Passive mine blast attenuators constructed of rock rubble for protecting ventilation seals

M.J. Sapko
Sapko Consulting Services, LLC, Pittsburgh, Pennsylvania

M.R. Hieb
West Virginia Office of Miners' Health Safety and Training, Charleston, West Virginia

E.S. Weiss, R.K. Zipf Jr., and S.P. Harteis
National Institute for Occupational Safety and Health, Pittsburgh, Pennsylvania

J.R. Britt
Applied Research Associates, Inc., St. Joseph, Louisiana

Abstract

The design requirements for mine ventilation seals have undergone a radical transformation in recent years, and these revisions have greatly increased the cost of the seal designs and their construction. For example, in the past two years, new federal regulations have increased the minimum design requirement to withstand explosion pressures from 138 kPa (20 psig) to 345 kPa (50 psig) or 827 kPa (120 psig), depending on whether the sealed mine volume is monitored continuously or not. Moreover, there is still a possibility that under certain conditions (such as detonations), even higher pressure requirements may be necessary. The ability of a monolithic, stand-alone mine seal to reliably withstand the full range of possible explosion pressures is becoming increasingly difficult and expensive. In an effort to develop a practical alternative, the West Virginia Office of Miners' Health Safety and Training (WVOMHST) and the National Institute for Occupational Safety and Health (NIOSH) have collaborated in a research effort to develop a practical, economic and safe mine sealing technique that can enable mine seals to meet the full range of new explosion pressure design requirements. The basic idea is to use a barrier of common mine gob and rubble, in combination with a conventional mine seal, so that the pressure resulting from a gas explosion is reflected, absorbed and attenuated, and the pressure on the ventilation seal is reduced. This paper discusses some concepts and preliminary test results for a "passive mine blast attenuator" (PMBA) that can provide a useful alternative to increasingly larger and stronger stand-alone mine seals. Numerical models and full-scale experiments conducted at the NIOSH Lake Lynn Laboratory Experimental Mine (LLEM) show that the use of a PMBA can signficantly reduce the blast pressure and impulse on conventional ventilation seals.

Introduction

Recent explosions at the Sago Mine in West Virginia and the Darby Mine in Kentucky in 2006 have greatly heightened awareness of the need for high quality ventilation seals that can protect miners from the effects of violent explosions and also from the toxic gases resulting from ignitions inside the sealed volumes of underground mines.

These disasters have led state and federal regulators to adopt more stringent performance standards for mine ventilation seals, including, most notably, the Mine Safety and Health Administration (MSHA) Final Rule 30 CFR Part 75.335 (April 18, 2008) on Sealing of Abandoned Areas. This new rule requires that a mine seal shall be designed, constructed and maintained to withstand: (1) at least 345 kPa (50 psi) overpressure for a specified pressure-time curve, when the atmosphere inside the sealed volume is monitored and kept inert; (2) overpressures of at least 827 kPa (120 psi) for a specified pressure-time curve if the atmosphere is not monitored or is not kept inert;

(3) overpressures greater than 827 kPa (120 psi) if the ventilation seals are constructed around mine volumes that are not monitored and are not inert, and if any one of the following three conditions occurs: (i) a homogeneous explosive atmosphere exists, (ii) pressure piling could produce overpressures exceeding 827 kPa (120 psi) or (iii) detonation is likely. If the latter situation exists, then seal strengths must be designed to withstand more than 827 kPa (120 psi), as determined by a professional engineer. These regulations reflect a worst-case explosion pressure scenario that was discussed in a NIOSH study entitled, *Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines* (Zipf et al., 2007).

Given these new, more rigorous standards, it is necessary and desirable to explore new ideas and concepts for sealing mine gob volumes in ways that will protect miners against explosions. One such concept is to use a supplemental structure, such as a passive mine blast attenuator, or PMBA, to reflect, absorb and attenuate the explosion pressure before it arrives at the ventilation seal rather than relying on a single seal to contain the entire impulse. The West Virginia Office of Miners' Health Safety and Training (WVOMHST), the National Institute for Occupational Safety and Health (NIOSH) and Sapko Consulting Services, LLC, have collaborated on a research effort to evaluate practical, economic and safe methods for sealing abandoned volumes in underground mines. In the PMBA method, common mine gob and mine rubble are used to construct barriers that will reflect, absorb or otherwise attenuate the high explosive pressures that are produced by gas or dust explosions, before those pressures come into contact with the ventilation seals. The feasibility of using such an approach began with three-dimensional simulations based on the Second-Order Hydrodynamic Automatic Mesh Refinement Code (SHAMRC) and culminated with three large-scale, exploratory experiments on blast wave attenuators that were conducted at the Lake Lynn Experimental Mine (LLEM). SHAMRC is an Eulerian finite difference code widely used by US government agencies, particularly the Department of Defense (DoD), for calculation of air blast (and other transient gas dynamics) effects. Preliminary results show that the use of PMBAs in underground mines is a viable and potentially useful approach when conditions warrant protecting against pressures up to and exceeding 827 kPa (120 psi).

Passive blast wave attenuators in defense applications

Passive blast wave attenuation systems have been used for many years to protect against explosions in underground munitions complexes. The primary purpose of the attenuators in such applications is to reduce and absorb the explosive shock waves that emanate from a blast on the surface and prevent propagation of those forces down the ventilation shafts and into underground bunkers. Most such attenuators are composed of sand or rocks that permit the passage of some air for ventilation and cooling into complexes yet will significantly attenuate the shock waves produced by surface bombs. Blast attenuators are passive systems that reflect and absorb energy in such a way that they reduce the dynamic loading on the final containment structures, any pressure sensitive systems underground and, most importantly, personnel. When applied in a mine environment, passive attenuators can potentially reduce the dynamic loading on a ventilation seal and reduce the magnitude of the explosion pressure on the final containment seal.

Although granular filters are often used to protect against the large but short-impulse shocks produced by explosive detonations (~207 MPa [30,000 psi]), limited information is available about how they might influence mine explosions that produce relatively low shock pressures (~4.4 MPa [640 psi]) of longer duration. The most relevant results are those related to attenuation of shock waves by partitions, grids, and granular materials (Britan et al., 2001; Britan et al., 2004; Gelfand et al., 1987; Lind et al., 1999) and by using mine gob plugs (Hieb and Sapko, 2008; Hieb and Wooten, 2008; Unrug et al., 2008).

Conceptually, the overpressures on a seal may be reduced by placing a passive barrier in the tunnel between the putative explosion and the seal. When a shock wave impacts the barrier head-on, one portion of the wave is reflected, some is absorbed and the rest is transmitted through the open or porous parts of the barrier. These processes are referred to as shock wave reflection, absorption and transmission (or diffraction), respectively. By the proper choice of barrier geometry and construction, the peak pressure and the rate of pressure loading on the outby (or downstream) side of the containment seal can be significantly reduced. Further, PMBAs used in conjunction with 827 kPa (120 psi) mine seals have the potential not only to protect miners against 827 kPa (120 psi) overpressures, but also against the "worst-case" methane-air detonation scenario described by Zipf et al. (2007), wherein direct pressure loadings can reach and exceed 4.4 MPa (640 psi).

