PROGRESS TOWARD IMPROVED ENGINEERING OF SEALS AND SEALED AREAS OF COAL MINES

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ABSTRACT

Recent scientific studies by researchers at the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Army Corps of Engineers (USACE) presented the worst-case explosion pressures that can develop if a methane-air mixture of a certain composition and dimension accumulates and ignites within a sealed area of a mine. The Mine Safety and Health Administration (MSHA) issued its final rule on sealing of abandoned areas which considers potential explosion pressures and the risk of achieving the necessary conditions. The new MSHA seals regulation has increased the pressure design criteria an order of magnitude beyond the old standard of 140 kPa (20 psi) to 800 kPa (120 psi). However, there still are major knowledge gaps pertaining to seals and sealed areas including: (1) the composition of the sealed area atmosphere and how it changes in time and space, (2) explosion pressures that might actually develop within sealed areas, (3) engineering procedures to follow when designing seals and seal installations, and (4) guidelines to manage the atmosphere within sealed areas with monitoring or inertization. NIOSH has initiated a seals research program with collaborators from Safety in Mines Testing and Research Station (SIMTARS) in Australia, West Virginia University (WVU), the Naval Research Laboratory (NRL), and USACE. Highlights of progress so far include: (1) construction of a gas explosion tube at Lake Lynn Laboratory for studying large methane-air explosions, (2) computer simulation of the fluid dynamics of high pressure methane-air explosions, (3) development of seal analysis methods considering construction materials, reinforcement and the seal foundation, and (4) development and testing of innovative seal designs that utilize inexpensive, readily-available rock rubble to resist high explosion pressures. NIOSH researchers aim to provide sound engineering guidelines to better address the new MSHA seal regulations.

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INTRODUCTION

The Sago Mine disaster January 2, 2006 caused by an explosion within a recently sealed area precipitated many changes to mining regulations pertaining to seals. Mandates from the Mine Improvement and New Emergency Response Act (the MINER Act) of June 2006 required MSHA to increase seal design pressures by the end of 2007. Scientific studies of gas explosions within sealed areas provided a basis for the new MSHA regulations on sealing of abandoned areas (Federal Register, 2008). However, the behavior of the sealed area atmosphere and possible explosions within sealed areas is still fraught with uncertainties. The new regulations have moved the mining community to use engineering methods to design seals; however, professional engineers lack accepted guidelines to follow for seal design.

This paper will summarize the following:

1. New scientific knowledge and new regulations for sealed areas.
2. Knowledge gaps with seals and sealed areas of coal mines.
3. Research in progress to address these issues.

NEW SCIENTIFIC KNOWLEDGE AND NEW REGULATIONS OF SEALED AREAS

Upon enactment of the MINER Act, NIOSH researchers conducted scientific studies (Zipf et al., 2007) of methane-air explosions within sealed areas of coal mines by first considering the formation of potentially explosive gas mixtures that can develop in sealed areas upon sealing. Starting with an atmosphere that is pure air, the methane concentration may increase; the oxygen concentration may decrease; or some combination of these changes may occur. Figure 1, which plots oxygen concentration versus methane concentration, shows the various paths that an atmosphere may take toward some later sealed area atmosphere composition, beginning with normal air containing 21% oxygen and 0% methane and ending with lower oxygen and higher methane concentrations. Figure 1 also shows "Coward's triangle" where mixtures of oxygen and methane can ignite. As methane concentration increases and oxygen concentration decreases, the sealed area atmosphere may become explosive for some time while the average methane concentration is between about 5 to 16% and the oxygen concentration is greater than 12% as shown by paths A to B or A to C. In some cases, the sealed area atmosphere could become inert and never cross through the explosive range as shown by path A to D. If a mine pumps inert gas into a sealed area, the path toward a fuel-rich inert atmosphere may follow a path similar to A to E to F, and also never cross through the explosive range. The composition path followed by any particular sealed area atmosphere is most likely unique for each particular coal mine. Unfortunately, a methane-rich, oxygen-lean inert atmosphere may not necessarily remain inert. Such an inert sealed area atmosphere can become explosive again if air leaks into the sealed area through seals. Changes in atmospheric pressure caused by normal diurnal variation or passing high pressure weather systems can cause air to leak into a sealed area. Pumping methane from within sealed areas can also induce air leakage into the sealed area, which could then create a potentially explosive atmosphere behind seals.

Based on thermodynamics, chemistry, and physics, NIOSH researchers conducted a worst-case analysis of methane-air explosions within the sealed areas of coal mines and presented several important facts about possible explosions within sealed areas:

1. Combustion of stoichiometric (about 10%) methane-air mix in a closed volume increases the pressure about 807 kPa (117 psig). This pressure is called the constant volume (CV) explosion overpressure. The CV explosion overpressure is greatest for a stoichiometric mix and decreases for fuel-rich, fuel-lean, oxygen-deficient, or carbon dioxide-rich mixtures.
2. Combustion of coal dust in air in a closed volume produces a somewhat lower CV explosion overpressure of about 690 to 790 kPa (100 to 114 psig).
3. Due to dynamic effects, explosions in tunnels produce transient pressure waves that are greater than the CV overpressure.
4. When a blast-created shock wave with a quasi-static overpressure impacts a structure, it reflects with a transient

reflected wave overpressure that is 2 to 8 times greater than the incident quasi-static overpressure.

5. If detonation of a methane-air mix develops, the maximum detonation wave overpressure for is 1.66 MPa (241 psig). When a detonation wave impacts a structure, it reflects at a pressure of about 4.40 MPa (640 psig) which is about 2.54 times greater than the incident detonation wave pressure.

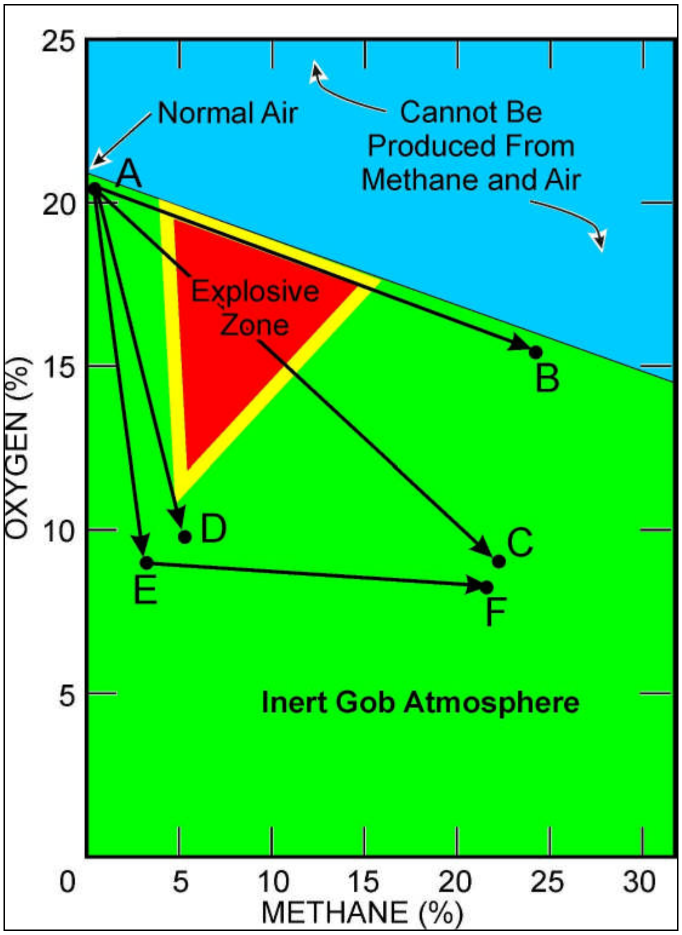

Figure 1. Coward triangle (Coward and Jones, 1952) showing explosive zone for methane in air mixtures and different paths toward an inert atmosphere.

