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A Simple 3D Printed Plane Wave Explosive Lens Based on Fritz Parameters

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Abstract. The development of additive manufacturing (3-D printing) has opened up avenues previously unexplored due to prohibitive cost and/or complexity. Printing of inert parts for use in shock property characterization has reached a new level by allowing high resolution (10's of µm) wave shapers to be designed and employed at varying dimensions; the ability to save time on HE machining, casting, and cost of HE is undeniable. Herein, we report the design of a PolyJet-printed wave shaper paired with a cast-cure HE formulation to generate a planar output shock; guided by CTH simulations, the design was iterated to increase planarity. Lens fabrication followed guidelines by J. Fritz, using PMMA Hugoniot data as a substitute for the chemically similar 3D printed acrylates. Front curvature characterization of these minimal explosive mass, small diameter (2.54 cm) charges showed reliable planarity below 100 ns and optimized to ~28 ns. Following this characterization, the plane wave generators were used to launch flyers at varying materials to investigate shock and particle velocities and chemical reactions. In this fashion, U_S-u_P curves were created and will aid follow-on gas-gun experiments.

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INTRODUCTION

The development of plane wave lenses for use in shock physics experiments has been explored significantly in recent decades for the pursuit of material properties and characterization of new explosives formulations. Contemporary efforts in designing new plane wave lenses normally utilize machined or pressed-to-shape explosives, machined lenses out of inert materials, as well as air-gaps created by a combination of the above components [1-6]. While effective for many applications, these processes can be both costly and time-consuming, especially when exploring new materials on a small scale. Recent advances in additive manufacturing technology now allow for production of small batches of high-resolution plastic parts, produced with a fraction of the number of man-hours required to machine a similar batch of parts. In addition, these parts may contain highly-complex geometries that are difficult or impossible to conventionally machine. Recent work at LANL has led to the design and implementation of a 3D printed plane wave lens (PWL) for small-scale explosive experiments; the experiments described herein are designed for exploring unreacted shock Hugoniots, reactive growth, and run-distance to detonation (Pop Plot) behavior of novel formulations.

DESIGN

The initial PWL design relied on guidance provided by a LANL technical report by J. Fritz in 1990 [1]. Fritz's design (Fig. 1a) was scaled down from a 100 mm (4 in) nominal charge diameter to 25.4 mm (1 in) in order to save net explosive weight (NEW) of the assembly and ultimately facilitate firing in a smaller chamber. The initial contour of the printed PWL was calculated assuming a constant shock velocity through the material in order to find a close approximation. Simulations were then performed using the hydrocode CTH with the contour and charge head-height

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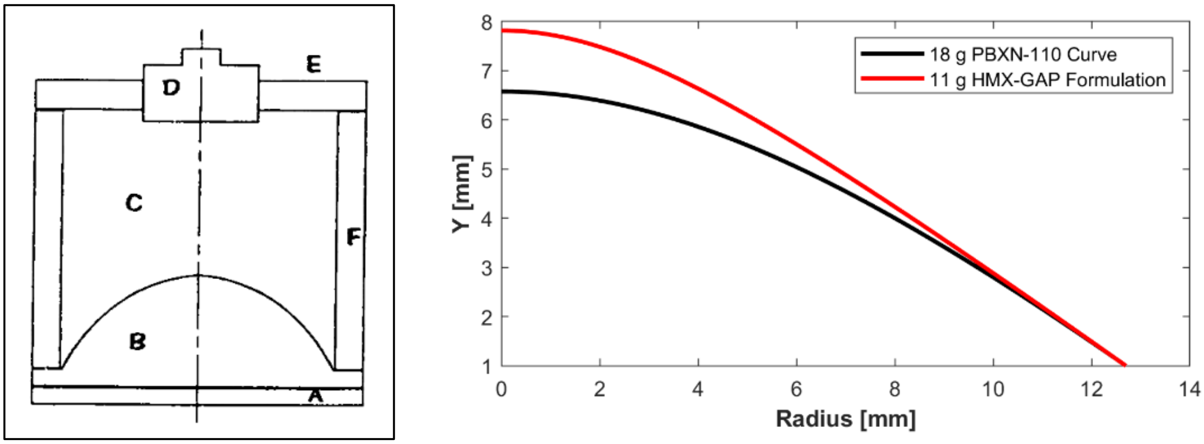
iteratively changed until a sufficient planar shock wave and output shock pressure (> 7 GPa) was achieved. Figure 2 below shows select frames from the 2D output simulation illustrating the detonation wave shaping. Two similar designs were developed for two explosive formulations, with NEWs of ~18 g and ~11 g (Fig. 1b-1c). All PWLs used in testing were printed on a Stratasys PolyJet printer (Objet30 Prime) with VeroBlue photopolymer, at a reported layer resolution of 16 µm. Each PWL is initiated with a commercially available RP-2 detonator manufactured by Teledyne-RISI.