Conceptual designs for a passive mine blast attenuator

Two basic approaches have been considered for constructing a PMBA in an underground mine; both utilize rock rubble or gob materials that are commonly found underground.

The first is a "shot-rock" design (Fig. 1), wherein a small section of the mine roof is shot down to close off a mine entry. Conceptually, this should be done between two mine crosscuts, rather than in a mine intersection, to reduce the amount of shot material that is needed to provide full closure of the entry. Optionally, and for the same reasons, mine gob can be placed on the mine floor and then 'walked-in' with a mine scoop or raised by other means to within approximately 1.1 m (3.5 ft) of the mine roof. The shot holes can be pre-drilled to a prescribed depth and shot such that a complete or nearly-complete closure of the mine entry is achieved.

The second approach is a "fully-stowed" design (Fig. 2), wherein the gob material is placed and compacted fully up to the mine roof without shooting down any of the mine roof itself. Although this approach requires significantly more material handling and more attention to the details of placement and compaction in order to achieve uniform closure along the roof and ribs, it was developed (and used) primarily for the convenience of conducting full-scale explosion experiments without permanently altering the LLEM test facility.

It is the authors' opinion that the "shot-rock" PMBA design (Fig. 1) is likely to be the most economical and effective design in practice. Shooting down the roof generates larger interlocking rubble, the weight of which increases normal forces to and confinement of the underlying particles, and this, coupled with roof hitching at the cavity walls, increases

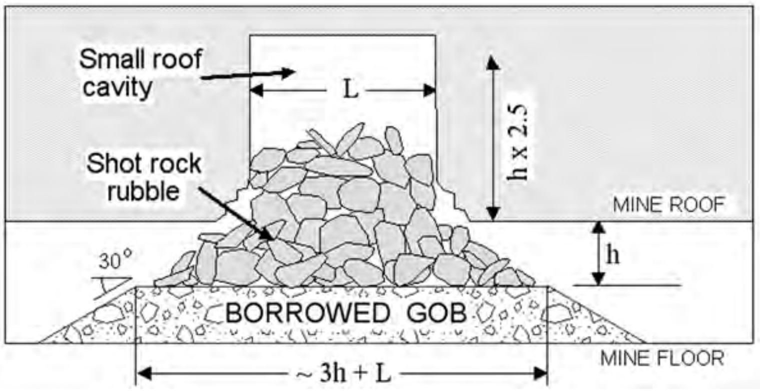

Figure 1 — The "shot-rock" optimum attenuator design, where a section of the mine roof is shot down with explosives using holes drilled prior to placement of an optional foundation layer of borrowed gob material.

resistance to particle displacement and erosion during the gas blow-by phase that accompanies the reduction of pressure inby the PMBA. With the 'shot-rock' method, any gob on the bottom will also facilitate blocking from the roof with minimum drilling depth. When the seam height exceeds 1.8 m (6 ft), it may be desirable to reduce the mine opening to about 1.1 m (3.5 ft) prior to shooting down the roof. As a practical matter, the drill holes could be pre-drilled as a first step, followed by gob placement and loading/shooting as the second and third steps, respectively. Conceptually, the drilling depth should be about 2.5 times the distance of the remaining entry height. It was not possible to test the "shot rock" design experimentally at the LLEM, but the "shot rock" design was evaluated using sophisticated computer simulations.

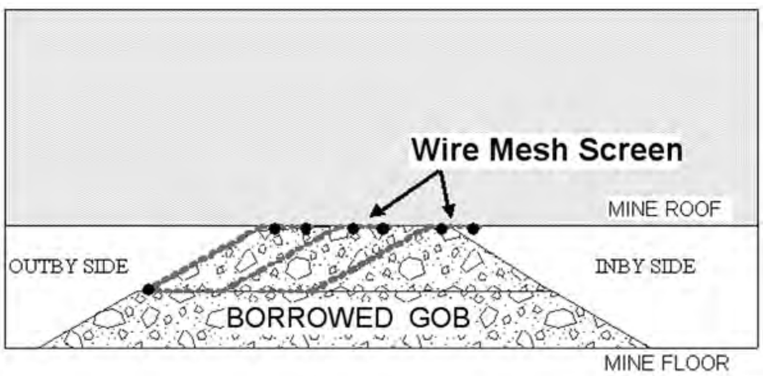

Figure 2 — The "fully-stowed" alternate attenuator design with sections of corrosion resistant wire roof mesh to provide confinement and passive reinforcement to minimize material erosion during the pressure blow down. This design was tested and evaluated in full-scale explosion tests at the NIOSH Lake Lynn Experimental Mine, but without the wire mesh screen.

Preliminary numerical simulations for a passive mine blast attenuator

The geometry of the LLEM three-entry system (see Figs. 3 and 4) was used in the computer simulations, so that the detailed pressure histories obtained in previous LLEM full-scale explosion experiments could be used to validate and calibrate the computer model. The SHAMRC code was used to predict the pressure profile of a "worst case" explosion where the A-, B- and C-drifts of the LLEM were all filled with a mixture of 9.5% methane/air and ignited at the face of the C-drift. Attenuators consisting of simulated ridge rock piles with 20% void spaces, distributed in 6.56 cm (2.58-in.) wide computational cells (Fig. 3), were located 164 m (509 ft) outby the face in A-, B- and C-drifts and inby the three seals, so as to intercept the methane-air detonation shock pressure before it arrives at the seals. The simulated rigid seals were located 195 m (640 ft) outby the ignition or about 30 m (100 ft) outby the attenuator. Figure 4 shows the relative orientation of the simulated attenuators and rigid seals that were placed in the A-, B- and C-drifts. It was also assumed that the region between the attenuator and seal was air. The simulation produced a deflagration-detonation-transition (DDT) event with about 107 m (350 ft) of flame propagation beyond the point of ignition. The detonation pressure (~1.7 MPa or ~240 psig) continued to propagate along the tunnel before it impacted the simulated PMBA. The impact of the detonation shock and its reflection produced a total pressure of ~4.4 MPa (~640 psig). Figure 5 shows the calculated explosion pressure versus time just inby the attenuator (C-510) and just inby the seal (C-640) in the C-drift for the geometry shown in Fig. 4. The pressure computations for both the A- and B-drifts are very similar to what is shown in Fig. 5. The reflected detonation pressure just inby the attenuator decays rapidly, and then stabilizes to a value that is close to the constant volume (CV) pressure of ~827 kPa (120 psi) in about two seconds. Combustion gases vented through the porous PMBA produce an initial reflected pressure of ~140 kPa (~20 psig) on the outby seal. As the gases continue to pass through the attenuator, the pressure on the outby seal rises more gradually to 353 kPa (57 psig) at ~two seconds, where the simulation was terminated. If the simulation was continued for another two seconds, the pressure between the attenuator and the seal would likely continue to rise to an equilibrium CV pressure of ~827 kPa (~120 psig). These preliminary numerical simulations, although not complete, clearly show that the use of a PMBA has the potential to reduce both the incident shock pressure and the subsequent average rate of pressure loading on the downstream containment seals. The simulations also show that a significant reduction in the explosion impulse can be achieved with relatively simple barriers.