The NIOSH report (Zipf et al., 2007) also presented simple numerical model calculations of explosion pressures within mine tunnels. Using the gas explosion models AutoReaGas and FLACS, which are commonly applied throughout the oil, gas, and chemical industries, researchers calculated explosion pressure at a seal. Figure 2 shows the simple mine layout and the calculated explosion pressure. The 160-m-long (525-ft-long) gas cloud that filled 3 entries and the cross-cuts developed explosion pressure ranging from about 2.4 to 3.3 MPa (350 to 480 psi). Independent calculations by explosion experts at USACE also produced explosion pressures of similar magnitude (McMahon et al., 2007). USACE engineers used a sophisticated computational fluid dynamics program called SAGE (SAIC Adaptive Gridding Eulerian) hydrocode (Gittings et al., 2005) to compute possible explosion pressures that developed during the explosion at Sago Mine. In the first simulation with infinitely strong seals and a homogeneous, near stoichiometric methane-air mixture, the USACE calculations produced reflected explosion pressures at the seals of 8.8 MPa (1,300 psig). In the second simulation with seal failure at 140 kPa (20 psig) and the same mixture, the calculated reflected pressure at the seals was 5 MPa (700 psig). In the third simulation where the sealed area contained a layered methane-air mixture that was inert near the seals, the calculated reflected pressure at the seals was 1.65 MPa (240 psig).

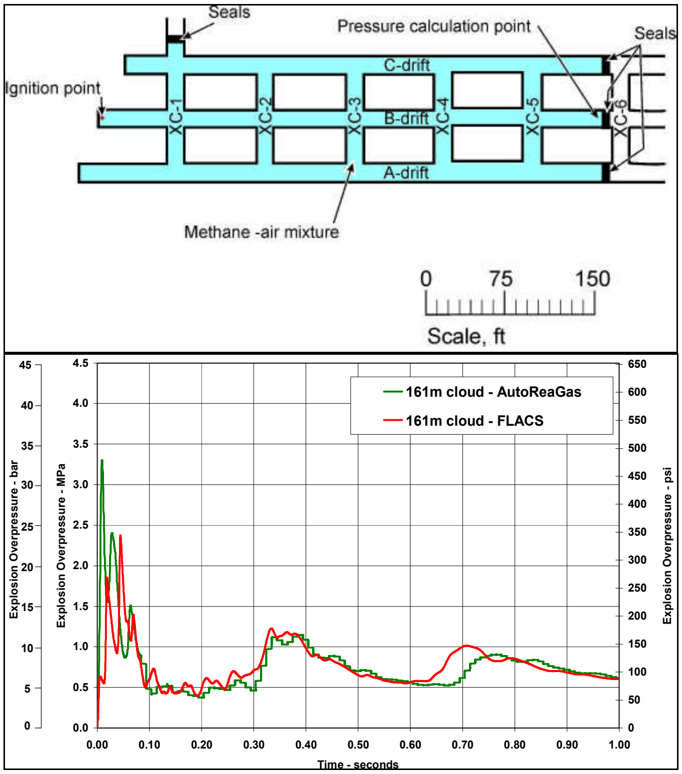

Figure 2. Calculated gas explosion pressure from numerical models at a seal from a 160-m-long gas cloud. The model gas cloud geometry is shown above. (Zipf et al., 2007).

To demonstrate the possibility of the high explosion pressures, recent experiments by NIOSH researchers at the Lake Lynn Experimental Mine produced such pressures from very small explosive gas clouds (Sapko et al., 2009). In one experiment as shown in Figure 3, a methane and coal dust cloud with an effective length of 38-m-long (125-ft-long) developed an incident quasi-static blast wave pressure of 324 kPa (47 psig) which then produced a reflected explosion overpressure of about 1.124 MPa (163 psig) on an experimental structure.

NIOSH researchers (Zipf et al., 2007) then presented a three-tiered recommendation for explosion pressure design criteria for seals as shown in Figure 4. Application of these criteria depends on the monitoring regimen applied. If the sealed area is monitored continuously during and after sealing and if the potential size of explosive mixture is limited to a less-than-5-m-long space (about 15 ft) right behind a seal, then a 345 kPa (50 psi) explosion pressure-time curve applies. However, if the sealed area atmosphere is not monitored, then much larger explosive gas volumes and much higher explosion pressures can develop. If the open entry behind the seal is small with a length less than 50 m (about 150 feet), then the 800 kPa (120 psi) pressure-time curve applies. If the open entry behind the seal is large with a length more than 50 m (150 ft), then the 4.4 MPa (640 psi) explosion pressure-time curve applies. Note that it is not necessary for an explosive methane-air mixture to detonate to achieve high explosion pressure. As shown in Figure 3, non-reactive blast waves from ordinary deflagrations can easily develop reflected pressures greater than 1 MPa (145 psi) as the experiments at LLEM have demonstrated for gas clouds as small as 26-m-long (85-ft-long).

Based in part on the analyses presented by NIOSH researchers and an assessment of the risk of developing high explosion pressure within sealed areas, MSHA issued its final rule on sealing of abandoned areas. According to the new regulation, the design explosion pressure for seals also has three tiers:

- At least 50-psi overpressure when the atmosphere in the sealed area is monitored and maintained inert.

- Overpressures of at least 120 psi if the atmosphere in the sealed area is not monitored and is not maintained inert.
- Overpressures greater than 120 psi if the atmosphere in the sealed area is not monitored and is not maintained inert and other conditions exist which could lead to higher explosion pressures such as likelihood of detonation or pressure piling.

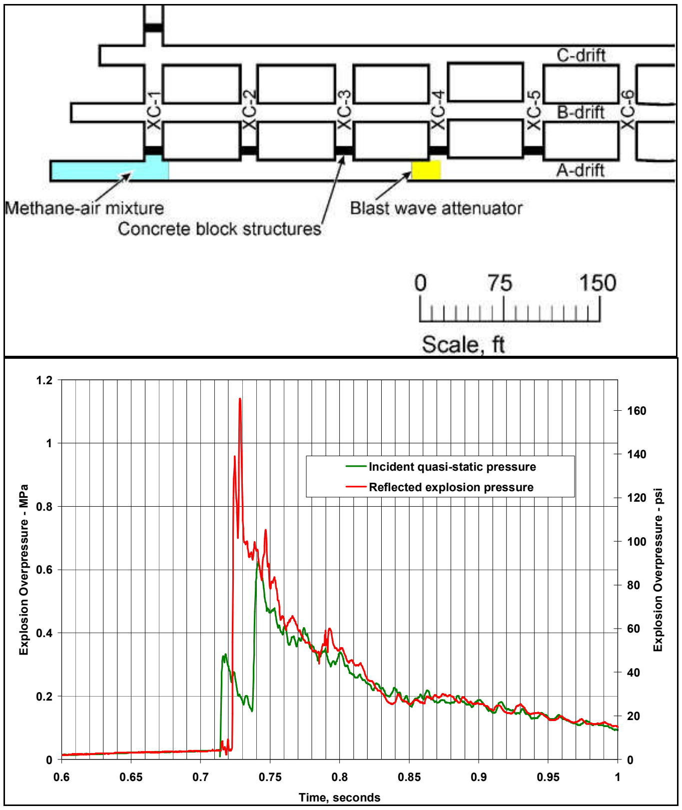

Figure 3. Measured quasi-static blast waves and reflected explosion pressure on a structure from a gas cloud equivalent to a 38-m-long (125 ft) methane-air mixture (Sapko et al., 2009).

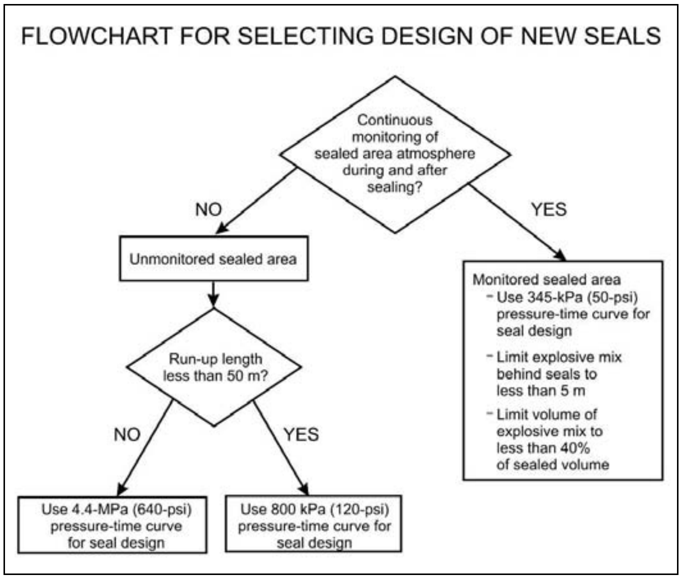

Figure 4. Design criteria for various sealing conditions (Zipf et al.. 2007).