(a) (b)

FIGURE 1. a) Original Fritz design showing inert lens (B) and outer shell/cup (F), along with detonator (D), main explosive charge (C), and output explosive (A). b) Contours of inert wave shaping lens for ~18 g NEW PWL (black) and ~11 g NEW PWL (red)

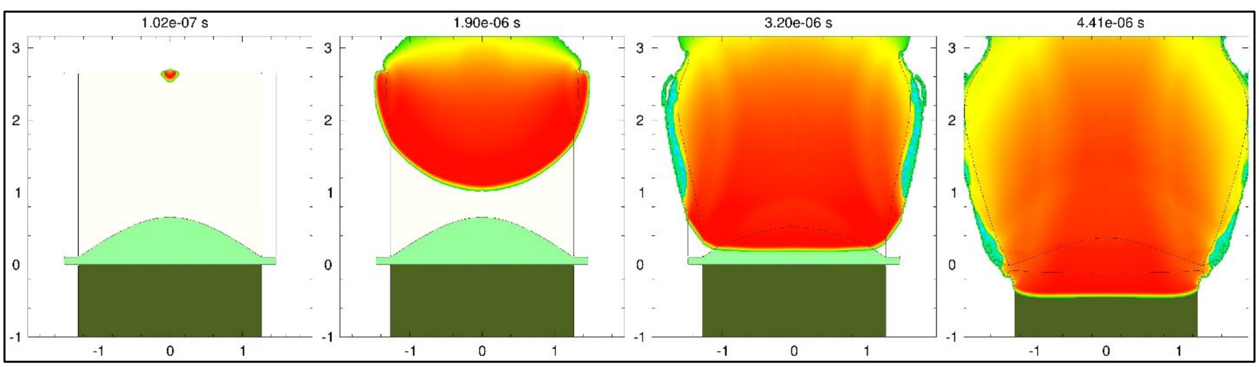


FIGURE 2. CTH model simulating detonation wave propagation through 18 g PWL geometry. Dimensions are in cm.

Formulations

Unique formulations were used for each of the two PWL designs. The 18 g PWL used PBXN-110, an HMX-based cast cure, while the smaller 11 g PWL utilized an HMX-based cast cure with glycidyl azide polymer (GAP) binder developed at Los Alamos. The HMX-based cast cure roughly mimics the material properties of PBXN-110, but a slightly lower solids-loading (80 wt. %) was used to account for the higher density energetic binder and provide a lower viscosity to aid in loading the formulation into the PWL body. Both formulations were mixed in a SpeedMixer (FlackTek Inc.) in approximately 100 g batches and hand-loaded into several PWL fixtures, then left to cure at room temperature for at least 24 hours.