Test facility and boundary conditions

In order to supplement and validate the numerical simulations of PMBA performance, several full-scale explosion experiments were performed at the LLEM in the summer of 2008. Since it would not be prudent to create permanent cavities in the roof of the LLEM test facility, a PMBA was constructed using the "fully-stowed" gob barrier method as shown in Fig. 2, but without the wire roof mesh. The PMBA was constructed using limestone gob materials borrowed from various parts of the test mine and supplemented (in the first test only) by 15-cm (6-in) by 0-cm material that was brought in from outside the facility.

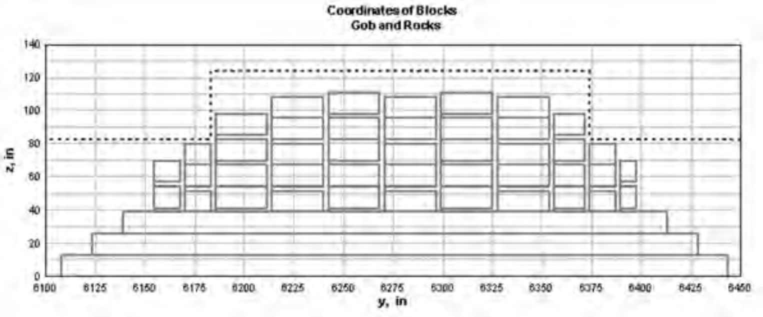

Figure 3 — The attenuator configuration used in the SHAMRC calculations. The lowest meter is assumed to be well-packed gob material and the upper composed of large rocks with 20% void spaces.

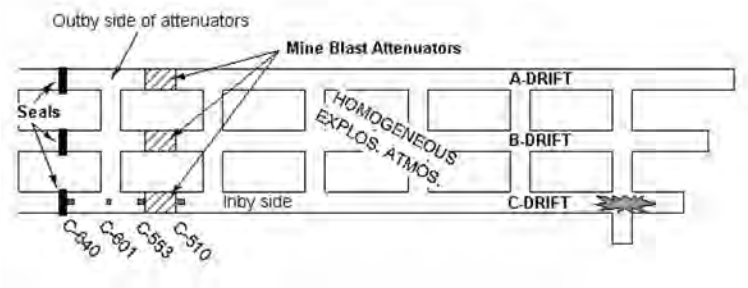

Figure 4 — Lake Lynn Experimental Mine layout of a passive mine blast attenuator used in SHAMRC numerical detonation simulations.

The LLEM facility (Triebsch and Sapko, 1990) is part of the NIOSH Lake Lynn Laboratory, which is located about 80 km (50 miles) southeast of Pittsburgh near Fairchance, in Fayette County, PA. The explosion tests were conducted in the A-drift entry area (Fig. 6). The entry and crosscuts are approximately 6.1m (20 ft) wide by about 2 m (6.5 ft) high, with cross-sectional areas of 12-13 m^2 (130-140 ft^2). Figure 6 gives a close-up, plan view of the seal test area in the multiple-entry area of the LLEM. In this example, there are pre-existing structures in the first four crosscuts from the face or closed end of A-drift. Note that the first crosscut is the one nearest the face (closed end). The flammable natural gas-air volume (ignition zone) is limited to a 26-m (85-ft)-long section of the ~30-m (100-ft)-long butt entry located inby crosscut 1 in the A-drift. The ignition zone is contained by a plastic diaphragm attached to a wooden perimeter framework.

Solid concrete block structures 400 mm (16 in.) thick, with a 800-mm (32-in.) x 400-mm (16-in.) center pilaster are located in crosscuts 1-4 between the A- and B-drifts. Each of these structures has been constructed as close as possible to the A-drift rib-line. The structure in crosscut 1 has a blast-resistant door located between the center pilaster and the inby crosscut rib. The structures in crosscuts 2 and 3 were reinforced along their contact perimeter with heavy steel angle securely bolted to the roof, ribs and floor on the B-drift side and along the floor on the A-drift side. Vertical steel angles reinforcements were placed on the B-drift side mid-width between the pilaster and rib.

For the explosion tests, 31 m^3 (1,100 ft^3) of natural gas (98% methane) was injected into the 26-m (85-ft)-long gas zone and mixed with air using an electric fan with an explosion-proof motor housing. The combustible gas mixture filled 22% of the (simulated) sealed gob volume. The gas was ignited at the face by three sets of two 100 J (~0.1 BTU) electric matches that were equally spaced at mid-height across the closed end or simulated face. Five water-filled barrels were placed ~8 and ~14 m (25 and 45 ft) from the closed end of the A-drift. The barrels were equally spaced across the entry at each location and served as turbulence generators. In addition to the 26-m (85-ft) gas zone, eight dust shelves were suspended from the mine roof; two shelves each at 27, 30, 33 and 36 m (89, 99, 109 and 119 ft). The total dust load was 14.5 kg (32 lbs) of Pittsburgh pulverized coal dust which, if suspended at a nominal dust concentration of 100 g/m^3 (0.1 oz/ft^3), is the approximate equivalent of an additional 12 m (40 ft) of gas zone. Therefore, the total equivalent length of the gas zone

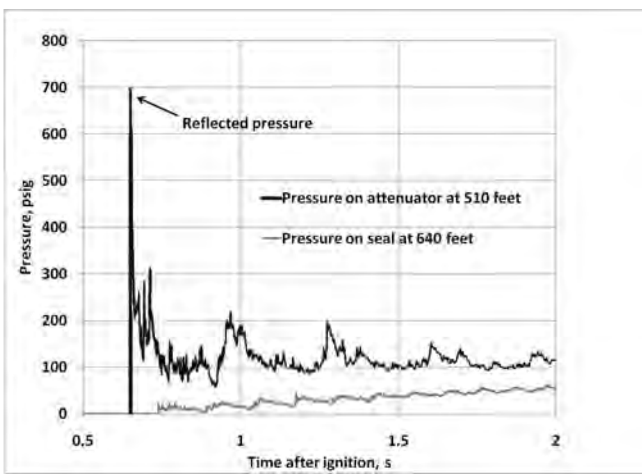

Figure 5 — SHAMRC-calculated pressures just inby the simulated attenuator (C-510) and just inby the simulated seal (C-640) located in C-drift of the Lake Lynn Experimental Mine (see Figure 4).

was 38 m (125 ft), which represents about 32% of the total volume between the mine face and the attenuator.

