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subject: DOE Packaging Certification Program, Explosives Engineering Class Demonstration Tests

INTRODUCTION

On Thursday August 11, 2022, a series of explosive demonstration tests were conducted at the Sandia National Laboratories 9920 Test Complex for the 2022 DOE Packaging Certification Program Explosives Engineering class. Class participants included both SNL engineering student interns as well as SNL and LANL staff members. The test series was designed by the class instructor, W. Gary Rivera Org. 6626, and 9920 site test engineer, Marissa Martinez Org. 6648, with help from Michelle Chatter Org 6514 and Luke Gilbert Org 6815.

The tests were developed and conducted to help demonstrate a number of explosive charge concepts taught in the classroom environment, as well as introduce the students to range processes and procedures, primarily range safety and the application of the golden rule "expose the minimum amount of people to the minimum amount of explosives necessary for the minimum amount of time".

In total seven explosive charge configurations, were evaluated in two explosive shot operations on test day. These included five barrel tamped flyer plate projectile charges, a small copper conical shape charge, and a 10-inch length of 600 GPF linear shape charge. The latter two charges were included for demonstration only, while the barrel tamped projectile charges were included for additional performance calculation.

The performance of each of the barrel tamped flyer projectile charges was calculated using Gurney theory and Barrel Tamped Explosive performance predictions laid out in Paul Cooper's Explosives Engineering text [1]. Per Cooper, for this configuration it is possible to calculate

- The induced pressure and particle velocity at the explosive/flyer interface.
- The velocity of the flyer plate projectile using both Gurney theory and Barrel Tamped explosive theory by calculating the effective amount of explosive acting on the plate.

Exceptional Service in the National Interest

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- The velocity of the metal fragments propelled radially from the barrel portion of the charge.
- The idealized pressure induced in the target aluminum by each of the flyer projectiles (assuming no flyer breakup).
- The idealized induced shock velocity and particle velocity in the aluminum target.

Explosive Charges

For this demonstration test series, seven explosive configurations were conceived to demonstrate various explosive loading and shock physics concepts. The first five configurations were similar barrel tamped explosively driven flyer plate projectiles, each with the same steel flyer plate design (3in. diameter 5/8" thick disk of 1018 carbon steel), but with different barrel tamping materials (cardboard, thin PVC plastic, thick PVC plastic, 6061 aluminum, and ASTM A53 steel). Each of the 4" long pipe barrels were configured to accept the 3in. diameter flyer plate internal to the pipe ID and leave room for an approximately 3in. diameter 3.38" long column of C4 explosive. Because each of the barrels had different relative masses, it was expected that each of the projectiles would have a different impact velocities. Each of the charges were initiated by NONEL detonators that were placed in foam det-holders placed on the back, exposed surface of the explosive. A small 1-gram booster of C2 Primasheet was used to transfer the initiation detonation from the detonator to the Comp C4 main charge. Including detonators, boosters, and main charges, the total net explosive weight (NEW) for this first shot was 8.85 lbs TNT equivalent.

The second explosive event involved a single 10 in. long length of 600 GPF copper-sheath linear shape charge and a single experimental copper liner conical shape charge. It was expected that the LSC charge would *not* penetrate the full 2" thickness of the aluminum target, but it was likely that the conical shape charge would penetrate the target. Here the total NEW was estimated to be no greater than 0.18 lbs TNT equivalent.

Test Setup

The explosive shots were conducted at the 9920 North Pad concrete enclosure to contain any shrapnel generated by the explosive charges. Two rectangular concrete blocks were placed parallel to each other, separated by approximately 32 in. within the enclosure to provide support for the flyer plate charge holder as well as mitigate radial shrapnel from the charge barrels.

The first explosive operation involved placing five explosive barrel tamped flyer projectile charges into a single charge holder configured in a sheet of wood OSB board. Holes were drilled into the OSB charge holder consistent with the barrel charge diameter allowing the charges to hang from the board. Each barrel charge was configured with an increased diameter of high strength duct tape such that the aft end of the charge would hang from the charge holder with the majority of the explosive and barrel below the concrete block surface.

A 25" x 25" x 2" thick aluminum target plate (assumed to be 6061-T6) rested on four concrete bricks and 2x4s above the ground (allowing for a free back-side surface condition) and approximately 11 in. below the flyer charges (3.67 times the charge diameter).

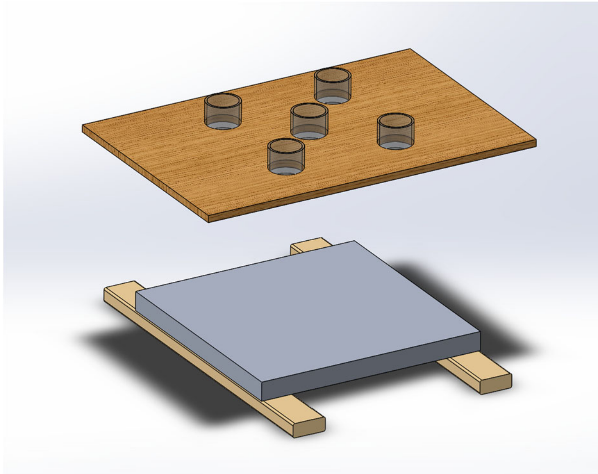


Figure 1. Flyer Plate Demonstration

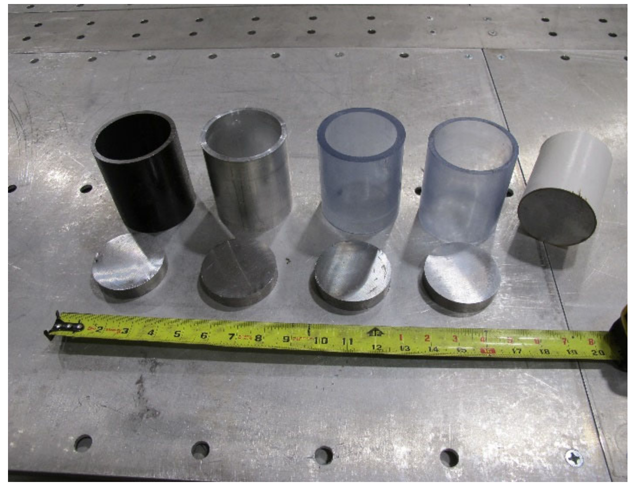


Figure 2. Barrel Tampers and Flyers

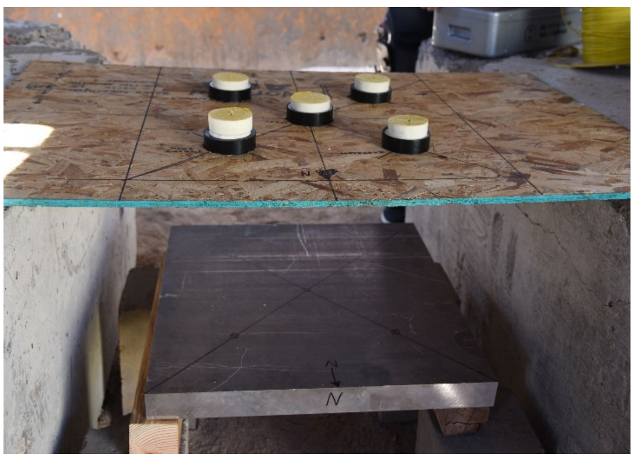


Figure 3. Flyer Plate Test Setup (North)

Figure 4. Flyer Plate Test Setup (South)

Initiation of the charges utilized NONEL detonators and the 9920 nonintegrated firing system. Charge initiation took place at the observer viewing area, which was approximately 678 ft from the North Pad enclosure. Due to funding constraints, only still pictures of setup and test results were recorded. No additional instrumentation (blast overpressure, flyer velocities, impact pressures, etc.) was available to this test.

