Modeling of propellant flow and explosively-driven valve for the Large-Bore Powder Gun

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Abstract. The Large-Bore Powder Gun is being developed to provide impact experiments on physics samples at the Nevada Test Site. A confinement system is required to seal the target chamber from the gun system to keep it free of hazardous materials from the impact event. A key component of the confinement system is an explosively driven valve (EDV), which uses a small amount of explosive to drive an aluminum piston perpendicular to the barrel axis into a tapered hole. The objective of this study is to evaluate designs of the confinement system via computational simulations using models validated with prototype experiments. A novel approach is adopted for this work, in which an energy source developed based on interior ballistic calculations was implemented in a hydrocode, which in turn was used to model the propellant flow, EDV operation, and their interactions. This paper describes the models and some simulation results leading to a proposed confinement system design.

1. Introduction
The Large-Bore Powder Gun (LBPG), with its 3.5-inch bore diameter, is being developed for dynamic experiments at the Nevada Test Site capable of providing impact velocities exceeding 2 km/s on multiple samples simultaneously [1,2]. Because of the requirement to reuse the gun for multiple experiments, a confinement system is used to seal the target chamber from the gun system to keep it free of hazardous materials from the impact event. Figure 1 shows the LBPG with its launcher and confinement subsystems. The explosively-driven valve (EDV) in the confinement subsystem provides fast closure by driving an aluminum piston vertically across the barrel into a tapered hole after the projectile passes and before it impacts the samples in the target chamber.

Figure 1. Drawing of the LBPG showing the launcher subsystem consisting of the breech and gun barrel and the confinement subsystem with the EDV and target chamber. The system length is 61 ft.

Integrated system tests described in [1] have shown that the EDV performed satisfactorily at projectile velocities up to 1.3 km/s but at higher velocities (e.g., 1.8 km/s) the piston was stopped in the barrel and did not seat in the hole at the bottom to provide an adequate seal. This failure is due to
the high-pressure propellant gas resisting the EDV piston as it enters the barrel. Furthermore, the high-speed flow imparts a lateral load on the piston. Therefore, complete characterization of the propellant flow (velocity, pressure, and density) is crucial in evaluating the design of the EDV and confinement subsystem. In the following sections, we first discuss modeling of the propellant flow in the barrel. Then we present an EDV model and results from selected simulations of the valve operation in the absence, as well as in the presence of propellant gas flow. Results from these and additional simulations show that a single EDV cannot provide the closure necessary for all projectile (i.e., propellant) velocities. A proposal was made to add a flow interrupter upstream of the EDV to lessen the load on the EDV piston. Some modeling results of this new design concept are described in section 4. Conclusions of this work are given in section 5.

2. Propellant flow modeling

The gun propellant used in the LBPG is M14 in 0.54” long, 0.25” diameter, cylindrical pellets with seven perforations along the length. Gun performance curves relating projectile velocity to the powder charge mass ratio have been established in tests for launcher qualification [1,2]. The gun performance has also been modeled with the Los Alamos Interior Ballistics Analysis Code (LAIBAC), which predicts the projectile displacement and velocity as well as the pressures at the base of the projectile and in the breech. The method in LAIBAC is based on the simplified ballistic model of Krier and Adam [3]. However, it does not track the thermodynamic state of the propellant gas, hence cannot predict the gas density, which is essential in determining the lateral momentum the EDV piston has to work against. Therefore, we developed an axisymmetric model of the breech and barrel system, with an energy source that is calibrated to generate the kinematics as predicted by LAIBAC. The model was implemented in the CTH (version 10.1) hydrocode [4], which can give a full description of the propellant gas (velocity, pressure and density) behind the projectile as it travels down the gun barrel. Figure 2 shows a schematic of this model with physical conditions corresponding to design qualification. Typical calculations used a 1-cm mesh resolution.