Seal design applications must address the design pressure-time curve, engineering design and analysis, material properties, construction specifications, quality control, and other considerations. New seal designs and their construction require certification by professional engineers and the local mine management for quality control.

The new MSHA regulation on seals has increased the pressure design criteria for seals an order of magnitude beyond the old 140 kPa (20 psi) standard. Prior to the Sago Mine disaster, the mining community relied upon a “build and test” approach (Gadde et al., 2007A) to develop seal designs to meet the old standard; however, to meet the new standard, the mining community has used engineering methods under the auspices of a professional engineer to analyze and design seals. In addition, the new standard requires quality control and accountability throughout the life of the seal from design through construction and operation, again under the supervision of professional engineers and the mine management.

KNOWLEDGE GAPS WITH SEALS AND SEALED AREAS OF COAL MINES

The recent NIOSH study (Zipf et al., 2007) coupled with the USACE report (McMahon et al., 2007) provided complementary, independent analyses of worst-case explosion pressures that could develop in sealed areas of coal mines. The discussions in the mining community ensuing from these reports and comments on the new seals regulation identified numerous unknowns and knowledge gaps with seals and the sealed areas of coal mines. NIOSH researchers categorize these knowledge gaps into three main themes:

1. Science of sealed areas including the sealed area atmosphere composition, explosion processes, and the explosion pressures that could develop.
2. Seal engineering including failure mechanisms of seals, analysis and design of seals, and engineering methods to account for the seal foundation and convergence in seal design.
3. Management of sealed areas and their atmospheres including ways to plan mines for future sealing along with monitoring and inertization techniques for sealed areas.

The composition of the sealed area atmosphere is not well understood. Prior to the Sago Mine disaster, few researchers had measured the composition of the atmosphere within sealed areas. The U.S. mining community erroneously assumed that the sealed area atmosphere would become inert rapidly upon sealing and then remained inert. In comments regarding the MSHA ETS on “Sealing of Abandoned Areas,” Gadde et al. (2007B, 2009) presented the first composition data from thousands of sealed area atmosphere samples from a few mines. More than 99% of the samples were inert and less than 1% were potentially explosive with oxygen concentration above 10% and methane concentration between 8 and 12%. Thus, it appears that the probability of encountering a potentially explosive atmosphere within a sealed area is low. However, the 12 documented explosions within sealed areas that occurred between 1986 and 2006 demonstrate the inadequacy of assuming an inert atmosphere.

To comply with the new regulations on sealed areas, mining companies and MSHA now sample the atmosphere behind seals on a regular basis. Questions remain concerning 1) whether potentially explosive gas mixtures really do exist within sealed areas, 2) how extensive such mixtures might be, 3) how the composition changes over time, 4) whether methane layering exists within sealed areas, and 5) how homogeneous the atmosphere is within extensive sealed areas. Answers to these questions may in turn answer questions concerning the adequacy of sampling techniques and sampling frequencies for sealed area atmospheres. Understanding the sealed area atmosphere’s composition both spatially and temporally is a key component in assessing the risk of explosion behind seals.

Explosion processes within sealed areas are not well understood. Some question whether the high explosion pressures presented in the recent NIOSH and USACE studies could ever occur in a mine. Others question whether detonation of methane-air mixtures is a physical possibility. The process by which a weak spark ignition grows from a laminar flame to a deflagration and then possibly a detonation is not well understood for methane-air. Whether deflagration-to-detonation transition (DDT) can occur in methane-air mixtures and whether the process can occur in a mine requires further study. Only two laboratory-scale studies exist in which researchers achieved detonation of methane-air (Bartknecht, 1993; Kuznetzov et al., 2002). Experimental apparatus of insufficient size may have hampered these experiments from developing and sustaining a true detonation. No experiments in full-scale mine tunnels have ever produced detonation beginning from a weak spark. Prior experiments to produce detonation initiated the detonation directly with a small quantity of high explosive and therefore do not represent realistic in-mine conditions. The largest experimental explosions at NIOSH's Lake Lynn Experimental Mine have only used limited quantities of methane-air mixture with an equivalent length of less than 26 m (85 ft). Such small lengths and quantities of methane-air may not be sufficient to develop DDT. Numerical gas explosion model calculations by researchers at USACE (McMahon et al., 2007) indicate the possibility of methane-air detonation. Finally, MSHA investigators of the Blacksville No. 1 explosion in 1992 (Rutherford et al., 1993) back-calculated explosion pressure of about 6.9 MPa (1,000 psi) which also suggests the possibility of detonation. However, Gadde et al., (2007B) presented a dynamic structural analysis using sophisticated numerical analysis methods and concluded that the back-calculated explosion pressure is much less than that reported by MSHA. Additional research should re-examine this failure and implied explosion pressure using the best available material properties and construction details for the shaft collar.

Guidelines for seal engineering require extensive development. As mentioned earlier, prior to 2006, the mining industry used a "build and test" approach for seal design, but now the community must follow engineering methods to design seals in a manner similar to building or dam design. NIOSH researchers recommended a four-phase approach to seal design: (1) information gathering to locate appropriate seal sites and assess their foundation, convergence, and air leakage characteristics, (2) seal engineering to choose the appropriate design pressure-time curve, analyze the seal design, and specify all dimensions and construction materials, (3) seal construction with quality control, and (4) post sealing inspections to ensure continued seal integrity and performance within the assumed design conditions (Zipf et al., 2007). The MSHA final rule on seals provides two separate design methods to apply for approval of a seal design: (1) an engineering design application and (2) an application based on full-scale explosion tests. A testing-based application could utilize full-scale, hydrostatic tests of seals to produce pressure loads on the seal equivalent to the required design pressure-time curve (Sapko et al., 2008). An engineering design application shall "address gas sampling pipes, water drainage systems, methods to reduce air leakage, pressure-time curve, fire resistance characteristics, flame spread index, entry size, engineering design and analysis, elasticity of design, material properties, construction specifications, quality control, design references, and other information related to seal construction" (Federal Register, 2008). The mining community needs engineering guidelines for professional engineers to follow during the design, evaluation, and approval of mine seals.

Additional guidelines to manage sealed areas also require development. Often, mine sealing plans are developed long after the initial mine plans. Lack of adequate pre-planning may result in complex seal lines, convergence, and leakage-prone sealed areas, and more seals used than necessary. Better pre-planning of sealed areas could eliminate many safety hazards and explosion dangers.

The NIOSH seals report and the MSHA final rule on sealing of abandoned areas provided an option for 345 kPa (50 psi) seals as long as monitoring of the sealed area showed that it remains inert at all times after sealing. Use of this seal design option may necessitate artificial inertization of the sealed area immediately after sealing and periodically thereafter. Continuous monitoring of sealed areas requires the use of sample-draw systems, for example tube-bundle systems to sample and analyze the atmosphere within sealed areas. Such monitoring systems and inertization systems are routinely applied at virtually all underground coal mines in Australia. NIOSH researchers plan to demonstrate these critical technologies to facilitate their possible adoption by the U.S. coal mining industry.

NIOSH RESEARCH PROGRESS TO ADDRESS SEALING ISSUES

Composition of Sealed Area Atmosphere

Understanding the composition of the sealed area atmosphere and how it changes across the sealed area and over time is important for understanding the blast pressure that could develop from an explosion and assessing the risk associated with this danger. NIOSH researchers have acquired from SIMTARS in Australia a monitoring system that is capable of measuring the composition of the sealed area atmosphere and tracking its evolution continuously over time. NIOSH researchers seek an appropriate coal mine with sealed areas in which to deploy this system for research and technology demonstration purposes. NIOSH researchers would place sampling tubes throughout an abandoned area prior to seal construction and final sealing.

