

Explosively driven fast closing blast shutter

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The Air Force Research Laboratory's Directed Energy Directorate has developed a fast closing shutter for the purpose of explosive debris mitigation. The shutter forms a high vacuum seal in 15 μ s by the plastic deformation and pinching off of an 8 mm inside diameter profiled cartridge brass tube by two explosively propelled Ti slugs impacting from opposite directions. Two explosive detonators, the tube itself, and steel disks which back the Ti slugs are the only sacrificial parts. Design and performance details, the developmental history, scaling issues, and advantages over other shutter designs are discussed. [S0034-6748(00)01210-7]

The blast shutter presented is designed to protect hardware exposed to the aftermath of solid liner implosions driven by the Air Force Research Laboratory's Shiva Star capacitor bank¹ and provide a subsequent high vacuum seal. The design concept should be of interest where shielding from high velocity debris is needed to protect items with line of sight exposure to energetic transient events, or as a fast shut-off valve.

Several designs for *reusable* fast closing shutters have been published having an obstruction accelerated into position upon triggering of pneumatic or electromagnetic drivers.²⁻⁷ Closing speed for these, defined as aperture length in the direction of closure divided by closing time, is limited to tens of m/s if component deformation due to impact is to be avoided. One way around this is to employ a rotating disk with an aperture that opens for a brief period every revolution.^{8,9} Hundreds of m/s can be achieved by this method, with tradeoffs being limited stopping power, lack of a tight seal, periodic reopening, and lack of external triggering. A triggerable uninterrupted vacuum seal with high stopping power and comparable closing speed can be achieved with explosively driven closures with significant sacrificial elements.^{2,10} Previously published designs generally involve surrounding a ductile tube with explosives and imploding. The pressure of a pulsed high magnetic field may be used in lieu of explosives for small devices.¹¹ The presented design, however, uses explosives to propel two slugs which impact a tube from opposite sides simultaneously, pinching it shut. Figure 1 summarizes the performance of the referenced and presented devices.

An exploded view of the blast shutter assembly is illustrated in Fig. 2. The device uses a profiled annealed cartridge brass (C26000) tube with minimum inside and outside diameters of 0.8 and 1.18 cm, respectively. The tube is crimped by two 3 g Ti (6Al 4V) slugs propelled by unboosted RP1(TM) Electronic Bridge Wire detonators (P/N

167-4314)¹² wired in series. The tube and detonators are confined by a 14 cm by 14 cm by 5 cm dual half-shell casing made of Cr-Mo steel (4340) heat treated to Rockwell 8. Grooves in the casing capture ridges on the tube to provide axial confinement. Vents in the casing release the explosive products after slug acceleration to minimize stress on the casing. The tube, RP1's, and two 2.2 g mild carbon steel disks placed behind the Ti slugs to protect the slugs from the explosive products are the only expendables.

Figure 3(a) shows various views of a slug. The leading end is a blunted wedge. Initially, there are no gaps between detonator, disk, and slug, but each slug is 1.25 cm from the tube. The slugs appear to be reusable, although the base forms a broad 0.4-mm-deep depression, and the blunted wedge is pressed in by 25 μ m in the middle. Figure 3(b) shows the traced outline of a photo of a closed tube sawn in half. The crimp forms a seal with a leak rate upper bound (background level) of 10^{-9} l/s standard temperature and pressure (STP) air, based on ion gauge measurements of a trapped volume's pressure rise rate. A uniform expanded HeNe laser beam transmitted through the tube then focused onto a linear optical receiver gives a signal proportional to the orifice area to within 5%. Figure 4 shows such a measurement versus time relative to the detonator trigger pulse. The 15 μ s time to closure implies a closing speed of 533 m/s.

Tube design concepts that did *not* work may be of interest to those who wish to try variations. The capture ridge on the tube was found to be necessary since simple straight annealed oxygen free high conductivity (OFHC) Cu and stainless steel (304) tubes used in early designs pinched into two halves ejected at high speed, tearing open any seal in the process. These tube materials were also tested with all other design features being the same as the final design (Fig. 2). Dimples that result in significant tensile elongation were formed at four places in the tube wall just beyond the sealed

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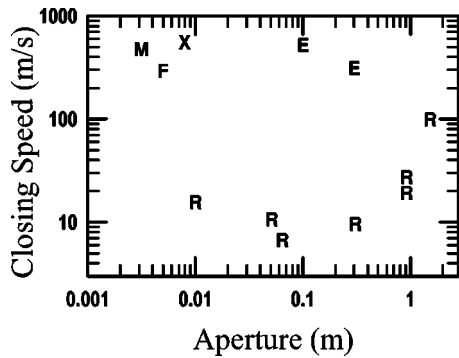


FIG. 1. Mean closing speed vs aperture for various fast shutter devices. Symbols R, F, E, and M refer to shutters with Reusable triggered obstructions, Fly wheels, and Explosive and Magnetic pressure direct drive. X represents the presented device. The 100 m/s “reusable” shutter (see Ref. 2) deforms components, requiring minor rebuilding (see Ref. 3).

region for all metals tested, as shown in Fig. 3(b). One of these dimples had a significant leak for the Cu test. The steel tube, meanwhile, did not seal, leaving a 0.1 mm gap in the orifice. Apparently, Cu is insufficiently ductile and the steel’s yield strength is too high. Annealed cartridge brass was ultimately chosen because of its low yield strength and high ductility.¹³