Copper Conical Shape Charge

The small copper conical shape charge demonstration was shot with the second explosive operation for the test series. The charge itself was a surplus experimental design that utilized a 0.75 in. diameter copper liner and a plastic (possibly Teflon or nylon) to hold the explosive and provide a holder for the NONEL detonator. The explosive was hand-packed into the machined cavity in the charge holder and was measured to be approximately 0.037 lbs. (17 gram) of C4. The charge was initiated from the aft end, using 1 gram of C2 Primasheet as a booster. Standoff above the aluminum target for this charge was provided by an approximately 2 in. plastic cap.

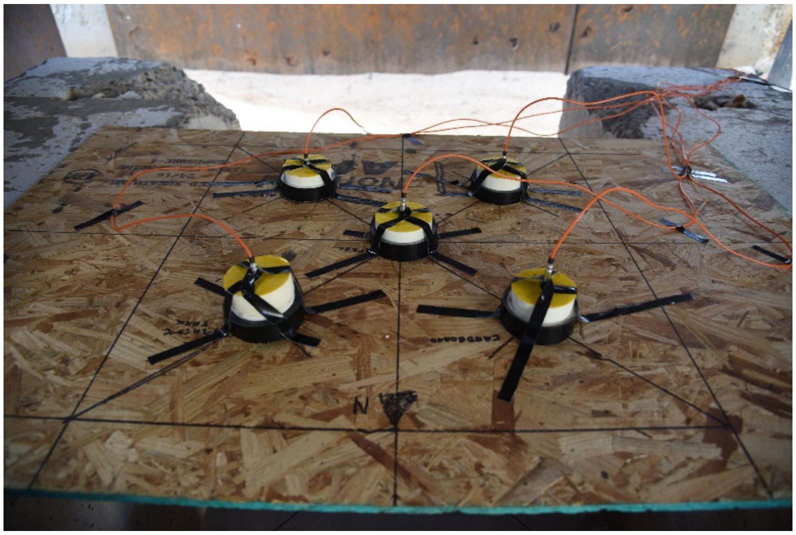


Figure 5. Detonators Installed

Figure 6. Distance to Target

Figure 7. Experimental 0.75 in. Copper Conical Shape Charge

Because this charge was a surplus experimental configuration, no pre-shot performance predictions were made, though it was expected that the explosive would fully detonate and drive the copper jet through the aluminum target.

600 GPF Linear Shape Charge

The small copper-sheath linear shape charge demonstration was also shot with in the second explosive operation in the test series against the 2 in thick aluminum target plate. The charge was setup at a location on the target plate with minimal prior damage using plastic 3D printed standoff/detonator holders. The standard standoff for 600 GPF is 0.60 in, and the expected jet penetration is 0.70 in. As the target was 2 in. thick, full penetration was not expected.

Figure 8. Commercial 600 GPF Copper Clad Conical Shape Charge

Target

The target for this demonstration test series was a single 25” by 25” by 2” thick aluminum plate (assumed to be 6061-T6). All five of the flyer impacts took place during the first shot, and the LSC and CSC charges were configured to impact the target in nearly undamaged locations on the previously impacted target during the first explosive operation.

Site Safety and Blast Overpressure

A site safety analysis was conducted to assure that the decibel levels experienced by 9920 personnel and class observers would not exceed 140dB. It was determined that the observation area be placed 678 ft. from the North Pad enclosure. These estimates are considered conservative.

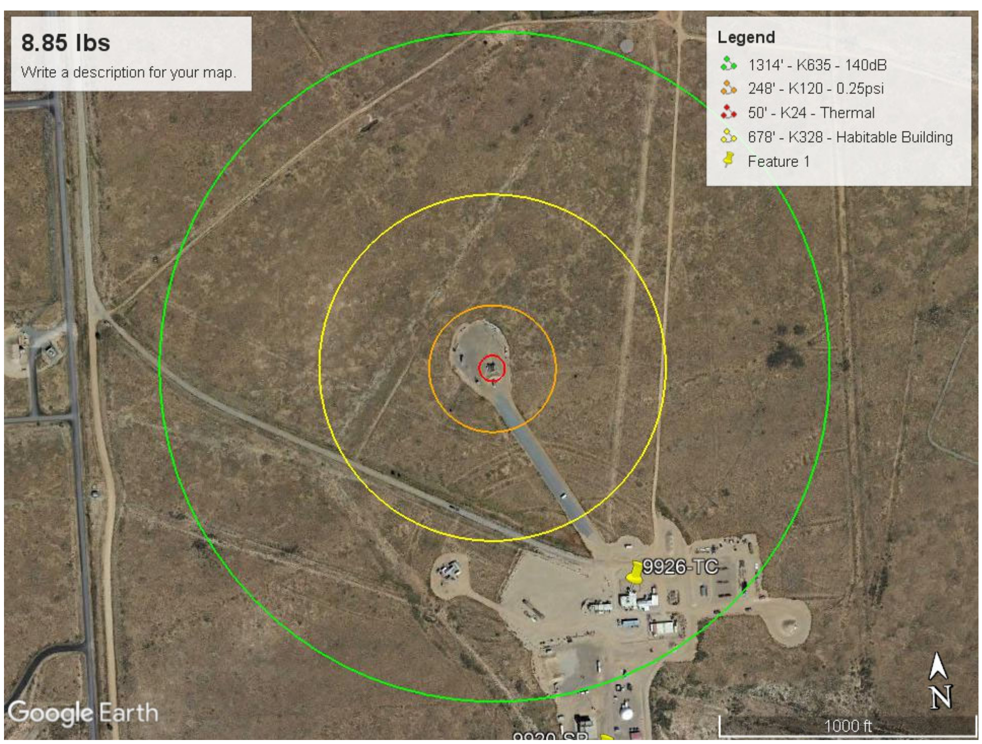


Figure 9. Air Blast Hazard Arcs for 8.85 lb TNT Equivalent Explosive Detonation

Flyer Plate Performance Theory

The barrel tamped flyer projectile portion of the test was designed to demonstrate the differences in performance between the five different flyer plates, as well as the resulting impact of the relatively higher-impedance steel flyer plates against the lower-impedance aluminum target.

Calculating the pressure induced by the explosive detonation at the explosive/flyer interface was accomplished using hand calculated P-u (Pressure-particle velocity) Hugoniot relations for the C4 explosive and 1018 Steel flyer. From reference materials, the detonation shock properties of C4 and physical shock properties of 1018 low-carbon steel are given in Table 1 below. The calculated hand-pack density of the explosive for these experiments was calculated to be approximately 1.476 g/cm^3 (0.059-lb/in^3), which is of course lower than the reported value of 1.601 g/cm^3 for theoretical maximum density for C4.