Figure 5 shows several photographs of a tube-bundle system for continuous monitoring of a mine atmosphere. Systems similar to the one shown are deployed in virtually all underground coal mines in Australia. The top left of Figure 5 shows a typical monitoring shed located on the surface above a mine. The monitoring tubes enter the mine via a borehole to the left of the shed. Typical tube-bundle installations will monitor from 20 to 40 points or more, with about half located in the active mining areas and the other half in the sealed areas. The top right of Figure 5 shows a close-up of a seven-tube bundle. The pumps shown in the bottom right of Figure 5 draw air samples continuously from each monitoring point. Left of the pumps is where the sample tubes enter the shed for analysis. Inside the shed is a solenoid-valve-manifold system activated by a programmable logic controller. The bottom left of Figure 5 shows the on-line gas analyzers, programmable logic controller, and some of the sample tubes inside the monitoring shed. Samples are sequentially directed to an on-line gas analyzer and analyzed for carbon monoxide, carbon dioxide, methane, and oxygen. It is assumed that nitrogen and argon comprise the balance. A typical tube-bundle system provides a gas analysis at each monitoring point every 1-3 hr or at intervals that can be individually programmed for each point. Real-time data are displayed at the mine's control center, where trained operators can respond as necessary.

Figure 5. Continuous atmospheric gas monitoring system used in Australia. Top left: Monitoring shed over mine showing borehole and sample tubes. Top right: Close-up of sample tube bundle. Bottom right: Sample tube pumps. Bottom left: Inside monitoring shed showing gas analyzers and controller (Zipf et al., 2007).

Figure 6 shows the layout of a longwall mine with several active mining faces, several mined-out and sealed panels, and the sample point locations for the tube-bundle system. Sample points are typically located in both intake and return airways of each working section.

Each set of seals usually has one monitoring point about 5 m (16 ft) behind the seal within the sealed area.

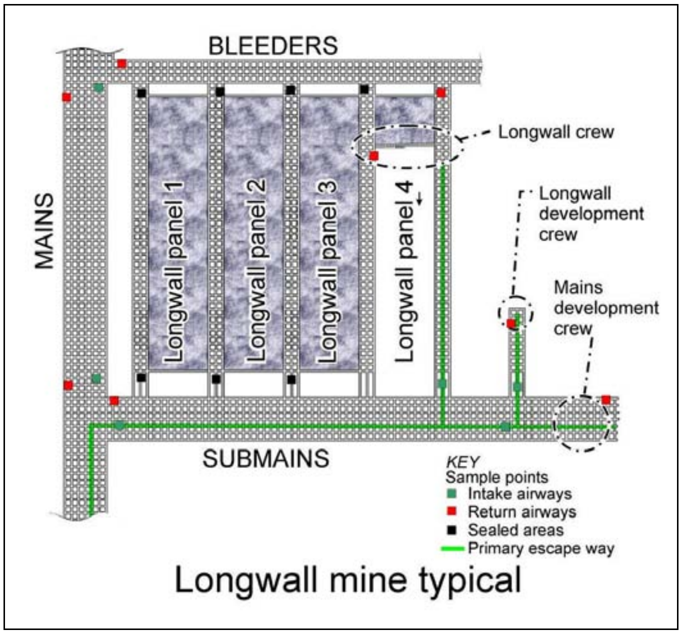

Figure 6. Typical longwall mine layout showing sample points for tube bundle monitoring systems throughout the active mine and within sealed areas.
Green–sample points in intake airways
Red–sample points in return airways
Black–sample points behind seals within the sealed area.

Continuous monitoring of the mine atmosphere both in the active mine and within sealed areas enables mine operators to identify potentially dangerous trends early enough to take proactive safety measures if necessary. The SIMTARS continuous monitoring software can display compositional trends on a Coward diagram as shown in Figure 1 or on an Ellicott diagram as shown in Figure 7. The Ellicott diagram is a modification of the Coward triangle where the X axis represents relative fuel concentration and the Y axis represents relative oxygen concentration. The Ellicott diagram has four quadrants to represent mixtures of methane, oxygen, and inert gases – (1) non-explosive, (2) fuel-lean potentially explosive, (3) fuel-rich potentially explosive, and (4) explosive. Upon sealing, when the methane concentration begins to increase, the trend may look similar to curve “A” on Figure 7. If a seal leaks air into a methane-rich atmosphere, the trend can look similar to curve “B”. Plotting these trends also enables mine safety personnel to estimate when a dangerous composition may form in a sealed area.

Understanding the process by which ignition of a methane-air mixture with a weak spark grows into a deflagration or detonation is crucial for understanding the explosion pressures that could develop and, in turn, for estimating the potential blast loads that could impact seals. NIOSH researchers are collaborating with researchers at the NRL to calculate explosion pressures from methane-air mixtures under various conditions and to design full-scale verification experiments (Oran and Boris, 2001; Oran and Gamezo, 2007).

To simulate high pressure methane-air explosions in coal mine entries, NIOSH researchers have constructed a gas explosion tube with a diameter of 1048 mm (42 in) and a length of 73 m (240 ft) as shown in Figure 8 (Zipf et al., 2008A). This tube is almost twice the diameter of a tube used for similar experiments by Kuznetsov, et al., (2002), and it should have sufficient diameter to support a true detonation of methane-air. The objectives for experiments with this tube are (1) to measure maximum explosion pressures for various mixtures of methane, air and inert gases, (2) to measure the distance required to accelerate a flame, achieve high pressure and develop possible detonations, and (3) to validate numerical gas explosion models of these processes. In addition to varying the explosive gas mixture composition, the experimental program will vary the number of turbulence-generating obstacles in the tube along with the blockage ratio.

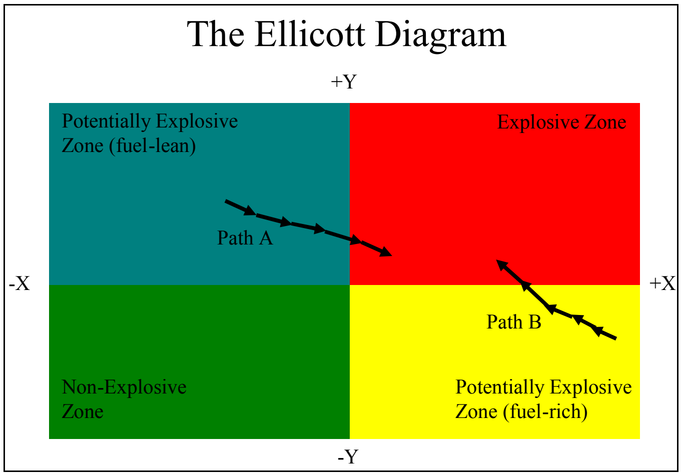

Figure 7. The Ellicott diagram divides mixtures of methane, oxygen and inert gases into four zones – non-explosive, potentially explosive (fuel-lean), potentially explosive (fuel-rich) and explosive. Measured compositions when plotted on the Ellicott diagram can show potentially dangerous trends.

Figure 8. 1,048-mm-diameter (42 in) gas explosion tube at NIOSH Lake Lynn Laboratory.

NRL researchers have recently simulated deflagration-to-detonation transition (DDT) of methane-air mixtures using state-of-the-art reactive flow programs (Kessler, et al., 2008). The NRL model solves numerically the Navier-Stokes equations for fluid dynamics using an explicit, second-order finite difference scheme and considering the viscosity, diffusion, and thermal conductivity of methane-air and the reaction products. To calculate turbulence and shock waves in the fluid, the model uses an adaptive mesh refinement scheme. A single-step Arrhenius burn model is used to describe the kinetics of energy release. Based on fundamental physics and chemistry, the NRL reactive flow model calculates laminar flame properties such as the flame speed and detonation properties such as the detonation wave speed that agree well with experimental measurements of the same. Figure 9 compares calculated flame velocity to measured flame velocity from experiments using two different tube sizes. Flame velocity increases with distance from the ignition point. These calculations based on first principles agree well with experimental determinations.