As for other failures, Ti slugs tested for which the wedge was left with a sharp edge shattered, breaching the tube wall with fragments. Slugs made of Al 6061-T6 splattered with insufficient force to cause closure. Omitting the steel disk behind the slug resulted in a large crater in the slug base, rendering it nonreusable. A smaller half-shell casing made of the same alloy but with dimensions along the detonator and tube axes and transverse to these being 6.0, 5.1, and 7.7 cm,

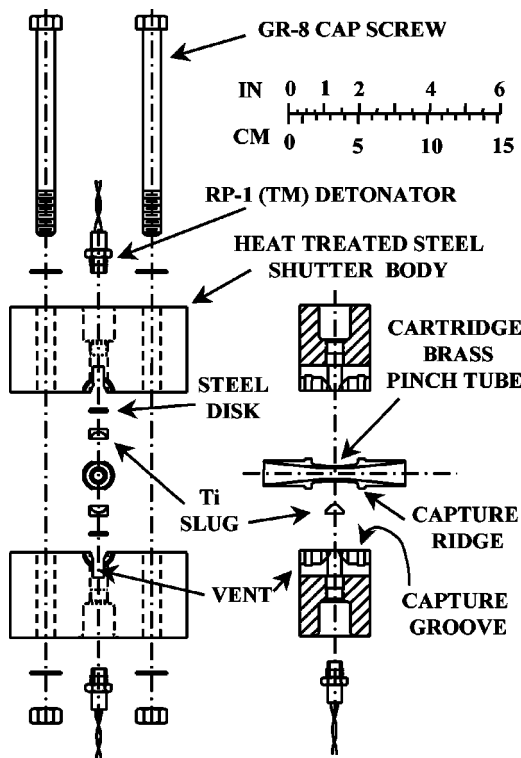


FIG. 2. Exploded view of blast shutter assembly.

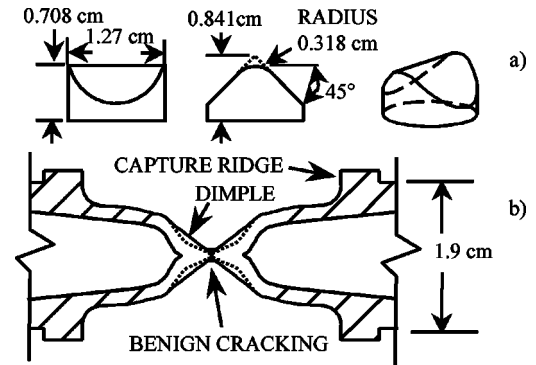


FIG. 3. Detailed views shown to scale are (a) edge line drawings of a titanium slug viewed from various perspectives and (b) cross sectional views of a cartridge brass tube after closure (the initial inside diameter is 0.8 cm).

respectively, severely cracked after one usage.

A refinement of the present design into one more suitable for size scaling is desirable. A simple scaling to a 5 cm orifice which closes at the same speed, for example, would result in a block of steel 85 cm by 85 cm by 30 cm containing 300 g of explosive. Each RP1 contains 0.25 g of pentaerythritol tetranitrate (PETN) and 0.365 g of Research Department Explosive (RDX)¹² which have heats of detonation of 5.8 and 5.4 kJ/g, respectively,¹⁴ giving a total energy of 3.4 kJ. The slug and steel disk have a combined mass of $m_0=5$ g and are propelled to velocity of at least $v_0=267$ m/s (half the closing speed), giving a kinetic energy of 0.18 kJ. This low conversion efficiency (5%) is due to the lack of blast containment; most of the energy vents out the sides and back of the slug barrel. Efficiency would improve if a sacrificial cartridge contained the blast on all sides except the one exposed to the disk/slug. The cartridge could also be designed to largely decouple the detonation shock from the casing. A significant reduction in explosive load and system mass would result.

We conclude with a list of advantages of dual slug closure over axisymmetric implosion schemes:^{2,10} (1) The high potential conversion efficiency of a piston/cylinder geometry and the less energetically demanding flattening of a tube (versus the large circumferential plastic strain required of an

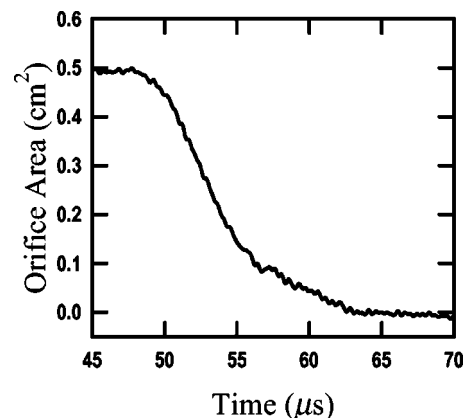


FIG. 4. Area vs time of the shutter orifice as measured by the intensity of a uniform expanded laser beam aperture limited by the orifice. Time $t=0$ corresponds to the RP1(TM) detonator trigger signal.

axisymmetric implosion) mean that less explosive is needed. (2) A larger solid angle may be exposed and/or the exposed item may be placed closer to the transient event since there is more flexibility in choosing a shorter region to seal (the shape of the slug largely determines the shape of the closed tube). (3) The circumferential stress of an axisymmetric implosion leads to wall fluting due to buckling instability, compromising seal integrity. (4) Spallation of the interior tube wall may interfere with the vacuum and mechanical integrity of the seal in designs where the explosive is in direct contact with the wall. In the presented design, the explosive shock is dissipated by the (high strength) slug while in transit. No spall is observed. (5) An axisymmetric implosion converges metal onto the symmetry axis, which may cause jetting. Our scheme, however, converges metal onto a symmetry *plane*, thereby distributing the impact over a large area. No jetting is observed. This last advantage, in particular, suggests that scaling to higher speeds is possible.

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