Table 1. Hugnoiot Shock Properties for 1018 Steel and Comp C4 Explosive

	Density (ρ)	Sound Speed (C_0)	U-u Hugoniot Slope (s)
1018 Steel	7.87 g/cm^3	4.605 km/s	1.465
	Density (ρ)	**Detonation Velocity (D)**	**CJ Pressure (P_{cj})**
Comp C4 (TMD)	1.601 g/cm^3	8.193 km/s	28.0 GPa
Comp C4 (HP)	1.476 g/cm^3	8.086 km/s	25.7 GPa

It is necessary to determine the explosive shock parameters for the hand-packed C4. The reduced detonation velocity is calculated using

$$D_1 = D_0 + 3(\rho_1 - \rho_0) \tag{1}$$

The measured density of the hand-packed explosive was 1.476 g/cm^3. The theoretical maximum density and detonation velocity for C4 is ρ_0 = 1.601-g/cm^3 and D_0 = 8.193-km/s respectively. Using Equation (5), detonation velocity for the hand packed C4 explosive (D_1) becomes 8.086-km/s. The CJ pressure for this reduced density C4 is calculated using

$$P_{CJ} = \rho_0 D^2 (1 - 0.7215\rho_0^{0.04}) \tag{2}$$

to be 25.67 GPa (256.7 kbar).

The P-u Hugnoiot equation for the solid steel flyer is

$$P = \rho_0 c_0 u + \rho_0 s u^2 \tag{3}$$

The P-u Hugoniot for detonated explosive is

$$P = 2.412P_{CJ} - 1.7315\left(\frac{P_{CJ}}{u_{CJ}}\right)u + 0.3195\left(\frac{P_{CJ}}{u_{CJ}^2}\right)u^2 \tag{4}$$

Where u_{cj} is calculated from the Momentum equation for detonating explosive.

$$P_{CJ} = \rho_0 u_{CJ} D \tag{5}$$

Solving for u_{CJ}

$$u_{CJ} = \frac{P_{CJ}}{\rho_0 D} \tag{6}$$

Considering that each of the explosive flyer charges use the same Comp C4 explosive at approximately the same hand-packed density and plate material, the calculated interface pressure and particle velocity, as well as the shock velocity in the flyer will be the same for all five charge configurations.

Using the Hugoniot equations (3), (4), and (6) above and the shock values for C4 and 1018 steel yield an explosive/steel interface pressure of 43.38 GPa (433.8 kbar) and a particle velocity of 0.927 mm/µs (3041 ft/sec). The shock velocity in the steel flyer is calculated to be 5.96 mm/µs (19,554 ft/s). It is noticeable that the particle velocity calculated here is 7% lower than the calculated Gurney velocity for the steel barrel tamped flyer configuration. This difference is assumed to be differences in Gurney and Hugoniot theory as well as an increased Taylor wave expansion due to the barrel tamping.

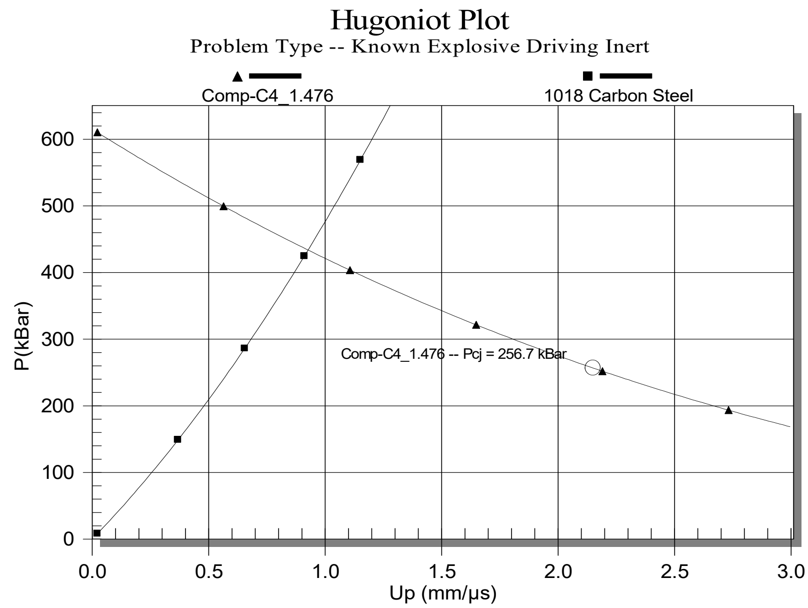


Figure 10. Hugoniot Interaction Between Comp C4 and 1018 Steel

Pressure induced in the Target from Flyer impact

All five of the barrel tamped explosive configurations utilized the same flyer plate projectile material, 0.625 in thick-3 in diameter 1018 low-carbon steel, and the same 6061 (assumed) aluminum target plate which was 25" by 25" by 2" thick. The shock impedance (Z) of a material is defined as the material density times the induced shock speed in the material at impact. The shock speed changes relatively little between materials for high-shock impacts, thus the relative shock impedance is typically dominated by the density of the materials. The steel flyer plates, with a density of 7.85 g/cm^3 have a significantly higher shock impedance than the aluminum target with a density of 2.3 g/cm^3.

$$Z = \rho U \tag{7}$$

Figures 11 and 12 below [1] indicate the idealized shock interaction between the higher impedance steel flyer and the lower impedance aluminum target.

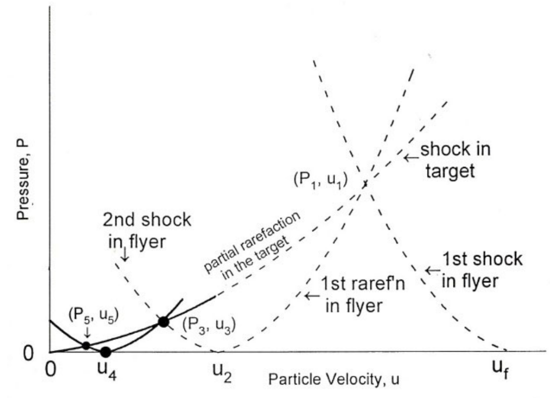


Figure 11. Flyer/Target Hugoniot Interaction [1]

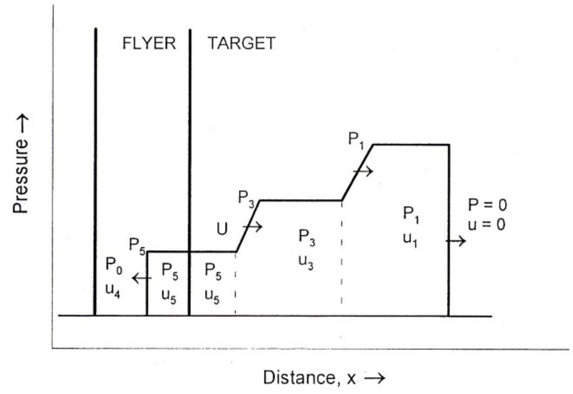


Figure 12. Shock Pulse Induced in Target [1]

It is expected that this combination of flyer/target impact will yield a long pressure pulse where shock pressures reduce incrementally with successive shock transits within the steel flyer. Ideally one would expect the steel flyer to remain in contact with the aluminum target after all shock transits have concluded.

Table 2. Calculated Impact pressure for Steel Flyer and Aluminum Target

Barrel Configuration	Flyer Velocity (km/s)	Shock Velocity in Flyer (km/s)	Shock Velocity in Target (km/s)	Particle Velocity at Impact (km/s)	Pressure at impact (GPa)
Cardboard	0.529	4.83	5.85	0.37	5.90
Thin PVC Plastic	0.682	4.90	5.99	0.48	7.77
Thick PVC Plastic	0.740	4.92	6.05	0.52	8.50
Aluminum	0.785	4.95	6.09	0.55	9.07
Steel	0.992	5.04	6.28	0.69	11.8

It is expected that spalling within the aluminum target may have occurred from the different impact. A potential follow-on sectioning of the target may show this to be the case or not.

