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ABSTRACT
The response of materials to shock loading is important to understand for a variety of applications. When shock physics emerged during and after WWII, direct explosive loading or explosively driven plate impact was the primary tool for these studies. Subsequent decades have seen the widespread use of large caliber guns for plate impact studies, laser-shock facilities and pulsed power facilities.

INL currently lacks a gun suitable for plate impact or explosives casting and machining facilities; however, it does possess explosives use and handling capabilities. An option for performing plate impact experiments was needed, therefore continuum scale models were utilized to explore a few simple donor-acceptor explosive plane wave lens designs, one of which could be hand packed with plastic explosives to launch flyer plates. 2D simulations were performed to study different geometries in an effort to minimize the difference in shock arrival across the central portion of a small copper flyer plate. A shock wave arrival time difference under 50 ns across 50 percent of the center of the flyer was achieved with a few designs. This work summarizes the computational models and results.

Keywords: Explosive, Lens, Shock, Flyer, Materials Characterization

INTRODUCTION
Explosives have been widely used to explosively launch flyer plates to perform shock experiments. Various approaches have been developed for doing this. Explosive lenses, precision machined from combinations of different kinds of explosives to yield a flat shock wave, were a common method for explosively driven shock-loading for many years [1], [2]. Variations on that theme have been developed for explosively launching projectiles. Marsh developed and patented a donor-acceptor plane wave lens with a variable thickness flyer to generate a plane wave without explosive machining [3]. Explosive lenses with shaped inserts [4] and even 3D printed explosive plane wave generators [5] have been demonstrated and all report good planarity.

Access to facilities which can machine, cast, or 3D print explosives was lacking so an alternative was sought. A very simple explosive lens design was required; something which could be fabricated very simply and at low cost but still provide adequate planarity over some central region of the flyer. One design stood out, that of Xiong et al. [6], as a design that did not require complex fabrication operations. An attempt was made to replicate their results, and a few attempts were made with related designs to see if it could be improved.

METHOD
Initial efforts focused on replicating the results of Xiong et al. [6], and then some excursions were made to explore other designs. All designs considered are donor-acceptor designs where a donor explosive is detonated resulting in shock wave, the shock wave is modified in some fashion, and the modified shock wave ignites an acceptor explosive to provide a plane wave which then either directly loads a sample or is used to launch a flyer plate.

To explore these designs, 2D axi-symmetric computational models were constructed using the ALEGRA hydrocode [7] to explore different designs. A uniform Eulerian mesh with a cell size of 0.2 mm was utilized for these computations and the model was run for 25 microseconds on 6 or 8 processors. Material was allowed advect through the mesh to address material deformation and vorticity. Material was allowed to flow out of the exterior boundary conditions. The boundary on the center axis allowed no material motion in the x direction, perpendicular to the motion of the shock front in the explosive.

The donor explosive was modeled as Composition B (Comp B) using the Jones-Wilkins-Lee equation of state model [7] and it was ignited using a programmed burn option [7] to initiate detonation at time zero on a line that was equal to the radius of an RP-1 detonator [8], 5.145 mm. The acceptor explosive was also modeled as Composition B using the History Variable Reactive Burn model [7] which detonates when shocked over its pressure threshold.

In some cases Composition C4 (C4) was used rather than Comp B; Comp B is a castable explosive but C4 is readily shaped by hand. When C4 was used, the donor portion of the plane wave lens was modeled using the Jones-Wilkins-Lee equation of state model [7] and it was ignited using a programmed burn option [7] to initiate detonation at time zero on a line that was equal to the radius of an RP-1 detonator [8], 5.145 mm. The acceptor explosive was also modeled as Composition C4 using the History Variable Reactive Burn model [7].

The nylon sleeve in the models derived from Xiong et al. [6] was modeled as a simple elastic-plastic material with a yield strength of 40.0 MPa and its pressure volume response was modeled using the Mie-Grüneisen equation of state [7]. In some models, polymethyl methacrylate (PMMA) components were used instead of nylon. A sesame table was used to model the pressure volume response of the PMMA and the strength response was modeled using the Mulliken-Boyce polymer model [7].