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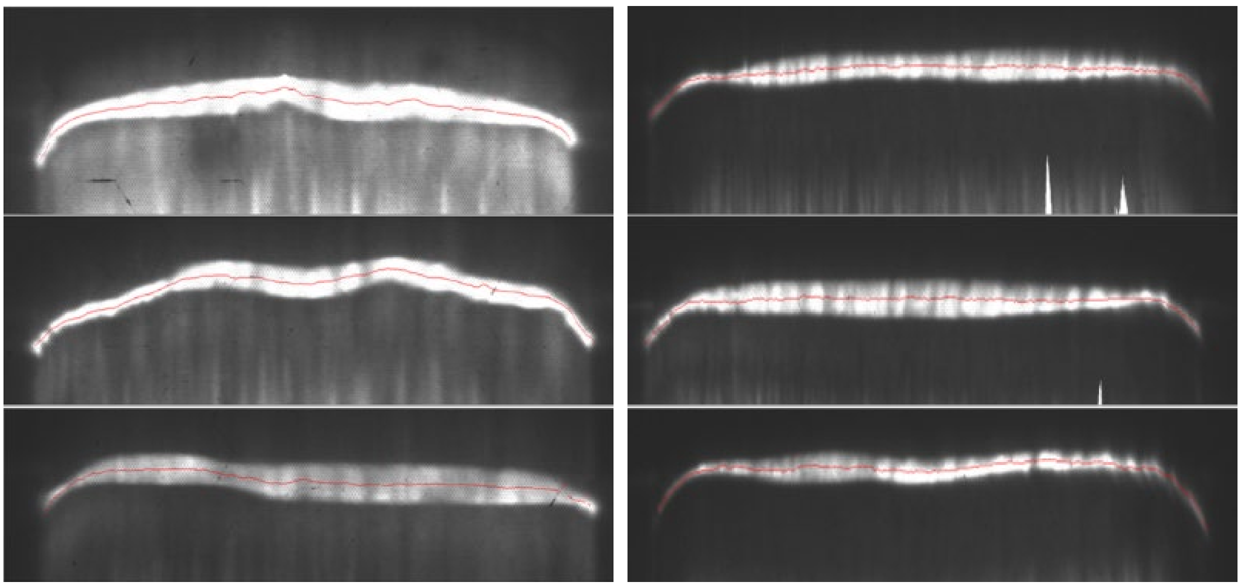
EXPERIMENTAL

Plane Wave Lens Characterization

Before implementation of the primary shock experiments, both PWL designs were characterized for breakout timing and uniformity. An Optronis SC-20 digital streak camera was used to collect images of the prepared PWL tests. Each lens was output into a 25.4 mm diameter by 4 mm thickness of output explosive (either Primasheet 1000 or PBX 9407), whose output face was then painted with an aluminum-filled spray paint to inhibit "prelight" seen from the detonation front before shock breakout. A thin air-gap of 0.2 mm was made on the surface with transparent tape for shock illumination, resulting in a well-resolved streak image. Figure 3 below contains images of both designs' front outputs. Note that each test was run at a 100 ns/mm sweep speed and recorded at a 9 μm/pixel spatial resolution.



a) b)

FIGURE 3. a) Streak outputs of 18 g PWL tests. b) Streak outputs of 11 g PWL tests

Results

The red lines in Fig. 3 correspond to the approximated breakout positions on the record; these were obtained by using MATLAB's Image Segmenter App to extract the region of interest, and the Image Processing Toolbox to perform image analysis and extract and convert the approximated front curve [7]. The extracted front curves are plotted in Fig. 4, and show a noticeable difference in the output of the two different designs; for each plot in Fig. 4, the black, red, and blue curves respectively correspond to the streak outputs in Fig. 3 from top to bottom. The larger 18 g PWLs (Fig. 4a) exhibit a much higher arrival time jitter of 30-60 ns across the center 12.7 mm diameter, compared to the 10-30 ns of jitter seen in the 11 g PWLs (Fig. 4b). Furthermore, the front curves on the smaller charges retained their flatness out to a larger diameter than required, whereas the larger PWLs saw a rapid increase in edge effects just outside of the diameter of interest. These results may also be indicative of the refined cast cure formulation used in the smaller charges, as large voids (> 1 mm diameter) were seen in the PBXN-110 cast parts upon curing and caused the irregularities seen in the streak outputs. These voids may be attributed to the higher viscosity of the formulation, which was lowered in the 11 g PWL charge formulation. The asymmetry seen in Fig 4b (red curve) may be attributed to a number of experimental errors, notably: irregularity in the output of the RP-2 used for initiation, poor alignment in the air-gap stack up, and potential non-uniformity in the spray paint layer used to block prelight. In addition, this test was noted as having a potentially poor alignment with respect to the optical axis of the streak camera, and required correction in the streak file for an angled slit; the corrected image is seen in the middle streak record of Fig. 3b.