Bare Explosive Flyer Charge

To calculate the induced flyer velocity from the explosive detonation, it is required to determine the amount of explosive that is acting to drive the flyer forward. It is known that an unconfined explosive will have a reduced Taylor wave expansion, thus the reduced impulse (area under the pressure-time curve) will not drive the explosive as efficiently. Per Cooper [1], for a cylindrical explosive charge with the detonation down the axis of the cylinder, the effective explosive mass (*Ce*) driving the flyer will be a cone with a base angle of 60°. The height of the cone, with a base radius of *R*, is calculated to be

$$h_{60} = R\,tan(60) \tag{8}$$

Assuming that the length of the explosive is greater than the calculated effective height of the cone, the full volume of the cone is calculated as

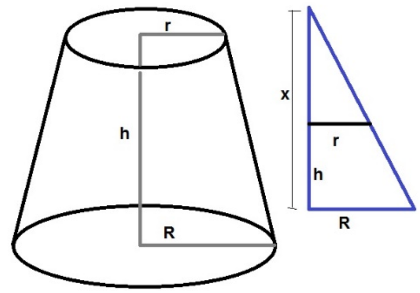
$$Vol_{60} = \left(\frac{\pi}{3}\right) R^3\, tan(60) \tag{9}$$

The effective mass is then

$$C_e = Vol_{60}\rho_{expl} = \rho_{expl}\left(\frac{\pi}{3}\right)R^3\, tan(60) \qquad (10)$$

If the calculated height of the effective cone is greater than the length of the explosive cylinder, then the volume of the resulting explosive frustrum must be calculated by

$$Vol_{frustrum} = \left(\frac{\pi}{3}\right)h_{frustrum}(r^2 + rR + R^2)$$



(11)

Where *r* in Equation/Diagram (11) is calculated as

$$r = \frac{R(x-h)}{x} \qquad (12)$$

Barrel Tamped Explosive Charge

The effective amount of explosive can be increased by adding barrel tamping around the explosive material to functionally increase the driving impulse by increasing the pressure withing the Taylor wave expansion, thus increasing the velocity of the driven flyer plate projectile. The barrel tamped base angle (Θ°) of the effective explosive cone is calculated as

$$\Theta = 90 - \frac{30}{\left(\frac{2\Psi}{C}+1\right)^{\frac{1}{2}}} \qquad (13)$$

It is required to calculate the ratio of barrel tamping mass (Ψ) to the *total* mass of explosive (*C*). Here, Ψ is calculated using the inner radius (r_i) and outer radius (r_o), the length (*L*), and the material density (ρ) of the barrel

$$\Psi = \pi(r_o^2 - r_i^2)L\rho_\Psi \qquad (14)$$

The total explosive mass is calculated as

$$C = \pi r_i^2 L\rho_{expl} \qquad (15)$$

And thus the height of the total explosive is calculated using

$$h = r_i\, tan(\Theta) \qquad (16)$$

Again, if the new calculated barrel tamped height of the effective explosive cone is greater than the height of the explosive charge, then the volume of the remaining frustrum using equation (11) with the appropriate variables for the new calculation. With the barrel tamped effective explosive volume now known, the effective explosive mass C_e is then calculated

$$C_e = Vol_{effective}\rho_{expl} \qquad (17)$$

The velocity of the flyer projectile is then calculated with the Gurney equation for an open face sandwich

$$V = \sqrt{2E}\left(\frac{1+\left(1+2\frac{M}{C_e}\right)^3}{6\left(1+\frac{M}{C_e}\right)} + \frac{M}{C_e}\right)^{-\frac{1}{2}} \quad (18)$$

where the Gurney Energy is calculated as

$$\sqrt{2E} = \frac{D}{2.97} \quad (19)$$

Explosive Charge Configurations

The following sections describe each charge configuration, with the expected results. It should be noted that all of the 1018 steel flyer plates for this testing were purchased from McMaster-Carr (Low-Carbon Steel Disc, 5/8" Long, 3" Diameter, part number 7786T32), and are considered to be equivalent.

Cardboard Barrel Tamped Flyer Projectile

The carboard barrel configuration was considered for this testing to functionally have no barrel tamping at all due to the light weight of the cardboard. Thus, the configuration was considered to be bare explosive Comp C4 driving the flyer projectile forward towards the target. As discussed in the previous sections, it is known that the entire explosive mass does not act on the round flyer to drive it towards the target, and it is assumed that the effective mass of the acting explosive would be a cone of explosive with the base diameter equaling that of the round flyer, 3 in in this case, with a base angle of 60°.

The flyer plate projectile used for this configuration was a 5/8 in. (0.625 in) thick 3 in. diameter 1018 low-carbon steel plate, ordered as a stock item from McMaster-Carr. The cardboard barrel was approximately 0.063 in. thick of a medium density paper cardboard, again assumed to be of negligible mass. This tube was also purchased from McMaster-Carr (round shipping tube with Slip-on end caps, part number 20545T31). The total length of the cardboard tube was 4 in, indicating that the Comp C4 hand-packed charge was 3.375in. long and 3.0 in. diameter.

Per the shot assembly sheet [Appendix A], the total C4 explosive used for this charge was 1.27 lbs (577 grams) with a calculated volume of 23.85 in^3 (390.0 cm^3). The calculated hand-packed C4 explosive density is 0.052 lb/in^3 (1.45 gr/cm^3).

Again, this charge is considered to have no barrel tamping, and the amount of explosive considered to be acting on the flyer plate is a cone with a base angle of 60°. This assumption results in a cone with a base diameter of 3.0 in, a height of 2.60 in, and a resulting volume of 6.12 in^3 (100.31 cm^3). The resulting effective explosive mass (C_e) for this charge is calculated to be 0.312 lbs (145.5 grams) of Comp C4.

The mass of the flyer plate projectile is calculated to be 1.25-lb (569.75-grams). The resulting flyer mass/effective explosive mass (M/C_e) for this configuration is calculated to be 3.91.

The resulting calculated flyer velocity for the cardboard tamped charge is 0.53 km/s (1739 ft/s). It is assumed that the cardboard tube is consumed by the detonation.

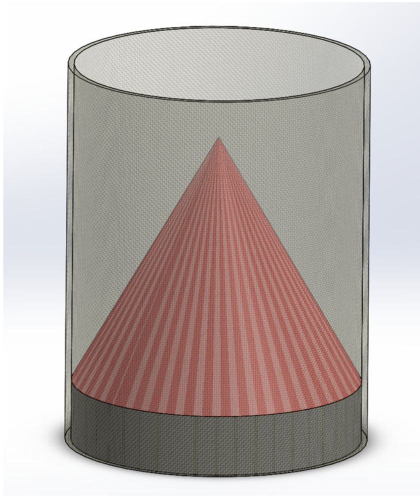
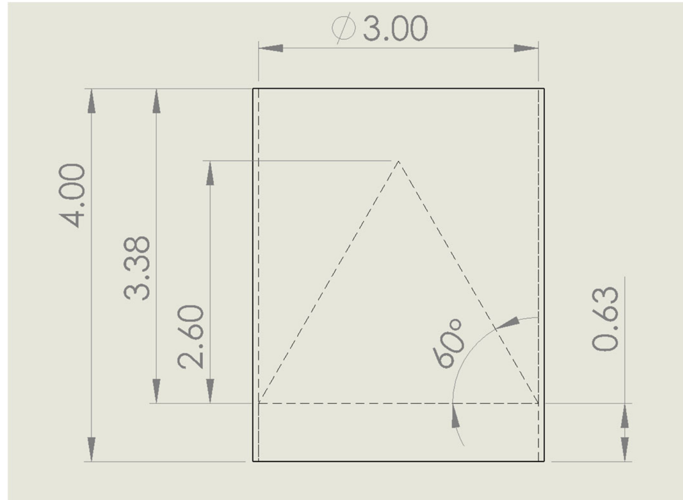



Figure 13. Cardboard Tube Charge Configuration

Thin PVC Barrel Tamped Flyer Projectile

The thin barrel configuration was expected to increase the effective explosive by 34.8% over the cardboard barrel configuration. Here, the relatively light plastic increased the effective base angle from 60° to 66.4°, resulting in an effective explosive mass of 0.440 lbs (200 gram) of Comp C4.

