

# Enhancing impact velocity with shock interactions in a restricting die

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**Abstract.** Shock compression and impact studies could benefit from the ability to increase impact velocities that can be achieved with gun systems. Single-stage guns have modest performance (0.2-2 km/s) that limits their utility for high-pressure and high-velocity studies, while more capable systems are expensive and complex. We are developing a technique that uses a low-strength sabot with a tapered die to increase the impact velocity without modifying the gun itself. Impact of the projectile with the die generates a converging shock wave in the sabot that acts to accelerate the front of the projectile, while decelerating the rear portion. Preliminary experiments using this technique have observed a velocity enhancement of up to a factor of two.

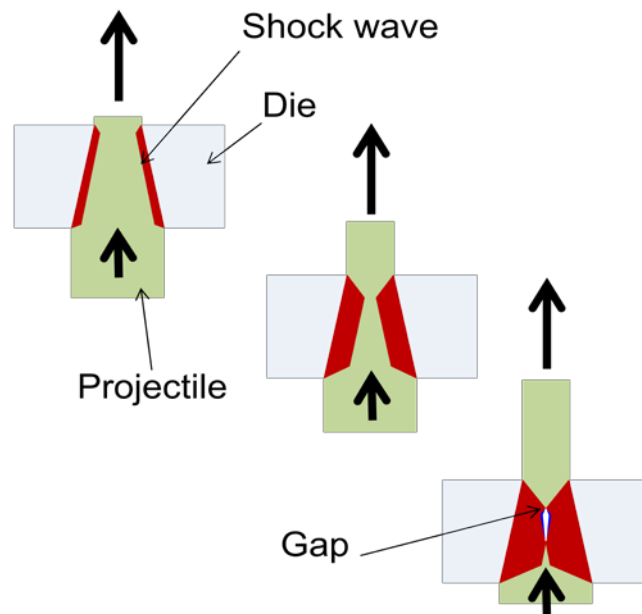
## 1. Introduction

The theoretical performance of a gun is dependent on the amount of potential energy that can be stored in the compressed working fluid of the gun and the efficiency with which that stored energy can be converted to kinetic energy of the projectile. Factors affecting these considerations include the maximum pressure allowed in the working fluid by the gun design, the molecular weight and sound speed of the fluid in the compressed state, and the mass of the projectile relative to that of the working fluid. Friction of the projectile with the launch tube and viscosity and nonideal behavior of the working fluid will degrade performance from the theoretical ideal. Typically, single stage guns have practical performance limits ranging from a few hundred m/s up to a little over 2.5 km/s. Two stage guns can extend the range to velocities of 4.5 to 11 km/s, depending on details of the gun design. Beyond that, other techniques have been tested and used. The common feature of systems designed for higher performance than single stage guns is that they are highly complex and expensive both to install and operate. Development of a means of enhancing the impact velocity performance of guns, particularly single stage types, would greatly increase the range of studies that could be performed by researchers having limited or no access to high-performance gun facilities. In this paper, we describe a concept for improving the impact velocity performance of research guns and present results of preliminary tests.

## 2. Concept

Our approach to improving gun performance is to allow the projectile, having a sabot manufactured from a relatively deformable material, to impact a tapered die. The restriction in the die can vary in





**Figure 1.** Schematic diagram of operation of the restricting die in accelerating the forward portion of a projectile.

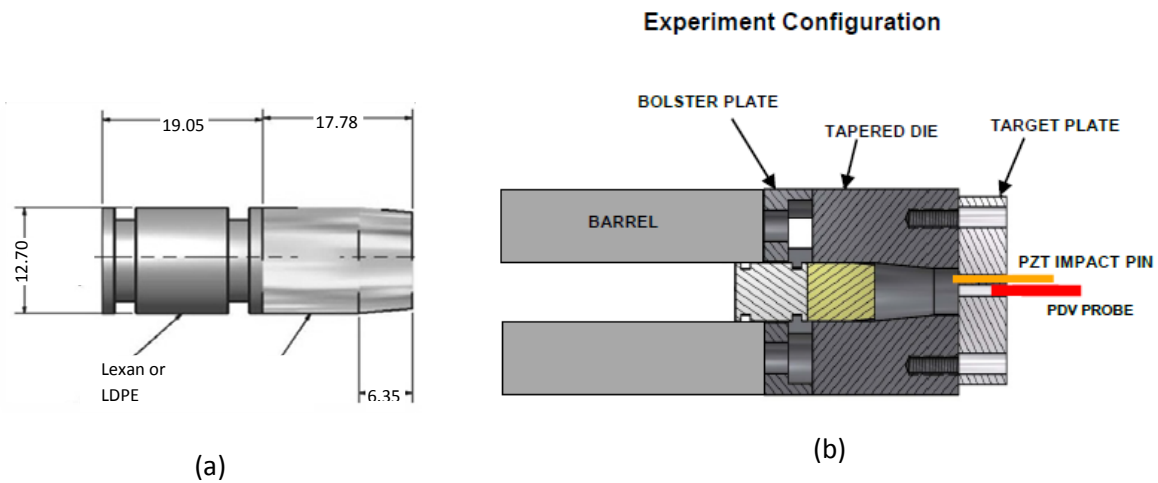
convergence rate and can have an arbitrary shape. The forward portion of the projectile may also deviate from a simple right circular cylinder so as to interact with the die in the most advantageous manner. The die is made of a material that is stronger, usually having a significantly higher shock impedance than the sabot. In this approach, the die is not an integral part of the gun and could be mounted in front of the gun or on the target plate, so that there is no need to make time-consuming and expensive modifications to use this technique with existing research gun facilities.