Where an aluminum ring was used to bridge two explosive components, it was modeled as 6061-T6 aluminum using Johnson-Cook strength and fracture models [9]; the pressure-volume response of the aluminum was modeled using a sesame table.

A 3 mm thick copper flyer plate was added. It was modeled using the Steinberg-Guinan-Lund strength model [7], a sesame equation of state table, and simple void growth model to allow for failure when a critical tensile pressure threshold was exceeded.

The regions of the computational domain not occupied by other mass were filled with air, which was modeled using a sesame equation of state. Unless otherwise specified, the parameters for the various models were drawn from the library supplied with the ALEGRA hydrocode.

RESULTS

A model of the plane wave lens reported by Xiong et al. [6] is shown in

Fig. ***1***. It produces a reasonably flat shock front. Xiong et al. [6] reported an arrival time difference of 39 ns over 70 percent of the diameter or 35 mm. In this work, it was found that the arrival time difference in the flyer between the center and 70 percent of the diameter was 33 ns which agrees well with the reported value. The arrival time difference in the flyer center at 50% of the diameter was 59 ns. This is somewhat surprising, but is simply due to some complex curvature in the shock front. Overall, the flatness in the shock front is very good across the plane wave lens.

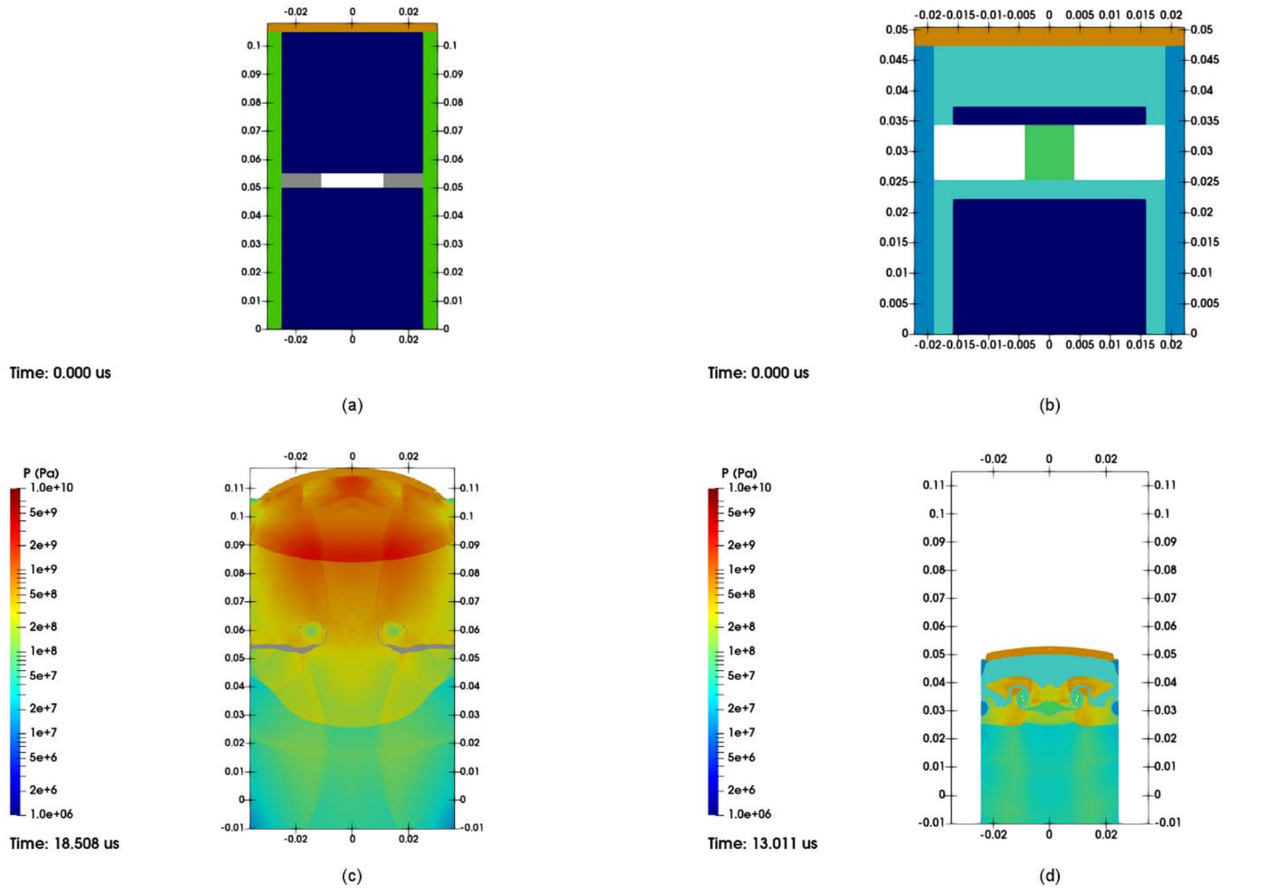