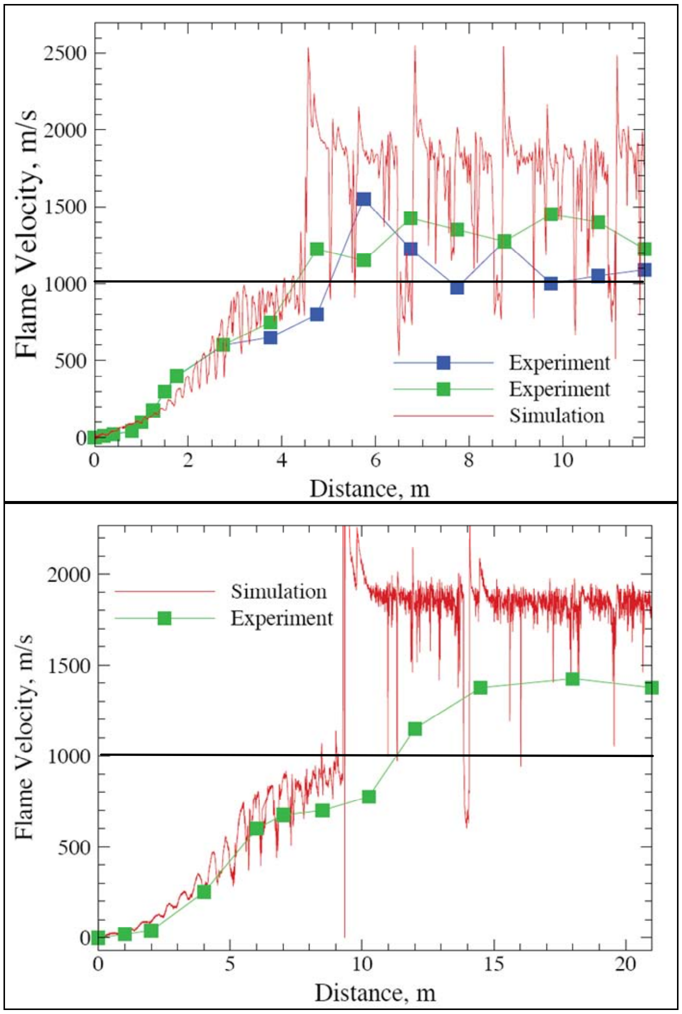

Figure 9. Calculations of pressure, temperature and turbulent flame speed for reacting mixtures of methane-air in channels agree with experimental measurements. Top – 174-mm-diameter tube, 12-m-long. Bottom – 520-mm-diameter tube, 34-m-long (Kessler et al, 2008). Note – The sound speed in hot combustion products is about 1,000 m/s. Flame velocity greater than 1,000 m/s indicates possible detonation.

Figure 10 shows calculations of a turbulent flame, shock wave development, and the initiation of a detonation in methane-air. The first two frames show the turbulent flame front and a shock wave traveling at the local sound speed ahead of the flame. When this leading shock wave impacts an obstacle (the second baffle), it ignites a detonation as shown beginning in the third frame. In frames 4, 5, and 6, the detonation front travels supersonically and rapidly overtakes the leading shock wave. Beginning in frame 7, the reaction continues as a detonation. Thus, the subsonic turbulent flame or subsonic deflagration has become a detonation in the process known as DDT. The fundamental calculations shown in Figure 10 also predict correctly the approximate distance required to develop detonation from a weak ignition source. Calculations of this caliber when coupled to sound experiments create a deep understanding of the process leading to DDT in methane-air and the factors controlling the behavior.

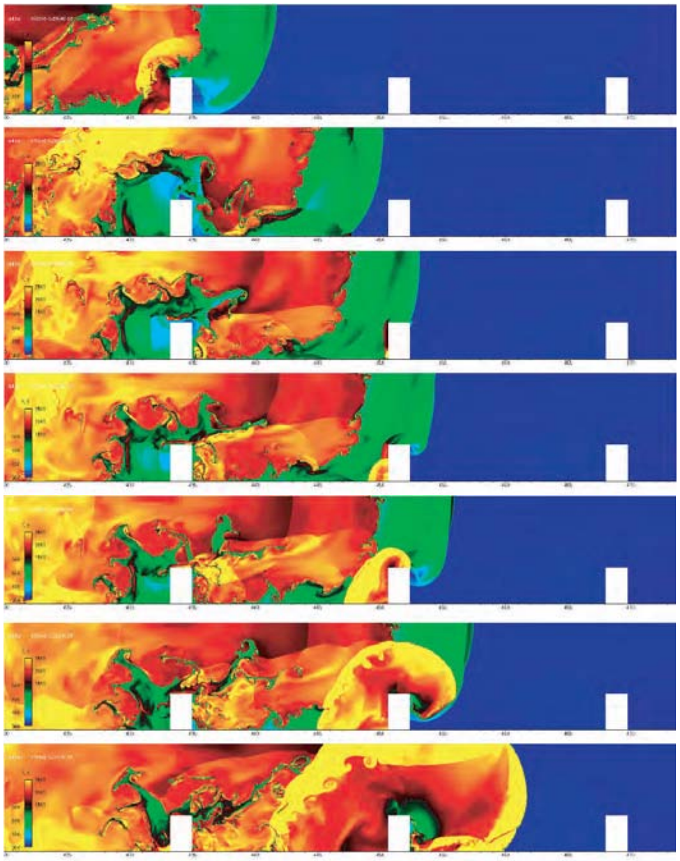

Figure 10. Calculations based on fundamental physics correctly predict distances to deflagration-to-detonation transition for stoichiometric methane-air mixtures in channels with obstacles [Kessler et al. 2008] Blue represents unburned mixture; the line between green and blue is a shock wave, and the line between yellow and blue is a detonation wave.

Seal Engineering

Developing engineering procedures for the mining community to use for new seal design is another key component of on-going research. NIOSH researchers recommended a four-phase approach to seal design and MSHA's final rule on seals provides the framework for engineered seal design applications. However, the details require additional development in order to produce engineering guidelines. NIOSH researchers are collaborating with researchers at USACE and WVU to produce these guidelines. Major efforts to date include: (1) cataloging existing 20 psi seal test data, (2) developing basic seal analysis methods, (3) developing seal foundation analysis methods, and (4) developing simple, cost-effective seal designs to resist high explosion pressures.

Compendium of Seal Test Data

Prior to 2006, NIOSH researchers conducted full-scale explosion tests at Lake Lynn Experimental Mine (LLEM) on a wide variety of old 140 kPa (20 psi) seal designs. The structural response and failure data obtained from these tests enable calibration and verification of numerical models of seal behavior at the 140 kPa (20 psi) design level, which then enables more reliable structural analysis of seal designs that meet the new explosion pressure design criteria of 345 kPa (50 psi) and 800 kPa (120 psi).

NIOSH researchers have organized the seal testing data into 6 broad categories of seal structures:

1. Concrete-like materials with steel reinforcement and reinforcement bar anchorage to rock.
2. Pumpable cementitious materials of varying compressive strength with no steel reinforcement and no hitching to the surrounding rock.

3. Articulated structures such as solid concrete block seals and ventilation stoppings made of solid and hollow-core concrete blocks.
4. Composite polymer and aggregate materials without hitching to the surrounding rock.
5. Wood crib block seals with and without hitching.
6. Articulated structures such as lightweight cementitious blocks with and without hitching.

The NIOSH compendium of 20 psi seals test data presents the applied pressure-time curve and the measured displacement-time response from over 100 explosion tests on 52 distinct seal structures (Zipf, et al., 2008B).

Figures 11 and 12 provide examples of how this seal test data is used to verify structural analysis models of seal response. Figure 11 from researchers at WVU shows the measured and calculated displacement response of a Category 1 seal constructed of 0.3-m-thick (12 in) reinforced concrete and subjected to a pressure-time curve with a peak pressure of about 400 kPa (58 psi). Calculated peak displacement using the finite element method program ABAQUS is 2.54 mm (0.10 in) compared to a measured peak displacement of 2.03 mm (0.08 in). Note that the measurements only capture displacement motion up to the peak and are not able to record subsequent vibration of the structure due to the nature of the instrument deployed. Figure 12 from researchers at USACE shows measured and calculated displacement response for a Category 2 seal made from 0.75-m-thick (2.5 ft) pumpable cementitious material. Peak pressure of the applied pressure-time curve is 198 kPa (28.7 psi). The displacement response is calculated with the Wall Analysis Code (WAC) which is a single-degree-of-freedom, equation-of-motion program with pre-defined resistance functions for different structures. Measured peak displacement response is 54.4 mm (2.14 in), and calculated displacement response is 55.9 mm (2.20 in).

