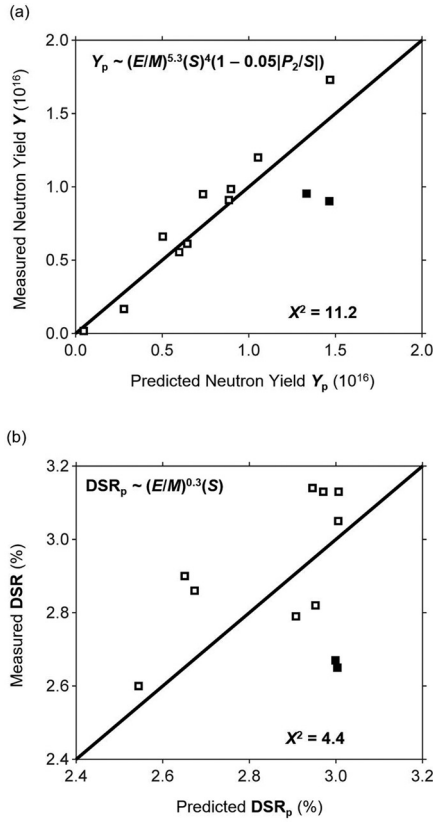
FIG. 4. The best models for (a) yield and (b) areal density vs laser energy per unit mass, target scale, and hot-spot symmetry without accounting for design adiabat. The residuals are 23.0% and 8.0%, respectively. Data at $\alpha_v = 4$ (3) are shown by the open black squares (solid black squares).

FIG. 5. BigFoot data (open black squares) are compared to previous results (open gray squares) on aspects of pulse shaping. Experiments at u_1 of 18, 32, 40, and 55 km/s correspond to α_v of 1.5, 2.3, 3.0, and 4.0, respectively. The solid line is the expected value for a BigFoot-type implosion assuming $C_p \sim \alpha_v^{-1/2}$ at a given velocity and DT mass.

to-shot variability (or reproducibility) is σ and we can average over multiple experiments, N, then we expect the accuracy of our inferences to scale as $\sigma N^{-1/2}$. It is only necessary to increase the total number of experiments by σ^2.

IV. IMPLICATIONS TO IGNITION

We now examine the peak compression ratio C_p in BigFoot data to check for self-consistency. This quantity is estimated from the areal density of the cold fuel since observations of the hot spot do not have to correlate with pdV work. We begin by defining the areal density at peak compression as $\rho R_{p,c} + \rho R_{p,h}$ and the areal density at peak burn as $\rho R_{b,c} + \rho R_{b,h}$ with contributions from the cold shell (c) and hot spot (h), respectively. We measure the latter, but note that alpha heating and electron conduction tend to offset the time(s) of peak compression and peak burn. As a consequence, we expect $\rho R_{p,c} \geq \rho R_{b,c} + \rho R_{b,h}$. If we also assume that the cold fuel at peak compression has the same mass as the initial DT layer (with areal density $\rho_0 t_0$) and is relatively thin (corrections for a finite hot spot and cold shell are typically 3% or less), then we can put a lower bound on $C_p^2 = (\rho R_{b,c} + \rho R_{b,h})/\rho_0 t_0 = 20\,\text{DSR}/\rho_0 t_0$. This formula can be used to compare implosions of different sizes and types when alpha heating is modest, and $\rho R_{p,h} \ll \rho R_{b,c} + \rho R_{b,h}$. Figure 5 shows C_p as a function
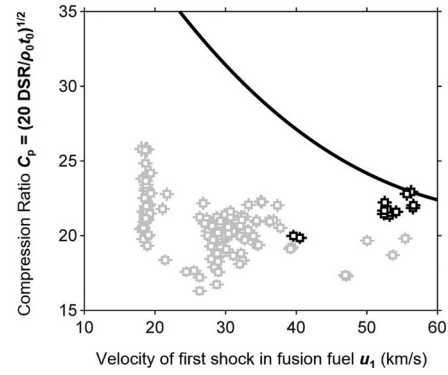
of the mass-average first shock velocity in the fusion fuel, u_1, in km/s. The first shock is the primary source of entropy in calculations and can be viewed as a surrogate for adiabat.[23,24] Energy deposition should increase as u_1^2, and in simulations, we find $\alpha_v \approx 1.2 + 1.0 \times 10^{-3} u_1^2$ for $u_1 \leq 60$ km/s. We remind the reader that the goal of pulse shaping is to control (and minimize) the adiabat to maximize compression. BigFoot implosions with a mass-average $\alpha_v = 4$ ($u_1 \approx 55$ km/s) have a compression ratio of 22–23. When BigFoot implosions are performed at a lower adiabat ($\alpha_v = 3$ and $u_1 \approx 40$ km/s), the compression ratio is 20 and more consistent with prior results. It is clear that performance correlates with compression but not as we typically expect. This analysis can also be used to infer discrepancies relative to theory. It is only necessary to decide which data can serve as a reference and project $C_p \sim \alpha_v^{-1/2}$. If we assume implosions at high adiabat are closer to theory, then this type of extrapolation is given by the solid line in Fig. 5. BigFoot data at $\alpha_v = 3$ appear to be deficient in compression by 25%. This is equivalent to 50% in the DSR, and significant, as the laser energy needed to ignite $E_{\text{ign}} \sim v^{-6}\alpha_v^2$ (Ref. 25). If $C_p \sim (v^2/\alpha_v)^{1/2}$, then we expect $E_{\text{ign}} \sim v^{-2}C_p^{-4} \sim v^{-2}(20\,\text{DSR}/\rho_0 t_0)^{-2}$. Discrepancies in compression should have a significant impact on performance and the probability of ignition.