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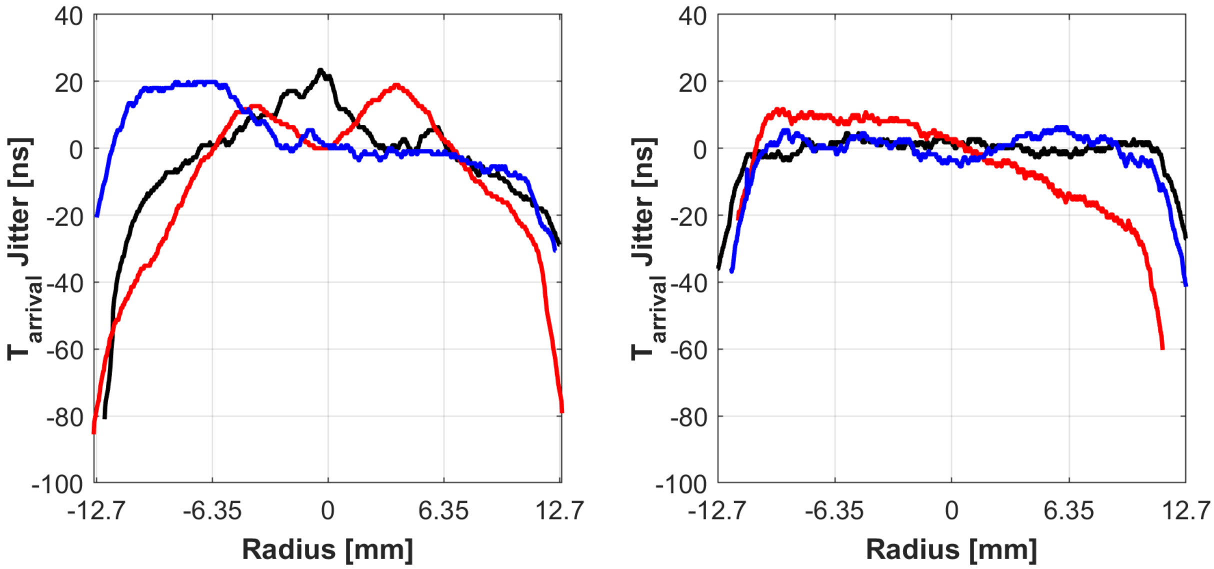

a) b)

FIGURE 4. a) Plot of 18 g PWL front curves obtained from streak images (Fig. 4a). b) Plot of 11 g PWL front curves obtained from streak images (Fig. 4b).

Small Planar Impact Fritz Flyer (SPIFFY) Tests

Based on the performance data obtained from the characterization of the two PWL designs (see above), it was determined that the 11 g NEW charge would be used in the following experiments. The Small Planar Impact Fritz Flyer (SPIFFY) test was developed as a low-cost method for probing the unreacted EOS of a new explosive before investigating the material further in higher-precision gas gun experiments. Based on similar cutback tests designed by R. Gustavsen et al., Figure 5 below shows the section view of a SPIFFY test apparatus [8]. A 25.4 mm PWL with an output explosive (Primasheet 1000 or PBX 9407) launches a metal flyer (Al 1100 or Cu C101) a controlled distance into a metal acceptor plate. The material, thickness, and separation distance of these plates is varied in order to provide a desired shock pressure into the material.

A HE sample of interest (shown here as a 12.7 mm x 12.7 mm pressed pellet, used due to availability) is glued to the back side of the acceptor plate and held coaxial to the PWL and flyer plates; glued to the backside of the HE sample is an approximately 10 µm thick Al foil, followed by a 12.7 mm x 12.7 mm machined right circular cylinder of PMMA. A PDV probe is placed along the central axis viewing the backside of the Al foil/HE interface through the PMMA window, while three more PDV probes are positioned equally on a 7.62 mm (0.3”) radius around the center axis viewing the back of the acceptor plate on the HE interface. This configuration gives data on both tilt of impact as seen by the shock impact into the sample, as well as output shock after it has run through both the HE sample and acceptor plate. Using known Hugoniot parameters of the acceptor metal and using a symmetric impact allows calculation of input pressure (via the 3 probes viewing the rear surface of the acceptor plate), output pressure (via the PMMA Hugoniot at the HE/PMMA interface), and shock velocity (via HE sample thickness and transit time between shock rise at the rear acceptor plate and shock rise at the HE/PMMA interface).