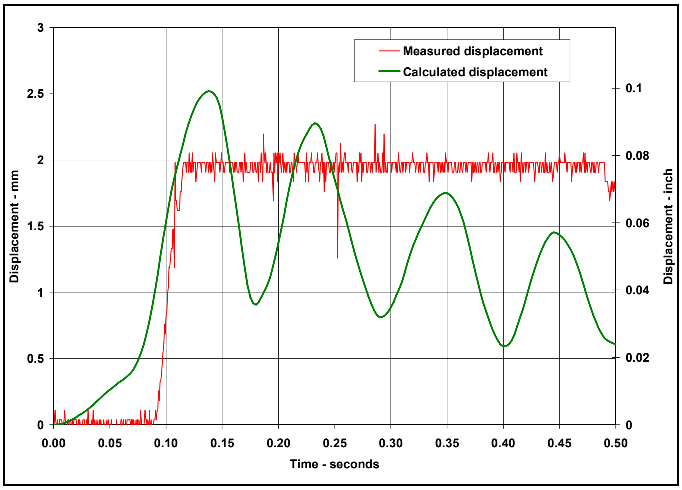

Figure 11. Calibration of seal analysis methods to seal tests at Lake Lynn Experimental Mine. Measured displacement of a reinforced concrete seal compared to calculated displacement using the finite element program ABAQUS. [Peng et al. 2008].

Further analysis of the structural data presented in the compendium of 20 psi seal test data will produce additional validations of different structural analysis methods for various types of seals. Additional analyses of this data may also produce generalized failure criteria for different seal types.

Seal Analysis Methods

USACE researchers recognize three distinct analysis methods for seals: (1) bending beams and plates shown in Figure 13, (2) shear plugs shown in Figure 14, and (3) arching shown in Figure 15. A bending-beam analysis applies when the thickness-to-span ratio for the structure is less than 4. The failure mode for a bending structure varies, but may involve tensile failure of the outer fibers opposite the applied load, compressive failure on the same side as the applied load or shear failure near the supports. All three failure possibilities require analysis and design consideration. As shown in Figure 13, the quality of the surrounding foundation rock influences the behavior of seal structures in bending. Seal structures located in weak foundations showed significant damage around the perimeter necessitating the use of engineered foundations. Seal structures located in competent foundation rocks survived without engineered foundations.

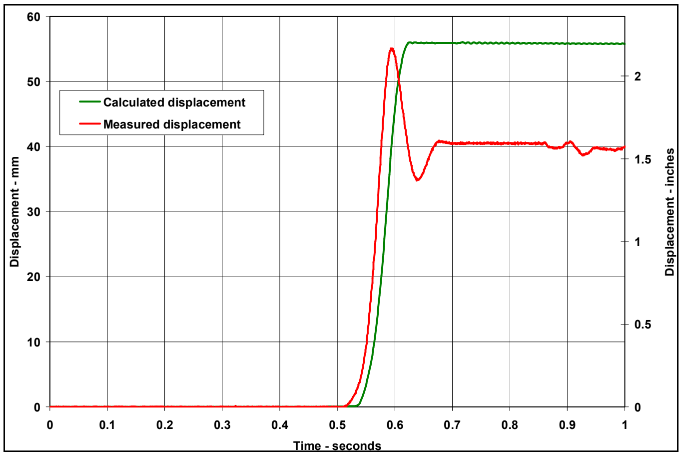

Figure 12. Calibration of seal analysis methods to seal tests at Lake Lynn Experimental Mine. Measured displacement of a pumpable cementitious material seal compared to calculated displacement using WAC from the USACE (Walker et al. 2009).

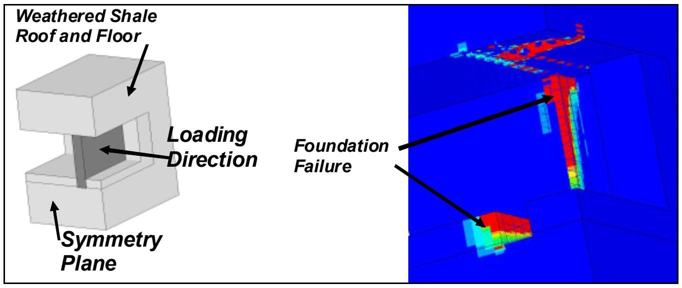

Figure 13. Seal analysis as a bending beam or plate. Red color indicates foundation failure; blue color indicates no foundation failure. Weaker foundation materials show significant damage and may require the use of extended seal foundations (O'Daniel et al., 2009).

Shear plug analysis applies when the thickness-to-height ratio for the seal is greater than 1. The failure mode is either via shear failure through the seal material or through the surrounding foundation rock. Figure 14 shows two shear plug analyses. In stronger foundations, the blast side of the shear plug displaces about 125 mm (5 in), but otherwise, the plug survives with little shear damage. However, in weaker foundations, failure occurs around the plug and the entire plug moves. The plug analysis shown in Figure 14 assumes weak foundation material on all four edges of the seal, which is not realistic in practice. Future analyses will consider weak material of finite depth in the floor only, which may be representative in general. However, seal structures located on weak foundations may require engineered foundations to survive the required design explosion pressures.

Note that for thickness-to-span ratio between 4 and 1, the failure mode may become a complex combination of bending and shear failure. Again, all failure modes require analysis and consideration in proper seal design.

Arching analysis applies to articulated structures where the thickness-to-span ratio ranges from about 2 to 5. As shown in Figure 15, the arching failure mechanism is via compressive failure of the seal material at the supports in the outer fibers opposite the applied load and also at the mid-span on the same side as the applied load. Development of the ideal arching mechanism requires an infinitely stiff or rigid foundation. USACE researchers investigated the effect of weaker foundations on the arching failure mechanism. Weak foundations prevent the development of arching, and average foundation conditions in a coal mine may only develop limited arching. Seal designers should not use an arching analysis to determine the load bearing capacity of a seal since; in general, the method tends to overestimate the strength of a seal and is therefore not conservative. However, if the soft foundation rock is excavated to competent material, then an arching analysis could apply.

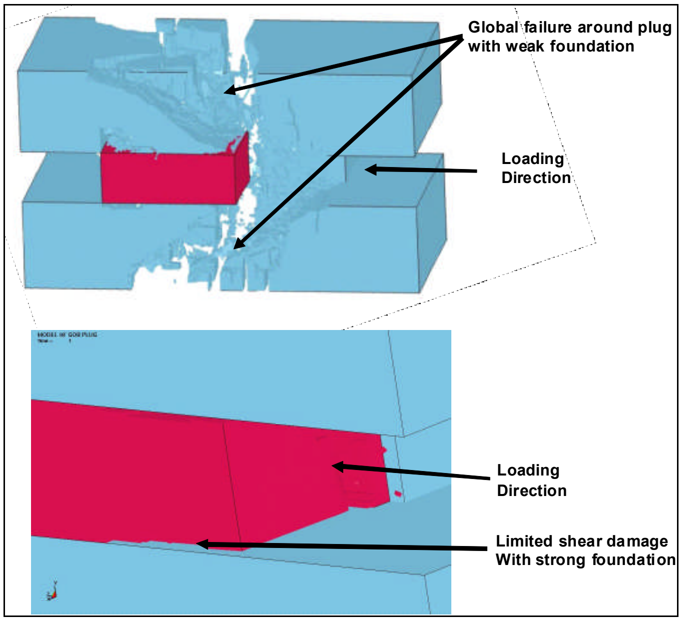

Figure 14. Seal analysis as a shear plug. In weaker foundation materials, failure occurs around the gob plug and the entire plug moves. In stronger foundation materials as shown, blast side displacement of about 5 inches occurs. The plug survives with limited shear damage (O'Daniel et al., 2009).