Each drift in the LLEM drift has ten data-gathering (DG) stations recessed into the rib wall and each DG station houses a strain gauge transducer to measure the explosion pressure and an optical sensor to detect the flame arrival. A wall pressure sensor is mounted perpendicular to the gas flow and measures the quasi-static or side-on pressure. Another pressure sensor was mounted in the middle of the entry just inby the attenuator to measure the total explosion pressure on the attenuator. A video camera recording at 35 frames/s was mounted on the rib 15 m (50 ft) downstream from the attenuator to record initial movement of the attenuator. A high-speed, PC-based computer data acquisition system collected the data from the various pressure transducers and flame sensors distributed along the A-drift, at a sampling rate of 5,000 samples per second.

A fully-stowed PMBA was installed in the A-drift starting 114 m (375 ft) from the closed end. It was constructed of limestone rubble stowed rib-to-rib and floor-to-roof (Fig. 7a) using a battery-powered mine scoop. The base (~0.9-1.2 m [~3-4 ft] high), shown as lifts "A" and "B," consisted of limestone rubble generally less than 46 cm (18 in.) in diameter. The top ~1 m (3 ft) consisted of processed limestone with particle sizes ranging from 15 cm (6 in.) in diameter to 0 material. The lifts were constructed with 15-cm by 0 limestone and are shaded in light gray in Fig. 7a. Lift 6 was constructed with 50% "limestone floor gob" (46 cm by 0) and 50% of 15-cm by 0 processed limestone and is represented by the patterned area in Fig. 7a. For LLEM Test #525, the overall thickness of the PMBA at mine floor level was approximately 15 m (50 ft) and tapered to about 4.6 m (15 ft) at the roof.

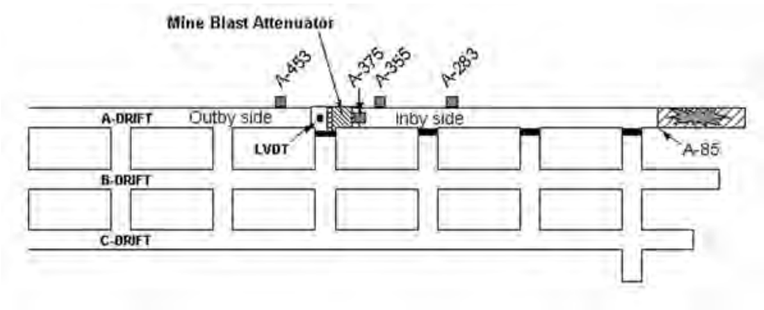

Figure 6 — Lake Lynn Experimental Mine layout of the mine blast attenuator tested against rather small methane-air deflagrations in the A-drift.

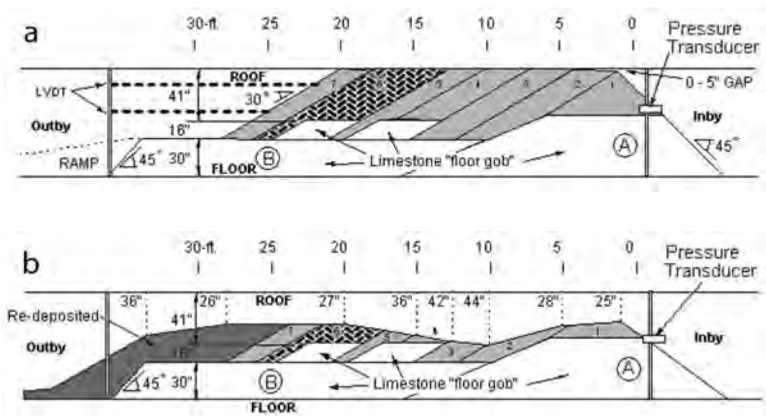

Figure 7 — Configuration of mine blast attenuator before (a) and after (b) the first test (LLEM Test #525). White: 46-cm (18-in.) x 0 limestone rubble; light gray: 15-cm (6-in.) x 0 crusher-run limestone; patterned: mixed 15-cm (6-in) x 0 and limestone; dark gray: Re-deposited material (undifferentiated).

The bulk density of the stowed gob material for LLEM Test #525, as well as the subsequent two tests, was measured periodically with a Troxler gamma density tool. The average maximum dry density of the 46 cm by 0 rock rubble was determined to be 2,146 kg/m^3 (134 lb/ft^3) and the actual average density of the material as placed during construction was approximately 1,800 kg/m^3 (112 lb/ft^3). The moisture content ranged between 3.5% and 4.2%. The average maximum dry density of the 15-cm by 0 processed limestone used to construct the upper half of the PMBA for Test #525 was 2,130 kg/m^3 (133 lb/ft^3) and the average density of the as-placed material was about 1,900 kg/m^3 (119 lb/ft^3). The moisture content ranged between 3.1% and 4.6%. The method of determining the maximum density values was the modified roller-pass method. During construction, a reasonable effort was made to achieve compaction, although this was hindered by the floor being solid concrete, combined with a general deficit of fines in the limestone rubble material used. Back-blading using the scoop bucket was not useful for compaction; however, using the weight of a fully loaded scoop bucket, combined with the downward pressure while producing side-to-side pivoting action, was useful. For this test, 15 cm by 0 rock was used for the top lift in order to facilitate full roof coverage. To assist in compaction, a small ram extension mounted on the stab-jack housing of the scoop bucket was employed.

Full-scale explosion testing of the passive mine blast attenuator

Three full-scale explosion tests (LLEM Tests #525 through #527) were conducted to evaluate the actual performance of a PMBA.

First Test (LLEM Test #525). The results of the first explosion test are shown in Fig. 8. The peak quasi-static (side-on) explosion pressure was 379 kPa (55 psig) at 86 m (283 ft) and 324 kPa (47 psig) at 108 m (355 ft), as measured from the closed end ignition zone. The incident explosion pressure produced a total reflected (head-on) explosion pressure of about 1,124 kPa (163 psig) on the PMBA at A-375.

When an air shock strikes a rigid structure head-on, such as the face of a seal or a PMBA, the theoretical reflected overpressure can be approximated by:

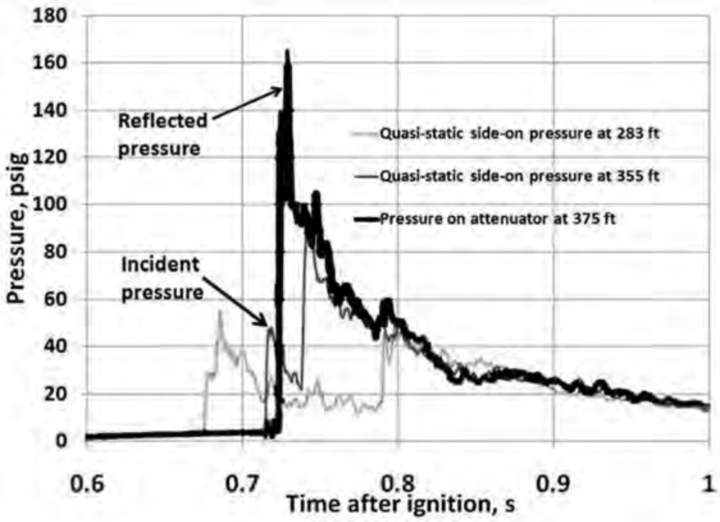

Figure 8 — Quasi-static side-on pressures inby the attenuator (A-283, A-355) and reflected explosion pressure at the attenuator (A-375) during the first test (LLEM Test #525) (see Fig. 6).