**Figure 2.** Schematic of an axisymmetric CTH model for LBPG propellant flow.

**Figure 3.** CTH propellant flow modeling results, (a) energy source, (b) breech and projectile base pressures, and (c) projectile velocity and displacement. The excellent agreement in the integrated projectile base pressure profile (i.e., total impulse on the projectile) leads to almost exact agreement in the kinematics.
The propellant is modeled as an ideal gas initially distributed in the breech volume at a density and temperature giving the right mass and atmospheric pressure. Figure 3 shows the energy source and CTH calculated pressures and projectile velocity and displacement, which compare almost exactly with the LAIBAC predictions. The energy rate profile represents the effect of the propellant burn, which completes at 10.5 ms. The results indicate the breech and projectile base pressures build up to a maximum at round 8 ms, then drop as the projectile begins to travel down the barrel which in turn increases the volume for expansion of the propellant gas. The gas accelerates the projectile to a velocity of 2 km/s at the EDV location, where the gas pressure and density are 3.6 ksi and 0.030 g/cc, respectively. Additional calculations assuming sudden and gradual (within 1 ms) blockage of the gas flow after the projectile passes the EDV location give estimates of the maximum stagnation pressure ranging from 25 to 39 ksi. We next turn to modeling of the EDV and its response to the high-speed, high-pressure and high-density gas flow.

3. EDV modeling

Figure 4 shows an axisymmetric CTH model of the EDV, which contains a 3.8-kg piston in a thick-walled housing with a total assembly mass of 254 kg. The PBX 9501 charge is modeled with programmed burn using a JWL EOS. The piston and mid-sleeve are modeled with the Mie-Gruneisen EOS and Steinberg-Guinan strength model for 6061-T6 aluminum. The baffle plate and inner and outer sleeves are modeled with the Mie-Gruneisen EOS and Johnson-Cook strength model for V-250 steel. The steel housing and locking nut are modeled as a rigid material. Typical calculations employ a 0.5-mm mesh resolution and begin with detonation at the top of the PBX 9501 disc.

![Figure 4](image_url) **Figure 4.** Axisymmetric CTH model of the EDV with geometric simplifications (e.g., plastic case holding HE charge ignored). The vertical scale numbers are in cm. The black dots are tracer particles for the calculations.

![Figure 5](image_url) **Figure 5.** Final piston position and closing time in stand-alone EDV simulations: (a) 55-g PBX 9501, (b) 110-g PBX-9501. (c) Technique for measuring closing time using PZT pins located at the top and bottom of the bore.

To validate the above model, we simulated the prototype experiments reported in [5] in which various amounts of PBX 9501 were used to drive the piston in a stand-alone EDV (i.e., no propellant flow). In most of the tests, the amount of explosive used was either 55 g or 110 g of PBX 9501 pressed to 1.80 g/cc. Figure 5 shows the final position of the piston as it seats at the bottom of the valve as well as the closing time, which is defined as the difference between the times when the front surface of the piston reaches the top of the bore and when it reaches the bottom. As expected, the higher HE charge leads to a faster closing time and deeper penetration of the piston.

In addition to PZT pins used for measuring the closing time, PDV probes were also used in the experiments to measure the piston velocity. As seen in Figure 6, the PDV data show that the piston accelerates to a maximum velocity, and then slows down as it enters the tapered hole. Averaged values for the closing time and maximum piston velocity were calculated from data corresponding to HE charges of 55 g and 110 g. Table 1 lists the calculated and measured velocity and closing time for the
two HE charges. Note that for the 55-g charge, the maximum piston velocity is 0.16 km/s in both experiment and simulation, an excellent agreement, while the calculated closing time is 8.5% lower than the measured value (0.75 vs. 0.82 ms). For the 110-g charge, the discrepancies between simulation and experiment are 8.7% in the piston velocity and -5.9% in the closing time. Therefore we judge that the EDV model developed is a reasonable representation (to within 10%) of the real system with regard to the piston velocity and closing time.

### Figure 6
PDV data from four prototype EDV tests reported in [5]: (a) 55-g PBX 9501 charge, (b) 110-g PBX 9501 charge, (c) 110-g PBX 9501 charge (new breech design), (d) 55-g PBX 9501 charge plus 100-g IMR 4340 hybrid charge. The velocity scale is from 0 to 0.25 mm/μs and the time scale is from -200 to 1600 μs except in (a) where the maximum time is 2000 μs. The times to reach maximum velocity range from 1 to 1.6 ms.