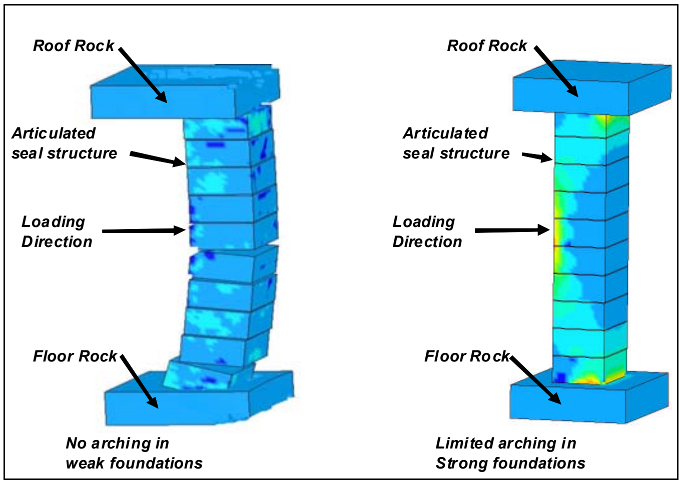

Figure 15. Arching analysis of articulated seal structures. Weaker foundations prevent development of arching. Arching cannot be assumed to determine load capacity of a seal (O'Daniel et al., 2009).

The prior examples illustrate the different seal failure mechanisms involving bending, shearing, or arching. When using analysis tools, seal designers need failure criteria in order to assess the adequacy of a structure. Failure criteria options include maximum stress, allowable displacement, tensile cracking, and others. Researchers at WVU presented a method to assess overall failure damage in a structure based on a "weighted average damage factor" which is a single value describing the overall damage in a seal. Based on finite element analysis, the damage factor for an element varies from 0 to 1, depending on the level of plastic strain within the element. A damage factor of 0 indicates no failure, and a damage factor of 1 indicates complete failure. The weighted average damage factor (WADF) is then computed as:

$$WADF = \frac{\sum(element\,volume \times element\ damage\ factor)}{\sum(element\ volume)}$$

As shown in Figure 16, the WADF provides a means to compare quantitatively different seal designs. A 30-cm-thick (12 in) seal has about 44% damage and has failed, whereas a 50-cm-thick (21 in) seal has minimal damage of about 5%. Figure 16 also indicates that little reduction in damage occurs in going from a 50 to 75-cm-thick (21 to 30 in) seal for this particular design.

The WADF expresses structural damage as a single value, and that value may or may not indicate overall structural failure, since the WADF does not consider the location of the damage. Conceivably, a structure with low WADF value could fail if all the damage were concentrated around the seal perimeter for example. Evaluation of the integrity of a structure requires consideration of stress and displacement failure criteria to fully assess integrity.

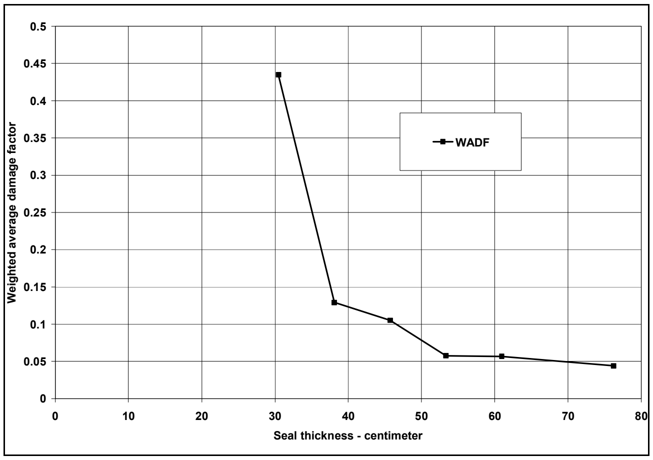

Figure 16. Weighted average damage factor for seals of different thickness (Peng et al., 2008).

Seal Foundation Analysis

Just as a seal structure requires analysis and design, a seal foundation requires similar engineering consideration. While the seal structure must resist the internal stresses induced by the design explosion pressure-time curve, the seal foundation must adequately anchor the seal to the surrounding rock. In effect, the seal structure must remain connected to the seal foundation during the explosion loading. Proper seal foundation engineering should consider the quality of the surrounding rock mass and its strength. The seal foundation design must specify the depth of any hitching or excavation into the surrounding rock and the length and size of any rock bolts or reinforcement bars.

Using well-accepted foundation analysis methods, USACE researchers have developed preliminary bearing capacity recommendations for seal foundation design. As shown in Table 1, the bearing capacities of the seal foundation are related to the compressive strength of the foundation rock whose quality is described by the Coal Mine Roof Rating (CMRR) which is an accepted method to quantitatively describe the quality of coal mine rocks. From these recommended bearing capacities, seal designers can engineer the required seal foundation including depth of hitching and reinforcement.

Innovative Seal Designs

NIOSH researchers in collaboration with USACE and the West Virginia Office of Miner's Health Safety and Training (WVOMHST) have developed several concepts that should provide simple, cost-effective seal designs to resist the explosion pressures specified in the new MSHA final rule on seals or even higher worst-case explosion pressures. Figure 17 shows a Gob Seal with Load Collectors concept developed by military experts at the USACE. This seal uses dry-stacked, large concrete block “load collectors” to compress a gob pile. Upon compression from an explosion loading, the gob pile expands laterally and locks into the surrounding rock. Preliminary analyses by USACE researchers showed that a 2.4-m-high (8 ft), 5.6-m-thick (18 ft) gob pile with the load collectors could resist the 800 kPa (120 psi) design pressure. Constructing this seal would require about 100 to 150 tons of gob, which could be placed in several work hours using an underground mine scoop.

Table1. Foundation analysis and design for seals. Bearing capacity design applies to seal foundations. The required depth of hitching depends on the bearing capacity of the rock which depends on the rock quality (Walker et al., 2009).

Material Name	Description	CMRR	Lab UCS (MPa)	Bearing Capacity q_u (MPa)
Soil 1	Paste	N.A.	0.04	0.020
Soil 2	Very soft soil	N.A.	0.07	0.041
Soil 3	Soft soil	N.A.	0.14	0.081
Soil 4	Firm soil	N.A.	0.29	0.160
Soil 5	Stiff soil	N.A.	0.63	0.349
Soil 6	Very stiff soil	< 30 – very weak rock	3.6	2.008
Rock 1	Claystone, fireclay	31 – weak rock	6.4	3.558
Rock 2	Black shale	33 – weak rock	11	6.043
Rock 3	Black shale, gray shale	38 – weak rock	18	10.163
Rock 4	Gray shale	47 – average rock	25	14.127
Rock 5	Siltstone, gray shale	56 – average rock	34	19.204
Rock 6	Siltstone	65 – average rock	48	26.628
Rock 7	Siltstone, sandstone	72 – strong rock	63	34.641
Rock 8	Sandstone, limestone	78 – strong rock	77	43.297
Rock 9	Sandstone	82 – very strong rock	95	52.660
Rock 10	Limestone	86 – very strong rock	139	78.504
Coal 1	Banded, bright coal	N.A.	3.6	2.037
Coal 2	Banded coal	N.A.	6.3	3.464
Coal 3	Banded, dull coal	N.A.	12	6.716
Coal 4	Dull coal	N.A.	17	9.742

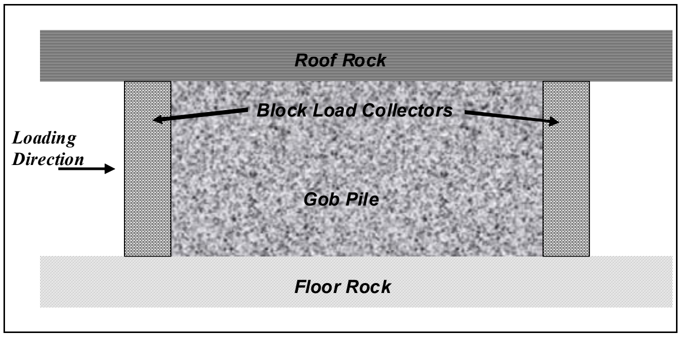

Figure 17. Innovative seal designs for the mining industry showing schematic side view of gob seal with block load collectors. This design from the USACE uses concrete-block “load collectors” to compress a gob pile when loaded by an explosion. Expansion of the gob transfers the blast load to the surrounding rock. (NO SCALE) (Walker et al., 2009).