Several iterations of flyer thicknesses and standoff gaps were tested unsuccessfully before the tests described below. Thinner flyers (2 mm and 4 mm) and equally thin acceptor plates were unsuccessful, as the drive from both Primasheet 1000 and PBX 9407 was too strong and the flyers tended to break up before impact. While thicker flyers worked with the current setup, they became bowed before impact, with the center reaching a higher velocity than the outer probes and impacting the acceptor plate earlier. It was thus decided that the below tests would use 4 mm Cu and 6 mm Al flyers, with a 1.6 mm gap distance to minimize bowing.

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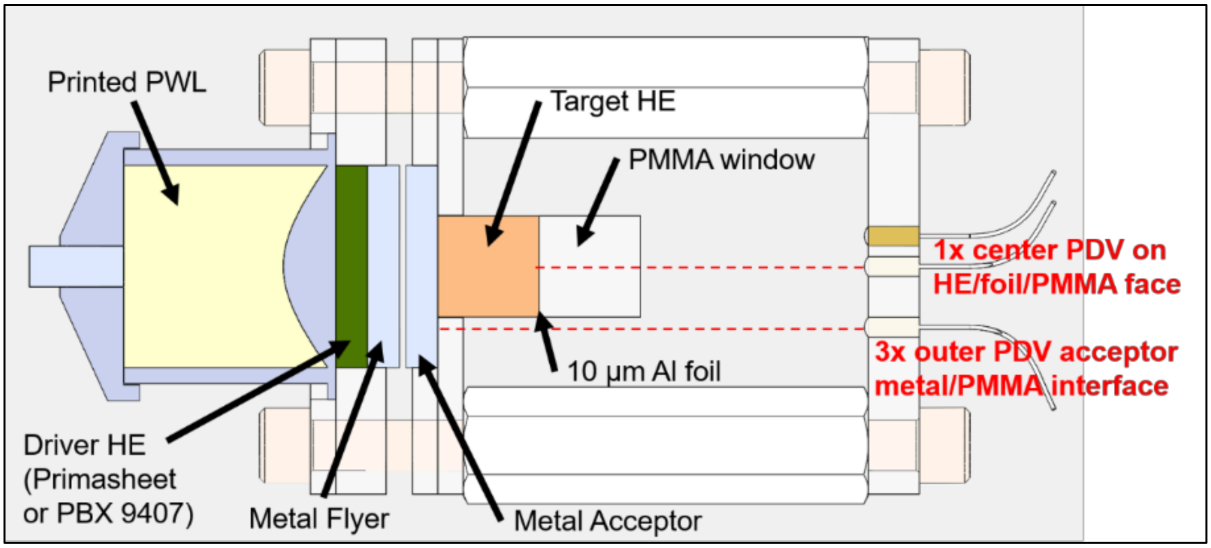

FIGURE 5. SPIFFY detailed view describing all parts within the assembly.

Results

Two successful SPIFFY tests were run on a pressed explosive formulation of 30 wt. % diaminoazoxyfurazan (DAAF), 67 wt. % nitrotriazolone (NTO), and 3 wt. % Viton A binder, previously evaluated as an insensitive, relatively high performance formulation [9]. The first of these tests intended to input a low-pressure shock into the DAAF/NTO pellet using a 4 mm Cu flyer into a 4 mm Cu acceptor with a 1.6 mm flight gap distance. As seen in the PDV plots in Fig. 6a, this produced a peak input pressure of 2.4 GPa, with a sustained pressure of 0.6 GPa. The three probe traces clustered together represent the outer PDV probes, and have an initial rise time scatter of roughly 200 ns. The fourth trace is the center probe, which shows no reaction in the sample; it does, however, give a reasonable u_p value for use in fitting the unreacted U_s-u_p Hugoniot once more points are collected.