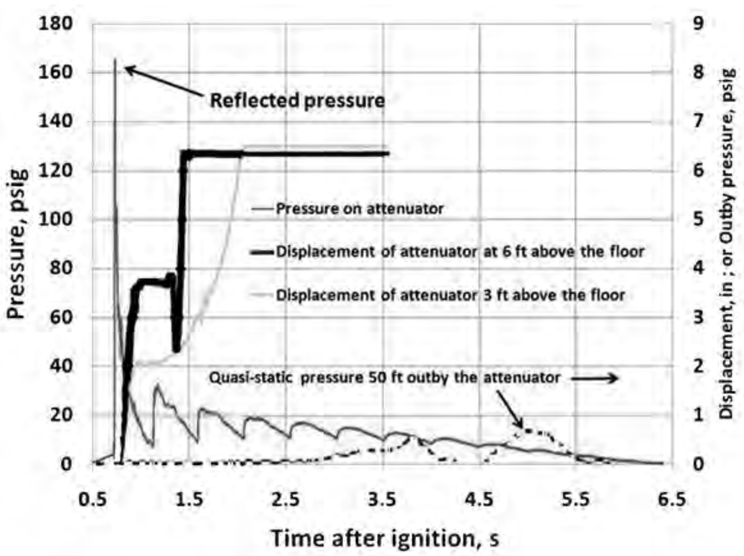

Figure 9 — Reflected explosion pressure inby the attenuator (A-375) and the quasi-static pressure 15 m (50 ft) outby the attenuator (A-453) during the first test (LLEM Test #525). Displacement of the attenuator as measured with LVDTs is also shown.

$$p_R = 2p_S\left(\frac{7p_o + 4p_S}{7p_o + p_S}\right) \qquad (1)$$

where

p_S = incident quasi-static side-on overpressure,
p_o = initial atmospheric pressure and
p_R = reflected overpressure (Zucrow and Hoffmann, 1985).

Equation (1) predicts an overpressure of 1,259 kPa (182 psig), due to the head-on impact of a 324-kPa (47-psig) incident shock wave, and the measured overpressure was lower than this by about 11%. This discrepancy is due in part to the fact that the incident shock wave had an impact angle of about 45 degrees instead of 90 degrees (head-on). Figure 8 shows that the reflected wave propagated back towards the face and decayed with distance. Behind the PMBA were two linear variable displacement transducers (LVDTs) mounted to the posts via strings of 5.5 m (18 ft) and attached to 1.3-cm (0.5-in.)-diameter rods driven into the gob material. One LVDT was located vertically at 0.3 m (1 ft) and the other at 0.9 m (3 ft) from the roof. The LVDTs were used to measure the displacement of the outby side of the gob pile relative to the inby caused by pressure loading. The reflected shock wave loaded the attenuator to ~1,124 kPa (163 psig) and then decayed to about 276 kPa (40 psig) in about 0.1 seconds, while part of the energy was reflected inby and part was absorbed by the attenuator. During this time, no movement was detected at the opposite end of the PMBA as indicated by the LVDTs (Fig. 9). At about 0.77 seconds, the outby end of the attenuator started to move and it stopped at about 0.94 seconds; the LVDT located 0.3 m from the roof showed a displacement of ~9 cm (3.6 in.), while the LVDT located 0.9 m from the roof showed a displacement of ~5 cm (2 in.). At 1.43 seconds, the roof LVDT registered a rapid displacement to 15 cm (6 in.), the maximum range of the LVDT. The LVDT located 0.9 m (3 ft) from the roof showed a more gradual rise to its maximum range of deflection and that occurred at two seconds. The pressure inby the attenuator showed multiple pulses that were produced by reflected waves of pressure traveling between the PMBA and the face at ~114 m (375 ft). At about three seconds, a ~0.7 kPa (0.1 psig) side-on rise in pressure was detected ~15 m (50 ft) outby the PMBA (Fig. 9), indicating that gas was starting to vent through the attenuator. The maximum quasi-static side-on pressure recorded outby

Table 1 — Maximum quasi-static side-on pressures and impulses recorded 6 m (20 ft) inby and 15 m (50 ft) outby the attenuator.

Test	LLEM Test #525		LLEM Test #526		LLEM Test #527	
Location (ft)	6 m inby (20)	15 m outby (50)	6 m inby (20)	15 m outby (50)	6 m inby (20)	15 m outby (50)
Max pressure kPa (psig)	628 (91)	4.8 (0.7)	524 (76)	145 (21)	621 (90)	~6 (0.85)
Impulse kPa-s (psi-s)	448 (65)	6 (0.9)	131 (19)	14 (2)	372 (54)	5.5 (0.8)

was 4.8 kPa (0.7 psig) at ~4.9 seconds, while the corresponding inby pressure had decayed to ~35 kPa (~5 psig). If a rigid seal had been placed 15 m (50 ft) outby the PMBA, the calculated reflected pressure on this seal, as determined from Eq. (1), would be ~10 kPa (~1.4 psig) from the impact of 4.8 kPa (0.7 psig).

Video footage for this test confirmed the movement of the PMBA pile indicated by the LVDTs. Initially, the top third of the attenuator started to displace slightly outby and then it stopped moving for ~0.4 seconds as shown in Fig. 9 (for the LVDT located ~0.3 m [1 ft] from roof), while the compressed gases vented along the roof on the outby side. Gas venting continued while the inby pressure fluctuated from ~55 kPa (8 psig) to 207 kPa (30 psig) due to multiple pressure reflections between the attenuator and the face. During this initial venting process, dust or small particles of rubble were displaced from the roof on the outby side and then this process progressed inby. The erosion rate increased with gas venting until the peak pressure outby the seal rose to a maximum of 4.8 kPa (0.7 psig) as shown in Fig. 9. This erosion is similar in appearance to the scouring that occurs during bedload transport in stream hydraulics. Particle movement appears to begin near where the roof contacts the attenuator on the outby side, where particles were least confined and readily set in motion by escaping gases. It takes approximately 2.5 seconds for the erosion to start and once started, it takes another 1.5-2 seconds to reach conclusion. Erosion appears to have proceeded generally from the outby side of the PMBA toward the inby side and from the top down. Similar to bedload transport, it is the material that is smallest and least confined that moves most readily. The majority of the transported material stayed within ~8-15 m (25-50 ft) of the attenuator, despite the floor being concrete and sloping about 5% to the outby side.

This rudimentary PMBA, without erosion protection, effectively reduced the 6-m (20-ft) inby peak side-on pressure of 628 kPa (91 psig) to a maximum side-on outby pressure of 4.8 kPa (0.7 psig). The corresponding pressure impulse was reduced from 448 kPa-s (65 psi-s) inby to about 6 kPa-s (0.9 psi-s) at 15 m (50 ft) outby as shown in Table 1.