The flyer plate projectile used for this configuration was a similar 5/8 in. (0.625 in.) thick 3 in. diameter 1018 low-carbon steel plate. The thin PVC plastic barrel was approximately 0.25 in. thick. This tube was also purchased from McMaster-Carr (Standard-Wall Clear Blue Rigid PVC Pipe for Water, part number 49035K49). The total length of the PVC tube was 4 in., indicating that the Comp C4 packed charge was 3.375 in. long and 3.0 in. diameter. The flyer mass/effective explosive ratio for this charge was 2.85.

The resulting calculated flyer velocity for the thin PVC tamped charge is 0.68 km/s (2231 ft/s). The PVC material is expected to have been consumed in the detonation.

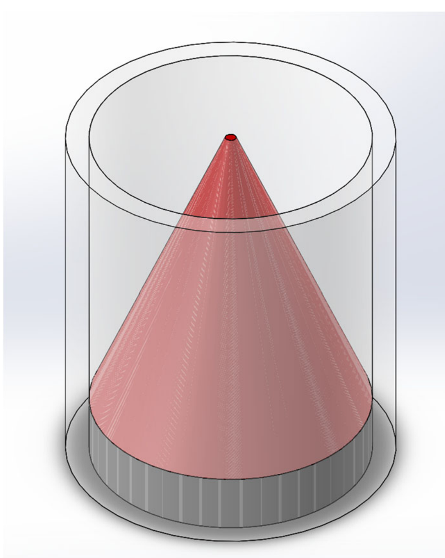
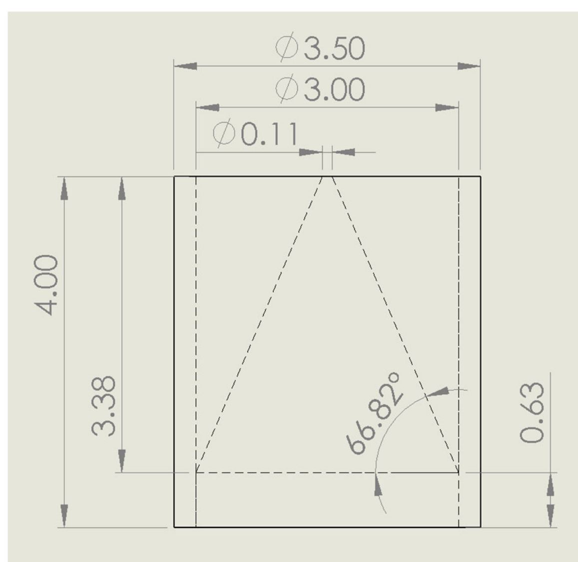



Figure 14. Thin Wall PVC Barrel Tamped Charge Configuration

Thick PVC Barrel Tamped Flyer Projectile

The thick barrel configuration was expected to increase the effective explosive by 35.7% over the cardboard barrel configuration. Here, the relatively light plastic increased the effective base angle from 60° to 67.8°, resulting in an effective explosive mass of 0.443 lbs. (285 gram) of Comp C4, keeping in mind that the ID of the thick wall barrel is 2.864 in. instead of 3.0 in.

The flyer plate projectile used for this configuration was a similar 5/8 in. (0.625 in.) thick 3 in. diameter 1018 low-carbon steel plate. Again, the ID of the barrel and OD of the explosive is 2.864 in. The thick PVC plastic barrel was approximately 0.318 in thick. This tube was also purchased from McMaster-Carr (Thick-Wall Clear Blue Unthreaded PVC Pipe for Water, part number 4740K69). The total length of the PVC tube was 4 in., indicating that the Comp C4 packed charge was 3.375 in. long and 2.864 in. diameter. The flyer mass/effective explosive ratio for this charge was 2.58, the lower ratio due to again the difference in ID of the thick PVC Barrel.

The resulting calculated flyer velocity for the thick PVC tamped charge is 0.74 km/s (2428 ft/s). The PVC material is expected to have been consumed in the detonation.

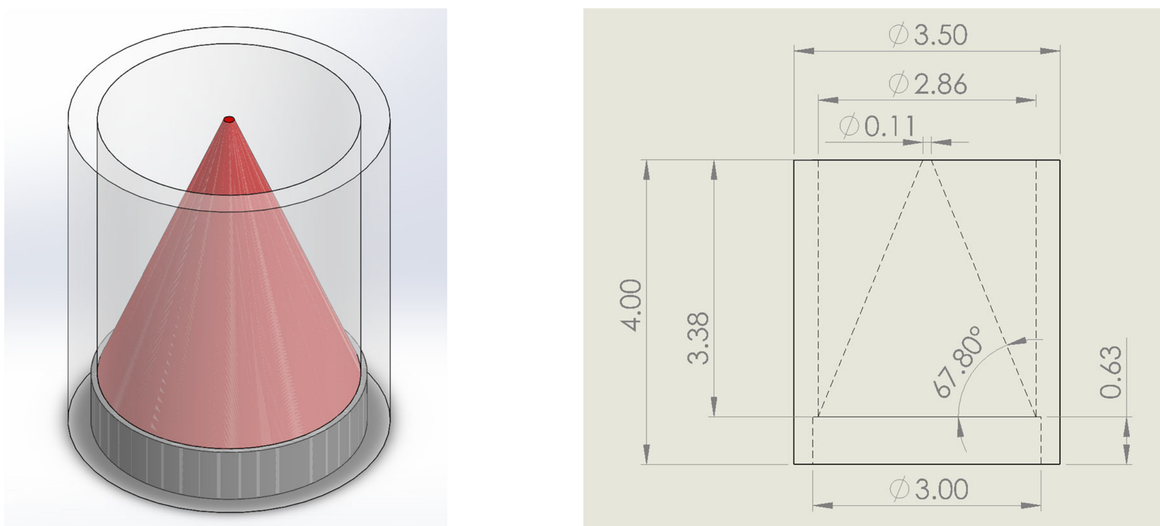


Figure 15. Thick Wall PVC Barrel Tamped Charge Configuration

Aluminum Barrel Tamped Flyer Projectile

The aluminum barrel configuration was expected to increase the effective explosive by 60.1% over the cardboard barrel configuration. Here, the aluminum increased the effective base angle from 60° to 70.3°, resulting in an effective explosive mass of 0.523 lb (237 gram) of Comp C4.