### Table 1
Maximum piston velocity and closing time from simulation and experiment for 55-g and 110-g PBX 9501 charge masses. The maximum % difference between simulation and experiment is 8.7% in the velocity for the 110-g charge.

| HE Mass | 55 g | 110 g |
|---------|------|-------|
| Maximum Velocity Simulation | 0.16 km/s | 0.21 km/s |
| Maximum Velocity Experiment | 0.16 km/s | 0.23 km/s |
| Closing Time Simulation | 0.75 ms | 0.54 ms |
| Closing Time Experiment | 0.82 ms | 0.51 ms |

The above axisymmetric model by itself cannot directly represent the operation of the EDV in the presence of lateral propellant flow because the real problem is 3D. However, a 3D model was judged to introduce complexities not justified given the scope of this study. Therefore, a planar 2D model (preserving the length scales in the directions of both the piston axis and gun barrel axis) with the same HE charge-to-piston mass ratio as the axisymmetric model was developed. Simulations of selected prototype EDV tests were repeated to verify that the 2D planar and axisymmetric models give equivalent results.

We then used the planar model to study the response of the EDV in the presence of gas flow as characterized in section 2. Figure 7 shows results (at 1.6 ms after ignition of 110 g PBX 9501) from modeling two cases of different gas velocities. As depicted in figure 7(a), where the gas velocity is 1.0 km/s, the EDV piston is seated at the bottom and provides a seal on the target side, where some soft aluminum piston material is peeled back as the result of cutting by the wall of the tapered hole. This case is similar in conditions to integrated system test (IST) #3 [1], although the gas velocity in the test is higher at 1.3 km/s. As seen in figure 7(b), where the gas velocity is 1.8 km/s, the EDV fails to provide confinement against this higher flow. Also shown are pictures taken of IST #7 with similar operating conditions as the simulation, indicating that the piston has broken into at least two pieces, with one piece lodged in the bore extending into the target side, and another penetrating deep into the
bottom of the valve. In the simulation, no fracture model is used for the piston, which therefore just deforms plastically (instead of breaking) because of the relatively weak strength of the material.

Further simulations were performed to evaluate various design modifications of the EDV. It was determined that no practical design of the EDV could work successfully against the gas load at the higher velocities required for the LBPG.

**Figure 7.** Simulation of EDV response to lateral propellant flow at two velocities and comparison against integrated system test (IST) results.

**Figure 8.** Proposed design of confinement subsystem with flow interrupter added upstream of EDV.

4. **Confinement subsystem with EDV and flow interrupter**

A design concept was proposed to reduce the gas flow before it reaches the EDV by use of a device called flow interrupter, which is designed to operate with two colliding pistons that meet at the center of the bore. Figure 8 shows a drawing of the flow interrupter design and its placement upstream of the EDV. The pistons in the flow interrupter are made of the relatively stronger (than the EDV piston) aluminum alloy 2024 with a T351 temper, which should better withstand the dynamic gas load. Each piston in the flow interrupter weighs 6.6 kg and the total assembly mass is 440 kg.

**Figure 9.** Simulation of operation of EDV with flow interrupter in presence of 2-km/s propellant flow, with two configurations using 60 g (a) and 100 g (b) of HE charge in each half of the flow interrupter.
A 2D model of the flow interrupter was developed following the same approach as for the EDV. The flow interrupter model was successfully validated against an experiment measuring the closing time. We then combined this model and the EDV model to study how the new confinement system would perform under a 2.0 km/s propellant gas load. Figure 9 shows results of two simulations using different amounts of PBX 9501 charge (60 g and 110 g) in each half of the flow interrupter. As seen in figure 9(a), the flow interrupter with a 60-g HE charge does not reduce the flow enough for the EDV to work properly. (The pistons actually collide but then bounce back, not offering sufficient flow stoppage.) However, with a 100-g charge, the colliding pistons stay in contact and provide adequate flow blockage to enable the EDV to function as desired. The penetration of the EDV piston as depicted in figure 9(b) is so deep that a smaller EDV HE charge of 55 g (instead of 110 g used in the simulation) would be sufficient to give a leak tight seal.

5. Conclusions
Computational models have been developed to characterize the propellant gas flow in the LBPG and study the operation of the EDV and flow interrupter under the gas load. These models are invaluable in providing engineering insights to analyze and understand experiments and confinement system designs and explore alternative ideas. We conclude that no design of the EDV alone can work across the entire range of operating projectile velocities. However, modeling results show that, with the right amounts of PBX 9501 charge masses and proper triggering of the devices, a system consisting of an EDV and a flow interrupter upstream will provide the necessary confinement for the LBPG.

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