Given these results, we will briefly discuss the mechanisms that could play a role. This could include one or more errors in the strength or timing of shocks, as explained in Ref. 24. We find this unlikely, as these inferences have repeatedly been validated.[26] It is also possible that we do not fully understand the DT equation of state, the stagnation adiabat, or both. Although not presented here, simulations can match the measured yield, temperature, and DSR of BigFoot implosions if they use a higher adiabat than intended by a factor ≥ 1.4. For capsules that absorb 200 kJ of x rays, this is equivalent to adding 80 J to the cold DT shell. Simulations would have to underestimate sources of instability, mix at the fuel–ablator interface, or vorticity at small scales.[27] An increase in the effective adiabat would result from residual motion in the cold DT proportional to u_1, which would increase internal energy as u_1^2 after hydrodynamic growth (compression and thermalization). Calculations expect instability to increase at lower adiabats (in general) but do not predict the results shown here. Mix

between the ablator and DT fuel would increase its absorption of hard x rays and further reduce compressibility. Any impact(s) would be magnified if the ablator were to emit photons that directly couple to DT fuel at 10–100 eV. This part of the spectra is not a focus of most calculations. For insight, we will continue to quantify sensitivities in pulse shaping and work to characterize the state of the DT fuel.[28] We have also proposed to test aspects of stability and, as a start, have made capsules with different levels of high-Z dopant and crystallinity to address hypotheses regarding preheat and microscopic sources of turbulence.[29]

V. CONCLUSION

We have used an implosion platform that simplifies experimental interpretation(s) to test small changes in the shape of the drive pulse. If the laser energy per unit mass, hydrodynamic scale, hot-spot symmetry, and design adiabat are given by E/M, S, P_2, and α_ν, respectively, then we find $Y \sim (E/M)^{7.5}(S)^4(1 - 0.05|P_2/S|)(\alpha_\nu)^{2.0}$ and DSR $\sim (E/M)^{0.9}(S)(\alpha_\nu)^{0.6}$. All terms behave as expected with the exception of the adiabat. This is important to the optimization of NIF because calculations are typically used to set the strength and timing of p1–p3. We will use these findings to interpret future work, and this will be particularly helpful when small and inadvertent changes are made in the laser pulse. If we consider Fig. 5, this should have important implications to compression and the proximity of ignition. For the experiments reported here at $\alpha_\nu = 3$ having a laser energy $E = 1.8$ MJ, a 25% deficit in compression should increase the energy needed to ignite by a factor of $1.25^4 \approx 2.4$.

ACKNOWLEDGMENTS

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