Reviews and Responses
"Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines"

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Comment

I took a quick look at most of the report but concentrated on sections 5 and 6 given the time constraints. These structural sections are succinct and articulate well how you arrive at your seal design charts. Per our phone conversation, I saw nothing that should be of major concern. I am including only the two files on which I've made comments (mainly editorial).

Response

Thank you for your prompt review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." Your assurance of the absence of major blunders in the structural dynamics area is most appreciated.

With regard to the simple seal design charts, we acknowledge their simplicity and the presence of potentially non-conservative assumptions within our analysis. We do not intend for these charts to become a substitute for proper structural analysis and site specific design of seals. Their intent is to show approximately the kind of seal necessary to resist the three design pressures using a variety of typical seal materials. This approximate seal thickness information is vital for a decision to 1) seal with monitoring, 2) seal without monitoring or 3) continue ventilating an area.

We are sincere in our intent to collaborate with Sandia National Laboratories to further examine the structural design of mine seals. Tentatively, we envision two objectives for structural analysis and design work, first to selectively verify a few points on the design charts and second to develop practical methods to protect seals from transient dynamic pressures due to reflected blast or shock waves. For the case of unmonitored sealed area atmospheres, we believe it is necessary to design for the constant volume explosion pressure, since there appears to be no way to avoid it. However, there may be simple ways to protect such seals from transients with simple countermeasures that are well developed for other applications.

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Comment

I have attached my comments and editing of the report associated with the combustion modeling. For the most part, my editing is minor with the exception of correcting the detonation overpressure equation. When one uses the correct relationship the isentropic index for the detonation products is 1.28 (instead of 1.1) - this value is very consistent with CHEETAH results (1.26) and will give consistent pressure ratio. This correction has only a minor effect on reflected pressures. I did a little word smiting of the combustion section - I change the word "static" to "quasi-static" since that wording is more acceptable to explosives folks.

I hope this review is what you are looking for. By in large, I have no problem with the content and a good engineering approach has been set out. I added a reference (Dorofeev, et al.) that may help to justify why DDT and detonation needs further study.

Response

Thank you for your prompt review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." Your assurance of the absence of major blunders in the gas explosion sciences area is most appreciated.

We are sincere in our intent to collaborate with yourself and Sandia National Laboratories to examine gas explosions within sealed areas of coal mines. Tentatively, we envision several objectives for such gas explosion work, first to model such explosions with proper CFD codes that correctly account for DDT and shock waves in typical coal mine geometries, second to verify such models against select methane-air detonation experiments, and finally to develop ways to suppress DDT in coal mines. We hope to benefit from your experience in these matters.

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Comments by United Mine Workers of America, Department of Occupational Health and Safety on the NIOSH draft report "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" and NIOSH Response

Comments - General

The United Mine Workers of America, International Union (UMWA or Union) is pleased to offer the following comments regarding NIOSH's Draft, *Explosion Pressure Design Criteria for New Seals in U. S. Coal Mines* (draft or draft criteria). The Union would like to express its general support of the draft and commend the professional at NIOSH for their dedicated efforts on behalf of miners and all working people.

However, the record would not be complete if we did not point out some unfortunate truths regarding this matter. The history of the mining industry is one of resistance to change and regulation when the health and safety of miners are at stake. Developments over the years since the writing of the 1969 Coal Act and the 1977 Mine Act have reinforced this understanding. While mine operators have toned down their rhetoric and open hostility to regulatory agencies they have moved aggressively to circumvent the pillars of these two important pieces of mining legislation from within.

The necessity to create a draft criteria for seals by NIOSH is a glaring example of the fruits of the mine operators efforts. Over the objections of the UMWA and many miners nationwide the federal Mine Safety and Health Administration (MSHA) at the insistence of mine operators virtually eliminated the language of the Acts requiring "explosion-proof or bulkheads" to isolate abandoned or worked out areas of the mine from active workings, to a 20 PSI standard. To further exacerbate the problem they permitted the use of lesser (substandard) materials to be used to construct these seals.

The mine disasters at Sago and Alma mines in 2006 can be traced immediately to the efforts of industry and the acquiescence of MSHA regarding the construction of seals. Other accidents that have maimed or killed miners over the years since the Acts were passed can likewise be shown as the result of the weakening of mining laws. The desire of mine operators, the weakness of the policymakers and leadership at MSHA and years of neglect by some in Congress have permitted in the mining industry to operate unrestricted. Many of the conditions that currently exist in some segments of the industry are reminiscent of those before the 1969 Coal Act was passed.

This can no longer be tolerated. The UMWA and the frames of the 1969 Coal Act understood that mine operators could not be trusted police themselves. Regulatory agencies must exert sufficient control over mine operators if all miners are to return home safely at the end of each shift.

With a few minor exceptions, that the Union will address in these comments, NIOSH has moved aggressively to address the inadequacy of the current seal requirements. They are to be commended for these efforts and MSHA should move just as aggressively to propose a rule that reflects the recommendations of the draft criteria.

Response

Thank you for your kind remarks on the dedication and professionalism of NIOSH staff on behalf of all working people in the United States. The authors recognize the controversy surrounding the issue of seals and it is our sincere hope that this report provides the necessary science and engineering to guide future seal regulations and practice.

Comment

The Union understands NIOSH's rationale, based on their research, for offering three design criteria for seal designs based on current mining practices.

1) Unmonitored seals with the possibility of detonation - 640 psi requirement
2) Unmonitored seals without the possibility of detonation - 120 psi requirement
3) Monitored seals with specific provisions - 50 psi requirement

However, the Union does not support the practice, given the circumstances that can exist, that areas of the mine to be sealed in the future should be permitted to be left unmonitored. Current technology exists that permit the mine operator to monitor this area at in all instances where seals are to be constructed. The existence of a 640 psi may be significantly more protective than the current requirement, but it is not as protective as monitoring such an area would be. The Union supports the 640 psi requirement, but seeks to have the area sampled at a sufficient number of locations to ensure the safety of miners to the greatest degree possible.

Response

From a technical perspective, the authors favor the use of monitoring coupled to an appropriate action plan to detect the accumulation of an explosive mix and prevent an explosion from ever occurring in the first place. The authors developed a worst-case scenario for an explosion where detonation occurs within an unmonitored sealed area. The design pressures are based on the so-called constant volume explosion pressure of 800 kPa (120 psi) and the reflected detonation wave pressure of about 4.4 MPa (640 psi). Many factors such non-homogeneous or non-stoichiometric mixes could lead to lower explosion pressures; however, other factors could lead to pressures much higher than the 4.4 MPa (640 psi) reflected detonation wave pressure. For example, the MSHA Accident Investigation Report of the 1992 Blackville #1 shaft explosion estimates explosion pressures of 6.9 MPa (1000 psi). The authors do not know the probability of achieving explosion pressure in a sealed area greater or less than the 4.4 MPa (640 psi) reflected detonation wave pressure. This criterion represents our best scientific estimate of a worst case explosion pressure on which to base engineering decisions. However, as mentioned earlier, the authors prefer to prevent an explosion from ever occurring within a sealed area through monitoring and inertization as required and thereby enable the use of 345 kPa (50 psi) seals.

Comment

The Union is also concerned with the assertion of NIOSH that there are instances where sealed areas may exist that do not present the "possibility of detonation." The Union is unaware of any area of a mine to be sealed that would not surpass the "run up" distance described in the draft as necessary to permit detonation. In fact, given the dimensions of most entries in the mine it is likely there would be no sealed area that did not include a sufficient area to allow an explosion to move from ignition point to detonation. This potential would be further enhanced by the conditions that exist over time in sealed areas, such as roof falls or convergence.

Response

The UMWA reviewers are correct in stating that most unmonitored seals could have a run-up length of more than 50 m (165 ft); however, there are many exceptions. Cross-cut seals used to isolate the longwall gob are one example. If the gob caves right into the cross cut, the length of open entry behind a cross-cut seal is generally less than 30 m (100 ft).

Roof falls and convergence could work to either promote or suppress the development of detonation from an ignition. Such entry deterioration creates roughness and turbulence that promotes detonation. However, if the entry caves in sufficiently, the smaller cross section area could prevent the development of detonation.

Comment

The environment within the sealed area, like the active workings of a mine, are ever changing. It does not seem prudent to assume an area will not be prone to detonation if the conditions, once the area becomes sealed, are not monitored. This would require information that cannot obtained under the proposed circumstances. Sequentially sealing areas without monitoring the area could add significantly to this problem. Should a seals within a larger sealed area become compromised the conditions necessary for detonation could be permitted to exist. Without monitoring stations this would not be known unless a catastrophe occurred.

Response

In future research NIOSH plans to explore the processes by which sealed areas become inert and processes that could lead to the accumulation of explosive mixes anywhere in a sealed area. Air leakage through seals may be a significant factor in the development of many potentially dangerous explosive mixes within sealed areas.

Comment

The Union would therefore recommend that mine operators not be permitted to construct future seals without ability to actively monitor the area they are designed to isolate from active workings. Such monitoring must be facilitated through the seals themselves and at a sufficient number of boreholes from the surface to offer a comprehensive understanding of the conditions that exist in the sealed area. Based on current mining knowledge the construction of seals that can withstand in excess of 120 psi may be plausible. Other applications may require seals to be constructed to control forces at 640 psi.

Response

For reasons outlined above, the authors disagree with the position that all sealed areas require monitoring even with the use of 4.4 MPa (640 psi) and 800 kPa (120 psi) seals. These criteria represent our best scientific estimate of a worst case explosion pressure on which to base engineering decisions. However, as mentioned earlier, the authors prefer to prevent an explosion from ever occurring within a sealed area through monitoring and inertization as required and thereby enable the use of 345 kPa (50 psi) seals. The authors caution that the seals must achieve their design strength, i.e. be fully cured, prior to continuing with other mining activities.

Comment

NIOSH also suggests that mine operators should consider utilizing inertization systems to control explosive mixture that may accumulate in sealed areas. The Union agrees with this recommendation, but would strengthen it by requiring mine operators to immediately inert sealed areas that approach explosive methane air mixtures. This type of system would need to be part of the mines overall sealing plan, as approved by MSHA.

Response

The authors agree that mine operators should consider inertization systems to control explosive mixtures within sealed areas. Fortunately, many mines can "self-inert" with methane in a short time frame; however, seals can leak and explosive mixes can still develop behind seals. Many mines can take a long time to self-inert with methane, and such operations may require artificial inertization.

Comment

The type of materials used for seal construction must also be given proper consideration. The Union believes that in order to meet the mandates of Congress, which must be the threshold established for new seal construction, only solid and substantial materials should be approved. Poured concrete, reinforced concrete or solid cement blocks laid wet in an overlapping pattern, all constructed at thickness applicable to the specific application are the only realistic options. Construction would also require hitching these structures into the ribs and bottom. These materials are readily available to the mining industry and would not require extensive or specialized training for installation.

Response

The NIOSH authors recognize the potential benefits of a wide range of seal construction materials and requiring certain materials for seals could stifle creative solutions. For seal structures, the seal material must have sufficient strength to resist the design explosion forces, and it must have sufficient durability to survive in the mine environment. The installation procedure also requires consideration, and for example, should not expose workers to repetitive stress injuries. The authors recommend that a licensed professional engineer design the seals and certify their installation according to specification.

Comment

Under no circumstances should alternative construction materials be permitted. The use of concrete foam, wood or other similar materials should be banned for such use in underground mining applications.

Response

As mentioned above, the authors recognize the potential benefits of many different seal construction materials. However, rigorous quality control standards are essential. The proposed materials must meet the required strength for a seal design, and quality control during installation must assure that the design strength is achieved.

Comment

Seal construction should be routinely monitored by a certified engineer. Such monitoring would include routine inspections to verify compliance with MSHA approvals. The results of inspection findings must be recorded in a book on the surface for such information and any defects or deviations from plans must be immediately reported and corrected. Finally, the engineer must certify that construction was completed according to required specification and MSHA approval.

Response

The authors agree with these recommendations. Section 7.2 of the draft report recommends certification by a licensed professional engineer during seal design and during seal construction.

Comment

The Union also recommends the air used to ventilate seals be immediately directed away from active working sections into a return air course. The operator should also be required to constantly monitor this air for methane and other hazardous gases, using an atmospheric monitoring system, at a location immediately outby the last ventilated seal in each bank of seals.

Response

The authors note this suggestion for ventilating and monitoring the area around seals.

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Comments by International Union of Operating Engineers, Local 953 of New Mexico at the San Juan Coal Mine on the NIOSH draft report "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" and NIOSH Response

Comments

I am responding to the above draft report on behalf of the coal miners represented by the International Union of Operating Engineers (IUOE), Local 953 in New Mexico at the BHP San Juan Mine. As a Representative of Miners for our work group, I have been asked to .issue comment on the draft report and offer other suggestions as to the implementation of legislation. Namely, the "Mine Improvement and New Emergency Response Act of 2006" or the "Miner Act".

First, the report is fine work. Many aspects of seal evaluation and construction that have not been previously examined are considered in this report. Aspects of prevention and monitoring are also noted which is greatly welcomed by our miners.

Rather than attempt to second guess or contest the results that are presented in the report, we would like to offer additional considerations that will help increase the safety of our mines as well as protect the operators and miners from undue burden.

Response

Thank you for your kind remarks on the quality of this NIOSH report. The authors recognize the controversy surrounding the issue of seals and it is our sincere hope that this report provides the necessary science and engineering to guide future seal regulations and practice.

Comments

An increase in the protective strength of mine seals is welcomed. However, an examination of the dangers associated with seal construction seems to be missing. Materials handling is a constant danger and source of injury to the miners who actually construct seals on site. As "bigger" can equate to "better", bigger means an increased potential for injury both repetitive and catastrophic. When the guidelines for seal construction are finalized, please include consideration for the welfare of the construction crews and some measure of protection from injury from the additional materials handling that is sure to accompany new seal construction.

Response

The reviewers raise an excellent point that new seal construction practices developed to meet new seal design criteria must not increase the injury potential of the workforce who must install the new seals. The seal materials and installation procedure should not expose workers to repetitive stress injuries. The NIOSH authors recognize the potential benefits of a wide range of seal construction materials and requiring certain materials for seals could stifle creative solutions. For seal structures, the seal material must have sufficient strength to resist the design explosion forces, and it must have sufficient durability to survive in the mine environment. However, another important seal design and construction criteria is the prevention of repetitive stress injuries in the workforce who must construct the seals.

Comments

All of the mine disasters and explosions listed in the report have one thing in common that was not examined in the report. An explosive mixture was present and was not detected. Apparently, there were no action plans present to withdraw miners from the mine if indication of an explosive mixture were detected. While the "bigger is better" mindset would definitely have a positive effect on the safety of miners, prevention of an explosion in the first place is the real key to success. The current sampling regimen allowed under law could easily allow and explosive mixture to arise in the time it takes to get results back from a laboratory. In the report, consideration for "real time" monitoring is given. This is a positive step in prevention of sealed area gas explosions. Relief from the highest standards of seal construction is even given when monitoring is incorporated in seal management to encourage this methodology and is also welcomed as prevention is often more important than cure. Promotion of monitoring and development of appropriate action response plans needs to be given more emphasis in the final version of the report. Clarification of where and how often monitoring is to be done would also help operators and inspectors as it is unclear if each seal or each sealed area requires monitoring.

Response

The NIOSH authors would like to commend the reviewers for their excellent point that the sealed area explosions listed in table 2 of the report all had an explosive mixture develop that went undetected. The authors agree with the reviewer's statement that it is best to prevent an explosion from ever occurring within a sealed area through monitoring and inertization as required and thereby enable the use of 345 kPa (50 psi) seals. The authors hope that more mines in the U.S. will follow the lead of the San Juan mine and adopt monitoring and inertization practices that prevent an explosive mix from ever developing. Future NIOSH research will examine the processes by which sealed areas become inert and provide further guidelines to monitor and control the process.

Comments

The report examines placement of seals based on a distance from an area of free expansion for explosion pressures away from a seal. As operators will tend to select methods that will reduce cost and time of construction, placement of gob seals less than 3 meters from a caved area may prove problematic. By reducing the distance to the gob and preventing the explosion volume from being large enough to encourage the additional energies of an explosion from occurring, operators could use a less costly and time consuming seal. As breakage of the mine roof close to a caved or gob area isn't easily predicted, construction of a less substantial seal closer to a more geologically active area could cause the seal to be structurally compromised due to loading. Rather than increase the size requirements for a seal so close to a questionable area, it would be advised to move the seal further back from the cave line. If this distance is increased but not to a point that encourages increased energies from reaching the seal face, then the strength of the seal could be preserved. Observations indicate that a distance of at least 30 feet from the gob side rib line would increase a seal's survivability and help preserve its strength.

Response

The authors agree with the reviewer's suggestion to place a seal sufficiently far from the cave line adjacent to the gob to prevent seal damage during the seal's short lifespan. The authors believe that such placement is possible within the design constraints for 345 kPa (50 psi) seals put forth in the NIOSH report, namely that the explosive mix not exceed 5 m (16 ft) in length and that the explosive mix not fill the sealed volume more than 40%.

Comments

Consideration of the positive effects of supplemental roof support for the protection of a seal should also be given in the design and evaluation steps for new seal construction. For instance, if roof to floor supports such as can cribs help protect a seal from the effects of convergence, wouldn't they also serve as protection for the seal from explosive forces by being a shield to some extent for the seal. If evaluation could show this to be so, this would encourage operators to install this type (or similar) of roof to floor support and gain relief from the higher strength standard that will prove to be more costly and time consuming.

Response

The authors note this suggestion for guidance on supplemental support to protect seals from convergence damage during their lifespan. Future NIOSH research may examine means to protect seals from the high transient pressures associated with detonation waves. This research may lead to a design pressure less than the 4.4 MPa (640 psi) criterion. However, the 800 kPa (120 psi) and the 345 kPa (50 psi) criteria would be unaffected.

Comments

Installation of anchoring bars in the body of a seal to hitch it more effectively to roof, rib, and floor is also examined in the report. This is proposed for the purpose of gaining an additional0.5 safety factor for the overall performance of a seal in terms of blast resistance. As a typical seal installation at our coal mine would require over 200 anchor points, this would also increase the potential for injury during the construction of a seal. As the proposed guidelines already incorporate a safety factor of 2.0, is this additional work necessary? As the mass of a seal and the required notch hitching noted in the report are great resistors of movement due to blast impulse, these two factors should be examined as to their effectiveness and incorporated into seal design as opposed to the additional anchorage requirements.

Response

The section on seal anchorage reinforcement (section 6.4) of the draft report has been largely removed from the final report. The authors stand by recommendations to anchor seals in shear to the surrounding strata, but do not provide any specific guidance. This aspect of seal design may be addressed in a future NIOSH research project.

Comments

There are eight construction materials shown in Figures 25, 26, and 27. Allowance for new or different materials for construction should be noted in the seal design portion of the report. Operators and miners would greatly welcome the possibility of reducing materials handling and increasing mechanized installation of seals. This is probably inherent in the design phase but could be more clearly stated.

Response

The NIOSH authors recognize the potential benefits of a wide range of seal construction materials and requiring certain materials for seals could stifle creative solutions. For seal structures, the seal material must have sufficient strength to resist the design explosion forces, and it must have sufficient durability to survive in the mine environment. The installation procedure also requires consideration, and for example, should not expose workers to repetitive stress injuries.

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Comments from Peabody Energy Company by Murali M. Gadde, David A. Beerbower, John A. Rusnak and Jay W. Honse on the NIOSH draft report "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" and NIOSH Responses

Comments – 1.0 Introduction

The National Institute for Occupational Safety and Health (*NIOSH*) has recently produced a draft report [1]* on new seal design criteria for U.S. coal mines. *NIOSH* has requested public comments on the research presented in this report. The following sections in this review address some of the problem areas in the *NIOSH* report, which may require further research before finalizing the seal design criteria document.

First of all, the authors of the *NIOSH* report must be applauded for their effort to standardize the terminology used in connection with mine sealing process and related explosion events. This report is perhaps the first document that has made such an effort to address this long overdue requirement. The report also provides a nice summary of seal design practices in different major coal producing countries in the world, although South African experiences were not included. As is the case with mining practices, this *NIOSH* summary of worldwide experience also brings forth the contrasts in seal design practices that exist between the various countries.

The intention of the reviewers in providing the following commentary is to point out the deficiencies in the research presented in the *NIOSH*'s draft report. It is hoped that by addressing some of these problem areas, more realistic seal design criteria would be formed which will improve the safety of miners and promote the interests of the nation's coal mining community.

Response – 1.0 Introduction

The authors thank the reviewers for their kind words on this report. The subject of seals remains controversial, and the authors hope the report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines, ultimately. NIOSH has collaborated with Peabody Energy in research on many aspects of mine safety and health, and the authors hope to do so in the future.

The authors are aware of seal standards and practices in South Africa, but chose not include them in the summary. The South African industry uses a risk management based approach to safety management and has apparently accepted the old 345 kPa (20 psi) U.S. standard with no modification. The authors hope to educate the U.S. industry more about sealing practices used elsewhere in the world, particularly the associated monitoring and inertizing practices.

The authors will strive to rectify perceived deficiencies in the draft report as discussed in the reviewer's review.

Comments – 2.1 Constant Volume Combustion

In deducing the pressures to be resisted by mine seals, the *NIOSH* report starts with the "worst-case" analysis of the methane-air deflagration. In the following, the validity of some of the assumptions made in the constant volume explosion analysis is examined. The focus of this analysis is not to criticize the "worstcase" type analysis, but rather to highlight how unrealistic and improbable for some of the idealizations to be realized in a coal mine.

In estimating the constant volume explosion pressure, the following four key assumptions were made:

- the process was adiabatic,
- the gas mixture was homogeneous,
- the entry was completely filled with the gas mixture, and
- the methane content was at the stoichiometric level.

Let us examine each one of these assumptions in some details.