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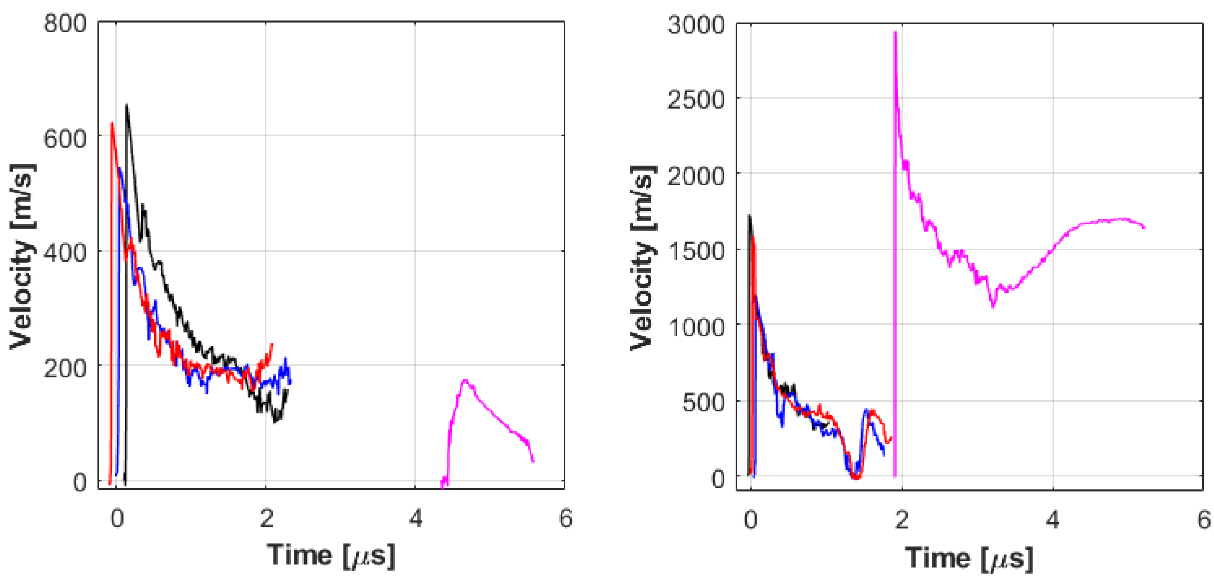

a) b)

FIGURE 6. a) PDV traces from unreacted SPIFFY test. b) PDV traces from reacted SPIFFY test

The second test (Fig. 6b) on the same DAAF/NTO formulation achieved a higher input pressure by using a 6 mm thick Al flyer and a 2 mm Al acceptor plate with the same 1.6 mm gap thickness as the previous test. The use of Al flyer and acceptor plates resulted in a peak input pressure of 6.3 GPa, with a sustained shock pressure of 1.3 GPa. This resulted in a reaction of the sample, indicated by the high particle velocity (u_p) seen in the center PDV probe trace; this value also agrees with previously reported data which saw an initiation pressure of 4.43 GPa in the same formulation [10]. Based on the approximate u_p = 2.7 km/s at the Al/PMMA interface, the detonation pressure in the material calculates to 21.5 GPa. This is less than the published P_{CJ} for this material (28.1 GPa seen in a ½ scale CYLEX test [9]), which is likely due to the short run-distance in this test (12.7 mm); it may be that the observed P_{CJ} is lower due to release wave interaction within the sample HE pellets due to their L/D of 1. The shape of the input wave and error associated with the approximated particle velocities is a cause for concern as well, and better control over these parameters would lead to a more reliable U_s-u_p investigation.

CONCLUSIONS

A versatile, low explosive-weight, cost-effective PWL was developed for small-scale testing and shock experiments, and reliably outputs a planar shock wave with an arrival time jitter of less than 20 ns using 11 g of a cast cure explosives formulation. The feasibility of using this PWL in low-cost shock experiments has been seen in the success of two SPIFFY tests which bracketed the expected initiation pressure of a novel DAAF/NTO formulation between 2.4-6.3 GPa. Future work on improving the SPIFFY test configuration will investigate the optimal flyer/acceptor thickness and standoffs required to achieve planar shock inputs. Additional methods of shock attenuation will be investigated, including an air gap "barrel" design for attenuating the drive into the flyer [2]. From there, the PWL designs will be scaled up to a 50.8 mm (2") diameter, allowing for more samples of the same material at varying axial lengths to be contained in each experiment, and provide insight into where precision gas gun experiments should investigate the material's unreacted EOS and reaction growth parameterization.

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