Again, the flyer plate projectile used for this configuration was an equivalent 5/8 in. (0.625 in.) thick 3 in. diameter 1018 low-carbon steel plate. The aluminum barrel was approximately 0.25 in. thick. This tube was purchased from McMaster-Carr (Standard-Wall Aluminum Pipe, 4" Long, part number 5038K597). The total length of the aluminum tube was 4in., indicating that the Comp C4 packed charge was 3.375 in. long and 3.0 in. diameter. The flyer mass/effective explosive ratio for this charge was 2.40.

The resulting calculated flyer velocity for the thin PVC tamped charge is 0.79 km/s (2592 ft/s).

The radial velocity of the aluminum barrel fragments was calculated using Gurney theory for the cylindrical configuration

$$\frac{V}{\sqrt{2E}} = \left(\frac{M}{C} + \frac{1}{2}\right)^{-\frac{1}{2}} \tag{17}$$

Here the *M/C* ratio is the ratio of the total mass in the aluminum cylinder and the mass of the total explosive charge. For this configuration, *M* is calculated to be 0.84 lbs. (381 gram) and the total explosive measured to be 1.27 lbs. (577-gram), resulting in an *M/C* ratio of 0.66. The calculated radial velocity of the aluminum barrel is therefore 2.52 km/s.

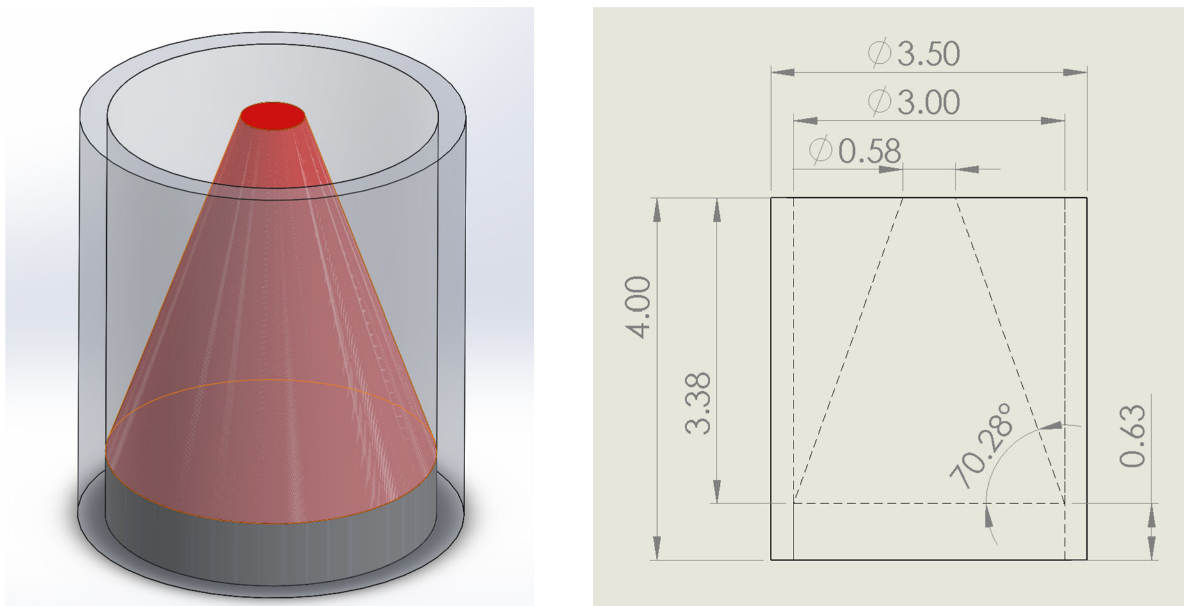


Figure 16. Aluminum Tube Charge Configuration

Steel Barrel Tamped Flyer Projectile

The steel barrel configuration was expected to have the greatest flyer plate projectile velocity tested due to the increase of the effective explosive by 115.9% over the cardboard barrel configuration. Here, the steel barrel increased the effective base angle from 60° to 76.4°, resulting in an effective explosive mass of 0.70 lbs. (319.6 gram) of Comp C4.

Again, the flyer plate projectile used for this configuration was an equivalent 5/8 in. (0.625 in.) thick 3 in. diameter 1018 low-carbon steel plate. The steel barrel was approximately 0.25 in. thick. This tube was purchased from McMaster-Carr (Standard-Wall Steel Pipe Nipple, Unthreaded, part number 7750K118). The total length of the steel tube was 4 in., indicating that the Comp C4 packed charge was 3.375 in. long and 3.0 in. diameter. The flyer mass/effective explosive ratio for this charge was 1.78.

The resulting calculated flyer velocity for the steel barrel tamped charge is 0.99 km/s (3248 ft/s).

The radial velocity of the steel barrel fragments was calculated using Gurney theory for the cylindrical configuration. Here the *M/C* ratio is the ratio of the total mass in the steel cylinder and the mass of the total explosive charge. For this configuration, *M* is calculated to be 2.45 lbs. (1111 gram) and the total explosive measured to be 1.27 lbs. (577 gram), resulting in an *M/C* ratio of 1.92. The calculated radial velocity of the steel barrel is therefore 1.75 km/s.

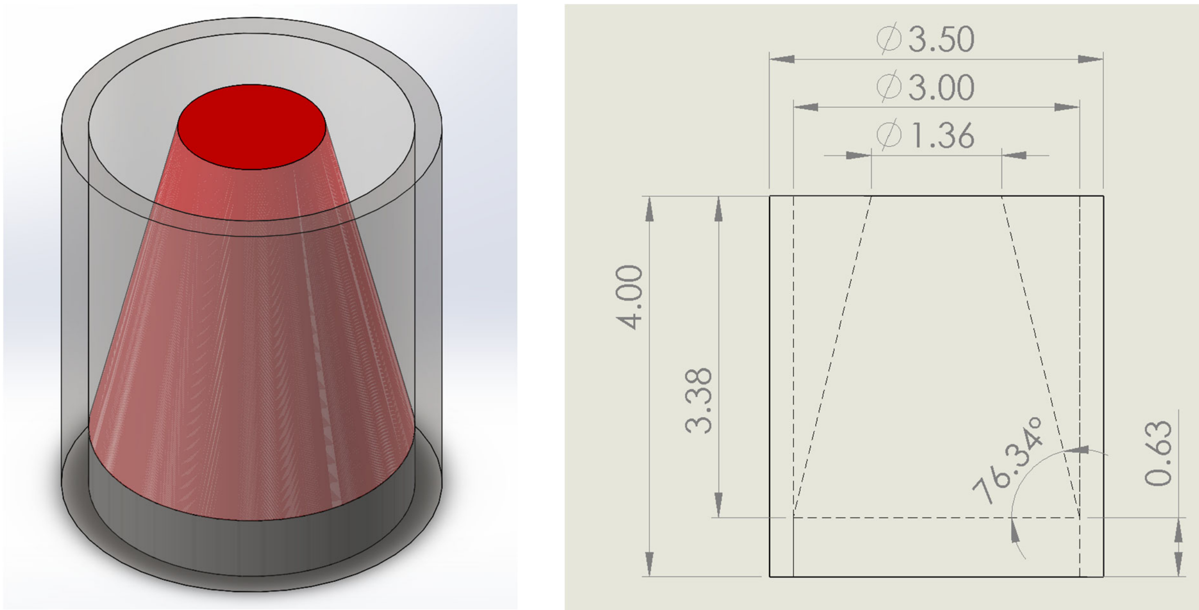


Figure 17. Steel Tube Charge Configuration

Testing and Results

Two Explosive operations were conducted on the morning of Thursday, August 11. In preparation for the testing a Test Plan & Readiness Review (TPRR) was conducted on Wednesday August 3 with 9920 site personnel, SNL Explosive Safety, 6648 Management, and the class/experiment designer (Org 6626). On test day and prior to explosive setup, a PJB (pre-job briefing) was conducted at building 9926 for all explosive operations personnel as well as observers from the Explosives Engineering class. After the PJB, class participants were escorted to the 9920 explosive assembly room for small-group "tours" of the assembly area and explanation on how the charges were assembled and packed. Finally, site operations personnel escorted the class to the North Pad enclosure to observe the test setup. At all times, the cardinal rule of "minimum number of people, minimum amount of explosive, and minimum time" was observed.