In operation, impact of the projectile into the tapered portion of the die (figure 1) generates a conically converging shock wave, creating a time-dependent stress field in the sabot. The conical convergence, the details of which depend on the die and projectile geometries, produces a stress gradient that is positive in the rearward direction, both spatially and temporally, resulting in acceleration of the leading portion of the projectile at the expense of decelerating the rearward portion. Ideally, the target is placed so that impact occurs at a time when the velocity of the forward portion of the projectile has reached a plateau.

The shock wave itself decelerates the portion of the sabot it is acting on, conserving momentum as the front of the projectile accelerates. At late times, divergence causes tensile stresses and fracture, separating the rear of the sabot from the front. Because the amount of momentum actually deposited in the die is small, the bulk of the momentum redistribution takes place in the projectile. The details of that redistribution are expected to depend critically on the initial velocity of the projectile, the properties of the sabot material, and the details of the sabot and die geometries.

### 3. Experiments

In order to test this velocity enhancement method and to collect data to aid model development, we conducted a series of tests using the 0.5-inch-bore IMPULSE gun located at the Advanced Photon Source at Argonne National Laboratory [1,2]. For these tests (figure 2), the forward portion of the sabot was made of low-density polyethylene (LDPE), with an aluminum or polycarbonate rear portion, and the die was made of steel. Two series of tests were performed. In the first series, the die had a conical taper with a  $5^\circ$  half-angle. There was no flyer plate carried by the sabot. In the second series,



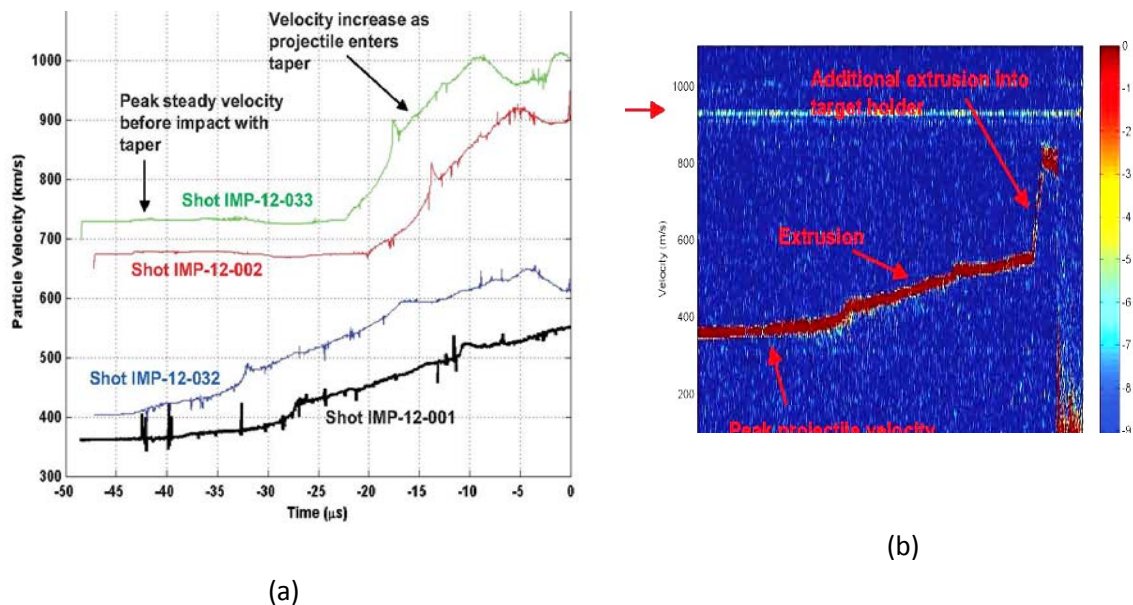
**Figure 2.** Design of experimental tests. (a) Projectile design. (b) Schematic of full experiment showing the position of the die relative to the gun barrel and target plate. A bolster plate on the muzzle is used to mount the target. In these tests, the die is mounted between the bolster plate and target.