Figure 7b shows the PMBA configuration after LLEM Test #525. About 55,800 kg (123,000 lb), or 30%, of the pile (primarily the 15 cm by 0 fine dust materials) had been eroded from the top and folded over the outby end of the attenuator. The amount of 15 cm by 0 material that was removed or redistributed, as shown in Fig. 7b, is a numerical average of measurements of the resultant roof gap made along each profile line, at 0.6-m (2-ft) intervals (dashed lines).

Second Test (LLEM Test #526). A second test was conducted without rebuilding the PMBA, using the same explosive force to initiate the pressure loading. Figure 10a (identical to Fig. 7b) shows the

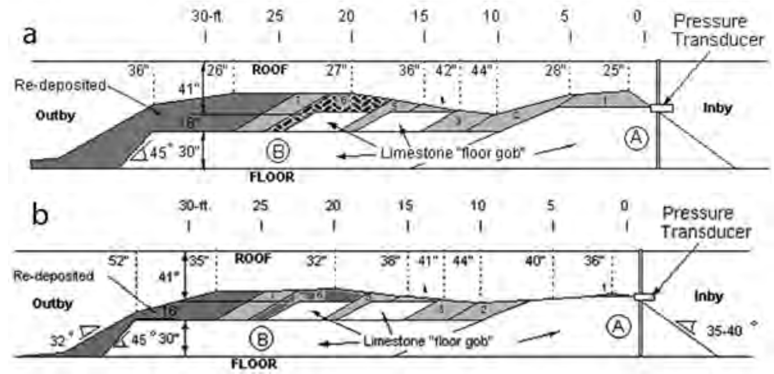

Figure 10 — Configuration of the mine blast attenuator before (a) and after (b) the second test (LLEM Test #526).

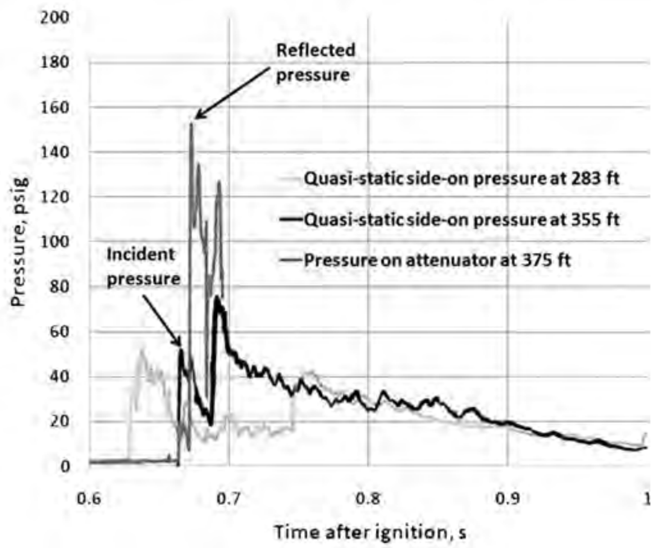

Figure 11 — Incident quasi-static pressures inby the attenuator (A-283, A-355) and reflected explosion pressure at the attenuator (A-375) during the second test (LLEM Test #526).

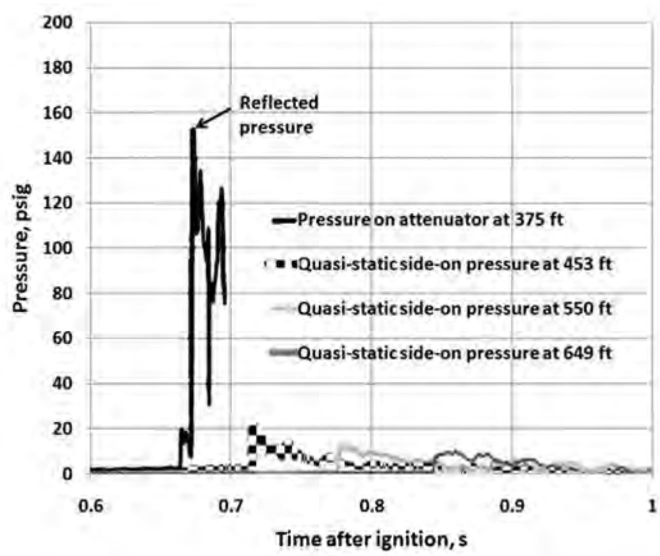

Figure 12 — Reflected explosion pressure inby the attenuator and the quasi-static pressure 78, 175, 274 and 432 ft outby the attenuator during the second test (LLEM Test #526).

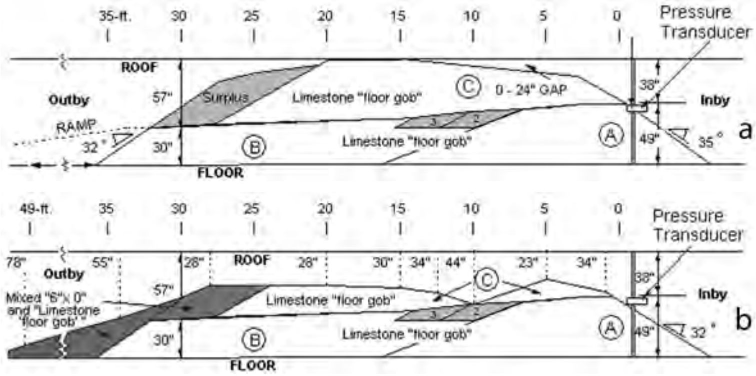

Figure 13 — Configuration of the mine blast attenuator before (a) and after (b) the third test (LLEM Test #527).

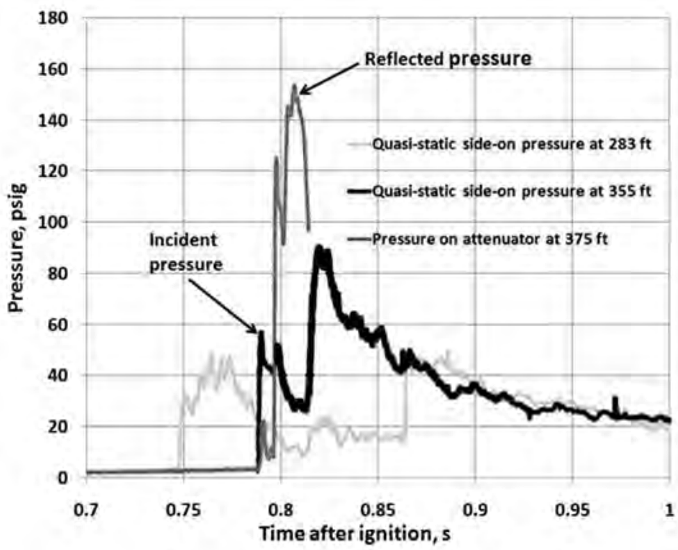

Figure 14 – Incident quasi-static pressures inby the attenuator (A-283, A-355) and reflected explosion pressure at the attenuator (A-375) during the third test (LLEM Test #527).