Response – 2.1 Constant Volume Combustion

The authors disagree with the position that the worst-case analysis as presented in the NIOSH report is unrealistic and improbable. As discussed in section 1.4 and shown in figure 3, whenever a mined out area is sealed, methane gas will accumulate and at some time, the sealed area atmosphere will cross through the explosive range. Depending on methane emission rates, that atmosphere could become fuel-rich and inert within a few days or it could remain in the explosive range for several weeks.

Developing a homogeneous methane-air mix without layering is likely since, in the absence of airflow, diffusion processes will lead to homogeneity within a matter of hours.

Our "worst-case" analysis is that of a methane air detonation, not a deflagration. The calculated adiabatic overpressure for 10 % methane air mix starting at 101 kPa (14.7 psi) produces 908 kPa (132 psi) for a system overpressure rise of 807 kPa (116 psi), which the authors chose to round this to 800 kPa (120 psi). You are correct there will always be some heat loss in process and that this heat loss depends on many unknown interacting factors. Some factors increase the heat losses while some can decrease heat loss from the system. Factors include surface to volume ratio for convective cooling; the surface properties for heat transfer; amount of rock dust dispersed for particle cooling behind the flame front; the amount of rock dust that decomposes in the flame, and moisture in the air. The presence of turbulence generators (cribs, roof and rib wire mesh) may significantly increase the combustion rate and minimize the time scale over which heat loss can take place before the combustion is complete.

Comments – 2.1.1 Adiabatic Combustion

An adiabatic process is one in which no heat is added to or extracted from the working fluid (methane-air mixture). While the assumption of adiabatic process greatly simplifies the calculations, one can easily see how unrealistic such an assumption is for coal mine strata, which have finite thermal conductivity properties. Considering the high thermal gradients created in the explosion process, it is physically impossible for heat not to transfer to the surroundings. While the above arguments are common sense based, experimental data on gas explosions in closed vessels even under controlled conditions also disprove the adiabatic assumption. For instance, even in the first ever measurement of gaseous explosion pressure by Hirn (1861), the noted differences between the values estimated based on adiabatic assumptions and measured values were ascribed to heat loss from the vessels. To quote Bone and Townend (1927), who discussed Hirn's experiments, "*He [Hirn] attributed the low pressures attained in such explosions to the fact that the metal sides of the explosion vessels were at so low a temperature compared with that of the explosion itself that the heat was rapidly conducted away.*" In terms of heat conduction, coal mine entries are similar to the closed vessels used in Hirn's experiments. To quote some recent data, Razus et.al.(2006) have compiled constant volume methane-air explosion pressures measured at ambient temperature and pressure at nearly stoichiometric concentrations from ten different research works. These absolute pressures varied from 700 to 870 kPa, much less than that estimated by the *NIOSH* report.

Response – 2.1.1 Adiabatic Combustion

Assuming an adiabatic process is realistic for full-scale explosions in coal mines. The data by Razus et al. (2006) that the reviewer mentions is developed from explosion vessels ranging in volume from 4.2 to 20 liters, although one test was from a 204 m^3 vessel. The ability to achieve close-to-adiabatic conditions depends largely on the ratio of surface area for heat loss to the combustion volume. At the laboratory scale, this ratio is large, so achieving adiabatic conditions is difficult. However, at the coal mine entry scale, this ratio is small, so adiabatic conditions are more closely approximated. No matter how close the process approaches adiabatic, the important questions are the magnitude of the pressure increase and the length of time that the pressure remains high. The authors contend that this data agrees well with theoretical calculations. Better understanding of actual coal mine explosion processes and the heat transfer to the surrounding rock may one day enable more realistic and perhaps lower values for the constant volume explosion pressure; however, at this time, the authors continue to recommend a conservative value of 908 kPa (131 psi) as per Fact 1 of the report.

The ratio of surface area of the containment vessel to the volume of the chamber along with the speed of reaction affects the convective heat loss. The heat loss rate is proportional to ~3/radius for a spherical vessel and 2/r for a cylindrical vessel. Experiments have shown, given the same ignition source and stoichiometric methane-air, the maximum explosion over pressure for a 1 liter sphere is lower than measured in a 1000 liter sphere. The larger the vessel the closer one approaches the adiabatic 800 kPa (120 psi) constant volume overpressure. The authors believe, given all the unknowns, 120 psig is a reasonable value and not much different from that presented by the reviewer through his reference; Razus' publication with a range of measured values of 700 to 800 kPa (86.6 to 111.5 psi).

Comments – 2.1.2 Homogeneous gas mix

The density of methane is about 0.55 times that of air (Creedy et al., 1997 and Kissell, 2006). As a result, there is a natural buoyancy effect that causes methane to accumulate more at the roof level, which is familiar to miners as 'methane layering.' In order to create a homogeneous mix, there would need to be sufficient ventilation air to disperse the methane layers. In a sealed-off panel, no circulating air is available to disperse and create a homogeneous methane-air mix. The buoyancy effect of methane also adds to the variability of the methane concentrations from roof to floor in an entry. Due to these well known processes, it is very unlikely to find a homogeneous methane-air mix that completely fills a coal mine entry from roof-to-floor and rib-to-rib in an abandoned panel.

In fact, as the constant volume calculations show, if the filling ratio (ratio of the area occupied by methane-air mix to the entry cross-sectional area) is less than 1.0, then the constant volume pressure is reduced by that extent. For example, if the filling ratio is 0.8, then the explosion overpressure becomes 20% less than that predicted assuming complete filling.

Also, due to the turbulent currents created by the explosion, rock and coal dust mix with the reactants to further reduce their homogeneity, if it exists.

Response – 2.1.2 Homogeneous gas mix

A common misconception exists that methane layering will develop within the still air of a sealed area. This misconception arises because it is common knowledge that methane tends to collect along the roof, especially in pockets, and that miners are instructed to measure methane concentrations in a coal mine about 1 foot from the roof and ribs. The density of methane is about 0.55 times that of air, so buoyancy effects do exist. However, in the completely still air within a sealed area, diffusion processes will dominate over buoyancy effects, which will lead to a homogeneous methane-air mix within a matter of hours.

When the gob is sealed, it contains mostly air. Shortly after sealing, methane begins to enter the sealed volume and mix with air via a combination of convection and diffusion and eventually the atmosphere passes into and through the 5 to 15 % flammable range. Depending on the methane liberation rate, location or combinations of methane sources (ribs, floor or roof) will drive the rate of mixing. If methane enters the sealed area very slowly from the roof the degree of layering and mixing with air is controlled by diffusion. If the influx is more rapid then the diffusion plus a convective mass transfer component will enhance component mixing. If methane enters from the floor them the mixing is much faster. Based on kinetic theory of gases, if a component of a continuous gas phase is present in the non-uniform concentration, and at uniform constant temperature and pressure in the absence of external fields, that component diffuses in such a way as to tend to render its concentration uniform. The rate upon which this occurs under most conditions is proportional to the concentration gradient times the diffusion constant. This is called "Fick's" first law of diffusion. The diffusion constant for methane in air is 0.157 cm^2/s. (Unit Operations of Chemical Engineering by McCabe and Smith, McGraw hill Book Company 2nd edition 1967, pg. 990).

The Loschmidt diffusion apparatus is used to determine the diffusion coefficient for binary mixtures of gases. Methane in placed in the top 50 cm long tube and air is placed in the bottom 50 cm long tube separated initially by a valve. The valve is opened and the gases are allowed to mix through diffusion. (Experiments in Physical Chemistry by Shoemaker and Garland, McGraw Hill Book Company 2nd edition 1967). In the 50 cm tube methane will mix with air and form a average 50-50 mixture in the top and in bottom tube in 55 minutes. If the methane liberation rate is low and the influx of methane occurs near the roof only, diffusion will control the mass transfer or mixing process. If methane enters via the floor the mixing rate is much faster as the methane rises up through where mass transfer and mixing is promoted by diffusion and buoyant convection. The gas uniformity within a mine is difficult to predict at the time of ignition so the authors chose to design for the worst case.

Comments – 2.1.3 Existence of stoichiometric methane-air mix in abandoned panels

In a regular mine atmosphere, if the methane concentration by volume is between 5% and 15%, the mixture is considered explosive. If the methane content is around 10%, the composition is considered stoichiometric. In the sealed-off area, however, due to the lack of any mechanical ventilation, the air composition changes for several reasons. This fact is very well known to coal miners and is demonstrated very nicely with actual data obtained at a South African coal mine through remote monitoring using the "tube and bundle" system (Hardman et al., 2001). The data shown in Figure 1 was obtained from an abandoned room and pillar mine, which has not been retreat mined. Curves in the Figure 1 show how the percent of oxygen in the gob air decreased over time while the methane content progressively increased before stabilizing, over the same time period.

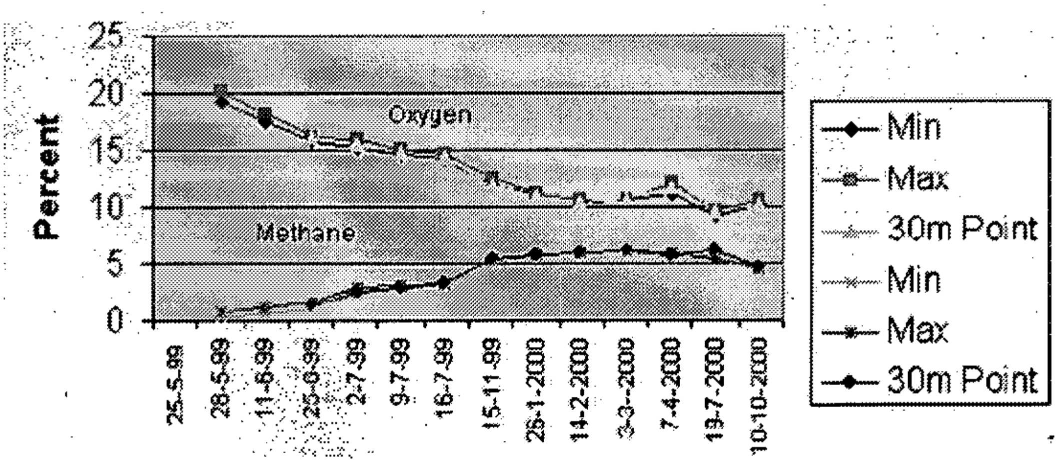

Figure 1. Change in the oxygen and methane content in gob air over time (Hardman et al., 2001).

In the early 1900s, R. V. Wheeler and his colleagues working for the Safety of Mines Committee in U.K. have shown that decreasing oxygen content in air has a drastic effect on the upper explosive limit (UEL) of methane while the lower limit is not affected to the same extent. Referring to Wheeler's work, Bone and Townend in their book on 'Flame and Combustion in Gasses' (1927) have given the data in Table 1 below to show the effect of decreasing oxygen content on methane explosibility.

Table 1. The effect of decreasing oxygen content on methane explosibility (Bone and Townsend, 1927).

Atmosphere		Percent Methane at the	
Oxygen percent	Nitrogen percent	Lower Explosive Limit	Upper Explosive Limit
20.90	79.10	5.60	14.82
17.00	83.00	5.80	10.55
15.82	84.18	5.83	8.96
14.86	85.14	6.15	8.36
13.90	86.10	6.35	7.26
13.45	86.55	6.50	6.70
13.25	86.75	No mixture capable of propagating flame at atmospheric temperature and pressure.	

Data in Figure 1 and Table 1, clearly show that what constitutes a stoichiometric methane-air mix in normal mine air is not the same in an abandoned mine working. Also, if the oxygen content falls below a certain limit, methane explosions will not even occur. Of course, in the Wheeler's experiments, the decreasing oxygen content was compensated for by an increasing percentage of inert Nitrogen gas, which may be the reason why no methane explosion was noticed at the lowest tested oxygen content.

Bone and Townend (1927) also refer to a 1926 Safety of Mines Research Board paper in which the effect of black-damp (a mixture of nitrogen and carbon dioxide) on methane inflammability was studied. This study showed the higher extinctive power of carbon dioxide over nitrogen.

In an abandoned coal mine panel, the depleting oxygen content is most likely not due to an increase in the nitrogen but due to other gases like carbon dioxide, carbon monoxide and others. As a result, in an abandoned panel, the explosiveness of methane may be affected at least as much or even more than that indicated in Table 1. Despite this difference, Wheeler's data is very illuminating in pointing out the significant differences that might exist between methane explosiveness in 'normal' mine air and in sealed-off areas. If the stoichiometric mix in a gob is not the 10% noticed in the normal mine air, then the final temperature of the combustion products calculated for a constant volume explosion may not hold good and thus the predicted explosion pressures may not be correct.

Response – 2.1.3 Existence of stoichiometric methane-air mix in abandoned panels

The authors are aware of the effect of nitrogen, carbon dioxide and other inert gases on the explosibility of a methane air mix. Table 1 from the reviewer's comments provides early data on the effect of decreasing oxygen content on methane explosibility. The data can also be presented as a "Coward's triangle", now included in the report, which provides another way to envision how an explosive mix can develop within a sealed area.

The reviewer points out that some coals, in this example, a coal from South Africa, may oxidize quickly, thereby consuming significant amounts of available oxygen in the sealed atmosphere, while slowly emitting methane. It is possible that such sealed atmospheres migrate from a fuel-lean inert status to a fuel-rich inert status without crossing the flammable range. However, as stated in the report, it was the authors' basic assumption that a worst case be considered initially, without consideration for the multitude of possible mitigating factors.

As indicated in figure 6 of the NIOSH report, laboratory experimental data and theoretical calculations show that constant volume explosion pressure exceeds 689 kPa (100 psi) from 8 to 12% methane in air by volume. Furthermore by figure 10, the CJ detonation pressure exceeds 1.38 MPa (200 psi) and the reflected detonation wave pressure exceeds 3.8 MPa (550 psi) over this same range. Non-homogeneous mixes will also develop high constant volume explosion pressure as long as the overall methane-air ratio for the volume is within the explosive range. Thus the possibility for achieving high pressure is not limited to a near stoichiometric, homogeneous mix.

Our reviewers are correct in that one may not know the exact path that a sealed area atmosphere will follow upon sealing and on the way to possible inertization. That is why the authors advocate the use of monitoring to ascertain the sealed area atmosphere composition along with artificial inertization to control that atmosphere and keep it out of the explosive range while people are present underground and exposed to a sealed area explosion hazard. With proper monitoring and inertization to manage the sealed area atmosphere as is done elsewhere in the coal mining world, 345 kPa (50 psi) seals are recommended in the NIOSH report consistent with other world practices. However, if the sealed area atmosphere is not monitored and an explosive mix of unknown size and composition is allowed to accumulate, then the authors recommend planning for the worst case situation which could involve detonation of a stoichiometric methane-air mix and reflected detonation waves imparting a pressure of 4.4 MPa (640 psi). Other coal mining countries recognized the difficult engineering and expense associated with seals designed to withstand the detonation pressures and elected to go the monitoring and inertization route.

Comments – 2.1.4 General remarks on CV combustion

In addition to the above major assumptions, some more idealizations are inherent in the constant volume combustion process, which include a complete combustion of the gaseous reactants and no dependence of specific heats on the temperature (Bone and Townsend, 1927). Indeed, it was the departure from all the foregoing assumptions that was responsible for the measured **lower**

pressures in the constant volume explosion experiments compared to their corresponding theoretical estimates.

Additionally, the strata surrounding a coal mine entry consists of a number of minor and major discontinuities, which include cleats, bedding planes, joints etc. When an explosion occurs, owing to the high pressures developed, some of the combustion products may find their way through these fractures thus reducing the estimated overpressure further. Although, as far as the reviewers are aware, no real mine-scale explosion studies were conducted under ideal constant volume conditions, for all the above reasons, it is probably a more realistic estimate that the actual deflagration overpressures will be in the range of 60-70% of the theoretical maximum value given in the *NIOSH* report.

Response – 2.1.4 General remarks on CV combustion

Since the "reaction vessel" of a coal mine entry has a large volume relative to its surface area, a full-scale underground approaches adiabatic more closely than laboratory-scale explosions. Our calculations of CV and CJ pressures using the Cheetah and NASA-Lewis thermodynamic codes, consider the temperature dependence of the specific heats.

The pressure rise from an underground explosion is rapid. The authors agree with the reviewers thoughts that the explosion gases will dissipate into the rock mass through fractures and coal cleats; however, the authors believe this pressure dissipation occurs over a long time-scale. For structural analysis purposes, this pressure decrease with time is negligible and the highest pressure must be considered. Finally, the authors disagree with the reviewer's statement that a realistic estimate of the actual CV overpressure is 60 to 70% of the theoretical maximum as given in the NIOSH report.

Comments – 2.2.1 On Deflagration-to-Detonation Transition (DDT)

The selection of 50 m (150 ft) as the run-up distance required for the DDT event to occur is one aspect of the *NIOSH* report that has very little scientific basis. In the prelude to suggesting this DDT distance, the authors quote some research, which suggest a run-up distance of 50 to 100 times the pipe diameter. Similar run-up length-to-diameter ratios were also reported by Lewis and von Elbe (1987). In adopting these numbers for coal mine methane-air explosions, one must be aware that **a majority of the research on gas explosions was conducted on gas mixtures that are many times more reactive than methane-air mixtures**. In fact, the amount of research done on methane-air DDT process is negligible compared to other gases. Therefore, the data produced for highly reactive gases should not be applied for methane-air mix..

Research on DDT shows that the processes involved are not totally understood and thus there are many uncertainties associated with its prediction. A nice review of DDT research is contained in a recent paper by Oran and Gamezo (2007). Also, Li et.al. (2005) have pointed out that even in controlled laboratory experiments, determining DDT is fraught with uncertainty due to several factors, the main emphasis being on identifying the DDT event itself.

The *NIOSH* report discusses the effect of detonation cell size on DDT and based on a λ value of 30 cm and a D/λ ratio of 5 concludes that DDT event may occur if the minimum size of a tunnel exceeds 1.5 m (5ft). While that is a possibility, research by Kuznetsov et. al. (2000) shows that the DDT event is correlated not only with the size of the detonation cell but also whether the cell is regular or irregular. Further, some other laboratory studies showed the dependence of DDT on the scale of the experiment (2000).

The limited research done on DDT in methane-air mix shows that it is very difficult to create detonations in such "low" reacting mixtures. To quote Kuznetsov et.al. (2002), *'Studies performed in tubes have shown that it is very difficult to achieve deflagration-to-detonation transition (DDT) in methane-air mixtures. The only reported observation of DDT in a methane-air mixture was by Lindsted and Michels (1989) in a very long tube equipped with a "Schelkin spiral",* the conclusion being that laboratory experiments on methane-air mixtures could not produce DDT unless a large amount of blockage is included. In fact, Kuznetsov et.al's (2002) research shows that at a blockage ratio of 0.3, although they considered the event as detonation, the detonation velocity measured was much less than the ideal Chapman-Jouguet (CJ) detonation velocity. Further, at a blockage ratio of 0.6, they could not observe any DDT. Based on these experiments, Kuznetsov et.al. classified two types of steady-state explosions in methane-air, "quasi-detonation" and "Choking" detonation. In the first case, the measured flame speed was slightly less than CJ velocity, where as in the later, it is about half the ideal velocity.

In summary, DDT is a very complex process and the available data for methane-air mixtures is very limited. Therefore, more studies are required before formulating criteria to determine DDT in a real mine situation. Such a research study may start with laboratory experiments using **a network of rectangular pipes** – not the single circular tube used in gas explosion studies – with **different configurations of ignition points**. Data generated from such controlled studies may be used in conjunction with numerical gas explosion modeling to predict DDT on a coal mine scale. Although a majority of the available commercial codes still do not simulate DDT and detonation events well, recent research (Oran and Gamezo, 2007; Tegner and Sjorgreen, 2002; and Parra-Santos et al., 2005) on the subject shows promise.

Response – 2.2.1 On Deflagration-to-Detonation Transition (DDT)

Scientists at the U.S. National Laboratories, the Army Corps of Engineers and in Europe agree that detonation of methane-air mixtures is possible under mine scale conditions. Most non-military DDT studies are conducted in laboratory-scale small tubes (less than 30-cm-diameter, smoothed walled tubes, straight pipe) with no crosscuts, no variable cross sectional areas or other factors that produce reflective wave reinforcement, which are conducive to promoting DDT processes. Most studies are done using more reactive mixtures under small scale conditions where cell structure to tunnel size is not significant. DDT is much easier in mine size tunnels where the tunnel diameter is over 6 times the methane air cell size of 30 cm. The reviewer's recommended additional small scale laboratory studies would be of little value given these limitations. The tunnel and crosscut should be 3 to 5 times the diameter of the methane-air detonation cell size 30 cm most important in DDT process.

The authors are well aware of all the issues surrounding DDT such as gas reactivity, detonation cell size and run-up length, and the authors recognize that the estimate of run-up length is largely based on empirical methods. However, the authors stand by the 50 m estimate for run-up length to DDT as applicable to typical conditions in U.S. coal mines.

The selection of 50 m is based primarily on empirical data stating that DDT occurs at a run-up length of 50 to 100 pipe diameters in smooth pipes. The authors use primarily the data of Bartknecht which is for methane-air. Other researcher's data also supports this empirical rule (Lee, 1984). The authors recognize that the majority of research on DDT based on gases much more reactive than methane such as hydrogen and ethylene. However, the authors did apply an empirical rule developed from observations of methane-air DDT. It is interesting that this same rule also applies to other gases more reactive than methane.

The authors are aware of the uncertainties associated with the prediction of run-up length to DDT. In addition to run-up length, two other factors affect DDT, namely the detonation cell size and turbulence. In addition to the empirical rule for run-up length to DDT, the pipe or tunnel diameter must exceed the detonation cell size by a factor of 5. The detonation cell size for methane-air is about 30 cm, and this dimension represents a minimum pipe size in which detonation and DDT can occur. The detonation cell size for methane in air is large compared to many other reactive gases. Most laboratory experiments used shock tubes with diameters less than 30 cm, and for this reason, many laboratory researchers suggested that it is very difficult to achieve detonation in methane-air. Since the least dimension (height) of a coal mine entry is typically 1 to 3 m, the authors conclude that detonation of methane within coal mine entries is a real possibility. Various experiments at Experimental Mine Barbara in Poland have created sustained detonation of methane plus coal dust in air. Finally, the authors cite the Blackville #1 shaft explosion described in an MSHA Accident Investigation Report (1993) in which investigators back-calculated pressures of 6.9 MPA (1000 psi) based on the observed structural damage.

As the reviewers correctly point out, turbulence is the other factor affecting the run-up length to DDT. Turbulence generators in a coal mine entry such as rough tunnel walls, timber roof supports, cribs, crosscuts, changes in entry height or width and machinery obstructing the airway will generate turbulent flow of the methane-air mix, which will enhance the combustion process and increase the likelihood of DDT. The empirical rule of 50 to 100 pipe diameters for DDT is developed from observations in smooth pipes. Turbulence generators can only decrease this run-up length. However, if the blockage ratio of a pipe exceeds 0.3, per research by Kuznetsov (reference), the restricted flow may suppress or arrest detonation and it could delay the onset of DDT. Congested flow conditions certainly exist in many coal mine entries, such as longwall tailgates and belt entries. However, many other entries within sealed areas of coal mines are wide open with modest roughness and present prime conditions for a methane detonation, if an explosive mix is permitted to accumulate.

NIOSH researchers will conduct research on DDT of methane-air with the aim of preventing its occurrence and thereby preventing the development of very destructive detonation waves and reflected detonation waves in mine. The authors hope to provide the industry with simple operational procedures to follow that will decrease the risk of DDT developing. These procedures might include additional rock dusting of sealed areas prior to sealing or the use of rock dust or water barriers to quench deflagrations and hence DDT. NIOSH will conduct the research in collaboration with the U.S. National Laboratories using numerical simulation, laboratory experiments and select full-scale tests of methane-air DDT and its suppression.

Comments – 2.2.2 On CJ detonation pressure

Assuming that detonation of methane-air mixture has occurred, the *NIOSH* report uses ideal Chapman-Jouguet (CJ) equation to estimate the resulting detonation pressure. The equation given in the *NIOSH* report is

$$\frac{P_2}{P_1} = 1 + \frac{\gamma_1}{(1+\gamma_2)}\left(\frac{D}{c_1}\right)^2 \qquad \text{Equation 1}$$

Where P_1 and P_2 are the pressure ahead and behind the detonation wave; γ_1 and γ_2 are the specific heat ratios of reactants and products, respectively; c_1 is the sound speed, and D is the detonation wave speed. Based on equation (1), a pressure ratio of 17.37 was computed.

Although no mention was made about the source of equation (1) in the *NIOSH* report, the reviewers found two more versions of the same equation. A 1968 USBM Report of Investigations (Burgess et al., 1968) gives the equation as

$$\frac{P_2}{P_1} = \frac{1+\gamma_1\left(\frac{D}{c_1}\right)^2}{1+\gamma_2} \qquad \text{Equation 2}$$

For the same inputs as in the *NIOSH* report, equation (2) gives a pressure ratio of 16.8.

One more version of CJ detonation pressure equation was found in Landau and Lifshitz (1959). While the *USBM* version in equation (2) was not derived from the first principles, Landau and Lifshitz (1959) give a step-by-step derivation of the equation. Their version reads as

$$\frac{P_2}{P_1} = \frac{\gamma_1\left(\frac{D}{c_1}\right)^2}{1+\gamma_2} \qquad \text{Equation 3}$$

Again, for the same *NIOSH* report inputs, equation (3) gives a pressure ratio of 16.37.

Of course, the results produced by equations (1) to (3) differ only slightly. But, when calculating the reflected pressures, such small error could also be important. For instance, if equation (3) is used to calculate the CJ detonation pressure and if the reflected pressure equation given in the *NIOSH* report is used, then the peak overpressure will fall from 649 psi (this number is given as

653psi in the *NIOSH* report due to round-off errors) to 611 psi.

While the above discussion highlights the uncertainty about the form of the CJ detonation pressure equation, there are more problems with the assumption of the CJ conditions itself. A very enlightening review of the Chapman-Jouguet hypothesis is presented by Cheret (1999), in which he states, "*...thus the idea of Chapman-Jouget 'law' flourishes as a belief that the work by the first as well as by the second guarantees some well-established law, according to which one and the same detonation velocity exists: D•.*" He further states that, "*Actually, such a gap between experimental results and the Chapman-Jouget 'law' is not unknown even by the most enthusiastic users, and does not leave them unconcerned. But, surprisingly enough, none of them goes back to the origins; all of them have chosen an escape way and state that, instead of being 'completely' true, the Chapman-Jouguet 'law' is 'asymptotically' true, i.e. when the flow is plane and steady.*"

The point of the above discussion is that while the CJ detonation assumption may be used as a first approximation and is in tune with *NIOSH*'s over all "worst-case" analysis approach, the predicted pressures may not be accurate as the CJ hypothesis is not an irrefutable 'law' like Newton's laws. This is an aspect that requires attention in the future studies.

Response – 2.2.2 On CJ detonation pressure

The authors commend the thoroughness of the reviewer's review in checking the sources and accuracy of all the theoretical equations presented in the NIOSH report.

The CJ detonation pressure equation presented in the draft report is wrong; the authors made a mistake due to a miscommunication. The correct equation is as follows:

$$\frac{P_2}{P_1} = \frac{1+\gamma_1\left(\frac{D}{c_1}\right)^2}{1+\gamma_2} \qquad \text{Equation 2}$$

This equation appears in several USBM publications by Burgess et al. (1968) and Kuchta (1985), and the authors checked its validity in two other sources, namely Weir and Morrison (1955) and Fickett and Davis (1979). Weir and Morrison derive the equation based on the heat of reaction and conservation of momentum across a shock wave. Fickett and Davis follow a slightly different approach and arrive at a similar result.

The authors also re-checked and modified the input parameters to this equation. These input parameters come from the NASA-Lewis thermodynamic equilibrium code which gives the following values:

Parameter	Value
γ_1 (specific heat ratio of reactants)	1.3877
γ_2 (specific heat ratio of products)	1.1697
c_1 (sound speed)	352.6 (m/s)
D (detonation wave speed)	1815 (m/s)

The authors also double checked these values against the Cheetah thermodynamic equilibrium code and found good agreement. Use of these input parameters in the corrected equation gives a pressure ratio P_2/P_1 of 17.4 which is the same ratio as what is reported in the draft report. In addition, both the NASA-Lewis and the Cheetah thermodynamic equilibrium codes compute detonation pressure ratio of 17.4 for a methane-air detonation.

As an aside, the detonation wave speed for methane-air of about 1,800 m/s is reported by Lewis and von Elbe (1987) and GexCon's Gas Explosion Handbook available on the web.

The authors also re-examined an apparently similar equation for the CJ detonation wave pressure presented by the reviewers. That relation is as follows:

$$\frac{P_2}{P_1} = \frac{\gamma_1\left(\frac{D}{c_1}\right)^2}{1+\gamma_2} \qquad \text{Equation 3}$$

Landau and Lifshitz (1959 and 1987) present a complete derivation of this relationship, which is based on the classical work of Zeldovich (1940), von Neumann (1942) and Doring (1943) or the so-called ZND model of detonation. The derivation begins with a detonation adiabatic, which is a special pressure-volume relationship, based on conservation laws for mass, momentum and energy. The next step in the derivation requires a critical assumption, which leads to the difference with the prior pressure ratio relationship. If the heat of reaction is much greater than the internal energy of the original gas, it is possible to neglect terms that contain the pressure P_1. Continuing with the derivation produces equation 2 for pressure ratio. This assumption, which neglects certain pressure terms in the initial state, applies to solid explosives (so called condensed phase explosives), but does not apply to detonable gaseous mixtures. Thus, equation 3 does not apply to this situation.. However, the authors note as the reviewers do that the differences in computed pressure are small and may be negligible compared to all the other factors that can influence the pressure developed in a coal mine explosion.

The reviewers are correct, the CJ hypothesis is not an irrefutable law like Newton's laws however a reasonable approach given all the uncertainties in predicting in the worst case scenario. Even though NIOSH authors called this the "worst case" it is not the worst case. The CJ pressure is not the highest pressure that one may see within a large-scale detonation. It does assume the wave is plane and steady; however, it could be much higher if multiple waves interact and reinforce each other. For example where DDT takes place, the pressures could be well over 20 MPa (3000 psi); however, these pressures are short-lived and decay over a couple of tunnel diameters of propagation to about the CJ pressure.

Comments – 2.2.3 On reflected detonation wave pressure

There is a minor point to be made on the reflected overpressure computed in the *NIOSH* report. The equation used to compute the reflected pressure is given in the report as

$$\frac{P_R}{P_I} = \frac{5\gamma + 1 + \sqrt{17\gamma^2 + 2\gamma + 1}}{4\gamma}$$ Equation 4

But, in the reference given in the *NIOSH* report for equation (4), the equation reads as

$$\frac{P_R}{P_I} = \frac{5\gamma + 1 + \sqrt{17\gamma^2 + 3\gamma + 1}}{4\gamma}$$ Equation 5

Equation (5) is given in an example problem in Landau and Lifshitz's book (1959). If the subordinate equations used to derive (5) are solved, the correct solution is obtained as equation (4), which is what was given in the *NIOSH* report. A careful reading, however, shows that the subordinate equations used in the derivation of equation (5) or (4) may themselves be questioned, if the mechanics of the 'shock adiabatic' are properly followed. But in a paper by Shepherd et al. (1991), the derivation of equation (5) was credited to Zeldovich and Stanyukovich, who derived the equation in 1948 long before the publication of Landau and Lifshitz's book. Since Shepherd etal. reproduced equation (5) from the original authors' paper, it may perhaps be used in the *NIOSH* final report instead of equation (4).

Of course, the above discussion on the reflected pressures is only to be "technically correct." Otherwise, the difference in the pressure ratios estimated by equation (4) and (5) is unnoticeable.

Finally, in all the theoretical explosion pressure calculations, the *NIOSH* report did not explain how the inputs were estimated. This applies to final temperature of the combustion products (T_f), detonation velocity (D) and ratio of specific heats (γ_1 and γ_2). It will be useful if *NIOSH* includes references and complete calculations for the estimation of these numbers in order to allow for further and complete review.

Response – 2.2.3 On reflected detonation wave pressure

The authors re-checked the derivation presented in Landau and Lifshitz's books (1959 and 1987) for the reflected detonation wave pressure. Solving a quadratic equation for the pressure ratio results in equation 4 for pressure ratio as presented in the NIOSH report. Indeed, the Landau and Lifshitz (1959) book does contain a typographical error, but it was corrected in the 1987 edition. Fortunately, the consequences of that small error in computing reflected detonation wave pressures would be very small. The authors will continue searching for the original derivation by Zeldovich and Stanyukovich, but have not yet located the work.

The input parameters used in the calculations come from the NASA-Lewis thermodynamic equilibrium code (reference). This program gives the final explosion temperature (T_f) along with the specific heat ratio for reactants and products (γ_1 and γ_2). The detonation wave speed for methane-air is reported in a variety of sources such as Lewis and Elbe (1987) or GexCon's Gas Explosion Handbook available on the web. In preparing the final report, the authors added many more references to substantiate the source of every number and concept utilized.

Comments – 2.3 Experimental mine explosion studies

In the *NIOSH* report, much has been said about the Polish large-scale mine experiments conducted by Cybulski et al. (1967). Drawing from these experiments, the *NIOSH* report says, "*Two tests in which the explosive mix completely filled the tunnel produced peak pressures greater than 3.2 MPa (450 psi).*" A careful reading of the Cybulski's paper shows that the data has been taken out of context. Let us reproduce some facts from the Cybulski's paper:

• "*The tunnel was narrowed down at the site of the blasting bulkhead.*"
• "*The ground support consisted of TH-rings lagged with reinforced concrete staves.*"
Examining the pictures of the tunnel in the paper shows that the tunnel is supported by arches, which creates a significantly higher blockage in the entry compared to a typical coal mine in the U.S.)
• Most importantly, the type of ignition used was, "*...three electric caps the shells of which were topped with fuse powder, were attached to the face of the rock tunnel at half height. A charge of 100 gram black powder and 3strong electric blasting caps was used in all of the future experiments.*"
• In fact, in all the "Barbara" mine experiments, some kind of solid explosives were used as the ignition source.
• Finally, the reported pressures in the paper were basically the reflected pressures at the bulkhead location.

Let us combine the above experimental conditions with the following observations on DDT reproduced from Vasil'ev's paper (2006):

"*According to the current classification, a combustible mixture can be excited by three basic methods:*
– weak initiation (ignition) where only laminar burning is excited with velocities at the level of tens of centimeters per second;
– strong (direct) initiation where a self-sustained detonation wave (DW) is formed in the immediate vicinity of the initiator and then propagates over the mixture with a velocity at the level of several kilometers per second;
– intermediate case where the mixture is ignited at the initial stage and then the flame is accelerated owing to natural or artificial reasons up to (visible) velocities at the level of a hundred meters per second. Under certain conditions, even the deflagration-to-detonation transition can occur."

So, what essentially happened in the Polish experiments is the second condition described by Vasil'ev, whereas the real coal mine situation corresponds to the third one. In other words, the Polish explosions, except probably for one test, were started as detonations or weak detonation waves, which were further reinforced by the turbulence created due to arch supports and finally culminating as a very strong detonation due to a sudden cross-section reduction near the bulkhead. Therefore, those results are not directly applicable to coal mine explosions. Even considering such worst-case conditions simulated in the Polish experiments, the measured reflected overpressures were in the range of 450psig as compared to the *NIOSH*'s recommended 640psig. Of course, in estimating the run-up distance for DDT, the Polish data is not useful at all.

Finally, in the Polish studies, the flame speed was measured as 1200 m/s. However, as the *NIOSH* report quotes, the CJ detonation velocity in methane-air mixtures should be around 1800 m/s. This discrepancy suggests one of the two possibilities: either there was no detonation event or if there was a detonation, which is more likely for the reasons given above, then the conditions for applying CJ hypothesis did not exist.

Response – 2.3 Experimental mine explosion studies

Contrary to the opinion of the reviewers, the Polish large-scale test explosion data is not taken out of context, and to conclude that the Polish experiments are not directly applicable to coal mine explosions is a dangerous misconception. The NIOSH report utilizes these Polish experiments to verify, in part, the contention that reflected detonation wave pressures can reach a theoretical pressure of 4.5 MPa (653 psi) as per fact 4 of the report. While the two tests described in Cybulski (1967) only reached pressures of 3.1 MPa (450 psi) with flame speeds of 1200 m/s (3,900 ft/s), which is short of 4.5 MPA (653 psi) at a flame speed of 1800 m/s (5,900 ft/s), that shortfall is insufficient reason to dismiss the contention for high reflected wave pressure. Additional tests in Poland also described in the NIOSH report, showed pressures of 4.1 MPa (595 psi) at a flame speed of 1600 to 2000 m/s (5,300 to 6,600 ft/s) (Cybulski, 1975). In smaller tests, Genthe (1968) measured flame speeds up to 1200 m/s (3,900 ft/s) that correlated to static pressures (not reflected pressures) in excess of 1.86 MPa (270 psi). Finally, the authors cite the Blacksville #1 explosion in 1992 where MSHA investigators back-calculated explosion pressures of about 6.1 MPa (1000 psi) based on the observed damage to the concrete structures.

As the reviewers correctly point out, the Polish experiments at "1 Maja" mine were in a tunnel that narrowed down at the site of the blasting bulkhead. Inspection of figure 1 in the Cybulski (1967) paper suggests that the tunnel cross-sectional area decreased suddenly by about 20% several meters in front of the blasting bulkhead. However, unlike subsonic fluid flow, this sudden area change does not result in significant flow velocity and pressure increases at the area change. In fact, the detonation wave is hardly affected a short distance beyond the constriction. Thus, the high pressures observed at the seal are not an artifact of the experimental set-up and procedure.

The experimental tunnel in these Polish tests is horse-shoe-shaped and supported with steel arches and a concrete lining. While such geometry and support is not typical of U.S. coal mines, the roughness of the tunnel with respect to fluid flow is similar to a typical coal mine entry with rough walls and occasional timber support. The authors maintain that the details of the ground support conditions in the Polish tests are unimportant because the turbulence conditions are similar.

Finally, as pointed out by the reviewers, the ignition source for the Polish experiments was multiple electric blasting caps enhanced with black powder. Obviously, this strong ignition source has nothing to do with the weak ignition source, i.e. a minute electric spark, most likely to initiate an explosion in a real coal mine. However, the purpose of the Polish experiments was not to investigate the run-up length to DDT, but rather to investigate the effect of a very strong detonation wave on a blasting bulkhead. The experiment needed to create a strong detonation wave immediately to satisfy its primary purpose.

Comments – 2.4 Numerical modeling of gas explosions

The *NIOSH* report deserves a lot of credit for initiating the numerical computational fluid dynamics (CFD) modeling as a means to study coal mine gas explosions. As Gadde *et al.*(2007) point out, despite the limitations, numerical modeling seems to be the best available tool for conducting gas explosion studies in coal mines. They also listed two major sources of errors that could cause problems with CFD modeling, namely, the selection of parameters for combustion and turbulence models. The *NIOSH* report has made an attempt to 'calibrate' the inputs required for two commercial CFD packages with some success. These efforts must be continued as that is probably the best available course to address several challenges in predicting methane-air explosion output.

Even though the *NIOSH* report claims a good match between the modeled and measured pressure-time curves from Lake Lynn, major differences could be seen from the output given in the *NIOSH* report. Interestingly, the output from the two codes, AutoReagas and FLACS used in the report, also show noticeable differences. One reason for the discrepancy is probably the use of two different combustion models in these two codes. While the initial CFD modeling results in the *NIOSH* report are praiseworthy, they also reveal how much more work remains to be done in this direction before confident gas explosion output prediction is possible.

Response – 2.4 Numerical modeling of gas explosions

The authors thank the reviewers for the kind comments regarding the numerical modeling efforts of gas explosions. The authors recognize the limitations of these initial efforts, particularly with respect to DDT and high pressure waves in general. However, it is a start for coal mine explosions, and the authors plan to continue the efforts over the next few years.

Comments – 2.5 Design pressure-time curves

After the initial rise or fall period and attaining the constant volume pressures, the suggested pressure-time curves in the *NIOSH* report impose very high impulses on mine seals. As far as the reviewers could see, the only supporting statement for the long plateau portion of the pressure-time curves as given in the NIOSH report is, "*Several computed pressure-time histories from the large gas explosion models indicate that the initial pressure peaks equilibrate to the 800 kPa (120 psi) constant volume explosion overpressure after 0.1 second.*" From this and other statements in the *NIOSH* report, it seems that the numerical CFD modeling formed the basis for deriving the suggested design pressure-time curves.

Again, the suggested pressure-time curves represent the "worst-case" loading possible. Since in the CFD modeling in the *NIOSH* report, the process has been assumed adiabatic, the constant volume explosion overpressure will be maintained until the combustion products find someway to expand and cool. For the same reasons given in section 2.1 of this review, the validity of the *NIOSH* suggested pressure-time curves is also questionable.

Response – 2.5 Design pressure-time curves

The basis for the 800 kPa (120 psi) portion of the 4.4 MPa (640 psi) pressure-time curve and also the 800 kPa (120 psi) pressure-time curve is the theoretical calculation of the constant volume explosion pressure for methane-air as confirmed by laboratory measurements. Numerical modeling was not used here. The numerical modeling efforts verify that for a large explosion, the pressure eventually equilibrates to the CV pressure as expected after the transient high pressure waves dissipate in about 0.1 seconds. The CV pressure of 800 kPa (120 psi) is a fundamental pressure associated with methane-air explosions.

While the theoretical and numerical calculations of gas explosion pressures assumed adiabatic conditions, the authors continue to believe that the adiabatic or quasi-adiabatic condition is applicable to coal mine explosions. In laboratory-scale explosions, the ratio of surface area to volume is large and therefore heat loss occurs rapidly, and it is difficult to achieve adiabatic conditions experimentally. By contrast, large-scale coal mine explosions have a low surface area to volume ratio and therefore approach adiabatic conditions readily. Granted, the hot gaseous explosion products will cool as heat is lost to the surrounding rock. In addition, some high pressure gas will leak off into the surrounding rock through cracks and faults. However, the authors maintain that the time it takes for the cooling and leakage processes is much longer than the natural period of seals. Therefore, for the structural design calculations of seals, the 800 kPa (120 psi) pressure effectively remains forever.

Comments – 2.6 Structural seal design

The structural analysis in the NIOSH report is extremely simplistic and hence may not be useful for practical designs. With the state-of-the art dynamic modeling tools available, it is not necessary to make so many unrealistic assumptions to solve the problem. For example, Gadde *et al.* (2007) have provided a comprehensive structural analysis approach for mine seals using three-dimensional numerical modeling. In the modeling approach, there is very little need to make many simplifying assumptions to find the solution. Nevertheless, in connection with the *NIOSH*'s structural analysis, some comments are in the order:

- The WAC code used is a single-degree-of-freedom (SDOF) analysis tool. Hence, it suffers with the limitations pointed out by Gadde *et al.* (2007);
- Since WAC is not a public domain code or is not available for purchase for a regular user, it is difficult to design seals using this approach for situations not covered in the *NIOSH* report;
- The one-way analysis used is conservative. Moreover, the rigid roof-seal and floor-seal links do not exist in a real coal mine unless the seal is 'hitched' to sufficient depth;
- The way the safety factor was implemented in the WAC analysis is not clearly explained. It is not immediately clear how a 2 scaling will double the applied load on the structure;
- The quasi-static analysis using 'plug' and 'arching' actions are unrealistic;
- The steel-bar reinforcement analysis is simplistic, conservative and is not based on seal deformation mechanics.

Finally, the recommended design safety factor value of 2.0 in the NIOSH report has very little basis. Similar safety factor value was recommended by Gadde *et al.* (2007) but that was only to account for the uncertainty in the estimated pressure-time curves used in their analysis. If the NIOSH report has already undertaken a "worst-case" type approach to estimate the pressure-time curves, what is the need to have such a high safety factor as 2.0? Since the probability of having any pressures higher than suggested in the NIOSH report are extremely low, the only uncertainty to account for in the design is limited to the construction of the seal itself. For the latter purpose alone, there is no need to have a very high safety factor. Indeed, the "worst-case" pressure-time curves and a very conservative safety factor requirement will only make the built seals impractical.

Response – 2.6 Structural seal design

The primary purpose of the structural analyses presented in the NIOSH report is not to provide final design recommendations for seals to resist the three proposed explosion pressures, namely 345, 800 and 4,400 kPa (50, 120 and 640 psi), but to provide approximate seal design thickness, so that engineers can judge the relative merits of alternative sealing strategies. With the new proposed explosion pressure design criteria, the mining industry faces choices of sealing with thicker seals and not monitoring or sealing with thinner seals and monitoring or not sealing and continuing to ventilate. To weigh these alternatives and decide on a strategy, the authors provided these approximate design charts that will provide engineers with approximate values for relative seal thickness using the different design pressures and a range of typical seal construction materials. Again, these design charts are not intended as a substitute for proper or complete structural design of seals with site investigation, structural analysis and quality control during construction.

The authors agree with most of the reviewer's remarks concerning the simplistic structural analysis. State-of-the-art dynamic modeling tools are available that preclude the necessity to make simplifying assumptions. With specific reference to the NIOSH analyses using the Wall Analysis Code (WAC) from the U.S. Army Corps of Engineers, the authors recognize its shortcomings.

- Single-degree-of-freedom models do not include higher-order failure modes that might develop.
- WAC is a controlled technology and not readily available to the general public.
- One-way arching analysis is conservative; however, assumptions regarding rigid roof and floor contact with the seal, tight contact between the roof and the seal, and adequate shear resistance around the seal periphery may render the analysis not conservative in practice.

Independent calculations provided verification of the charts at select points. A review by Esterhuizen verified a few points using high UCS materials. His analysis used UDEC.

In section 6.2, the authors present a simple equation based on Anderson's arching analysis that gives seal thickness as a function of the seal height (H), the applied pressure (P_S), the compressive strength of the seal material (f_k), and an empirical factor n. That equation is –

$$t_S = H\sqrt{\frac{P_S}{0.72\, n\, f_k}}$$

The form of this equation for simple one way arching matches the WAC calculations that also contain an arching analysis. As can be seen by inspection of this equation, doubling the design load (or applying a load-based safety factor of 2) has the effect of increasing the minimum required seal thickness by a factor of $\sqrt{2}$. Scaling WAC calculations, that use an arching analysis, by a factor of $\sqrt{2}$ achieves the same effect as applying a load-based safety factor of 2. This contention has been verified with direct calculations using WAC.

The equation for anchorage reinforcement and the associated design chart are removed from the final report. In section 6.4 and 6.5 of the report, the authors recommend proper hitching and anchorage to the roof and floor. The authors also recognize the necessity of steel reinforcement for both flexural reinforcement and anchorage to the surrounding rock and recommend the use of such steel reinforcement where necessary.

The authors apply a safety factor of two in the analyses to account for uncertainties of the seal material properties, a poor foundation or hitching of the seal to the surrounding rock and the effect of convergence loading on the seal. If an operator can demonstrate that rigorous quality assurance standards exist at a particular site, then the authors recommend that lower safety factor receive consideration.

Comments – 3.0 A Proposition

Considering the importance of the *NIOSH*'s work and the possible implications for future seal designs in this country, the reviewers propose the following approach to answer several outstanding issues:

- A large number of studies have already been conducted on the methane liberation potential of many coalbeds in this country. It will be more realistic if the explosive potential is classified based on the methane liberation rates. Also, probabilistic modeling and risk analysis must be conducted for different panel and gob configurations while accounting for the methane liberation and other thermal properties of the surrounding strata. Such studies will help estimate the likelihood of an explosion and the resulting overpressures.
- As a part of the broader research study, systematic data acquisition must be done on the atmosphere in the abandoned panels for a select number of mines with different methane liberation properties to answer such questions as the filling ratio, homogeneity of the mixture, methane layering and change in the composition of the mine atmosphere.
- Laboratory studies must be conducted to study the influence of the change in the composition of mine atmosphere, particularly the effect of decreasing oxygen and increasing carbon-dioxide, on the explosibility of methane.
- Just after the initiation of an explosion, turbulent currents are set in motion which will make the rock and coal dust mix with the gob atmosphere. Some lab studies may also be conducted on the effect of different levels of coal and rock dust in the gob atmosphere on methane explosibility.

- Experimental studies may also be conducted using rectangular pipes for estimating the deflagration-to-detonation transition distances. Also, such studies may be conducted on a network of interconnected pipes instead of a single pipe, which has been used in the gas explosion studies. Such lab studies may also focus on the effect of different locations of the ignition sources.
- Since the adiabatic combustion is an extremely unrealistic model, thermal modeling of the coal mine strata must be undertaken to assess the processes involved in the heat loss and its effect on the explosion pressures.
- CFD gas explosion modeling may be continued with an emphasis on conducting several parametric studies to predict the changes in explosion output for different panel and gob configurations, ignition location and several other variables identified, for example, by Gadde *et al.*(2007).
- A reasonable seal design criteria must be established considering the confidence in the estimates of the explosion overpressures and the quality control issues related to seal construction underground.
- Finally, the structural design of seal should be based on more realistic modeling of the real-world conditions. Based on the results of such an analysis, it may be necessary to explore the need for a multi-tiered seal design criteria based on the intended service and longevity of the seal installation.

Response – 3.0 A Proposition

NIOSH appreciates the suggestions by the reviewers for future research. At this time the authors are considering a new seals project to provide critical information pertinent to successful implementation of new seal practices in the U.S. and to refine specific scientific data connected with this report. At least five tasks are anticipated to produce these need results:
1) Methane distribution within sealed areas – NIOSH researchers will report on methane distribution within sealed areas and how the distribution changes in time.
2) Suppressing detonation within sealed areas – In collaboration with the U.S. National laboratories, researchers will conduct detailed studies of methane-air detonation within sealed areas of coal mines, the factors that control it, methods to avoid detonation, and practical techniques to suppress DDT.
3) Methane detonation experiments – In collaboration with other government facilities, researchers will conduct select methane-air detonation experiments to verify numerical models and validate methods to suppress DDT using practical, simple techniques.
4) Structural dynamics of seals – In collaboration with the National Laboratories, researchers will develop practical methods to protect seals from transient dynamic pressures due to reflected blast or shock waves.

The authors agree with many of the research ideas expressed by the reviewers and must respectfully disagree with others.

1) The authors recognize that methane liberation rate may influence the choice of sealing strategy. Many mines may self-inert quickly, and if monitoring is utilized, can utilize the 345 kPa (50 psi) design pressure-time curve. Future NIOSH studies may examine the risk of high pressure explosions in unmonitored sealed areas.

2) The authors agree with the reviewer's suggestion to systematically collect data on the atmosphere of abandoned panels at select mines. Such data would answer questions concerning the homogeneity of the mixture, methane layering and change in composition over time of that sealed area atmosphere.
3) The effect of decreasing oxygen content on methane explosibility is already well known and is expressed by the Coward triangle diagram now included in the NIOSH report. The effect of changing CO_2 content also may have been studied already.
4) Again, many of these effects are known in part. Rock dust might slow a methane deflagration and can act as a heat sink to decrease the constant volume explosion pressure that develops. The authors agree that additional studies in this area are needed with the aim of refining guidelines for sealing.
5) Laboratory-scale studies of DDT using rectangular pipes may be impractical since pipes with a least dimension of 30 cm, the methane-air detonation cell size, may be required to initiate DDT. Such pipes must also have substantial strength since the pressure at the point of DDT can be much greater than the CJ detonation wave pressure. The authors plan to conduct additional studies of DDT using other government facilities in conjunction with numerical modeling of gas explosions.
6) For reasons mentioned earlier, the authors disagree with the reviewer's statements claiming that adiabatic combustion is an extremely unrealistic model. While it is difficult to achieve adiabatic conditions at the laboratory scale, larger scale mine explosions approach that condition readily. NIOSH researchers conducted a few tests at LLEM where a volume was completely filled with a methane-air mix. The tests quickly reached the CV pressure, as expected, and the pressure took several seconds to dissipate. For structural analysis purposes, the pressure effectively acts forever, which is exactly what the authors assume in the NIOSH report.
7) The authors plan to continue with CFD gas explosion modeling with more sophisticated models that account for complex behavior such as DDT. The authors may also examine inhomogeneous gas clouds, such as those that might develop behind a leaking seal. Coal mine explosions have never been explored using numerical models, in part owing to the complexity of the phenomenon.
8) The authors do not consider the explosion pressures presented in the NIOSH report unrealistic or unreasonable. When an area is initially sealed, the methane concentration in the sealed area atmosphere will cross through the explosive range at some point in time. If the mine operator chooses not to monitor the atmosphere within a sealed area especially during this transition period, then one must assume that a worst case explosive gas cloud can develop. If the length of that gas cloud adjacent to a seal exceeds 50 m (165 ft), detonation is possible and a seal could be subjected to the reflected detonation wave pressure of 4.4 MPa (640 psi). The alternative the authors present is a monitored sealed area atmosphere, where sufficient monitoring assures that the amount of explosive mix behind a seal is strictly limited to less than 5 m (16 ft) behind the seals. If the volume of explosive mix is controlled and limited, then 345 kPa (50 psi) seals are adequate.
9) While the structural designs presented in the NIOSH report are simplistic, they provide approximate estimates of required seal thickness to resist the three design pressure-time curves for seals. The intent of the NIOSH design charts is not to provide seal thickness recommendations in lieu of proper site-specific structural analysis. These charts merely provide estimates of seal required seal thickness, so mining engineers can choose between alternative sealing strategies such as sealing with unmonitored seals or sealing with monitored seals.

Comments – 4.0 Conclusions

Anyone involved with research and writing papers would know it is a lot easier to "critically review" somebody else's work than to come up with a "perfect" research work of his or her own. The reviewers are very well aware of this. So, the comments in this review should not be seen as an attack on some work; rather, they should be viewed in the right spirit to spur further research before producing a document that might very well be the basis for formulating new statutory seal design guidelines.

Admittedly, in a real coal mine situation, the possible combinations of situations that require analysis for explosiveness are too many to be included in a project that has strict time constraints. Also, there are uncertainties associated with obtaining some of the inputs needed for any reliable analysis. Therefore, it is perhaps acceptable to conduct a 'worst case' type analysis as an interim solution. But, for the reasons given in this review, even the worst-case type study should not make extreme assumptions that are unrealistic, have extremely low probability of occurrence or are not supported by real-world mechanics.

The work presented in the *NIOSH* report is a good start and may form the basis for thorough research in the future to address several of the outstanding issues before formulating final seal design criteria.

If the 20 psi peak overpressure criterion is criticized for its lack of sound scientific basis, then the results presented in the reviewed *NIOSH* report will also receive similar criticism, if the deficiencies cited here are not addressed and the objectives identified in section 7.3 of the *NIOSH* report are not achieved. It will be premature for the *NIOSH* report in its current form to be the basis for formulating final statutory seal design criteria.

Response – 4.0 Conclusions

The authors sincerely appreciate the thorough review provided by Peabody Energy. NIOSH's desire is to provide scientific information for the creation of proper mining regulations. The authors plan to continue the research and refine their recommendations as new information becomes available.

While the authors recognize the many shortcomings of the "worst case" type analysis, the authors do not believe that the analysis is based on extreme assumptions and unsupported by real-world mechanics. Prior to the NIOSH report, the mechanics of gas explosions in coal mines had not been thoroughly presented to the coal mining community, and the possible impact of high pressure gas explosions were unknown to most technical people in coal mining. The authors hope that the analyses presented in the NIOSH report spur the coal mining community to re-think their sealing practices armed with new information about the potential dangers presented by uncontrolled, unmonitored and potentially explosive mixes that can develop within sealed areas. The authors agree that proper risk analysis must enter into difficult economic choices on how to properly manage abandoned areas of coal mines. NIOSH plans to carry out additional research on the sealing strategies as outlined above. This future research may provide a basis to modify seal regulations that must be in place by the end of 2007.

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Comment

The document appropriately reflects the physical phenomena being investigated. The bounding cases of explosion pressure appear to be properly described based on experimental and anecdotal evidence as well as theoretical analysis. If this is the limit of the scope of the investigation, the report is effectively complete. However, even though the authors may have envisioned a limited scope, the practical necessity is much different.

Because of an extreme need for business continuity by mine operators, and urgent needs for approval guidelines by regulatory officials, this report will probably be the defining descriptive- and design-document with respect to explosion pressures and blast resistant mine seals. There is also a nearly year-end deadline for the emplacement of mandated regulations. All of these factors considered, the scope of this document should be expanded to include at least minimal discussion of factors relevant to end-users. It is also important that the authors elaborate on their thinking in the development of the design examples, as interpretation by third-parties will fill the gaps, errantly in some cases and with excess conservatism in other cases.

Although the authors correctly identify that this analysis describes the ***upper limit of explosion pressures***, it should be emphasized as such. The authors acknowledge that various factors exist that can diminish the pressure pulse to be resisted by the mine-seals, but do not develop the subject in detail. It is an *imperative* to discuss, at least conceptually, how the governing parameters can interact to yield diminished explosion pulse pressures in the 95-percentile of actual or potential explosion events underground. The 90-percentile or 95-percentile limit would more correctly describe the required design pressure for a seal.

This must be conceptually correct, since there are 10,000s to 100,000s of seal-years of acceptable performance from seals nominally designed to 20 psi, and often performing at lesser levels. It is further believed that overseas seals designed to 72 psi have never had a reported failure. It is not likely that this largely acceptable performance is attributable to the absence of gob-explosions. With a largely acceptable performance history, there needs to be a societal cost-benefit analysis (CBA) to justify much higher design standards and the companion costs to mine operators, altered hazard exposure to miners, and increased cost to the public through increased electricity cost. This type of CBA is a well established principle by the FAA, DOT, and other governmental agencies. It often involves statistical assessments as suggested herein, with phased solutions over time instead of a step-change in requirements with mandates for rapid implementation on an industry-wide basis. Although it is recognized that the authors of the Draft Report do not create or implement regulations, they must recognize their importance as inputs to a larger process.

For operators and regulators to achieve their individual and mutual needs, a number of considerations need to be described in some detail by the authors. These considerations include the following:

- The site risk-assessment should include event consequence, as well as event potential, leading to seal resistance selection.
- What design pressure pulse is required for specific seal-design cases? (Pressure vs. Time)
- If balance chambers with inert gas are used, what explosion pressure pulse is required? In concept, no oxygen can be introduced through "in-gassing". This should select the lowest possible pressure-pulse.
- What design benefit can be assigned to monitoring of gob atmospheres? Is a reduction of pressure resistance for seal-design possible?
- What method or frequency of monitoring is acceptable to define safely inert gob atmospheres?
- What monitoring point location should be defined to insure that explosive compositions are safely removed away from seals?
- Should samples be cross-sectional, roof-floor, or point samples near the roof?
- What response should arise from the detection of explosive compositions behind approved seals vs. un-approved seals?
- Can recirculated coal mine methane be used to maintain inert atmospheres? Initial inertization with methane is not possible.
- What physical performance defines acceptable explosion resistance to a structure? I believe that 100 cfm through the structure, at 1 in. water gauge pressure differential across the structure, was defined as acceptable by past investigators.
- Would a 1 degree rotation as analysed by the Wall-Analysis-Code be an alternate failure threshold? Would a larger rotation be acceptable for structures tested in the field?
- What pressure differential for design purposes is required from mine-to-gob, and gob-to-mine for each mine scenario? 20 psi mine-gob and 50 psi-650 psi gob-mine? The testing by earlier investigators should still be valid for it's intended purpose.
- If 100 cfm flow, or 1 degree of rotation after an event is acceptable, what failure mechanisms must be considered?
- Must seals "successfully" resist only one pressure-pulse event, or multiple repetitions without "failure"?
- Is keying (shear connecting) structures into the roof necessary? What about floor and/or ribs? Disturbance of the roof can be a safety hazard in many mines.
- What options are available if shear-connection to the mine entry is required?
- What analysis method and boundary conditions are appropriate for design purposes?
- Can geometric shapes other than a straight wall be used?
- What efficient design considerations can be recommended?
- It is my assertion that design tables include data where the factor of safety is 1.0, with higher factors of safety being tabulated if so desired. I think that having a factor of safety of 2.0 included in the design example is excessive, particularly for the detonation pressure case.
- I believe that the Wall-Analysis-Code case(s) presented should include constraint on 3- or 4-sides to reflect the likely construction underground, particularly where shear-connection is provided by keying, hitching, or dowels.

- It would be useful to show an example of a two-walled structure analysed by the Wall-Analysis-Code. The filling between the walls could be assumed to be Micon or Minova material. The walls could be composed of solid blocks stacked in staggered rows.
- What design verification testing is appropriate? Please suggest a method, i.e. air-over water static or dynamic pressure pulse. Are in-situ underground and/or laboratory experimental demonstrations acceptable for design validation or in-lieu of design analysis? This is particularly important where significant analyst judgment must be invoked to facilitate the analysis. (Analyst judgment is often a source of contention between designers and reviewers, and can be difficult to objectively resolve)
- Must the prevention of projectiles be integrated into structures that are determined to successfully sustain the prescribed pressure pulse? Such a capability seems un-necessary.
- What factor of safety is required for design purposes? Can this be based on statistical process analysis of materials and construction methods to yield a minimum structural outcome? (FS= 1.0 or higher for field outcomes)
- What consideration should be made for site convergence at seals to prevent damage?
- Can roof-support such as "cans" or cribs be used to shield seals from blast damage?
- Is it possible to have a simple robust rule-of-thumb design as one alternative and rigorous independent analysis as another route to acceptable designs? Some operators cannot support significant engineering design efforts, and others would seek customized designs.
- Should potential ignition sources be addressed? Lightning, spontaneous combustion, etc.

If the authors address these concerns, and others from additional stakeholders, this complicated subject may find successful resolution in the near-term. If these concerns cannot be addressed, inappropriate regulations are likely to be promulgated by regulatory agencies leading to un-necessary adverse impacts to mine-operators, mine-workers, and the public which depends on coal mining to fuel electricity generation.

For, my part, I thank the authors for their diligent and rigorous work on this important matter and for offering me the opportunity to participate as a reviewer.

Response

The authors present an upper limit of explosion pressures, and the need for risk-based analysis is acknowledged. However, we simply do not have adequate information to even speculate where the 95th or 90th percentile exists for potential explosion events underground. Developing a relationship between explosion pressure and cumulative probability of occurrence should become a top priority research goal for our next research effort in seal design.

The authors agree that a statistical analysis of past seal performance is critical information missing from the present report. Some of the critical factors to consider that might affect seal performance and explosion potential might include methane emission rate, gob gas production, ventilation system layout, the seal foundation and the seal construction material. Quantifying these factors in terms of seal-years of acceptable and unacceptable performance is crucial data for a cost-benefit analysis. NIOSH has done many statistical performance analyses for mine safety, particularly with respect to ground control issues, and such a task should also become high priority in future seals research.

With regard to the itemized comments provided, the authors will try to incorporate as many thoughts as possible into the near-term final report, but because of immediate needs, the remainder will be addressed by future research within a few years. From this list, the authors see a need for several major tasks:
1) risk analysis to define the probability of occurrence for an explosion event of a given pressure
2) performance analysis of seals to provide cost-benefit analysis data
3) design guidelines for sealed area atmosphere monitoring systems to provide location and frequency information
4) design guidelines for seal structures to provide procedures for site investigation, seal design and construction
5) recommendations for safety factors commensurate with in-place quality control processes
6) design guidelines pertaining to seal leakage to define acceptable and unacceptable limits
7) design guidelines for ventilation systems to promote safe sealing

NIOSH will undertake a new longer-term seals research project to provide critical information pertinent to successful implementation of new seal practices in the U.S. and to refine specific scientific data connected with this report. At least four tasks are anticipated to produce these need results:
1) Methane distribution within sealed areas – NIOSH researchers will report on methane distribution within sealed areas and how the distribution changes in time.
2) Suppressing detonation within sealed areas – In collaboration with the U.S. National laboratories, researchers will conduct detailed studies of methane-air detonation within sealed areas of coal mines, the factors that control it, methods to avoid detonation, and practical techniques to suppress DDT.
3) Methane detonation experiments – In collaboration with other government facilities, researchers will conduct select methane-air detonation experiments to verify numerical models and validate methods to suppress DDT using practical, simple techniques.
4) Structural dynamics of seals – In collaboration with the National Laboratories, researchers will develop practical methods to protect seals from transient dynamic pressures due to reflected blast or shock waves.

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Comment

Minova offers the following comments to the NIOSH report titled Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" by Karl Zipf, Michael Sapko, and Jurgen Brune:

The theoretical explosion yield estimations are very unlikely in actual coal mine conditions. The presence of limestone rock dust and water in the sealed areas would work to quench the explosion and limit the load on an actual seal.

The construction of a seal in an actual coal mine environment would be far more complicated and expensive than the report implies. The highly variable nature of coal measure rock was ignored in the report. The history of success with the Minova 20 psi seal has been ignored in the rush to damn all the alternative seals. Both the Sago and Darby Mine disasters were the direct result of the failure of an alternative seal, significantly different from Minova's Tekseal in design and performance.

Australia has had success with 20 psi rated seals providing the gob area is monitored to ensure an inert atmosphere. The Poles use relatively weak Durafoam (Tekfoam) where there is no explosive risk. What is the justification for recommending 50 psi rated seals in these circumstances? Have there ever been any recorded instances anywhere in the world where underground explosive pressures have reached anything close to 640 psi? Should we be designing structures to resist explosive forces that realistically will never occur?

Page 35. It is stated that a wall of concrete blocks 18 ins thick could meet the challenge of a 120 psi pressure pulse. RI 9477 states " a standard type seal with no pilaster, but with floor keying also failed structurally ". This seal was a double row of block 1.3 ft thick. It failed at less than 20 psi. This result does not appear to accord with the statement that a 1.5 ft wall could withstand a 120 psi blast.

Hardstop, which is chemically, beta hemihydrate gypsum has been used in the past to make plug seals in British Coal mines. Its strength is not 600 psi as stated but is about 100 psi. It can only generate high strengths when it is allowed to dry out which is impossible in the large bulk of a seal. Nevertheless the fact that seals made from very weak Hardstop reliably withstand test explosions is a testament to the efficacy of plug seals.

Response

We disagree with the position that the worst-case explosion pressure analysis as presented in the NIOSH report is unrealistic and improbable. Unfortunately, developing high pressure explosions is relatively easy. We recognize that many variables can affect the strength of an explosion, such as the composition of the explosive atmosphere and the presence of inerting or quenching substances like rock dust. However, we believe that mines must plan for the worst case unless active monitoring and control of the sealed area atmosphere demonstrates that it is inert or contains only a limited amount of potentially explosive mix.

We agree with your assessment that construction of seals in mines is very demanding and that the site specific conditions require attention at each seal installation. Our report advocates the involvement of a licensed Professional Engineer at all steps in the process, beginning with the information gathering phase, followed by seal engineering and then seal construction. Our report provides critical information on what the possible pressure-time curves could be from an explosion, and hopefully our report alerts the mining community to the serious hazards that can develop from a sealed area atmosphere. We commend you and your company for all your efforts to promote safety in mines through your products.

The 640 psi design criterion applies to unmonitored seals with no control whatsoever of the atmosphere behind the seal. True, other countries around the world use lower design pressures. In Europe, a 72 psi criterion with a safety factor of 2 (effectively, 145 psi) generally applies, and in Australia, a 20 psi criterion applies. However, the Europeans and the Australians monitor and control the atmosphere behind seals especially immediately after sealing during the initial inertization phase. Because of their monitoring and inertization practices, the Europeans and the Australians can use lower design pressures for their seals.

Regarding the possibility of ever developing explosion pressures of 640 psi, we cite the MSHA report on the 1992 explosion at the Blacksville No. 1 shaft. That report estimated the explosion pressures at about 1000 psi based on back-calculation from the observed damage. Of the 12 explosions reported in table 2 of the NIOSH report at least 8 of the MSHA reports indicated blown out seals. Generally, it is difficult to back-calculate explosion pressures, because access to the sealed area to collect the necessary forensic evidence is not possible. Recent experiments at the NIOSH Lake Lynn Experimental Mine show that it is not possible to precisely assess the explosion pressure within a sealed area from seal debris downstream of an explosion. We believe that until now, everyone has seriously underestimated the explosion pressures that can and have developed in sealed area explosions.

We base our calibration of the 120 psi design chart on tests at LLEM described by Sapko et al. (2005). In those tests a 2.62-m-high (8.6 ft) seal constructed 0.4-m-thick (16 in) was subject to four explosions of increasingly high pressure. Hairline cracks were visible after the third explosion at 651 kPa (95 psi) and the seal finally ruptured at 688 kPa (100 psi). According to the 120 psi design chart, a seal of this height should be 0.6 m thick (24 in) to have a safety factor of 2, and would be 0.4 m thick (16 in) to have a safety factor of 1. That the 16-in-thick test seal failed after four explosions provides evidence of the validity of this simple chart.

The primary purpose of the structural analyses presented in the NIOSH report is not to provide final design recommendations for seals to resist the three proposed explosion pressures, namely 640, 120 and 50 psi, but to provide approximate seal design thickness, so they engineer can judge the relative merits of alternative sealing strategies with typical construction material possibilities. With the new proposed explosion pressure design criteria, the mining industry faces choices of sealing with thicker seals and not monitoring or sealing with thinner seals and monitoring or not sealing and continuing to ventilate. To weigh these alternatives and decide on a strategy, we provided these approximate design charts that will provide engineers with approximate values for relative seal thickness using the different design pressures and a range of typical seal construction materials. These charts were developed following specific assumptions stated explicitly in our report and are only valid if these assumptions are met. Again, these design charts are not intended as a substitute for proper engineering design of seals with site investigation, structural analysis and quality control during construction. Furthermore, they should not be accepted as a substitute for the required structural engineering.

The publication "Sealing-off Fires Underground" published 1985 by the IMM lists the compressive strength of Hardstem as 500 psi after 2 hours and 1700 psi after 24 hours. The latter figure also agrees with USBM test results. We are supportive of plug seals made from weak materials provided excellent engineering is conducted from design through construction.

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Comment

Enclosed are comments to the NIOSH Seal report that we have received from our mining operations.

INERTIZATION BEHIND NEW SEALS

- To inert behind new seals it would be necessary to inject a gas through a borehole on the surface and also inject through a pipe underground that penetrates through a set of seals back into the sealed area.
- The seals proposed in this report do not provide for any pipes to penetrate the seals, not even a water trap.
- Some surface boreholes would require U.S. Forest Service approval, if approved this would require an Environmental Impact Statement prior to any surface disturbance. This process would require a considerable amount of time.
- At some remote surface locations the necessary site could not be made accessible to the needed mechanized equipment due to the topography.
- If it becomes necessary to inert the area behind the seals, the process should be mine specific and developed based on the mines unique circumstances and the risks presented at that location.

MITCHELL/BARRETT SEALS

- If reinforcement bars are required in a Mitchell/Barrett Seal, how are the bars to be placed in the cement block structure?

HITCHING OF SEALS

- The theoretical sharp curves of a hitch cannot be effectively duplicated in most floor materials especially if you are using mechanized equipment to prepare the site.

MONITORING BEHIND NEW SEALS

- It appears that even the 640psi "not managed, not monitored" seal would require monitoring until the seal material gains full strength.
- The continuous monitoring envisioned by NIOSH is a system that involves multiple tube bundles with a surface collection site and extensive gas evaluating instrumentation. This sampling system may not be a reasonable option for some mines especially when needed only for very short time frames.
- This report provides for no other monitoring system options except for the Australian model.
- NIOSH should consider an evaluation of each set of seals on a mine by mine basis utilizing a risk based analysis and then developing a sampling protocol for that specific situation.

EXISTING SEAL AREAS

- When evaluating the area behind existing seals, consideration should be given to the sampling history and the stability of that gobs inert status.
- If a seal is to be rebuilt in a remote area that is difficult to access, consideration should be given to the material handling exposure of the miners who are trying to move the needed supplies into that location.
- Some existing seals do not have adequate space in front of them to build another seal, in order to replace a seal in this situation, it would be necessary to remove the original seal first.

Response

Regarding inertization behind new seals, many coal mines will self-inertize within a few days of sealing, and therefore, artificial inertization may not be necessary. By monitoring during this critical initial inertization phase and keeping people out of the mine during this short critical time, the use of 50 psi seals is possible by our report recommendations. Continuous monitoring to make sure the sealed area atmosphere remains inert is also required by our report. The method to develop and maintain an inert sealed area atmosphere depends on the unique circumstances of each mine.

While the NIOSH report recommends the use of reinforcement with pumped seal materials, such a requirement is incompatible with concrete block seals. We have modified our report to give more options for anchoring a seal firmly to the surrounding strata. Hitching is one option; reinforcement bars is another, and there can be others.

Regarding monitoring, use of the 640 psi seal does not require monitoring at any time, either during the "cure time" or after the seal has reached its design strength. However, until the seal achieves its design strength, which may take 24 hours or more, personnel must be removed from the mine and the danger posed by a potentially explosive atmosphere behind the seal. Using 50 psi seals requires monitoring while the seal reaches its design strength, during the initial inertization period and periodically after the sealed area has become inert. Again, personnel should be removed from the mine until the seal design strength is developed and the sealed area atmosphere becomes inert as planned.

The NIOSH report does not specify any particular approach or system. The tube bundle systems with gas analyzers that are commonly used in Australia are but one option, but certainly not the only possibility. For short term applications, bag samples may make sense, provided the frequency and location of samples is sufficient to demonstrate a safe, inert sealed area atmosphere.

Regarding existing sealed areas, subsequent monitoring should convince all mine personnel that the atmosphere behind seals remains safely inert if air leakage occurs due to barometric pressure changes, ventilation pressure differentials and gob gas production from boreholes. To accomplish this goal, monitoring behind seals should demonstrate that the size of a potentially explosive mix is sufficiently small. Figure 18 of the report provides guidance in this respect. Monitoring must also occur with sufficient frequency and consider how fast an explosive mix could accumulate depending on the leakage rate. Developing sensible monitoring guidelines based on sound science is a high priority task for future NIOSH research on seals.

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Comment

I was the lead MSHA investigator on the explosion at the McClane Canyon Mine on November 27, 2005. This explosion occurred in an active, ventilated area of the mine and not within a sealed area. The nine Omega block seals were blown into the sealed area and destroyed by the explosion.

Response

Thank you for your review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." This NIOSH report has stirred much discussion in the U.S. coal mining community, because the high pressures that can develop from a methane-air explosion are not widely known to mining engineers. The subject of seals remains controversial, and we hope our report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines.

In table 2, we deleted the reference to the explosion at McClane Canyon Mine. We were mistaken about this incident and thank you for pointing out this mistake. Three other explosions within abandoned areas were identified and added to table 2, namely, the 1986 Roadfork #1 mine explosion, the 2002 Big Ridge Mine Portal #2 explosion and also the 1992 Blacksville No. 1 shaft explosion. If you can identify any other explosions in sealed areas, please let me know.

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Comment

I've read your guidelines with interest and pleasure. I think they are comprehensive and reasonable. Below, there are a few remarks that came to my mind while reading the text.

1. It seems the choice of 50 m as the detonation run-up distance is a very conservative assumption. I don't know how different the cross-sections of your mine tunnels are, but may be it would be more appropriate to use L/D ratio to define the run-up distance instead of the length alone, as is was formulated by the authors you mentioned in the report.
2. Apart from the test No. 1397 we registered another detonation in a dust/air mixture. I'm attaching the wave diagram of the test No. 2399 where the explosion was initiated at the closed end of our 400 m underground entry. Although in the test we used grain dust its explosibility parameters (pmax, Kst) were quite similar to typical coal. We used 10 bar pressure sensors so they failed to register initial peak pressure but I believe the rest of the curve is correct. Comparing to your 4.4 MPa design pulse, the width of initial peak is similar but the pressure reminding behind the peak was higher in our test.
3. As you probably already know, FLACS is not designed for very strong explosions. In FLACS the SIMPLE numerical method is used. The method was designed for subsonic, incompressible flows so basically you should expect smearing of steep pressure pulses. How strong the effect is manifested depends also on how fine grids you used. More appropriate for your purposes would be so called 'shock capturing' methods.
4. Among the parameters affecting the explosion strength I would add the complexity of the geometry of the sealed area. Almost all experimental tests were done in straight tunnels, the simplest possible geometries. In real cases the interconnected straight sections form geometries that, together with random locations of explosion initiation, can produce explosions developing in different directions and then further interacting one with another. The interactions may lead to unpredictable pressure rise. For example, I'm not sure that explosion initiation at the closed end will produce the strongest pressure effects. In your FLACS simulations, have you tried to ignite methane at different locations, not only at the points A, B and C?
5. It would be much easier to compare results obtained with FLACS and AutoReaGas if time axes had the same range

Response

Based on reliable reference material, the run-up length to the onset of DDT for methane-air is about 50 to 100 times the pipe diameter for smooth pipe. The height and least dimension of most underground coal mine entries in the U.S. is between 1 to 3 meters averaging about 2 meters.

For smooth conditions, the run-up length may be 100 meters; however, most coal mine entries are rough and contain obstructions. These turbulence generators will likely accelerate DDT and for that reason, we selected the conservative distance of 50 m. We agree with your position that the run-up length to DDT is best expressed in terms of an L/D ratio; however, for practical mining guidance, we believe a simple conservative distance is best.

Thank you for providing additional experimental data to support the 4.4 MPa design pressure-time curve. We are grateful for the independent confirmation that the form and magnitude of this design curve is correct.

We are aware of the limitations of AutoReaGas and FLACS. Per your suggestions, we have added discussion on the smearing of steep pressure waves due to the grid size. In future research, we plan to continue using the above CFD models to examine other aspects of coal mine gas explosions when pressures are low. We also plan to use more sophisticated models that correctly include shock capturing and DDT.

Thank you for your good suggestion that the complexity of the sealed area geometry also affects the pressure rise. We agree that such complexity could lead to unpredictable and probably adverse results. In future research with simple CFD gas explosion models, we will examine the effect on explosion pressure of different ignition locations and other factors.

The time to peak in the AutoReaGas and FLACS calculations differed significantly. The FLACS simulations were totally blind with no advance knowledge of the LLEM calibration data. The AutoReaGas simulations had the LLEM data in advance. Except for the differences in arrival time, both simulations replicate the LLEM data remarkably well.

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Comment

The report provides a logically developed and well written account explaining the development of new criteria for seal design for underground coal mines. My review has focused on the mechanical stability aspects of the report, specifically reviewing the calculations and assumptions regarding the required strength of seals. I am unable to comment seal loads by methane and coal dust explosions since these topics are outside my area of expertise. My comments follow:

1) The requirement for a safety factor of 2.0 in seal design seems to be adequate, given the uncertainty in loading and strength of seals in coal mines.
2) The failure mechanisms of arching for slender seals and plug failure for wide seals are realistic for assessing seal stability under side loading. The simple equation for plug failure is correct and I obtained similar results using a similarly developed equation.
3) Since I do not have access to the WAC code, I carried out a number of preliminary numerical analyses using the UDEC software of Itasca Inc (Minnesota) to evaluate the failure mechanism and ultimate strength of 2m high seals subject to a static side load. The results obtained are very similar to the results you reported, see Figure 1 attached. Interpolation of the UDEC results show the following seal sizes for 24 MPa concrete blocks at a factor of safety of 2.0 and are compared to the recommended values from the design charts in your report:

Table 1. Preliminary UDEC model results for 2m high seals constructed with 24 MPa concrete blocks

Static Pressure	Udec required wall thickness (m)	Design chart required thickness (m)	Figure in report
4.4 MPa (640 psi)	0.85	0.9m	Figure 25
0.75 MPa (120 psi)	0.35	0.4m	Figure 26
0.5 Mpa (50 psi)	0.27	0.27	Figure 27

4) I carried out a number of spot checks to see if the design charts are in agreement with the provided equations. Except for the 3.5MPa line in Figure 25 which seems to be too low(?), the results shown in the charts appeared to be correct.

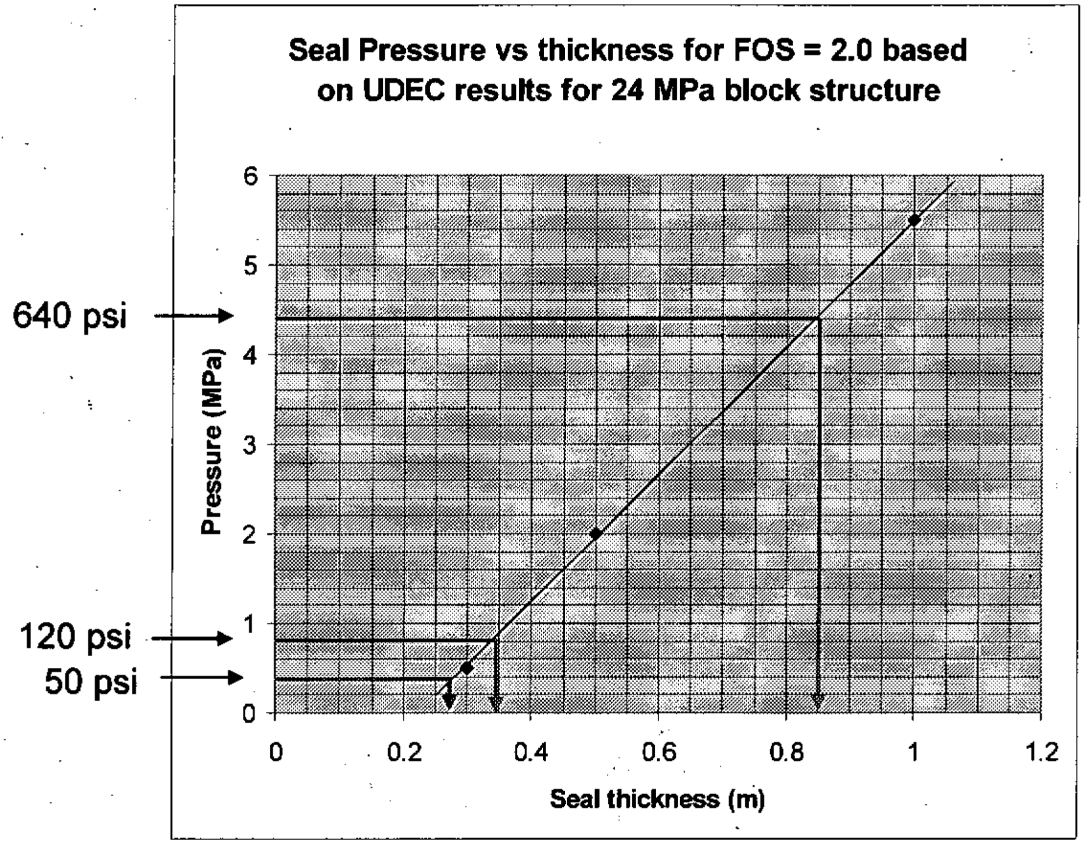

Figure 1: Preliminary UDEC model results showing relationship between required seal thickness and static pressure for 24 MPa strength concrete walls constructed in a 2m high entry.

Response

Your comment on the logical development and well written nature of the report is most appreciated. Below, I address your 4 comments in order.

The safety factor of two addresses uncertainty in the seal's material properties, its foundation and construction quality. It seems to be in line with other safety factors employed in the mining industry.

Your assessment of the realism of both the arching failure mechanism and plug failure is appreciated. Your independent check on the accuracy of the arching analysis and plug analysis equations is also appreciated.

Finally, your structural analysis of a seal using UDEC to spot check the accuracy of our WAC calculations has helped tremendously. Your UDEC calculations used 24 MPa (3600 psi) concrete, and they agreed with the seal thicknesses presented in the design charts to within 10%. Your calculations also showed that seal failure occurred when the outward displacement exceeded about 1 inch which again coincides with the assumptions in our simplistic analyses with WAC.

Thank you for pointing out a discrepancy with one curve on the 640 psi design chart. That curve was based on the assumption that a 300 psi static pressure could approximate the time-dependent 640 psi pressure-time curve. We have removed that assumption and that particular design curve from the report, pending future research to develop a static equivalent to the 640 psi pressure-time curve.

Per our verbal discussions, we also added many references to equations and statements throughout the report that are clearly not our prior work. In the haste to assemble the draft report, I was negligent in giving proper academic credit where it was due.

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Comment

First I would like to compliment NIOSH researchers for the very detailed analyses provided to reach the recommendations set forth in the study. The approach in searching the literature, interacting with foreign researchers, and working with the non-mining experts reflects sincerity in pursing the charge and in protecting the lives of miners. Generally I find the study enlightening scientifically and conservative in its approach to designing seals that will protect miners. My specific comments on the report follow.

In the discussion of seals and ventilation systems in underground coal mining (§ 1.2), one additional important reason for the transition from bleeder ventilation to sealing of abandoned areas was the difficulty of managing bleeder system ventilation temporally. Also bleeder entries were very difficult to maintain in passable condition over time, and the inability to inspect them in the entirety became problematic or even impossible.

In § 1.3A it would be helpful to the reader if 'outer gate entries' and 'inner gate entries' were defined before using the terms, or at least indicated in Figure 2A. The use is not clear in Figure 2A, especially when considering the statement that "inner entries may remain open for three to four kilometers or more in larger mines." Also in this section, in addition to judicious placement of the seals, it could be noted that operators certainly could design pillars surrounding the proposed locations for seals to be much large and more stable.

Similarly, a more clear definition of 'completely confined' and 'partially confined' would be useful. The terms are linked with the degree of venting, and knowing the level of venting that characterizes a partially confined condition would be useful to know.

The report does a good job in describing the inability to estimate accurately the level of methane and oxygen in many locations in a sealed area. In § 1.4, in paragraph one and/or two, I believe it is important to note that at least 10% oxygen is necessary for an explosion to occur, even though methane may be in its explosive range and an ignition source exits. This is the primary reason for making the sealed atmosphere inert.

Also in § 1.4, I do believe that the existence of an explosive methane-air mixture in the entire length of a sealed area, as shown in Figure 3A, is very conservative, and would have a low probability of occurrence; however, I certainly could not rule out the possibility of it occurring in a particular sealed area. I do believe further research, as discussed in the report, will eventually reveal an estimate of the probability for such occurrences, but not for a long time. This is an important consideration for potential revision of recommendations at a later date.

Concerning the discussion of the scenario presented in Figure 3C, often only immediate-roof falls during retreat mining when large barrier pillars are left in place, as shown. In essence the gob is not 'tight' but rather very open and thus would allow extensive venting. If, on the other hand, the barrier pillars were mined, as many mines do, then a fairly 'tight' gob would form regularly after the first fall on the panel occurs. These conditions would lead to variations on the scenarios presented in Figure 3.

In § 2.2, it would be helpful if a brief description was provided of the conditions of the United Kingdom and German full-scale tests. A discussion of the key parameters that influence explosions (volume of sealed area, run-up distance, degree of filling with an explosive mix, the degree of confinement or lack of it, and the degree of venting) would give the reader much greater understanding of the test results, and the ability to compare them with the U.S. results (USBM and NIOSH).

I am not sure what the stoichiometric requirement for oxygen is in relation to 10% methane. If a sealed area is depleted of oxygen, does the explosion become fuel rich at a certain level of oxygen (above 10%)?. This would be useful to cite in the report, and may figure into the calculations of realistic estimations for an explosion when continuous sampling is done in the future.

In § 4.2, upon scrutiny of Figure 12, I don't agree with the statement that "For these small volume gas explosions, experiment and model compare well." In addition to offset of arrival times, which was noted, the pressure peaks for the three scenarios are significantly different at 12 psi (measured) vs. 6.7 psi (-44.2%) vs. 10 psi (-16.7%) for the 32.9-m test and two models, respectively, and 7.2 psi (measured) vs. 4.2 psi (-41.7%) vs. 6 psi (-16.7%) for the 160.3-m test and two models, respectively. Although modeling has provided some useful insights into ballpark numbers for explosion pressures, it is a reach to state, "In summary, despite the offset in timing, the gas explosion models reproduced the measured experimental data well." The next section, § 4.3, begins with the statement "Having calibrated the models successfully ..." which is also a reach in conclusion from the data presented. It is certainly okay to acknowledge the pitfalls of the models versus experimental results, and still use the models to gain insight into larger explosions, but the possible errors in estimates should be noted.

I would reiterate in § 4.3, in the next to last paragraph, that NIOSH does plan experiments in larger volume explosions in out years. However, in the interim the best means for protecting miners now must be based on existing analyses from all sources, including this report.

Regarding Figure 15, I note large variabilities in modeling results for a given length of explosion, in particular around 160 m, 230 m, and 300 m. I didn't see any explanation of why this occurred when only modeling was done. This should be explained in § 4.3 where Figure 15 is discussed, so that the reader can understand the variation in pressure better. The range of pressures for each of the three lengths noted are quite large; specifically for 160 m, an overall range of approximately 390 psi is noted, considering both AutoReaGas and FLACS results, and a range of approximately 240 psi is noted considering only AutoReaGas. The variability should be explained for the other two lengths of explosion, too.

Regarding Figure 18, the relationship may not be linear, as suggested. No best fit regression line was calculated, and looking at the plotted data, there is quite a gap in available data between 30 m and 60 m. If the coefficient of determination for a linear regression is above approximately 0.60, then maybe this could be stated as a linear relationship.

Section 5 is largely founded on the results from section 4, and thus some of the above statements, if addressed, may influence the bottom-line numbers adopted in Section 5. I don't believe that adjustments would be large though. With this said, in the first paragraph, I believe the researchers correctly stated that "The large volume gas explosion models hinted at the much larger explosion pressures that can develop ...." And this is the key point, regardless of whether the number adopted is 600 psi instead of 640 psi, or even 550 psi. Either way, it will be a high pressure level.

Some of the statements in Section 5 are confusing, particularly concerning the level of venting. Most of us accept that abandoned areas 'breathe', which means that there is a level of leakage in and out of the sealed area depending on the barometric pressure. It would thus be very useful if terms such as 'with no venting possibility', 'partial venting', and 'complete venting' were defined. The same goes for 'completely confined', 'mostly confined', and 'partially confined'.

In § 5e and § 5f, I don't understand how 33 ft and 15 ft were selected. In contrast, I completely understand how 165 ft was determined. I read the report over a second time to try to determine the rationale. Please explain it so that all will know clearly how these distances were obtained. It would also be helpful to know how 40% was selected as the critical percent of the sealed area volume in determining scenarios.

Response

We appreciate your kind remarks on the research approach and analyses we developed to pursue this charge. We have attempted to make many clarifications to the report per your various suggestions, and in that regard, we offer the following explanations below.

We recognize the difficulties of managing bleeder systems over long times. Maintaining bleeder systems in safe travelable conditions has been problematic. The decision whether to 1) ventilate and not seal, 2) seal without monitoring using high explosion pressure seals, or 3) seal with monitoring using 50 psi seals is a difficult economic and risk management decision.

Instead of "inner and outer" gate entries in figure 2A, we now refer to the 1, 2 or 3 entry. This terminology is clearer and more in line with practice. We agree with your remark that operators could design pillars around future seal locations to be larger and more stable.

In section 5 where we develop the design pressure-time curves for structural analysis, we added explanation of the terms confinement, venting and the degree of filling as used in the context of gas explosions. The terms have different meanings, and it is important to understand the concepts.

In gas explosion terminology, an unconfined explosion occurs in open air and the reaction gases can expand freely in all directions. An open-air ignition of an explosive gas mix is an example of an unconfined explosion. A completely confined explosion occurs in a sealed volume where the gases cannot expand freely in any direction. An explosion in a sealed volume completely filled with explosive mix is an example of a completely confined explosion. The explosion pressure will equilibrate to the constant volume explosion overpressure of 120 psi independent of the size of the sealed volume. Many explosions are partially confined in that the gases can expand freely along an entry. The ignition of a limited-volume explosive mix behind a seal where the gases can expand into inert atmosphere deeper in the sealed area is an example of a partially-confined explosion.

Venting and confinement are almost antonyms, in that a completely confined explosion is un-vented and an unconfined explosion is totally vented. However, the degree of venting for partially confined explosions can vary. Using the prior example, the explosion of a limited volume mix behind a leaking seal where the gases can expand freely into inert atmosphere is a partially-confined explosion that is completely vented. However, in the case of a cross-cut seal the gob may restrict the gas expansion, so the explosion becomes partially vented.

The degree of filling refers to what percent full a sealed volume is of explosive mix. A newly sealed panel that is crossing through the explosive range may be 100% filled with explosive mix. An explosion within a completely confined sealed area that is 100% filled with explosive mix will develop 100% of the constant volume explosion overpressure of 120 psi. If the volume is only 40% filled, then the explosion pressure will equilibrate to 0.40 * 120 or 48 psi. After that panel has become inert, a leaking seal may develop an explosive mix behind it, but the degree of filling may only be a few % of the total sealed volume.

We agree that the report needs to state that methane-air is no longer explosive when the oxygen level is below 10%. We have added a Coward triangle diagram around section 1.4 to explain these concepts and to illustrate the various paths that a sealed area atmosphere may take to become inert.

The large volume explosive methane-air mixture shown in figure 3A may unfortunately occur more frequently than we would like. In many coal mines, the sealed area atmosphere could become fuel-rich and inert within a few days. However, in other coal mines, that atmosphere could remain in the explosive range for many weeks or it may never become a fuel-rich and oxygen-low inert atmosphere. Data on the occurrence of such atmospheres is lacking, and we cannot reliably assess the probability of occurrence. Monitoring sealed area atmospheres to collect information on how sealed area atmospheres become inert is a high priority task for future research.

We agree that many variations of figure 3C could occur. The degree of venting could vary considerably. Future NIOSH gas explosion research may examine venting into open and tight gobs to quantify the explosion pressures that might develop along with the decay times.

A brief description of the full-scale seal tests conducted in the U.K. and in Germany is added.

We have expanded the explanation of key parameters affecting explosion strength given in section 3.9. This section now includes more discussion of confinement, venting, degree of filling run-up distance and other terms. In addition, we tried to cross-reference the text and refer the reader back to section 3.9 when these key terms are used as design parameters in section 5

The NIOSH report now includes a Coward triangle diagram to illustrate relationships between methane concentration, oxygen concentration and explosibility. To answer your question, the Coward triangle shows that an atmosphere cannot sustain a methane-air explosion when the oxygen level is below 12 %, no matter what the methane concentration is. For mine safety, we prefer that the sealed area atmosphere becomes both fuel-rich with a methane concentration above 20% and oxygen-low with an oxygen concentration below 10%.

The NIOSH report statement that the gas explosion modeling results compare well with experimental data at LLEM may seem like an overstatement, but the agreement between experiment and these model calculations is within bounds for acceptance in practice. The table below compares model calculations to experiment for one particular test explosion at various measurement points. The calculations are within 50% of the measurements which is considered acceptable for calculations of these kinds. See the references by Lea and Lidin (2002) and Popat et al. (1996) for more comprehensive discussion of the expected computational accuracy for such models. We should also point out that the calculations with FLACS were done "blind" with no advance knowledge of the form and magnitude of the experimental data. We have made efforts to tone down our enthusiastic descriptions of these initial numerical models of gas explosions in coal mines.

Measurement point	LLEM calibration data	AutoReaGas calculation and % difference	FLACS calculation and % difference
3.05 m	0.100 MPa	0.110 MPa +10%	0.095 MPa - 5%
32.9 m	0.080 MPa	0.045 MPa - 44%	0.070 MPa - 13%
160.3 m	0.050 MPa	0.030 MPa - 40%	0.040 MPa - 20%

A statement is added to section 4.3 indicating that NIOSH researchers plan to conduct larger volume confined tests in the next few years and that we plan to use other models that correctly model shock waves, DDT and other high pressure phenomena.

Additional discussion is added to section 4.3 to clarify the interpretation of figures 14 and 15. The large-volume, confined explosion models calculated pressure-time history on three seals in drift A, B and C. Figure 14 shows these traces for seal B only. As the explosive volume increases, constructive and destructive interference of pressure waves occur along with reflections as the explosion develops within the LLEM geometry. These computations do not properly model these high pressure phenomena, in part because they do not properly account for the physics of shock waves and in part because the computational grid is too coarse. Figure 15 shows the computed peak pressures at seals A, B and C for the different sizes of sealed volume in the models. These peak pressures indicate that beyond a length of about 100 meters, the peak pressures are high enough that detonation becomes a possibility. These peak pressures generally exceed the CJ detonation wave pressure of 256 psi and suggest that the deflagration could transition to a detonation. Based on the empirical observations of the run-up length to DDT, we estimate conservatively that beyond 50 m detonation could occur, and this length is indicated on figure 15. Again, these model calculations are not used to predict what peak pressures can develop in a large volume confined explosion. Those pressures, namely the constant volume explosion pressure of 135 psi, the Chapman-Jouguet detonation pressure of 256 psi and the reflected detonation wave pressure of 653 psi, are developed from physics and thermodynamics. The computed peak pressures shown in figure 15 do confirm that 50 m is a conservative estimate of the run-up length for DDT.

The peak explosion pressure versus volume size behind a leaking seal may not be linear beyond 30 m. The design recommendations shown in figure 19 do not consider explosive mix volumes beyond that size. The LLEM experimental explosion data points at 4, 8, 12 and 18 meters coupled with the model calculations at 15 and 30 m produce a relationship that is visually linear, though we did not compute a best fit line or regression coefficient. Between 0 and 30 m, we are comfortable that the relationship is linear; however, between 30 and 60 meters, variability in the computed pressures increases and the relationship may become nonlinear.

The design pressure-time curves presented in section 5 are not founded primarily on the numerical model calculations rather they are developed from the physics and thermodynamics of explosions presented in section 3. The constant volume explosion pressure of 135 psi, the Chapman-Jouguet detonation pressure of 256 psi and the reflected detonation wave pressure of 653 psi are the primary basis of the design pressure-time curves. The numerical modeling presented in section 4 provided some insights into the time dependence of the pressures and also the amount of explosive mix that is tolerable behind a leaking seal based on figure 18.

We have added explanation of important terms that govern explosion strength, such as confinement, venting, degree of filling, run-up distance and other terms. The definitions are developed in section 3.9 and re-iterated in section 5 where they are used in design. We have added much discussion to explain development of the allowable volume of explosive mix behind monitored seals in 5d, 5e and 5f. These lengths are based on figure 18 and are the maximum length of explosive mix tolerable behind a 50 psi seal under different conditions. This length also specifies the tolerance for monitoring. Related to this length is the allowable filling of 40%. The confined volume of the sealed area can never contain more than 40% explosive mix, in order to keep the constant volume explosion pressure less than the seal strength. At 40% filled, the maximum CV pressure is $0.40 * 120 = 48$ psi < 50 psi.

Dr. Stewart Gillies
Gillies Wu Mining Technology
The Minserve Group
1 Swan Road
Taringa Qld 4068
Brisbane Australia

Comment

Please find attached a review of your report.
It is by and large a water-shed report in terms of aspects you have included, the depth of thinking and a major step forward from the past.
Congratulations to Jurgen, Mike and yourself for your efforts.

Response

Thank you for your kind remarks on our draft report. We hope it becomes the basis for much needed change in sealing practice in the U.S. In our opinion, we need to take a look at the Australian approach which involves monitoring and inertization as required in order to prevent potentially explosive atmospheres from ever developing within sealed areas.

Dr. Olav R. Hansen
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GexCon AS
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N-5892 Bergen
Norway

Comment

I do not think I have any severe comments on your design recommendations. As we discussed at the meeting in Bergen, there will be a range of possible measures that can be taken to minimize the risk for major explosions, like installing numerous weak barriers (to limit the homogeneity of gas), various kinds of partial inerting etc.

Regarding the presentation of FLACS, I am not 100% satisfied (not sure if you directly see the reasons for this, I will explain). Like we discussed last fall, we simulated 6 different scenarios blind (even if we got a glimpse of the results before sending our predictions to you). Through our discussions in the summer, I several times stated that calibration was not something we normally did when doing calculations with FLACS. All 6 scenarios were predicted within about +/- 10%, we were very happy with this.

In the report only one of these 6 "calibration" scenarios are shown, and our simulations are presented next to AutoReaGas simulations (AutoReaGas definitely needs calibration tests to produce reasonable results). So for the typical reader of the report, the efforts and predictions with FLACS may seem very comparable to that of AutoReagas. Only the critical reader will see that there is a significant quality difference between the FLACS predictions and the AutoReagas simulations (e.g. looking into multiple peak structures and 32m/160m predictions).

5-10 years ago in the UK, several companies decided to use AutoReaGas for their explosion work. Last year at least 4 companies that used AutoReaGas in the past started using FLACS instead (3 from UK, 1 from Canada). All of them clearly expressed how they could work more efficiently with FLACS, received competent support, and some of them also expressed that they enjoyed being able to trust results without the need for calibration.

What I fear is that based on your report, companies considering purchase of explosion software will consider FLACS and AutoReaGas for equals, and thus decide to use AutoReaGas since this tool is offered to a lower price.

Except for this, I enjoyed looking through your draft report.

Response

Thank you for your review of the NIOSH report “Explosion pressure design criteria for new seals in U.S. coal mines.” This NIOSH report has stirred much discussion in the U.S. coal mining community, because the high pressures that can develop from a methane-air explosion are not widely known to mining engineers. The subject of seals remains controversial, and we hope our report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines.

Your role in providing the first, simple numerical simulations of a coal mine explosion was indispensable. While we recognize the shortcomings of CFD models that do not consider DDT and other high pressure phenomena, such models can provide useful results for many practical situations.

We altered the report section 4 on gas explosion modeling in two ways. First, we included discussion and a table showing the model calibration for all 6 scenarios. The draft report showed just one modeled experiment and that was inadequate to portray the true reliability of the models. Second, we now emphasize in several places that the FLACS calibration experiments were completely blind, with no advance knowledge of the LLEM data. Please know that as an employee of a U.S. government research agency, I must be very careful making statements about any products whatsoever.

I appreciate your serious concern about comparing FLACS to AutoReaGas in an unfavorable way. Our intention has never been to portray anyone unfavorably. We hoped that two independent calculations using different software would provide reliable and convincing insights into gas explosions in mines. In that light, we are most pleased with the calculations that led to the development of figure 18 in the report that relates explosion pressure to length of gas cloud.

Mr. Tim Harvey
Group Ventilation Engineer
Anglo Coal Australia Pty. Ltd.
201 Charlotte Street
Brisbane 4000 Queensland
Australia

Comment

Enclosed are my comments for what they are worth over all I though it was a well presented argument. But I wonder if lack of monitoring and inertisation has made has made it more conservative than required. Once inert in a seam making gas then with reasonable seals Oxygen should not get into goaf even with Barometer as seals will say under positive pressure. (our experience in gassy mines. I look forward to receiving the final report but not some of the backwash from this report.

Response

Thank you for your review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." This NIOSH report has stirred much discussion in the U.S. coal mining community, because the high pressures that can develop from a methane-air explosion are not widely known to mining engineers. The subject of seals remains controversial, and we hope our report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines.

The primary purpose of our report is to present the worst-case explosion pressure that could develop within a sealed area if an uncontrolled explosive mixture is allowed to accumulate. Regrettably, the absence of monitoring and other means to control the atmosphere within a sealed area is the norm here in the U.S., and unfortunately, in the worst case, high explosion pressures can develop. We hope that our report causes more U.S. coal mines to take a look at the Australian approach which involves monitoring and inertization. Controlling the size of the potentially explosive volume within a sealed area negates the need for such high pressure seal design.

Dr. Walter Hermülheim
Vice President of Safety
Deutsche Steinkohle AG
Servicebereich Technik und Logistik
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Comment

Congratulations on your excellent paper. I feel it summarizes the subject of sealing in a very comprehensive way and leads to reasonable results and recommendations.

The influence of dynamic pressure may be a little bit over-emphasized since a lot of full-scale-tests showed that it was not so much the (very short) dynamic peak pulse, but the static pressure which really damages a seal. On the other hand the amount of fuel as well as the maximum propagation distance in an experiment is always quite limited in comparison with a real mine. So it should be o. k. to put it on the safe side.

When you go on with the subject of sealing in the future please let me notice that miners always like advice in the form of practical examples. Especially the anchorage of seals into the surrounding rock and coal could still be described with more details and with sketches.

Response

In our future research we plan to examine techniques to protect seals from high, but short-lived transient pressures such as reflected blast waves or detonation waves. However, at a minimum, it makes sense to design for the constant volume explosion overpressure of 800 kPa, as there is no possibility of escaping this long duration explosion pressure. Again, protecting seals from transient pressures will be an important component of future research.

The other problem we face is communication. First we need to alert the industry here about the explosion hazard within sealed areas, and the present report is part of that process. The changes we propose in our report are substantial for the U.S. coal mining industry and controversial. The choice is between much stronger, higher pressure seals with no monitoring or somewhat stronger seals but with continuous monitoring with inertization of the sealed area atmosphere. Educating the industry about how to manage the atmosphere within sealed areas is also a key component of our efforts over the next few years.

Dr. Francois Heuze
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94551

Comment

Several points in the text require clarification.

Response

Thank you for your review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." This NIOSH report has stirred much discussion in the U.S. coal mining community, because the high pressures that can develop from a methane-air explosion are not widely known to mining engineers. The subject of seals remains controversial, and we hope our report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines.

We corrected several statements in the report that were worded poorly. We also created an addition to table 5 that captures the simple engineering essence our report. This new design chart is aimed at mining engineers and MSHA ventilation specialists and gives simple guidance for which pressure-time curve to apply. Scientific communication of this sort is hard to do.

Dr. Allen L. Kuhl
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Comment

1. CRITIQUE:

Page 15, paragraph 2
Figure 7: data is below theoretical curve because of incomplete fuel consumption

Page 17, equation for p_V
This equation is false.
Pressure density and velocity are independent variables throughout the flow field.
For steady flow: $h + V^2/2 = h_0 = \textit{stagnation enthalpy}$
This leads to the following relation between p & V: $\gamma(\gamma-1)p + 0.5\rho V^2 = \rho h_0$ which is valid along an isentrope expanding from the stagnation condition
SOLUTION: this equation is true only at a shock front, so just say at a shock........

Page 19, equation for reflected pressure
Correct, I checked it with Stanyukovich (1960) p. 373 eq. (47;9)

Page 19, last paragraph
Method used to calculate the 2,300 psi is questionable.

Page 21, paragraph 4
The explosion pressure does not obey the linear relation quoted here (see figure 6 of this report).

Page 25, paragraph 1
"gas explosion models reproduced the measured experimental data quite well"
I have a different assessment of the comparisons

	AutoRealGas Code
3 m	waveform poor
32 m	waveform good, peak is low by factor of 2
160 m	waveform poor, but gives an upper bounding curve
	FLACS Code
3 m	waveform good, TOA late by 0.3 sec (⇔100m)
32 m	waveform good, TOA late by 0.3 sec (⇔100m)
160 m	excellent waveform, TOA late by 0.3 sec (⇔100m)

Waveforms are qualitative similar to experimental data, but numerical models are missing the fundamental physical mechanism that controls the energy release process. Nevertheless, waveforms have about the right impulse, so for seal design they are OK.

Page 26, paragraph 2
"simple linear relationship exists between explosive mix length and peak pressure developed at the seal".
The relationship is not linear, perhaps quadratic

Page 27, paragraph 6
"For a partially confined volume.... 50 psi..."
Please justify, I do not follow how you got this number

Page 28, paragraphs labeled (4), (5) & (6)
...50 psi... Figure 22
Please justify, I do not follow how you linked this scenario with Figure 22

Page 29, paragraph 5
You consider only methane-air explosions. What about methane/coal dust/air explosions? Do you recommended waveforms (Figures 20, 21 & 22) bound these cases also?

Page 30, paragraph 6
"approximate this pulse with a 2 MPa (300 psi) static load" The structural response depends on the impulse $I_+ = \int_0^\tau p(t)dt$ coupled into the system during the structural response time τ, so an equivalent pressure would be $\overline{p} = I_+ / \tau$. I doubt that this equals 300 psi.

Pages 31-35, structural response
No comment, as this is not my specialty.