**Table 1.** Velocity Enhancement Test Shots.

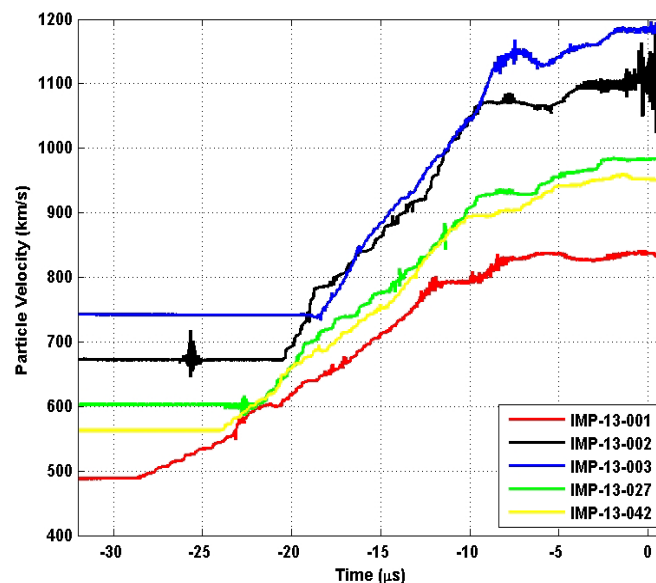
| Shot   | Taper<br>(degrees) | Rear Sabot<br>Material | Flyer Plate | $V_{\text{impact}}$<br>(m/s) | $V_{\text{final}}$<br>(m/s) | $\Delta V$ (m/s) | Ratio |
|--------|--------------------|------------------------|-------------|------------------------------|-----------------------------|------------------|-------|
| 12-001 | 5                  | Aluminum               | None        | 360                          | 560                         | 200              | 1.56  |
| 12-002 | 5                  | Polycarbonate          | None        | 677                          | 928                         | 251              | 1.37  |
| 12-032 | 5                  | Aluminum               | None        | 403                          | 655                         | 252              | 1.63  |
| 12-033 | 5                  | Polycarbonate          | None        | 734                          | 1014                        | 280              | 1.38  |
| 13-001 | 7.5                | Polycarbonate          | 1 mm Al     | 488                          | 833                         | 345              | 1.71  |
| 13-002 | 7.5                | Polycarbonate          | 1 mm Al     | 674                          | 1099                        | 425              | 1.63  |
| 13-003 | 7.5                | Polycarbonate          | 1 mm Al     | 742                          | 1184                        | 442              | 1.60  |
| 13-027 | 7.5                | Polycarbonate          | 1 mm Al     | 603                          | 972                         | 369              | 1.61  |
| 13-042 | 7.5                | Polycarbonate          | 1 mm Al     | 562                          | 952                         | 390              | 1.69  |

the die had a conical taper with a  $7.5^\circ$  half-angle and the sabot carried a 1 mm thick aluminum flyer plate. In both cases the sabot was made with a taper of the same angle as the die, but of shorter length. The die was mounted on a standard bolster plate attached to the gun muzzle and was backed by the target plate. In these tests, there was no sample in the target plate and the projectile front surface was observed by photonic Doppler velocimetry (PDV) [3]. Diagnostic recording systems were triggered by impact with a piezoelectric trigger pin.

Table 1 presents the details and results of the two test series. Figure 3 shows the velocimetry results for the sabot front surface from the first test series. In each case, the velocity record begins with the steady-state velocity achieved by the projectile prior to impacting the die. Upon impact with the tapered portion of the die, the velocity begins to increase, rising to a peak value and then decreasing. There are several features in the velocity profile during increase that we attribute to wave reflections within the sabot. The origin of the tensile waves causing the velocity to decrease after the peak value is reached is uncertain, but may result from the tensile stresses due to divergence at late times, as discussed earlier. In test 12-001, the sabot impacted the target plate, which acted as a second die with a half-angle of  $90^\circ$  reducing the bore to the diameter of the mounting hole for the PDV



**Figure 3.** Velocimetry records from first test series. (a) Velocity histories of all four tests. (b) Extended velocity history for shot IMP-12-001 showing further increase upon extrusion into PDV probe mounting hole in target plate.