In between explosive tests, the class was escorted to the North Pad enclosure to observe post-test results and observe the second shot setup. This step was repeated after the second shot as well.

Post-testing, a "hot wash" meeting was held in building 9926 to discuss what went well, what could have been improved, and overall lessons learned. All site 9920 operations were concluded by noon of that day.

Barrel Tamped Flyer Plate Results

Post-test, it was observed that all five of the barrel tamped flyer charges initiated and appeared to impact the target all within approximately 250 μs (calculated), the observation being that the target did not have enough time to physically move between impacts. Each of the impact craters appeared to be reasonably symmetric indicating a relatively planar impact.

Of the five flyer plates, only one was visible on the target (the center steel barrel flyer), laying inside of its impact crater. This result follows the theory that the flyer will continue to push against the target without rebound until the pressure is reduced to zero. The four other flyers were found adjacent to the target amidst other test debris. To demonstrate the shock heating of the flyer, water was poured over the target causing no reaction from the target temperature, though and centermost steel flyer was hot enough to cause the water to immediacy steam and evaporate.

The flyer impact onto the target caused a rigid body motion of the target plate with enough force to crush and splinter the 2x4 supports, and cause one of the four concrete blocks to break in half length-wise.

Figure 18. Aluminum Target Plate Resting Position Post-Flyer impact

After a period, the five flyer plates were recovered from either the target or the surrounding debris and placed on the concrete block for photo documentation using leather gloves. Each was noticeably hot to the touch, but not hot enough to burn the leather gloves. It was immediately noticed that the explosive force driving the plates, as expected, sheared off a portion of the edges of the plate as is commonly seen in explosively driven metal. Only the cardboard tube flyer and the steel tube flyer were identifiable due to the position and condition of the target crater. The PVC tube and aluminum barrel flyers had similar damage, and the driving barrel configuration was not able to be fully ascertained, though it is assumed that two of the remaining flyers with similar damage may have been from the PVC barrel configurations.

The following sections detail the flyer condition post-test.

Figure 19. Five Flyer Plate Remnants Post-Target Impact

Steel Barrel Flyer

The steel barrel flyer remained in the target crater after the impact. It was observed that compared to the other flyer plates, this one was the thickest post-impact. The edges of the flyer with the exception of one 5th or so of the circumference were sheared off, resulting in a near circular plate that was ~2.5 in. diameter with the remaining section adding ~0.29 in. The approximate measured thickness of the partially domed plate was 0.54 in. with no apparent separation in the plate (likely indicating that it was compressively deformed by ~0.085 in.

Explosive Surface **Impact Surface**

Figure 20. Steel Barrel Flyer

Cardboard Barrel Flyer

The cardboard barrel flyer was found adjacent to the target. It was observed that this flyer plate spalled into two pieces prior to impact with the impact crater showing deformation from both spall and main flyers. The main flyer was measured to be ~3.1 in diameter with a thickness of ~0.3 in. The spalled portion of the flyer was ~1.75 in diameter with a thickness of ~0.25 in.

Explosive Side **Impact Surface**

Figure 21. Cardboard Barrel Flyer

PVC Barrel Flyer

It is assumed that the of the three remaining flyers, the two that have similar damage are the two PVC barrel flyers. In both cases, the final dimensions of the flyer are ~3.1 in. diameter and 0.45 in. thick. Both flyers have a pedestal of metal that was not spalled off on the explosive side that is approximately 0.1 in. thick. The impact surface on both flyers had cracking damage near the outer circumference, and again both flyers were domed on the impact side but were spalled in a near perfect flat plane at the non-impact surface.

Back Spalled Surface **Impact Surface** **Domed Shape**

Back Spalled Surface **Impact Surface** **Domed Shape**

Figure 22. PVC Barrel Flyer Plates (assumed)

Aluminum Barrel Flyer Plate

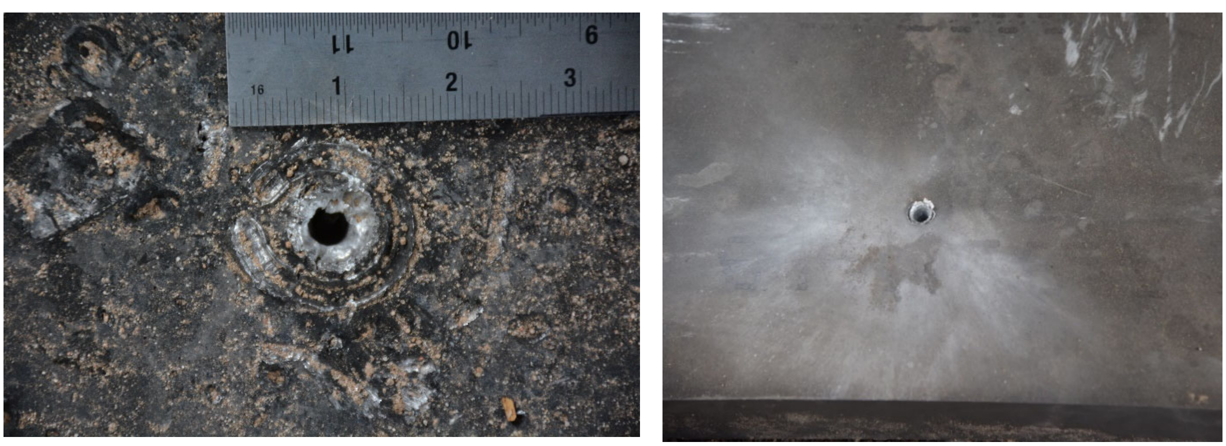
The (assumed) aluminum barrel flyer plate was very similar to the PVC flyer plates with a domed impact surface of ~3.0 in. diameter, a flat shear plane on the aft side of the flyer, again with a pedestal of approximately 0.1 in., and a thickness of ~0.55 in. There is a small fracture in the plate near the center on the impact side. The used orange shock tube remnant was melted to the aft surface post-impact when the flyer landed on the piece of plastic.

Back Spalled Surface **Impact Surface** **Domed Shape**

Figure 23. PVC Barrel Flyer Plates (assumed)

Experimental 0.75 in. Conical Shape Charge Result

The small conical shape charge performed well against the aluminum target. The explosively driven jet fully penetrated the 2 in. thick aluminum target and showed indication that additional thickness of the target plate would have been penetrated, of course to a point. The concrete block below the target was also damaged by the jet but a penetration hole was not observed. The slug or carrot of the jet appears to be stuck within the hole made by the jet. The entrance hole appears to be ~0.37 in. diameter, and the exit appears slightly smaller at ~0.25 in.