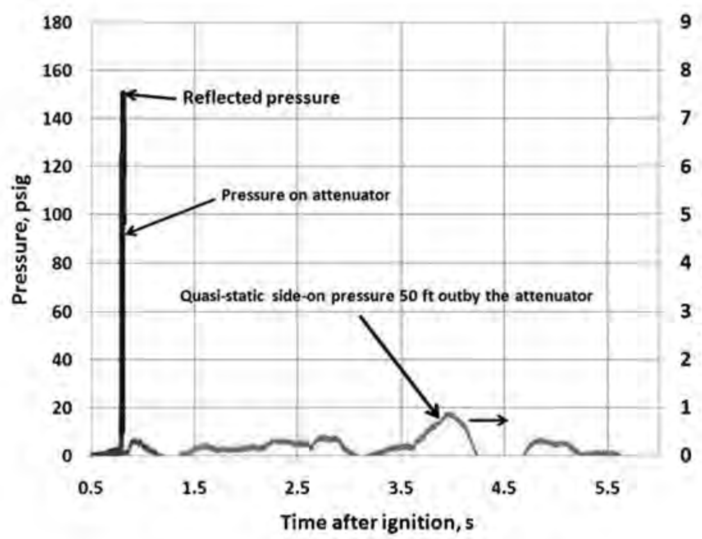

Figure 15 — Reflected explosion pressure inby the attenuator and the quasi-static pressure 15 m (50 ft) outby the attenuator during the third test (LLEM Test #527).

configuration of the PMBA before the second test. This test was done to determine the effectiveness of a PMBA when it only partially blocked the mine entry. As shown in Fig. 11, this test generated an incident quasi-static side-on explosion pressure of 352 kPa (51 psig) at 283 ft (86 m) and 345 kPa (50 psig) at 355 ft (108 m) before it impacted the attenuator. The incident explosion pressure produced a reflected pressure that peaked at about 1,048 kPa (~152 psig). Figure 12 shows plots of the inby reflected explosion pressure and the side-on explosion pressures as a function of time outby the attenuator. The inby pressure transducer failed shortly after impact, causing the signal to end abruptly at about 0.7 seconds. The peak side-on pressure 15 m (50 ft) outby the attenuator was 145 kPa (21 psig) and the corresponding impulse was 14 kPa-s (2 psi-s). Figure 10b shows the configuration of the PMBA after the second explosion test and it should be noted that it indicates additional erosion of the 15-cm-by-0 material. It should also be noted that during the second test, there was a reduction in the peak side-on pressure by a factor of 3.8 and a reduction in the side-on impulse by a factor of 9.5 (Table 1), even after ~0.6 m (2 ft) of the top of the attenuator had been eroded by the first explosion test. If a stand-alone ventilation seal had been constructed 15 m (50 ft) outby the attenuator and impacted with a 145 kPa (21 psig) quasi-static side-on peak pressure, the calculated reflected pressure (Eq. 1) would be about 435 kPa (63 psig). Some additional erosion of the 15-cm (6-in.)-by-0 limestone aggregate (light gray) occurred along the entire top portion of the PMBA, some of which was re-deposited on the leeward side (dark gray), but the PMBA was still effective in lowering the explosion pressure.

Third Test (LLEM Test #527). For the third test, the attenuator was modified as shown in Fig. 13a. Most of the 15-cm-by-0 material from prior tests was removed and some 46-cm-by-0 limestone floor gob ("C") was added on top of the original base layers ("A" and "B"). A ramp, 15-cm-by-0, was constructed with waste to accommodate the scoop and some of this surplus material was stacked against "C." This was done to delay the removal of the material until completion of the test, but it served little, if any, structural purpose. Note in Fig. 13a that the best roof closure only existed for about 1.5 m (5 ft) (between the 4.6-m [15-ft] and 6.1-m [20-ft] marks), while along the ribs there were larger openings. As shown in Fig. 14, the third test generated a side-on incident quasi-static explosion pressure of 338 kPa (49 psig) at 86 m (283 ft) and 393 kPa (57 psig) at 108 m (355ft) before impact with the attenuator. This incident quasi-static pressure produced a reflected peak explosion pressure of ~1,048 kPa (152 psig). Figure 15 shows the inby peak explosion pressure and the outby quasi-static side-on explosion pressure 15 m (50 ft) from the attenuator. Again, the inby pressure transducer failed shortly after impact; therefore, this signal ends approximately at 0.8 seconds. The peak quasi-static side-on pressure 15 m (50 ft) outby the attenuator was ~6 kPa (~0.85 psig) with a corresponding impulse of 5.5 kPa (0.8 psi-s) (Table 1). Figure 13b shows a schematic of the attenuator after the third test (LLEM Test #527). About 54,400 kg (120,000 lbs), or 30%, of the top material had been eroded and was mostly folded over the outby end of the attenuator and smaller material traveled ~45 to 60 m (150 to 200 ft) outby. If a seal had been constructed 15 m (50 ft) outby the attenuator and impacted with a peak ~6 kPa (0.85 psig) quasi-static side-on pressure, the approximate peak reflected pressure, as calculated by Eq. (1), would be ~12 kPa (~1.7 psig). The amount of material eroded off the top of the PMBA was comparable to the first explosion test (LLEM Test #525), except for some isolated "large rocks" that did not move from their location.

As noted above, a comparable volume of material was eroded from the top of the PMBA during the third test (LLEM Test #527) and was eroded during the first test (LLEM Test #525). Better compaction and roof coverage were achieved for the top half of the PMBA in LLEM Test #527. Notably, several relatively large rocks, + 45 cm (18 in.), on the explosion side of the attenuator were not displaced, which indicates that the larger rock sizes had a higher level of resistance to displacement during the erosion that began at the roof line during gas venting.

These test results clearly show that even a rudimentary PMBA constructed inby a mine seal has the ability to significantly reduce the peak explosion pressure, the rate of pressure loading and the impulse load on outby ventilation seals. We are not proposing that a PMBA or any other type of blast wave attenuator replace mine seals, but clearly these attenuators could be used in conjunction with classic, time-tested seals, i.e., designs such as the hitched Mitchell/Barrett seal, to contain larger explosion pressures than would be possible without them. The 400-mm (16-in.)-thick, solid concrete block Mitchell/Barrett seal has demonstrated the ability to withstand static pressures of at least 655 kPa (95 psi). While this seal has recently fallen into disfavor with federal regulators because of an uncertainty about its ability to resist shearing effects during the initial shock loading at higher design pressures, the PMBA appears to be generally capable of mitigating this hazard. Over time, as well as in the case of multiple explosions, PMBAs in conjunction with ordinary mine seals may be more durable and dependable than current mine seal designs, which place the entire burden of containing both the explosion and the gases on a single, stand-alone seal. Further, should design engineers determine that i) a homogeneous explosive atmosphere exists, (ii) pressure piling could produce explosion pressures exceeding 827 kPa (120 psi) or (iii) detonation is likely, the use of PMBAs would provide a practical alternative solution where none currently exists.