**Figure 4.** Velocimetry records for the second series of tests.

probe, and experienced a second velocity increase to a value greater than twice the initial projectile velocity (figure 3(b)).

Figure 4 shows the velocimetry results from the second test series. The velocity histories are qualitatively similar to those for the first series, but many of the finer features are suppressed because of the greater strength of the flyer plates. The velocity decrease following the peak is also suppressed.

#### 4. Discussion

In simple incompressible nozzle flow of a uniform density fluid, the ratio of final to initial velocity is strictly proportional to the entry to exit area ratio of the nozzle, so it is instructive to examine the appropriate velocity and areal ratios from our tests. In the first set of experiments, the ratio of the final velocity to the initial velocity is near or significantly exceeds the areal ratio of the projectile front to the taper exit, which is 1.344. The maximum ratios observed are similar to the areal ratio of the maximum sabot cross section to the taper exit, which is 1.614. In shot 12-001, the total velocity enhancement was a factor of somewhat greater than 2, while the relevant areal ratios are 22.5 and 27.1 for the sabot front and maximum cross section of the sabot, respectively. In the second series, all of the observed velocity ratios are close to the areal ratio of the projectile front to the taper exit, which was 1.632. The presence of the denser impact plate is likely the direct cause of the lower velocity enhancement, relative to the areal ratios, in the second series. We also note that the ratio decreases with increasing impact velocity in the first series, which is likely related to changes in the relative timing of wave interactions as the impact velocity increases, rather than the difference in the material used for the rear portion of the sabot.

These results lead us to two conclusions. First, the density ratio of the sabot and impactor affects the results of the projectile-die interaction, as likely will the thickness and strength of the impactor. Second, details of the taper may critically alter the results. The optimal taper shape and convergence rate is likely to vary with both the sabot material used and the impact velocity. While the current results seem to be consistent with simple nozzle flow, we expect that performance can be increased significantly by tailoring the details of the shock wave interactions in the sabot.

#### 5. Future Work

We plan to continue experiments to investigate our approach to enhancing impact velocity. In the tests conducted thus far, deformation of the impactor plate has not been characterized. Using the radiographic capabilities associated with the IMPULSE gun, we plan to conduct experiments in which the sabot is imaged as it exits the taper. Also, because strength effects do not scale with dimension, we expect that a scaled version of the same experiment using a gun with a different bore diameter may produce different results. To study this issue, we plan to conduct some experiments on larger guns located at Los Alamos National Laboratory.

It is expected that a more complicated taper geometry, possibly a compound conical taper, will be required to optimize the impact velocity while maintaining the impactor in a planar geometry. While an exhaustive number of experiments might be performed in an attempt to refine the design of the die and projectile, a more efficient approach is to develop a reliable model to aid in studying the effects of various changes, validated by a limited number of experiments. We plan to develop a model that sets one parameter, namely the die geometry, constant and then provides a means for designing the projectile front geometry and launch velocity (and, possibly, material parameters) required to obtain a specific final impact velocity for a given flyer plate areal mass. We are presently working to develop such a model that can be used to define the details of a shot to achieve a specific outcome. Preliminary calculations using hydrodynamics codes have met with limited success because of mesh tangling issues in the highly-deformed regions of the sabot in Lagrangian codes, issues following the front of the sabot in the Eulerian codes, and incorrect behavior of the sabot, presumably due to inadequacies in the existing material model for low-density polyethylene.

#### 6. Summary

We have developed an approach to enhancing the performance of guns by allowing the sabot to extrude through a tapered die. Interaction of shock waves generated by the impact allows this technique to achieve higher final velocities than would be expected from simple extrusion alone. A series of tests has shown the effectiveness of this technique. Current efforts are aimed at improving the performance of this technique and testing the ability to obtain planar impacts using strong impactor plates. We expect this technique to be useful for launching small projectiles for impact and

penetration studies and for improving the performance of guns used for shock compression experiments. We suggest that this approach should be broadly applicable to existing guns. However, details would be gun- and shot-dependent.

We expect to obtain performance that is better than would be expected by simple extrusion of an incompressible fluid, where the velocity enhancement is simply controlled by the ratio of the entrance and exit areas. However, achieving this performance requires careful optimization of the design and materials used, which will require use of an accurate computational model of the system.

### Acknowledgements

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