Jet Entrance Wound **Jet Exit Wound**

Figure 24. Copper Conical Shape Charge Target Penetration

600 GPF Linear Shape Charge Result

The commercially available copper-sheath 600 GPF linear shape charge performed as expected creating a groove in the target plate. The measured depth of the groove was ~0.88

in. which exceeded the design performance of 0.70 in. penetration. Full penetration through the 2 in. aluminum plate was not expected. The cutting jet was found rebounded but attached to the groove. The cutting length was as expected ~10 in, but had a smaller run-up penetration of approximately 1 in.

Groove Created in Aluminum Target **Groove Depth**

Figure 25. Copper Sheath Linear Shape Charge Target Penetration

Conclusions

This demonstration test series and range has been considered a success by all parties involved. The processes demonstrated, from range scheduling, test design, safety implementation, test conduct, data collection, range closeout, and finally reporting has exposed the Explosives Engineering students to valuable calculation, safety, and operations involved in even a small-scale test. The DOE Packaging Certification Program has benefitted from this exercise by both exposing students to explosive range operations, but also from exercising the system for future classes and demonstrations.

Future Work

At this time, the only remaining work to be done is to section the target plate to determine if spall occurred within the aluminum target. No additional analysis is scheduled, nor anticipated, for these tests. If the target is sectioned and spall is observed, this memo will be updated with additional information. It is anticipated that this memo will become part of the teaching materials for the DOE-PCP Explosives Engineering class in the future.

Acknowledgements

The authors would like to acknowledge the work of the many individuals who made this test series a success. The entire 9920 Facility test team, Jose Molina, Paul Buya, Ronald Wilder, Mathew Tosh, Travis Cochran, and Michael Lee all did an incredible job of completing all of the necessary planning and processes required to conduct an explosive test. Special thanks to Phil Sandoval (6626) for building/assembling all of the physical parts of the explosive flyers as well as Michelle Chatter (6514), Luke Gilbert (6815) and Vanessa Tsai (10669) for being instrumental in planning the classroom logistics, class handouts and solutions, and transportation of the students to and from the test site.

REFERENCES

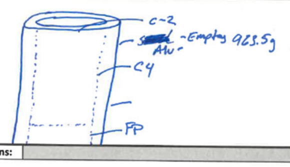
[1] Cooper, P.W. (1996). Explosives Engineering. Wiley-VCH

APPENDIX A. BUILD SHEETS

Charge build sheet:

Charge Ref.:	Charge 1	Build Date:	8-11-2022

Sketch:



Dimensions:

Explosives:

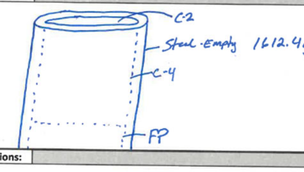
Explosive:	Type:	Quantity:	TU:	Resistance	End Disp?:	New sticker?:
Detonator:	nonel Det	1	148701	N/A		
Detonator:	209 ft	1	168371			
Booster 1:	C-2	1g	140843			
Booster 2:						
Main charge 1:	C-4	577g	161393			
Main charge 2:						
Main charge 3:						
Main charge 4:						
~~Main charge 5:~~	J-Hook	1	123766			
Shock tube	lead Line	800'	158824			

Date tested:

Charge build sheet:

Charge Ref.:	Charge 2	Build Date:	8-11-2022

Sketch:



Dimensions:

Explosives:

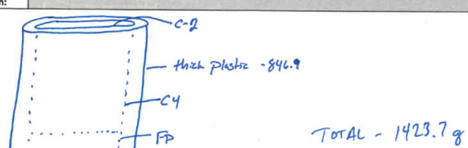
Explosive:	Type:	Quantity:	TU:	Resistance	End Disp?:	New sticker?:
Detonator:	nonel Det	1	148701	N/A		
Detonator:						
Booster 1:	C-2	1g	140843			
Booster 2:						
Main charge 1:	C-4	577g	145228 ~~161393~~			
Main charge 2:						
Main charge 3:						
Main charge 4:						
Main charge 5:						
Shock tube						

Date tested:

Charge build sheet:

Charge Ref.:	Charge 3	Build Date:	8-11-2022

Sketch:



Dimensions:

Explosives:

Explosive:	Type:	Quantity:	TU:	Resistance	End Disp?:	New sticker?:
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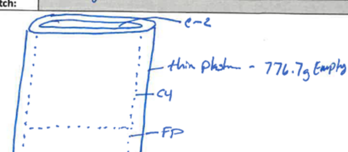
Detonator:						
Booster 1:	C-2	1g	140843			
Booster 2:						
Main charge 1:	C-4	577g	145228 ~~161393~~			
Main charge 2:						
Main charge 3:						
Main charge 4:						
Main charge 5:						
Shock tube						

Date tested:

Charge build sheet:

Charge Ref.:	Charge 4	Build Date:	8-11-2022

Sketch:



Dimensions:

Explosives:

Explosive:	Type:	Quantity:	TU:	Resistance	End Disp?:	New sticker?:
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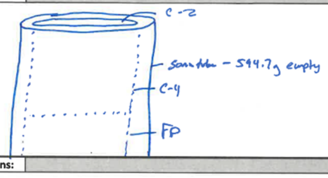
Detonator:						
Booster 1:	C-2	1g	140843			
Booster 2:						
Main charge 1:	C-4	577g	145228			
Main charge 2:						
Main charge 3:						
Main charge 4:						
Main charge 5:						
Shock tube						

Date tested:

Charge build sheet:

Charge Ref.:	Charge 5	Build Date:	8-11-2022

Sketch:



Dimensions:

Explosives:

Explosive:	Type:	Quantity:	TU:	Resistance	End Disp?:	New sticker?:
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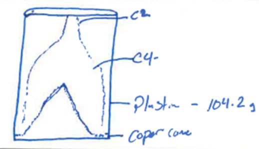
Detonator:						
Booster 1:	C-2	1g	140843			
Booster 2:						
Main charge 1:	C-4	577g	145228			
Main charge 2:						
Main charge 3:						
Main charge 4:						
Main charge 5:						
Shock tube						

Date tested:

Charge build sheet:

Charge Ref.:	Charg 6.	Build Date:	8-11-2022

Sketch:



Dimensions:

Explosives:

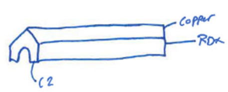
Explosive:	Type:	Quantity:	TU:	Resistance	End Disp?:	New sticker?:
Detonator:	nonel Det	1	148701	N/A		
Detonator:	209 Prim	1	168371			
Booster 1:	C-2	1g	140843			
Booster 2:						
Main charge 1:	C-4	17g	145228			
Main charge 2:						
Main charge 3:						
Main charge 4:						
~~Main charge 5:~~	J-Hook	1	123766			
Shock tube	nonel line	800'	158824			

Date tested:

Charge build sheet:

Charge Ref.:	Charge 7	Build Date:	8-11-2022

Sketch:



Dimensions:

Explosives:

Explosive:	Type:	Quantity:	TU:	Resistance	End Disp?:	New sticker?:
Detonator:	nonel Det	1	148701	N/A		
Detonator:						
Booster 1:	C-2		140843			
Booster 2:						
Main charge 1:	600 LSC	10"	145214			
Main charge 2:						
Main charge 3:						
Main charge 4:						
Main charge 5:						
Shock tube						

Date tested: