EXPLOSION PRESSURE DESIGN CRITERIA FOR SEALS IN U.S. COAL MINES – AN UPDATE ON WORK AT NIOSH

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ABSTRACT

A fatal explosion in a sealed area at the Sago Mine in 2006 prompted researchers and regulators in the United States to re-examine the requirements for explosion-resistant mine seals. Seals are used in underground coal mines to isolate abandoned mining areas from active workings. Prior to the Sago disaster, mining regulations required seals to withstand a 140 kPa explosion pressure. Recent research at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory showed that pressures from explosions can far exceed this pressure. U.S. mining regulations now require much stronger seals. Current research focuses on understanding the science, engineering and management of sealed areas of coal mines. Scientific efforts seek understanding of how explosive methane-air mixtures accumulate using measurements and models of the sealed area atmosphere. Additional scientific efforts aim to understand the explosion pressures that can develop using a combination of numerical modeling and experiments. Engineering efforts aim to produce design guidelines for seals that can resist the new higher pressure design criteria. NIOSH researchers are also developing guidance for monitoring of sealed area atmospheres and inertization of potentially explosive gas mixtures within sealed areas. This paper seeks to encourage scientific discussion among international peers since preventing explosions within sealed areas is of interest to underground coal operators and regulators.

1. 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 the Mine Safety and Health Administration (MSHA) to increase seal design pressures by the end of 2007. Scientific studies of gas explosions within sealed areas (Zipf *et al.*, 2007) provided a basis for the new MSHA regulations on sealing of abandoned areas (Federal Register, 2008).

NIOSH researchers conducted scientific studies 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.

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. 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.
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 stoichiometric methane-air mix develops, the maximum detonation wave overpressure is 1.66 MPa. When a detonation wave impacts a structure, it reflects at a pressure of about 4.40 MPa which is about 2.54 times greater than the incident detonation wave pressure.

The NIOSH report also presented simple numerical model calculations of explosion pressures within mine tunnels. Using the gas explosion models AutoReaGas (ANSYS Inc., 2009) and FLACS (Gexcon, 2009), which are commonly applied throughout the oil, gas, and chemical industries, researchers calculated explosion pressure at a seal. Figure 1 shows the simple mine layout and the calculated explosion pressure. The 160 m long gas cloud that filled 3 entries and the cross-cuts developed explosion pressure ranging from about 2.4 to 3.3 MPa.

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

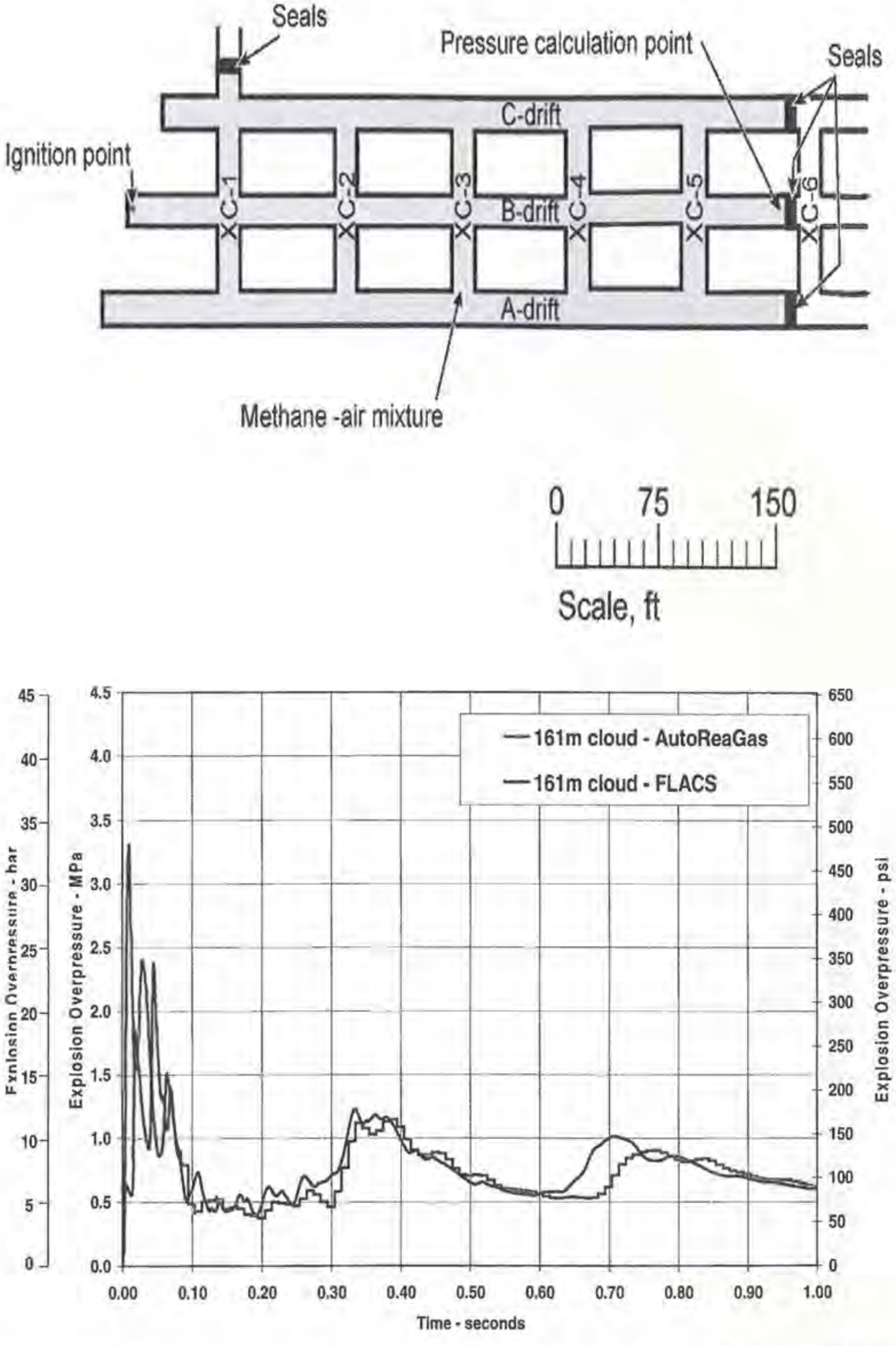

Figure 1: Calculated gas explosion pressure from numerical models at a seal fron 160 m long gas cloud. Model gas cloud geometry is above (Zipf *et al.*, 2007)

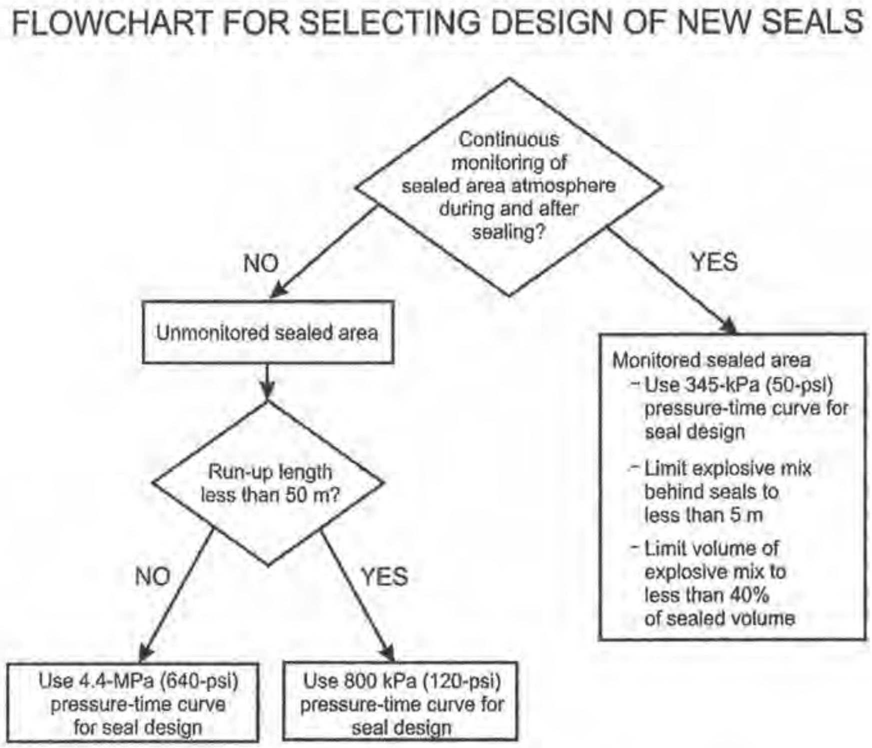

Figure 2: Design criteria for various sealing conditions (Zipf *et al.*, 2007)

NIOSH researchers then presented a three-tiered recommendation for explosion pressure design criteria for seals as shown in Figure 2. 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 right behind a seal, then a 345 kPa 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, then the 800 kPa pressure-time curve applies. If the open entry behind the seal is large with a length more than 50 m, then the 4.4 MPa explosion pressure-time curve applies. Note that it is not necessary for an explosive methane-air mixture to detonate to achieve high explosion pressure. Non-reactive blast waves from ordinary deflagrations can easily develop reflected pressures greater than 1 MPa as the experiments at LLEM have demonstrated for gas clouds as small as 26 m long.

2. KNOWLEDGE GAPS WITH SEALS AND SEALED AREAS

The recent NIOSH study (Zipf et al., 2007) coupled with the U.S. Army Corps of Engineers (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.

3. NIOSH RESEARCH PROGRESS TO ADDRESS SEALING ISSUES

3.1 Composition of Sealed Area Atmosphere

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. Gadde et al., (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.

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.

3.2 Gas Explosions – Numerical Simulations and Experiment

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.