Fig. 1 (a) A 2D model of the plane wave lens generator proposed by Xiong et al. [6]. (b) An alternative design using C4 explosive. The plastic components are PMMA and a 3 mm thick flyer plate is used. (c) A plot of pressure 5 µs after the shock wave arrived at the copper flyer for the design from Xiong et al. [6]. (d) A plot of pressure 5 µs after the shock wave arrived at the copper flyer for the alternative design. Note that the flyer is somewhat flatter than the flyer launched by the plane wave lens generator proposed by Xiong et al. [6]

A half-scale version of the Xiong et al. [6] plane wave lens was modeled to see if it would scale down to reduce the amount of explosives and still produce a flat shock front. The device was scaled geometrically by ½ except the nylon tube thickness and detonation region size which remained the same. Arrival time difference between the center and 50% of the diameter was 18 ns, less than ½ the arrival time difference of the full scale model, perhaps because of the fixed detonation region size. All of the model results are tabulated in Tab. 1.

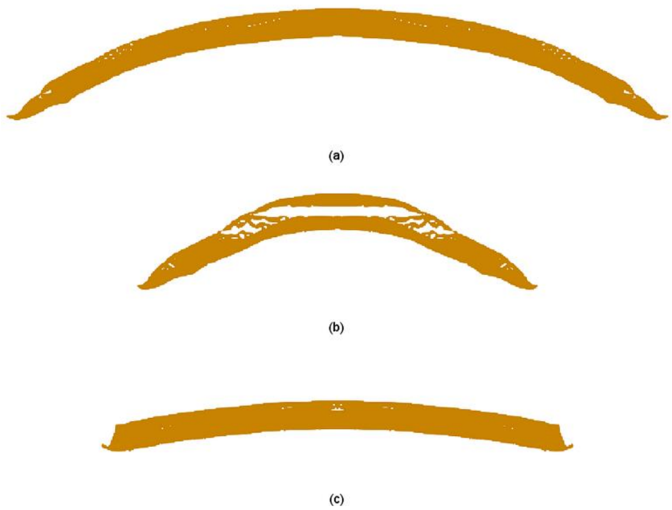

Fig. 2 A comparison of the flyer plates launched by the different designs 5 microseconds after the shock front reached the flyer plate (a) Xiong et al. [6] design, (b) half-scale version of the design published by Xiong et al. [6] (c) and the design shown in Fig. 1 at the same scale.

Unfortunately the ½ scale model also predicted that the copper flyer suffered from extensive spall damage as shown in Fig. 2, limiting its utility as a flyer plate launcher.

Other configurations were examined as well. A parameter study was performed using Dakota [10], a toolkit optimization and uncertainty quantification. The best design that has emerged from that study is shown in

Fig. ***1***b and d. Access to facilities for casting explosives was lacking so C4 was considered as an explosive driver due to its ease of fabrication by hand. In this design, C4 was contained within PMMA cups and the acceptor explosive was kept much smaller than the donor explosive. The cup containing the acceptor explosive had a thicker bottom to reduce spallation in the copper flyer plate and reduce the flyer plate velocity. Rather than using an aluminum ring between the donor and acceptor explosives, a PMMA plug was placed in between the donor and acceptor explosives. PMMA has a lower wave speed than C4, slowing the shock from the donor explosive into the acceptor explosive. Fragments from the donor cup break off and fly into the acceptor part of the plane wave generator, igniting the explosive around the plug which, in combination with the retardation of the shock through the PMMA plug, flattens the explosive shock front.

The design using C4 didn't provide as low an arrival time difference as the half-scale design at 42 ns. The arrival time results are shown in Tab. 1 for reference; however, there is less spall damage to the flyer plate than the half scale design as shown in Fig. 2. It also yielded a flatter launched flyer plate The reduced amount of explosive used in the design using C4 propelled the flyer at lower velocity than either of the other designs discussed here; the time history of the flyer plate velocities of all three designs are shown in Fig. 3.

Tab. 1 A summary of the difference in arrival time between the center and 50% of the diameter for three different designs.

Design	Arrival time difference at 50% of the diameter
Xiong et al. [6]	59 ns
½ Scale Xiong et al. [6]	18 ns
C4 Design	42 ns

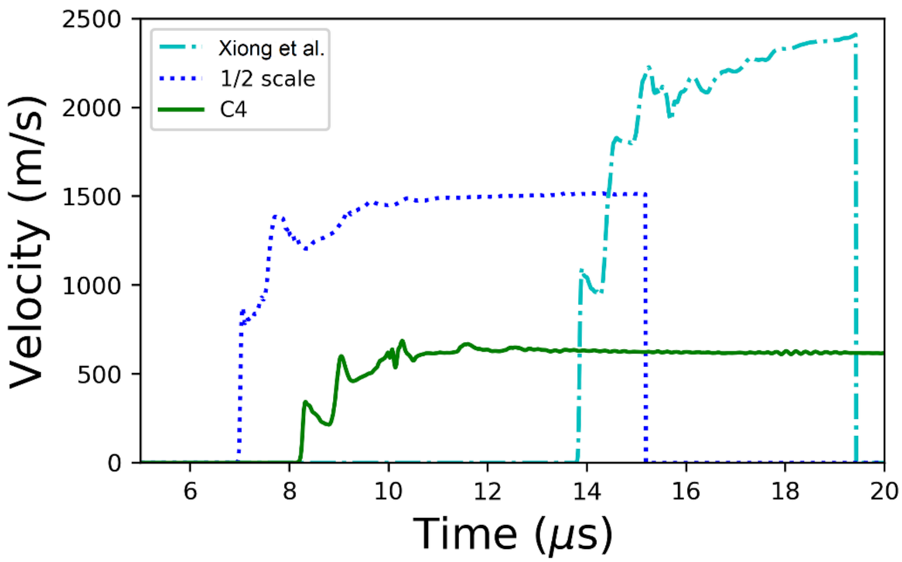

Fig. 3 Velocity of the center of the flyer of each design modeled here. The velocities drop to zero when the flyer moves out of the computational domain.

CONCLUSIONS

A simple plane wave generator design was sought to launch flyer plates. Several simple plane wave generator designs were examined. The design published by Xiong et al. [6] was modeled and found to produce a flat shock front. A half-scale version of that design was modeled as well and also found to produce a flat shock front. However, neither of these designs proved ideal for launching flyer plates. A third design was explored, and this design utilized a PMMA plug to retard the shock front in conjunction with a thick PMMA plate to reduce flyer plate velocity and damage. The computational model suggested this design would launch the flyer plate at lower velocities than the other two designs and cause less damage than the half scale design.

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