2. ASSESSMENT

- This report represents a professional engineering assessment of the seal design criteria; it seems to do a better job than previous reports
- **Executive Summary**: is quite valuable; it tells you where we are going
- **Introduction**: gives a good introduction to the subject, quite useful to those not knowledgeable in this field. Survey of recent coal mine explosion accidents puts things in perspective, and sets the stage for the remainder of the report.
- **Section 2:** gives a very valuable review of existing seal design criteria throughout the world, and their scientific basis (or lack there of),
- **Section 3:** gives a good over-view of pertinent explosion chemistry and physics related to this problem. **FACTS 1-4** give a good emphasis of the key numbers of the problem. The historical review of measured mine explosion pressures (Section 3.8) builds a strong case that the current "20 psi criteria" is not credible. Section 3.9 (mis-labeled as 3.8) gives a good summary of the problem parameters that affect the explosion severity.
- **Section 4:** applies the current state-of-the-art commercial codes (AutoRealGas & FLACS) to the seal design problem. Although their models are inadequate to perform a "First Principles direct numerical simulation" (i.e., without turbulence modeling, etc...) of the entire problem from inflammation to detonation, they are certainly technically adequate for predicting pressure waveforms for engineering studies of seal designs.

- **Section 5:** delineates explosion scenarios and the corresponding waveforms appropriate to each case. Very valuable.
- **Section 7:** recommends two approaches for seal design construction; very valuable. It also recommends additional research to further refine potential explosion environments.

3. RECOMMENDATIONS

Methane/coal dust/air explosions can have much more complex energy release modes (e.g. double detonations, etc) which lead to correspondingly more complex waveforms than those considered so far. This will involve stratified fuel-air systems. Such systems are relatively unstudied, and thus are an appropriate subject of future NIOSH research.

Response

Your assurance of the absence of major blunders in the gas explosion science area is most appreciated.

We made a sincere effort to address all the comments expressed in your critique as follows:

With regard to figures 6 and 7, a statement is added that the data is below the theoretical curve because of incomplete fuel consumption.

The equation relating static and dynamic pressure is qualified with the statement that it only applies at the shock front.

We checked and re-checked all the equations presented in the report for typographical errors. In most cases, we checked all equations via several references to insure accuracy.

We continue to make statements that pressures greater than the CJ detonation and reflected shock wave pressures are possible, but we eliminated any numerical calculations as examples. The calculation of 2,300 psi is removed.

The NIOSH report statement that the gas explosion modeling results compare well with experimental data at LLEM may seem like an overstatement, but the agreement between experiment and these model calculations is within bounds for acceptance in practice. In future gas explosion modeling, we hope to do much better. These simple CFD computations have at least two fundamental problems. First, they do not capture shock waves, in part because the grid is too coarse (about 1 meter) and because the proper physics is not included in the numerical formulation of the model. Second, their combustion model is too simple and inappropriate for DDT and detonation. Again we hope to refine our calculations with better models in the near future.

The table below compares model calculations to experiment for one particular test explosion at various measurement points. The calculations are within 50% of the measurements which is considered acceptable for calculations of these kinds. See the references by Lea and Lidin (2002) and Popat et al. (1996) for more comprehensive discussion of the expected computational accuracy for such models. We should also point out that the calculations with FLACS were done totally blind with no advance knowledge of the form and magnitude of the experimental data. We have made efforts to tone down our enthusiastic descriptions of these initial numerical models of gas explosions in coal mines.

Measurement point	LLEM calibration data	AutoReaGas calculation and % difference	FLACS calculation and % difference
3.05 m	0.100 MPa	0.110 MPa +10%	0.095 MPa - 5%
32.9 m	0.080 MPa	0.045 MPa - 44%	0.070 MPa - 13%
160.3 m	0.050 MPa	0.030 MPa - 40%	0.040 MPa - 20%

We corrected our description of the relationship shown in figure 18. It appears to be linear in the 0 to 30 m range, but begins to diverge beyond that.

There is no scientific justification for the 50 psi pressure design criterion based on first principles such as the constant volume explosion pressure of 120 psi or the reflected detonation wave pressure of 640 psi. Use of the 50 psi criterion depends on monitoring the atmosphere behind a seal at some distance behind the seal and at some frequency.

Figure 18 gives the explosion pressure on the seal that an explosive mix of increasing size would produce. A longer (and larger) volume of mix produces higher pressure on the seal. As a corollary, this figure also provides guidance for monitoring. The location of the monitoring point must assure that the length of explosive mix behind a seal cannot develop explosion pressure greater than the design strength of the seal. The frequency of monitoring must also assure that air leakage through the seal does not create an explosive mix greater than critical length.

The degree of confinement and the venting behind a seal also influences the explosion pressure that could develop even on a monitored seal. A completely confined explosion equilibrates to the constant volume explosion overpressure of 800 kPa (120 psi). For 50 psi seals, we limit the explosive mix in a sealed volume to 40% of the total volume (40% of 120 psi $\approx$ 50 psi). This limitation generally applies to cross-cut seals and does not affect panel or district seals.

The design strength for a monitored seal should depend on how well one can control the atmospheric composition behind a seal. If a seal has no leakage and if monitoring keeps the sealed area atmosphere inert, a lower strength seal is acceptable. However, if a seal leaks and some explosive mix exists behind the seal, then the design strength depends on the leakage rate and how well the monitoring effort can limit the potentially explosive volume to a tolerable amount. We chose 15 feet for the maximum amount of allowable explosive mix behind a seal and associated seal design strength of 50 psi. If proper monitoring becomes a commonplace practice in the U.S., it may be possible to decrease this design strength to a lower value depending on the demonstrated monitoring skill of the operator.

Our present study focuses on methane-air explosions only. We are assuming that the recommended pressure-time curves for methane-air will bound those for methane plus coal dust and air. We believe this assumption is conservative, and we plan to conduct additional research for verification.

The 300 psi static-equivalent approximation to the 640 psi pressure-time curve is removed from the report and no longer utilized.

Again, Allen, thank you for your kind remarks on the overall structure and content of our report. We are sincere in our intent to collaborate with Lawrence Livermore National Laboratory to examine gas explosions within sealed areas of coal mines. Tentatively, we envision several objectives for such gas explosion work, first to model such explosions with proper CFD codes that correctly account for DDT and shock waves in typical coal mine geometries, second to verify such models against select methane-air detonation experiments, and finally to develop ways to suppress DDT in coal mines. We hope to benefit from your experience in these matters.

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Comment

I have prepared technical comments regarding the Draft Report titled "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines." First and foremost I would like to commend the efforts of the research team in preparing a document that shows at great length the efforts undertaken to ascertain proper loading requirements for seals in underground coal mines. The technical comments that follow are in no way intended to degrade the value of the research described in the report. The findings described are well thought out, and supported with validation in most cases. For the most part, the document provides solid scientific information that will be an excellent tool for evaluating and designing seals in the future. Several serious problems do exist, however, if the recommendations are adopted by MSHA immediately. The mining industry (and technology advancement in general) is in no way prepared to handle the design requirements suggested in the report. The following paragraphs cite specific examples of how current technology does not allow for immediate implementation of the recommendations.

The most appropriate format for referring technical comments is by line or section within the report. Each comment is derived as response to specific portions of the report. Every effort has been taken not to take the portions out of context. A logical step for reviewing the document is to begin with the Executive Summary.

Major concern arises when the recommended code for analyzing the performance of seal structures is not commercially available. The Wall Analysis Code (WAC) from the U.S. Army Corps of Engineers is not available for unlimited distribution. This already puts mining operations at a disadvantage when attempting to secure a proper seal design. While the use of other structural analysis programs is deemed appropriate, a design safety factor of 2 or more is recommended. Guidance should be provided as to how this safety factor should be applied. In later sections of the report, safety factors are addressed, but a solid recommendation for how to apply the safety factor is not provided. Later comments will address problems that could be encountered when applying such a factor.

There are many advantages to separating seal types by their location within a mining system. Section 1.3 outlines four seal applications. It is certainly appropriate to assume different possible loading dependent upon location and orientation. When such classifications are made, it is important to address the event that a seal location may not match one described explicitly in the report. Some seal applications may not fall within the described categories, and thus provisions would need to be established for gaining approval. The report does not provide information to be used when sealing areas outby previously sealed areas. In this case, monitoring of previously approved 50 PSI seals may not be reasonable. Provisions need to be addressed for redundant seal configurations.

Section 1.4 outlines three types of explosive gas accumulation associated with sealed areas. The report and modeling does not address the natural effect of gas layering. The natural bedding of gases within a sealed area should at the very least be topically addressed. When discussing the first type of explosive gas accumulation on Line 218, a situation is described where accumulated gas would have no possibility of venting. There is no basis for believing that a large sealed area could act as a pressure vessel and not allow for any venting. Even experimental data shows that after some relatively short amount of time, a sealed area would return to its typical or undisturbed pressure. The concept seems overly pessimistic to assume that an explosive mixture could be created in an entire large sealed area. This feat is difficult to create in a laboratory setting, much less an ever changing mining environment.

The possibility of 100% filling of a sealed area with no layering of gases is unlikely at best. This is supported by the fact that typical seal designs for 20 psi have not been damaged in explosions. The use of Omega block seals has likely accounted for the vast majority of failures. A review of failures associated with alternative seal designs since 1992 is advisable to determine seal designs most likely to cause failures. Table 2 shows that seals were destroyed, but does not describe the type of seals in place prior to the explosions.

A reference to "static horizontal pressure" in Line 386 is evidence that the authors of this report understand the need to update and further define the terminology associated with dynamic pressure loading. Previous criteria do a poor job of defining the loading that should be designed for. The information provided in Section 3 is the most comprehensive explanation of pressure loading associated with methane and coal dust explosions available to the mining industry to date. The authors should be commended for providing this much needed tool to the industry. There are many methods available for calculating resultant pressures from gas detonations. The use of the Chapman-Jouguet (CJ) pressure is appropriate for estimating worst case detonation pressures. It should however be noted that there is limited understanding for the actual processes involved with the process of detonation. A more distinct explanation is needed for the difference between the free field or steady state pressures estimated through CJ calculations (Section 3.5), and the reflected pressures calculated using Landau and Lifshitz (Section 3.6). These pressures are completely different in nature, and should not be characterized as two different pressure criteria. The reflected pressures are dependent upon the orientation of the seal structure to the propagating detonation wave. The angle of incidence is the driving factor for reflected pressure with 90 degrees from the direction of propagation as the worst case. This factor is not addressed within the report, but could be an additional criterion for the design of seals.

Line 964 states that "at the extremely high pressures that could occur in a mining explosion, the models are not correct;..." While the validation process for lower pressures is outstanding, the use of these models for creating design pulses at higher pressures is not advisable. The codes were used to create the high pressure (640 psi) design pulse described in detail beginning in Line 1053. This decision is questionable when considering that a pressure of 450 psi is the highest pressure cited with experimentally produced or recorded data. Thus, citing a design pulse at 640 psi seems over-conservative. Also, a clear distinction was not established concerning the nature of the 450 psi measurement. It is important to know whether the measured pressure was reflected or side-one.

The peak pressures and rise times for the remaining two design pulses seem appropriate; however, the constant pressure condition following the initial pulse may not accurately reflect the loading of a seal due to a methane explosion. The design pulses are vitally important to proper seal design. The natural frequency of the structure is directly related to the seals effectiveness in sustaining integrity following a blast event. Even if pulse durations are much greater than natural frequencies of designed seals, harmonics of the seals motion may be affected by the duration of the pressure loading.

Requirements for monitoring starting on Line 1133 are not well defined. Currently, there is not a proven system for administering such a monitoring program in the U.S. The report describes systems currently in use in Australia, but these applications may not be sufficient for all applications in U.S. mining systems. Such requirements are subject to interpretation and should be well defined prior to implementation.

Section 6 includes the most concerning portions of the research described in the report. Line 1168 addresses an item of deep concern stating that "a general design for a mine seal is not possible." While this is a true statement, the consequences of mandating individual seal designs are serious. The mining industry does not have access to a great number of engineers capable of designing seals for dynamic response to blast events. Commercial finite element software is prohibitively expensive, most government codes are not available commercially at any cost, and engineers capable of performing the analyses are few and far between. With the current process for design submittal, the process would be overly backlogged, and timely approval is not a possibility. The scientific community is responsible for providing data which will allow mining companies to increase the safety of miners exposed to the risks associated with sealing. This report shows that pressures created by methane explosions in underground coal mines are much higher than previously expected. With this in mind, the mining companies are ultimately responsible for responding to and mitigating an increased risk to miners and this is an important task that is of utmost importance.

As stated in Line 1175, the recommended design approaches "only demonstrate two possible failure modes which are both dependent on the structural reactions of the surrounding strata." Later in the section (Line 1376), it is recommended that all other failure modes be addressed in seal designs, but no guidance is provided for how to accomplish this. If the nation's premier institute for mining research does not provide designs that factor all failure modes, how can the mining industry be expected to do so on a regular basis. The mining companies should be charged with developing these standards, but time must be allowed for technology development and transfer. Immediate compliance with higher design pulses could create an unreasonable burden to the mining industry. For this reason, interim rules are advisable until adequate designs can be developed and validated.

It should be noted that the design pulses described in Lines 1198-1201 completely ignore any effects of reflected pressure. While this is an assumption that could be made, it may not accurately depict real situations.

Line 1240 states that "The design engineer will need to verify that this (rigid contact with the roof, ribs and floor with no movement) assumption holds true before proceeding with this WAC analysis." Again, no guidance is given regarding how this verification should be accomplished. Furthermore, WAC is not available for unrestricted distribution. Another code such as SBEDS could be used, and should be suggested in the report due to its availability.

When considering arching failure, one-way arching is considered more conservative, but two-way arching would provide more accurate results. When applying safety factors, the most accurate calculations should be used, and safety factors applied later in the process.

Line 1269 should be clarified to describe how scaling the computed minimum seal thickness by a factor of 2^1/2 effectively doubles the applied load on the structure.

Line 1315 begins describing a design methodology for choosing between failure mechanisms. The methodology advises that WAC analysis should be performed when thickness to height ratios are less than ¼. Plug analysis should be used when that ratio exceeds 1. This becomes a problem when minimum thicknesses are calculated using WAC and then a safety factor is applied to that thickness. Raising the thickness of an arching seal could expose that seal to other failure mechanisms that were not designed for.

Line 1338 describes additional recommendations for the reinforcement of seal designs that already incorporate a safety factor of 2. This suggests that NIOSH engineers recommend a safety factor of well over 2. Furthermore, the effects of the additional reinforcement should be considered in the overall design of the seal rather than as an afterthought.

Line 1367 mentions the use of a "simple explosion-proof valve." Specifications and suppliers of these valves should be provided with the recommendation.

Overall, the development of design pulses was well outlined and supported by review of literature and validation. The issues cited above should be considered prior to implementation of the required design pulses. Nevertheless, the research described in this report characterizing pressure time curves associated with methane explosions in underground coal mines is important and will stand as a quality first step in dealing with the problem at hand. More serious concerns are raised when discussing the design of seals to withstand the loading environments possible. Currently the mining industry is ill prepared to handle these designs. A rush to judgment and implementation of final rules by MSHA at this point would be an egregious error. A limited number of engineers nationwide are adequately trained to handle dynamic analysis of seals, and the mining industry does not have regular access to these engineers. Technology transfer plans need to be addressed immediately. The future research outlined in Section 7.3 should be completed prior to final rulemaking. Legislative pressures and mandates should not overcome the need to create policy that is substantiated by quality scientific findings. Interim policies could be implemented to bridge the gap between the antiquated 20 psi standard and future design standards.

When final rules are promulgated, additional factors should be considered. MSHA must either provide standard design options, or accept designs that are approved by Professional Engineers at the liability of the approving Engineer.

I would like to stress the fact that I believe this NIOSH report is of superior quality. The research performed is essential to the protection of miners. Nevertheless, the mining industry must proceed with caution in order to avoid creating standards that will become quickly outdated once further research is performed. It is certainly much easier to pick apart someone else's work rather than perform original research. It is hoped that the technical comments listed here will be used to add to the quality scientific work described in this report. The results of the report will no doubt increase safety for underground coal miners exposed to the risks of sealing.

Response

A safety factor of two is used in our analyses to account for variability in seal material quality, construction quality and foundation quality.

We are aware that the WAC program used in part to develop our design charts is not available to the general public. Our structural analyses are meant to show approximately what seal structures are required to resist the design pressure-time curves. We selected a simple program that was used by NIOSH in past research for this demonstration.

While the seal classification presented in table 1 could have exceptions, most seals will fall into the district, panel or cross-cut categories. If in doubt about how to classify a seal for design purposes, the most conservative assumptions are made regarding explosion pressure load, convergence load and leakage potential. New seals constructed beyond old seals are unaffected by this classification. If new seals enclose older seals, the sealed area monitoring points would be moved accordingly.

An unfortunate misconception exists that methane layering will develop within the still air of a sealed area. This misconception arises because it is common knowledge that methane tends to collect along the roof, especially in pockets, and that we measure methane concentration in a coal mine about 1 foot from the roof. The density of methane is about 0.55 times that of air, so buoyancy effects do exist. However, in the completely still air within a sealed area, diffusion processes will dominate buoyancy effects, which will lead to a homogeneous methane-air mix within a matter of hours. To sections 1 and 3, we have added paragraphs on layering and homogeneous mixes to help readers to better understand these phenomena.

We have also added discussion on the concepts of confinement and venting. A sealed area, such as a room-and-pillar panel or a set of main entries filled with explosive mix, is a confined area. If an explosion occurs, the pressure will equilibrate to approximately the constant volume explosion pressure. As the hot gases cool, pressure will decrease and some high pressure gas may leak into the rock; however, these processes are slow. Conservative engineering design dictates that we design for the high pressure.

In table 2, we deleted the reference to the explosion at McClane Canyon Mine. We were mistaken about the nature. Three other explosions within abandoned areas were identified and added to table 2, namely, the 1986 Roadfork #1 mine explosion, the 2002 Big Ridge Mine Portal #2 explosion and also the 1992 Blacksville No. 1 shaft explosion. We make no mention of specific seals that met the old 20 psi design standard in these discussions of explosions within sealed areas.

The CJ detonation pressure of about 1.76 MPa (256 psi) does not become a pressure design criterion itself. This pressure is merely the steady-state shock pressure that leads to detonation of a methane-air mix. Reflection of this detonation wave at a seal creates pressure of 4.5 MPa (652 psi) and this becomes the basis for a design criterion. We recognize that this criterion assumes the detonation wave is perpendicular to the structure and that this is worst case. This assumption, though worst case, probably accounts for most explosions in practice.

The gas explosion models (FLACS and AutoReaGas) were not used to create the three-tiered pressure-time curves for seal design. These codes are inappropriate for that purpose since they do not correctly model high pressure phenomena such as shock waves or DDT. Analytic derivations based on physics and chemistry sets the pressure the magnitudes in the pressure-time curves. The gas explosion models provided some insights into the rise and decay times of the high pressure transients, but the basis for these design curves is physics and not the numerical models. We provide evidence of these high pressures from several sources. Detonation experiments in Poland developed pressures of 450 psi and one experiment produced 600 psi. Finally, we note the 1992 Blacksville No. 1 shaft explosion in which MSHA investigators back-calculated pressure of about 1000 psi.

The constant pressure following the initial pressure rise in the 120 and 50 psi design pressure-time curves is justified by preliminary calculations indicating that the pressure decay time of constant volume explosions in sealed areas is much longer than the natural period of seal structures. The time required for pressure to decay by bleed-off or cooling is long compared to the inherent resonance period of the structure. Therefore, this long-duration constant pressure is effectively a static pressure. Recent Australian research reached this same conclusion. We plan to refine these estimates in future research.

The primary purpose of the structural analyses presented in the NIOSH report is not to provide final design recommendations for seals to resist the three proposed explosion pressures, namely 640, 120 and 50 psi, but to provide approximate seal design thickness, so they engineer can judge the relative merits of alternative sealing strategies with typical construction material possibilities. With the new proposed explosion pressure design criteria, the mining industry faces choices of sealing with thicker seals and not monitoring or sealing with thinner seals and monitoring or not sealing and continuing to ventilate. To weigh these alternatives and decide on a strategy, we provided these approximate design charts that will provide engineers with approximate values for relative seal thickness using the different design pressures and a range of typical seal construction materials. We recognize that the structural analyses shown in section 6 are incomplete and do not consider all possible failure modes, all foundation conditions, all anchorage conditions and other factors. These charts were developed following specific assumptions stated explicitly in our report and are only valid if these assumptions are met. Again, these design charts are not intended as a substitute for proper engineering design of seals with site investigation, structural analysis and quality control during construction. Furthermore, they should not be accepted as a substitute for the required structural engineering.

Another reviewer provided independent verification of these structural analyses using UDEC. Those calculations assumed 24 MPa (3600 psi) concrete, and computed seal thicknesses agreed with the seal thicknesses presented in the design charts to within 10%. These calculations also showed that seal failure occurred when the outward displacement exceeded about 1 inch which again coincides with the assumptions in our simplistic analyses with WAC. While the calculations are simplistic and with many assumptions, they serve their primary purpose which is to demonstrate approximate seal thicknesses for the three pressure-time curves using typical seal construction materials.

At this time we are considering a new seals project to provide critical information pertinent to successful implementation of new seal practices in the U.S. and to refine specific scientific data connected with this report. At least four tasks are anticipated to produce these need results:
1) Methane distribution within sealed areas – NIOSH researchers will report on methane distribution within sealed areas and how the distribution changes in time.
2) Suppressing detonation within sealed areas – In collaboration with the U.S. National laboratories, researchers will conduct detailed studies of methane-air detonation within sealed areas of coal mines, the factors that control it, methods to avoid detonation, and practical techniques to suppress DDT.
3) Methane detonation experiments – In collaboration with other government facilities, researchers will conduct select methane-air detonation experiments to verify numerical models and validate methods to suppress DDT using practical, simple techniques.
4) Structural dynamics of seals – In collaboration with the National Laboratories, researchers will develop practical methods to protect seals from transient dynamic pressures due to reflected blast or shock waves.