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 and a length of 73 m as shown in Figure 3. 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 3: 1048 mm diameter (42 in) gas explosion tube at NIOSH Lake Lynn Laboratory

Naval Research 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 and considering the viscosity, diffusion, and thermal conductivity of methane-air and the reaction products. Figure 4 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 Figures 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.

3.3 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 are collaborating with researchers at USACE and West Virginia University (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.

USACE researchers recognize three distinct analysis methods for seals: (1) bending beams and plates, (2) shear plugs, and (3) arching. 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.

Figure 4: Calculations based on fundamental physics calculate distances to deflagration-to-detonation transition for stoichiometric methane-air mixtures in channels with obstacles (Kessler *et al.*, 2008)

Note: 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

All three failure possibilities require analysis and design consideration. *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. *Arching analysis* applies to articulated structures where the thickness-to-span ratio ranges from about 2 to 5. 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.

As documented by USACE researchers (O'Daniel *et al.*, 2009; Walker *et al.*, 2009), the seal foundation influences the behavior of seal structures. For example, as shown in Figure 5, 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.

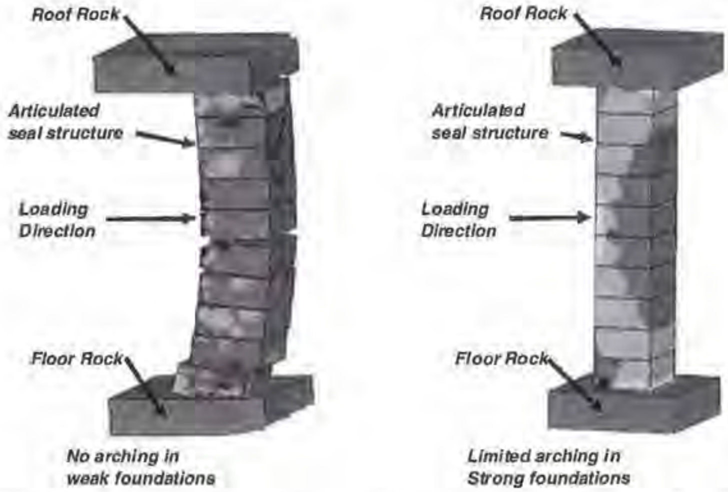

Figure 5: Arching analysis of articulated seal structures. Weaker foundations prevent development of arching. Arching cannot be assumed to determine load capacity of a seal (O'Daniel *et al.*, 2009).

3.4 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 (Sapko et al., 2009).

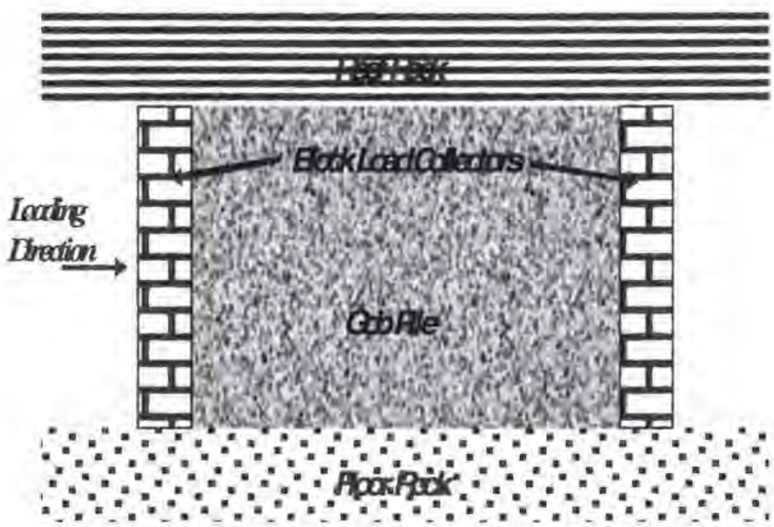

Figure 6: Side view of gob seal with block load collectors (Walker *et al.*, 2009)

Figure 6 shows the Gob Seal with Load Collectors concept developed by USACE. This seal uses dry-stacked, 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, 5.6 m thick gob pile with the load collectors could resist the 800 kPa design pressure.

3.5 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 seals. In Australian practice, continuous monitoring, coupled with inertization of the sealed area atmosphere as needed, eliminates the explosion hazard by preventing the accumulation of an undetected, potentially explosive mixture within the sealed area. The alternative approach is containment of a potential explosion with stronger seals. Tube-bundle gas monitoring systems are utilized at every underground coal mine in Australia, and NIOSH researchers hope to hasten their adoption by U.S. coal mining companies.

To facilitate the development and adoption of inertization technology for sealed areas, NIOSH 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 uses pressure-swing-adsorption separation technology, produces about 8.5 m^3 per minute, is less than 1.3 m high, and fits on a standard shield carrier used in underground coal mines (Trevits *et al.*, 2009).

4. SUMMARY AND CONCLUDING REMARKS

NIOSH is undertaking a major 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. 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.

DISCLAIMER

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