Figure 18 shows the Sapko-Hieb Mine Blast Attenuator concept advanced by the WVOMHST. NIOSH researchers (Sapko et al., 2009) constructed a prototype attenuator at LLEM by filling an entry with broken rock as close as possible to the mine roof. The attenuator measured about 6-m-long (20 ft) near the roof line and about 12-m-long (40 ft) at the floor. A test explosion subjected the Mine Blast Attenuator to an upstream or inby, quasi-static pressure of 324 kPa (47 psig) as shown by the test data in Figure 18. Downstream or outby of the attenuator, the test data showed that the pressure was less than 4.8 kPa (0.7 psig). This initial test of the Mine Blast Attenuator concept shows that simple constructs using inexpensive, readily-available broken rock can reduce downstream blast pressures by a factor of 10 or more. NIOSH researchers will continue work developing similar innovative seal designs.

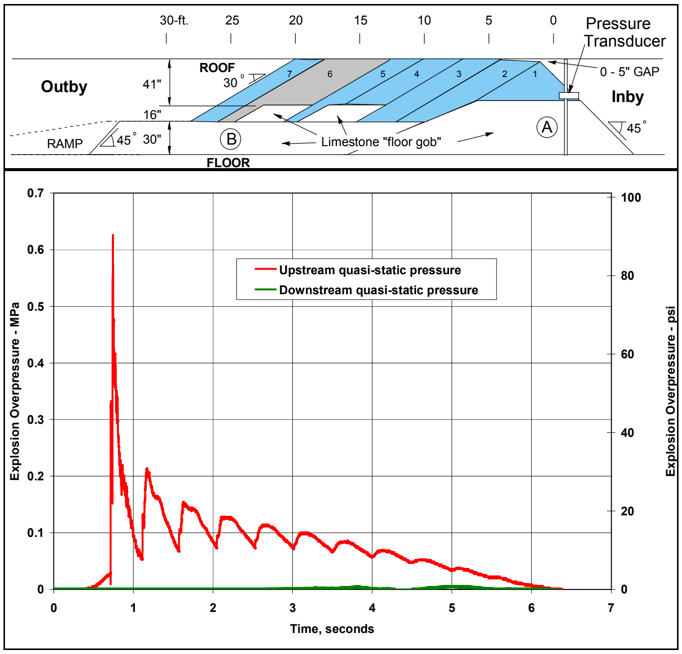

Figure 18. Innovative seal designs for the mining industry showing the blast wave attenuator concept which may reduce the downstream blast pressure by a factor of 10 or more (Sapko et al., 2009).

Management of Sealed Areas

NIOSH researchers have advanced several concepts and technologies relevant to the management of sealed areas: (1) mine planning practices, (2) monitoring practices and (3) inertization methods. The increases in explosion pressure design criteria for new seals have increased the cost of seals which now require more material and labor to construct. The mining community has expressed concern that the cost of seals may lead to abandonment of sealing and continued ventilation of mined-out areas. Alternatively, NIOSH researchers suggest that better planning for future sealing can decrease the number of seals required for lesser net increase in the cost of sealing an area. Better pre-planning for sealed areas can decrease the number of seals required and decrease the ventilation pressure differential across sealed areas. NIOSH researchers plan to document improved mine layouts that facilitate mine sealing.

Continuous monitoring behind seals to ensure that the sealed area atmosphere remains inert enables the use of 345 kPa (50 psi) seals. As mentioned earlier, NIOSH researchers have acquired a tube-bundle gas monitoring system from SIMTARS in Australia to study the atmosphere within sealed areas and to demonstrate this technology in U.S. coal mines. This type of monitoring system is utilized at every underground coal mine in Australia, and NIOSH researchers hope to hasten its adoption by U.S. coal mining companies.

Deployment of tube-bundle systems as an integral part of the normal daily monitoring regimen at mines could have a positive impact on mine rescue and response following an explosion, fire or other catastrophic event. If a sampling and analysis system similar to that shown in Figure 5 were part of the routine mine monitoring system at an operation, such a system should survive a catastrophic event largely intact and would continue to provide valuable data on the status of the underground mine atmosphere. The analysis system located on the surface should survive unaffected, and significant portions of the underground sampling tubes should also survive. Thus the system should continue to provide near-real-time data on the composition of the mine atmosphere at many points throughout the mine. Such atmospheric composition information should enable safer and more rapid mine rescue and response decisions in an emergency.

To facilitate the development and adoption of inertization technology for sealed areas, the NIOSH Office of Mine Safety and Health Research contracted with On Site Gas Systems (OSGS) to build an in-mine mobile gas generation plant to extract nitrogen gas from the mine atmosphere. The demonstration unit shown in Figure 19 uses pressure-swing-adsorption separation technology, produces about 8.5 m^3 (300 ft^3) per minute, is less than 3.3-m-high (4 ft), and fits on a standard shield carrier used in underground coal mines. In recent tests conducted at the NIOSH Safety Research Coal Mine, OSGS in collaboration with NIOSH researchers successfully inertized a sealed area of the mine using the demonstration unit (Trevits et al., 2009).

Figure 19. Photograph of On Site Gas Systems in-mine nitrogen gas generation plant (Trevits et al., 2009).

CONCLUSIONS

NIOSH is in its first year of a major new research effort on seals and sealed areas of coal mines. Recent scientific studies of explosions within sealed areas and the new regulations have made the mining community aware of the potential danger posed by seals and sealed areas of coal mines. Knowledge gaps include:

1. Composition of the sealed area atmosphere and how the atmosphere varies within sealed areas and changes composition over time.
2. Explosion processes within sealed areas and how the ignition of a flammable mixture develops into a deflagration, produces shock waves and reflected shock waves, and possibly transitions into a detonation.
3. Seal engineering procedures and how engineers should design seals that consider the explosion pressure, the surrounding foundation rock, and convergence effects on seal structures.
4. Sealed area atmosphere management procedures and how the mining community should plan mines for future sealing, monitor the atmosphere within sealed areas, and ensure that sealed area atmospheres are inert.

NIOSH researchers are collaborating with numerous research groups to address issues and knowledge gaps with seals and sealed areas of coal mines. Highlights include:

1. Acquisition of a tube-bundle system from SIMTARS in Australia to study the sealed area atmosphere and its evolution. NIOSH researchers seek a collaborating mine in which to demonstrate this technology and encourage its adoption by U.S. coal mines.
2. Construction of a gas explosion tube to study large-scale methane-air explosions and detonations. NIOSH researchers aim to measure the explosion pressures that can develop under various conditions similar to a sealed area.
3. Simulation of gas explosion processes and calculation of explosion pressures under varying conditions. NIOSH researchers are collaborating with gas explosion experts at the Naval Research Laboratory to study high pressure methane-air explosions based on first principles from physics and chemistry.
4. Compilation of all the 20 psi seals test data from Lake Lynn Experimental Mine for subsequent structural analysis. This compendium presents the applied pressure-time curve and the measured displacement-time response on 52 distinct seal structures organized into six different broad categories.
5. Development of methods for engineering design of seals. Researchers at WVU and USACE are analyzing seals as bending, shear plug or arching structures. Seal designers should not rely on arching to develop except in areas where the foundation conditions are rigid and unyielding.
6. Development of seal foundations analysis methods. Researchers at USACE presented a method to assess the bearing capacity of seal foundations that is related to the CMRR used to assess the quality of coal mine rocks.
7. Development of innovative seal designs to resist explosion pressures. Sapko et al., presented the Sapko-Hieb Mine Blast Attenuator concept that was tested at NIOSH's Lake Lynn Experimental Mine, and USACE researchers presented the concept of a gob seal with load collectors. In both concepts, a mine entry is filled for a length of about 6 m (20 ft) from floor to roof.
8. Development of new inertization technology. On Site Gas Systems, under contract to NIOSH, has successfully tested a new nitrogen gas generator for inerting sealed areas of coal mines.

NIOSH researchers aim to provide engineering guidelines for meeting all aspects of the new MSHA regulations. The new guidelines should provide multiple solutions for sealing that go beyond a "one-size-fits-all" approach. In developing proper engineering design codes for seals and sealed areas, the authors advocate seal designs to resist pressure-time curves that are based on an understanding of the risk involved and not just a simple worst-case analysis.

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