Conceptual attenuator designs for future research studies

One enhancement that in our opinion warrants further testing is to incorporate corrosion-resistant wire mesh between successive lifts in the top half of the attenuator (see Fig. 2). This would add passive resistance to particle movement and reduce transport by erosion during the gas blow-by phase that accompanies the reduction of pressure inby the PMBA. This concept is similar to the use of rock basket gabion walls to inhibit bank erosion along streams.

One method might employ standard welded 10-cm by 10-cm (4-in by 4-in) wire roof mesh installed and secured between selected lifts to keep rock particles confined during pressure venting (Fig. 2). This wire mesh could be attached to existing roof bolts and bent down over the previous lift. A second sheet of roof mesh could be applied over the previous sheet and the mine bottom could be covered with gob. The next lift could be applied and the mesh layering repeated. The wire mesh serves to prevent the erosion which starts from the outby side of the attenuator and moves inby. Other designs could utilize a well-anchored gabion basket wall that is backed by stowed mine rubble. The gabions fill material and rubble pile may also be bound together with injected grout or cementitious-type material.

Proposed theory of operation: analogy with blast hole stemming

We have proposed a passive mine blast attenuator that responds in a manner similar to the stemming in a blast bore hole, but at much lower shock pressures and impulses. Resistance to flow in the center of the stemming is limited because of the interlocking or wedging of the particles (Konya et al., 1981). A certain wall friction is essential to start the wedging action, but once this action is started, the resistance quickly increases. The interlocking of particles produces lateral forces that tend to pack the outer material against the wall of the blast bore and in doing so create material arches that are similar to those that cause "hang-ups" in ore passes. Total movement of the column of stemming occurs only if the particles against the borehole wall fail in shear or slip.

A similar process occurred in the first test (LLEM Test #525) with the "fully stowed" PMBA. The shock impact (~1,138 kPa or ~165 psig) initially compressed the inby end of the attenuator while the outby end did not move. The interior of the attenuator moved faster than the face near the edges of contact (at the ribs, floor and roof), because wall friction opposed movement of the edges during the inter-particle momentum transfer. This initial compression produced material arches and large lateral forces as it dissipated the shock energy. Further, lateral forces increased the overall frictional and shear resistance to plug movement. After the pressure decayed to about 138 kPa (20 psig), compressed gases began venting along the roof and this eroded particles from the attenuator starting at the outby end and moving inby.

Conclusions

The results of these initial experiments in rather small combustible methane-air volumes clearly show that a rudimentary passive mine blast attenuator constructed of common mine gob and mine rubble can significantly reduce the peak explosion pressure transmitted to outby mine structures such as ventilation seals. The use of a PMBA barrier in conjunction with a conventional mine seal shows great promise as a means of protecting against the effects of 827 kPa (120 psig) and higher gob gas explosions. Because these tests were conducted in a limestone mine where the surrounding boundary conditions were likely to be more stable than those found in coal mines, future research should focus on the potential differences between these mine types and their implications for attenuator performance. Although these computational and LLEM explosion test results are preliminary, on-going experimental and modeling research efforts within the NIOSH and WVOMHST will aim to refine the concept of passive mine blast attenuators and develop more design data and recommendations for optimum deployment.

Disclaimer

This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the National Institute for Occupational Safety and Health (NIOSH). It does not represent and should not be construed to represent any agency determination or policy.

Acknowledgments

The authors thank the following NIOSH contractors: Timothy W. Glad, James R. Rabon, Bernard T. Lambie and Brandin Lambie, Mechanical Technicians for the Ki Corporation, for construction of the attenuator and assistance in the underground materials handling and extensive cleanup operations. The authors acknowledge the following PRL personnel for their contributions: Kenneth W. Jackson and Walter P. Marchewka, electronic technicians, for sensor calibrations and for their participation in the data collection and analyses, and James D. Addis, Frank A. Karnack and Donald D. Sellers, physical science technicians, for their extensive participation in the installation of the sensors and the setup and conduct of the explosion tests. Special thanks to John Cruse, Technical Analyst III, WVOMHST, for his contributions to the oversight and documentation of construction.

References

Britan, A., Ben-Dor, G., Igra, O., and Shapiro, H., 2001, "Shock waves attenuation by granular filters," *International Journal of Multiphase Flow*, Vol. 27, pp. 617-634.

Britan, A., Karpov, A.V., Vasilev, E.I., Igra, O., Ben-Dor, G., and Shapiro, H., 2004, "Experimental and numerical study of shock wave interaction with perforated plates," *Journal of Fluid Mechanics*, May 2004, Vol. 126, No. 3, pp. 399-409.

Gelfand, B.E., Medvedev, S.P., Polenov, A.N., and Tsyganov, S.A., 1987, "Interaction of unsteady pressure waves and perforated baffles," *Arch Combustion,* Vol. 7, No.1-2, pp. 215-223.

Hieb, M.R., and Sapko, M.J., 2008, "A systems approach to gob sealing using mine blast attenuators constructed of available mine rock rubble," 2008 SME/PCMIA Annual Joint Meeting, Southpointe, Canonsburg, Pennsylvania, October 30-32, 2008.

Hieb, M.R. and Wooten, R., 2008, "Mine seals: West Virginia state safety issues," West Virginia Coal Symposium, Charleston, West Virginia, January 9, 2008.

Konya, C.J., Skidmore, D., and Otuonye, F., 1981, "Control of airblast and excessive ground vibration from blasting by use of efficient stemming," Office of Surface Mining Final Contract Report OSM G5195034, U.S. Department of Interior, Open File Report 8-84.

Lind, C.A., Cybyk, B.Z., and Boris, J.P., 1999, "Attenuation of shocks: high Reynolds number porous flows," *Proceedings of the 22nd International Symposium on Shock Waves, London, UK, Imperial College, July 18-23, 1999*, pp. 1135-1140.

Triebsch, G., and Sapko, M.J., 1990, Lake Lynn Laboratory: a state-of-the-art mining research facility," *Proceedings of the International Symposium on Unique Underground Structures,* Golden, Colorado, Colorado School of Mines, Vol. 2, pp. 75-1 to 75-21.

Unrug, K., Lusk, B., Perry, K., and Turner, D., 2008, "Mine seals – a rational base for design and construction," *Proceedings of the 27th International Conference on Ground Control in Mining*, Morgantown, West Virginia, West Virginia University, pp. 189-196.

U.S. Code of Federal Regulations, 2008, Title 30 CFR Part 75.335, Rules and Regulations: Sealing of Abandoned Areas—Final Rule, Vol. 73, No. 76, U.S. Government Printing Office, Office of Federal Regulations, Friday, April 18, 2008.

Zipf, R.K., Sapko, M.J. and Brune, J.F., 2007, *Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines,* Pittsburgh, PA, U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, IC 9500.