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Comment

1) A 640 psi seal would probably need engineering design for the adhesion to floor, ribs and roof. I imagine that you have specified the strength of concrete (many of our seals are 3.6 m high so they would be rather large structures)
2) A 120 psi seal for an area that is unlikely to detonate. This will encourage people NOT to seal an area. What is the definition of "unlikely". If a mine did not have any methane gas in it, would it still need a seal of that strength. How about a mine where traces of methane are only found (up to 3% layers)
3) The 20psi seal logic is interesting. How would an engineer limit a explosive zone to 15 feet behind a seal. With a low pressure storm from followed by a high pressure cell, a large gob area may well exceed this distance, particularly in a large longwall gob. Not sure I understand the engineering rationale for limiting the volume to 49% of the gob volume. Each US longwall would have between four and six seals. Would they be simulative of individual calculations
4) What is the risk that is being controlled by seals when the gob is inert? Our view is that it is the risk of an external explosion in the ventilated part of the mine. With multiple headings used throughout the industry, is it designed to withstand a coal dust explosion, in which case 50 psi might not be enough and in any cae there would be no survivors. Has MSHA found that gas explosions exceed 20psi . I would imagine that it would take a lot of methane gas to support an explosion above 20psi.
5) We have not had the experience of probable lightening strikes that you guys have had, all of ours have had identifiable ignition sources other that Moura No 4 in 1986 which was eventually put down to a faulty flame safety lamp. There are many who are yet to be convinced over that however--
6) The report appears to ignore what we see as the prime risk after a sealed area is inert, That is the failure of the seal. Seals can fail due to three events,

- overpressure due to use of explosives or a methane gas explosion elsewhere in the mine in the intake airways
- strata failure, floor heave or failure of the seal materials due to chemical action
- mechanical failure due to uncontrolled vehicle movement If the seals fail after a methane explosion such as Moura No 2, rescue teams cannot re-enter the mine safely due to the residual explosive atmospheres. We have proof from our gas monitoring records that there is a lot of oxygen left in a mine after a methane explosion and if new sources of methane are freed from old sealed areas, that will prevent re entry by mines rescue persons every time.

7) It is not clear why an inert atmosphere needs a 50psi seal. Is there some technical explanation in the report some where or is it introducing a factor of safety?
8) It appears that it is assumed that a risk of explosion exists where a sealed area leaks oxygen and makes an explosive atmosphere immediately behind the seal. Does this mean that the ignition source is either lightening of someone using oxycutting in front of a seal? We have yet to experience such a circumstance and considerate most unlikely
9) The scientific diagrams in the appendices are interesting with 120 psi figuring regularly. What happened to the early research of Nagy where the 20psi level was measured? Why was it so wrong? (or is this a computer generate figure)
10) We could not comply with a licensed professional engineer inspecting and certifying every seal was installed correctly to their design This would be a job with a lot of travel due to the spacing of mines throughout the state. I could only think that it would be worse in the US
11) If the only hazard is by damaging the seals from the intake side, then if the pressure is over 20psi, the chances of people surviving is approaching zero. What is the purpose of the seal for explosion pressures over 20 psi? the risk management logic is not clear here
12) The report from line 463 covering Australian practice, omits to identify the Queensland practice of designing seals to stay operational after a methane ignition in a multi heading panel. 20psi seals are designed to keep the gasses in, not prevent the area exploding.
13) What still seems to be missing is the big picture overview by MSHA. You have presented the science of explosions but what appears to be lacking is the logic of where it fits into practice. What is the risk regime that is being catered for? Is it to protect life or property and LIFE? These high numbers in the draft standard appear to be protecting "property and life".
The Qld approach is if the companies want to take the risk of blowing up their mines when no one is there, it is an insurance matter, not a health and safety matter The are two additional parts of the standard that I thought would be beneficial for mining engineers to make informed judgements
14) A statement of expected explosive pressures on seals from ignitions of methane gas in operating mining areas such as longwall faces and continuous miner panels. I think that this is an important omission. I for one would take a great deal of notice of what your studies determined. To me, this is the key part of the design for seals and will prove or disprove whether 20 psi of 50 psi seals are required for mines where inertisation practices are conducted. I do note that you consider that 20 psi would be fine and this is also my expectation.
Confirmation by science would be good.
15) Explosive pressures that would cause 100% fatalities for people working in areas of a mine. I know there has been a lot of research in the latter matter and that the armed forces have information developed during the Vietnam war. There is also a difference in the effects on a person of the shock wave from explosives and methane gas ignitions that I understand are considerable. To my knowledge it has not been documented. Jurgen Michelis from Tremonia might have some relevant information but I am not aware of any published information, especially in English.
16) A question that Jan Oberholzer and I have had over a long period is "what is the definition of a failed seal?" All seals leak and the surrounding strata, particularly the roof and floor.
17) Do you have any specification for sidewall adherence for the 50 psi seals?

Response

The 4.4 MPa (640 psi) seal would need extensive engineering especially of its attachment to the surrounding roof, floor and rib. We do not intend for our design charts in the report to become a substitute for proper structural analysis and site specific design of seals. We have not provided detailed material specifications for seal materials. Their intent of our structural analyses is to show approximately the kind of seal necessary to resist the three design pressures using a variety of typical seal materials. This approximate seal thickness information is vital for a decision to 1) seal with monitoring, 2) seal without monitoring or 3) continue ventilating an area. You are correct that a seal designed to resist the 640 psi pressure-time curve could be a substantial concrete structure a few meters thick. Our intention with these high explosion pressure design criteria is not to discourage companies from sealing, but we must portrait accurately the pressures that can develop from a worst-case explosion. Unfortunately, the pressures are far greater than the mining community realized prior to this scientific presentation. We hope to encourage the use of monitoring to limit the amount of explosive mix behind a seal and thereby enable the use of lower pressure seals.

The 800 kPa (120 psi) seal is for areas where the run-up length of a possible explosion within a sealed area is less than 50 m. With this short run-up length, experiments show that a methane-air deflagration is not likely to transition to a detonation. We offer no quantifiable definition of "unlikely." Experimental observations of DDT in pipes show that the run-up length is typically 50 to 100 pipe diameters.

If a company elects to use unmonitored seals and not manage the atmosphere within a sealed area, the 640 or 120 psi seals are needed depending on the possibility of detonation within the sealed area. The most serious hazard occurs in low methane emission mines that may take a long time to cross through the explosive range to become inert. Such mines can easily accumulate a homogeneous, explosive mix of large volume.

Figure 18 provides part of the underlying logic for monitored seal design as put forth in our report. That figure gives the explosion pressure on the seal that an explosive mix of increasing size would produce. A longer (and larger) volume of mix produces higher pressure on the seal. As a corollary, this figure also provides guidance for monitoring. The location of the monitoring point must assure that the length of explosive mix behind a seal cannot develop explosion pressure greater than the design strength of the seal. The frequency of monitoring must also assure that air leakage through the seal does not create an explosive mix greater than critical length.

The degree of confinement and the venting behind a seal also influences the explosion pressure that could develop even on a monitored seal. A completely confined explosion equilibrates to the constant volume explosion overpressure of 800 kPa (120 psi). For 50 psi seals, we limit the explosive mix in a sealed volume to 40% of the total volume (40% of 120 psi $\approx$ 50 psi). This limitation generally applies to cross-cut seals and does not affect panel or district seals.

There are at least two ways to limit the length of potential explosive mix behind a seal to 15 feet. First, control the leakage rate into a seal and/or limited ventilation pressure differential. Second, provide artificial inertization as needed.

If the gob is inert, then the location of an explosion is less likely to be within the sealed area and more likely to be in the active area. However, most sealed areas in U.S. coal mines are completely unmonitored, and we have no idea if the sealed atmosphere is inert or potentially explosive. In such unmonitored and completely uncontrolled cases, we advocate the use of 640 psi seals to resist a possible reflected detonation wave.

It appears that the mining community may have seriously underestimated the explosion pressures possible from methane-air explosions. The 1992 explosion at the Blacksville No. 1 shaft produced pressures of about 1000 psi according to back-calculations in the MSHA report. Other recent mine explosions and experimental data show clearly that high pressure methane explosions can and do occur. The amount of methane gas necessary to develop high pressures is small. A typical coal mine entry filled with a hundred meters of methane-air could reach detonation pressures.

Our objective with this report is not to promote the use of any one sealing technology. Again, we want to portray what the worst-case methane-air explosion could achieve and how easy it is to develop such conditions. We hope to encourage the U.S. coal industry to adopt the monitoring practices so well developed in Australia and thereby preclude the use of any 640 psi seals. Artificial inertization may be necessary at low methane emission mines, but many mines will self-inert in a few days, so with monitoring, they too could use the 50 psi seals. However, if a company elects not to monitor, then we believe that 640 psi seals are need to protect people from a potential methane-air detonation within a sealed area.

Regarding lightning strikes as an ignition source, we prefer to eliminate the explosive mix within a sealed area.

The present NIOSH report does not address failure of seals due to 1) overpressure from explosions in the active mine, 2) strata failure and 3) other mechanical failure. Most U.S. coal mines have no data about the atmospheric composition behind their seals. Many sealed area atmospheres may be inert and another unknown number could be somewhere within the explosive range. Here, not knowing presents the greatest risk since we have no idea if the sealed area is inert or not.

The design strength for a monitored seal should depend on how well one can control the atmospheric composition behind a seal. If a seal has no leakage and if monitoring keeps the sealed area atmosphere inert, a lower strength seal is acceptable. However, if a seal leaks and some explosive mix exists behind the seal, then the design strength depends on the leakage rate and how well the monitoring and inertization effort can limit the potentially explosive volume to a tolerable amount. We chose 15 feet for the maximum amount of allowable explosive mix behind a seal and associated seal design strength of 50 psi. If proper monitoring becomes a commonplace practice in the U.S., it may be possible to decrease this design strength to a lower value depending on the demonstrated monitoring skill and inertization readiness of the operator.

The present report considers the two kinds of explosive gas clouds. One arises during the initial inertization phase sometime after the sealed area is created and while the entire sealed area is crossing through the explosive range. The length of time that this potentially huge volume of explosive mix exists depends on the methane emission rate. The time to achieve initial inertization phase could range from a few days to months or more. The other explosive gas cloud develops after the initial inertization occurs. A seal that leaks could develop an explosive mix behind it. We make no judgments about ignition source. If an explosive mix exists, we assume that an ignition source will find it.

We believe there are some misconceptions in the mining community pertaining to the old 20 psi seal design criteria and its origins. As discussed in the report in section 2.1, Mitchell (1971) and others assumed that the sealed area would become inert quickly and that the explosion hazard originated in the active area. Apparently, these researchers did not conceive of large sealed volumes in mines with low methane emission rates where the sealed area remains in the explosive range for several weeks following sealing. These researchers did not consider leaking seals that accumulate large volumes of explosive mix behind them. Somehow, the 20 psi design criterion became synonymous with the maximum explosion pressure that can develop behind a seal. As discussed in Section 3 of the NIOSH report, a confined methane-air explosion will equilibrate to the 120 psi constant volume explosion overpressure. If the explosive gas cloud is large enough, it may achieve detonation where the detonation wave pressure is about 256 psi. If a detonation wave reflects from a solid surface such as a seal, the reflected wave overpressure reaches up to 640 psi. These facts are known to many experts in gas explosions, unfortunately, such knowledge has not reached commonplace acceptance in the mining community.

Our recommendation is to have seals designed, constructed and installed under the direction of a licensed professional engineer. The equivalent person in Australia might be your statutory ventilation officer.

The NIOSH report addresses explosions within the sealed area and these explosions can reach very high pressures. Provided the seals do not fail, these explosion pressures should be contained within the sealed area and hopefully leaving people unharmed. We will try to clarify this point about Australian practice where monitoring renders the possibility of explosion within the sealed area small relative to the possibility of explosion in the active area. In that sense, current Australia sealing practice appears more consistent with the situation envisioned by Mitchell (1971), but because of the lack of monitoring of sealed areas in the U.S., it does not apply here at all times.

The risk regime we cater to is protection of life only. In the past, most Unites States mines did not monitor their sealed area atmospheres at all, even during the initial inertization phase right after sealing. Accordingly, for such unmonitored cases, we recommend design for the worst case explosion pressure, namely that of a reflected detonation wave, where the pressure reaches 640 psi. People could be working underground while this explosive mix exists. If such large detonable mixes might exist, we recommend designing explosion resistant seals accordingly, namely 640 psi. If companies elect to monitor during and after the initial inertization phase and keep people out of harms way during self or artificial inertization, then 50 psi seals are recommended.

Again, the NIOSH report addresses the issue of explosions within the sealed area only. Because of the lack of sealed area monitoring, these explosions can develop high pressure. If such high explosion pressures would develop on the active side, we would not expect survivors.

We did not examine any recent data on human survivability of explosion overpressures. Again, our focus was explosions in sealed areas only.

We do not define a "failed seal" in our report. The seal functions stated implicitly in our report via table 1 are containment of the possible explosion load from within the sealed area and control of air leakage to acceptable tolerances. "Seal failure" occurs when the structure no longer performs according to its design specification.

We did not explicitly consider sidewall, roof and floor adherence for seals in our simplistic structural analyses. The seal must withstand all conceivable failure modes due to an explosion, and shear failure around the perimeter is a prime consideration. While our structural considerations are hardly exhaustive, we recommend anchorage to the surrounding strata with embedded steel anchors along with hitching to a depth of at least 4 inches or the equivalent to develop the necessary shear resistance along the perimeter.

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Comment

Thank you for having Richard send me a copy of the report concerning sealing underground. Jurgen I am concerned that this report has set the footprint that MSHA will use in allowing an operator to seal. If MSHA follows NIOSH's recommendation, which I think they will, then sealing will be very difficult if not impossible to do. I am not in the position to argue the physics of an explosion but it seems strange that we have gone from one extreme to another. To me it seems that to have a 640 psi explosion would require the different factors to line up perfectly. It is like having the perfect storm, what are the odds of this happening.
If the odds are favorable, why does the rest of the world accept 75 psi seals? I don't think the physics of an explosion has changed and I know other parts of the world have dealt with sealing methane latent atmospheres. Jurgen you have worked for a coal company and I think you know to build a 640 psi seal in remote areas of a mine will be virtually impossible to do. To build a seal out of concrete which I am assuming would be 2-3000 psi is much different than pumping 2-400 psi cement. I think we have overlooked the good that sealing can do for a mine such as controlling spontaneous combustion, more efficient ventilation, eliminating inspections in deteriorating areas of the mine, etc. (I think we have lost the practicality that must be blended with the science).

Several of the explosions you referenced in your report are believed to have ignited because of lightning. Did NIOSH consider trying to eliminate this potential by looking into how enough energy gets into the mine to ignite the gas? Could it be that steel protruding into the sealed area could be the conduit? What about stopping steel short of the mine or running non-conductive material into the sealed area such as fiberglass or some other material. Also closer inspections of seals underground to make sure steel does not enter the sealed area in these locations. In my conversation with experts in this area the primary control is to not have steel enter the sealed area, the surface is not the concern but underground.

In your report you discuss managing a gob, how do you do this when a sealed area can be several miles long by several miles wide. With the type topography that we have how do you do this. What about out west in the mountains. Managing leakage through a seal line implies pressure balancing this line that can be several miles long. This can be difficult for a seasoned ventilation man much less many of the people who will be responsible to manage this. To properly balance a seal line could mean frequent adjustment of the regulators. The sealed area reacts to the barometer and it is constantly changing some areas of the country worst than others.

In summary, to me, a much better approach would have been to provide a safer sealed environment by the following:

- Increase the strength of a seal to say 100-120 psi which would be far greater than 20 psi and stronger than what anyone else in the world requires.

- Reduce the ignition potential caused by lightning by not allowing steel to enter the sealed area once the area is sealed.

- Reduce leakage by requiring a minimum thickness of the seal or some way to reduce flow paths around the perimeter of seals.

- Have a responsible person at the mine to assure that seals are constructed properly. If it is a specialized construction insist that it is constructed with the assistance of the technical representative selling the seal material.

- Once an area is sealed under the above criteria it is sealed.

Response

Unfortunately, achieving high pressures is relatively easy. As discussed in section 1.4 and shown in figure 3, whenever a mined out area is sealed, methane gas will accumulate and at some time, the sealed area atmosphere will cross through the explosive range. In many coal mines, that atmosphere could become fuel-rich and inert within a few days. However, in other coal mines, that atmosphere could remain in the explosive range for many weeks or it may never become a fuel-rich and oxygen-low inert atmosphere. Developing a homogeneous methane-air mix without layering is very easy, especially in low methane emission mines, since diffusion processes will lead to homogeneity within a matter of hours in the absence of airflow. The odds of a large methane-air body accumulating along with a spark that leads to an explosion are not known well, but we believe that it does occur. The 1992 explosion at the Blacksville No.1 shaft produced pressures in excess of 1000 psi by MSHA calculations. Other recent mine explosions and experimental data show clearly that high pressure methane explosions can and do occur.

The 640 psi design criterion applies to unmonitored seals with no control whatsoever of the atmosphere behind the seal. True, other countries around the world use lower design pressures. In Europe, a 72 psi criterion generally applies, and in Australia, a 20 psi criterion applies. However, the Europeans and the Australians monitor and control the atmosphere behind seals especially immediately after sealing during the initial inertization phase. Because of their monitoring and inertization practices, the Europeans and the Australians can use lower design pressures for their seals. We hope to see the U.S. industry adopt sound monitoring practices to show that the atmosphere behind their seals is inert as presumed. With such monitoring practices in place, the NIOSH report calls for 50 psi seals consistent with worldwide practice.

The role of lightning in the ignition of methane-air accumulations is not well understood and is a topic of continuing research. Rather than seeking to eliminate and control all the possible ignition sources such as lightning and roof falls, we advocate maintaining sealed area atmospheres inherently non-explosive through either self- or artificial inertization.

Detailed recommendations for managing a sealed area atmosphere are not included in the present report; however, the most critical places to monitor are directly behind seals. Seals that leak air into a sealed area could develop a potentially explosive mix behind them of unknown proportions, unless adequate monitoring is in place. Controlling that leakage with thicker seals, inertization, pressure balancing, or alternative ventilation system layout are all options to minimize such leakage.

Thank you for your suggestions on future research for NIOSH to embark. We are planning a new seals research project that may provide detailed monitoring guidelines for sealed areas, ventilation techniques to minimize leakage through seals, and structural design guidelines for seals. We will keep you informed of progress.

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Comment

I believe you focus a little more toward the prevention of explosive risk behind the seals.

"There may not be enough motivation in the reduced cost of seals alone to encourage operators to adopt safe practices."

"Elimination of explosive mixtures should be the desired outcome ~ I would not like to accept the risk of a situation where there was:
- Explosive mixtures available but 4.4mpa seals to control (the explosion would find its way out through a water trap, a bleed pipe, a gob extraction fan, another face of the gob, an imperfection of the
seal.)
- A gob which was not monitored to determine if there gas mixture was of risk (un monitored seals)
- A gob which was unmonitored to determine if there was spontaneous combustion present.

I believe the paper should propose to prohibit un-monitored seals, And require mandatory Ellicott (explicability) and CO/O2def + CO/CO2 ratios (Sponcom) of any gob or sealed area for personnel to remain in the mine and 345Kpa seals as minimum for design.

Response

Thank you for your review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." This NIOSH report has stirred much discussion in the U.S. coal mining community, because the high pressures that can develop from a methane-air explosion are not widely known to mining engineers. The subject of seals remains controversial, and we hope our report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines.

The primary purpose of our report is to present the worst-case explosion pressure that could develop within a sealed area if an uncontrolled explosive mixture is allowed to accumulate. Data on what the real risk of developing such high pressures is probably difficult to develop, but we will attempt to estimate it in future work.

Our preferred approach for sealed areas is managing the sealed area atmosphere with monitoring and inertization as required, very much in line with Australian practices. Whether we can prohibit the use of unmonitored seals here is an open question, but I personally favor the use of monitored seals in most circumstances. I too share your skepticism about depending on 4.4 MPa seals to resist the explosion pressures that could develop within a completely unmonitored sealed area. The explosive forces could find a way out via a water-trap, bleed pipe or imperfection in the seal. The risk of failure somewhere in the system requires consideration.

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Comment

(transcribed by Karl Zipf from marked copy of draft)

1) several minor editorial corrections
2) page 6 – Shallow mines, mines that have breached into old works, and sealed areas that have high leakage rates may never go inert.
3) on table 2, add "Big Ridge explosion"
4) page 22 – What about direct detonation initiation via lightning?
5) page 22 – The upper explosibility limit will shift around when pressure piling occurs. What may be inert gas at atmospheric pressure becomes fuel for an explosion.
6) page 25 – You need to stress that mine conditions are much more confined than the normal chemical plants where many high pressure events have developed.
7) page 26 – Unless there are turbulence intensifying obstructions such as mine cribs or cans.
8) page 29 – Figure 20 – reverse order
9) page 32 – With reference to figure 14, is there a possibility of reflections superimposing?
10) page 35 – Addition of steel reinforcement also prevents shear failure.
11) page 35 – MSHA-CMSH has problems with water traps. Water-retaining bulkheads are more problematic than seals. We recommend float valves to eliminate this potential hazard.
12) page 36 – MSHA structural people think that arching is not feasible in many coal mines.
13) Figure 1A – No walk areas needed with flow-through bleeders.
14) Figure 6 – Take off the theoretical curve. It is not discussed and it is confusing.

Response

We added statements that shallow mines, mines that have breached into old works, and sealed areas with high leakage rate may never become inert. The 1986 Roadfork #1 mine explosion, the 2002 Big Ridge Mine Portal #2 explosion and also the 1992 Blacksville No. 1 shaft explosion have been added to table 2. Several paragraphs are added on the meaning of confinement and venting of explosions. The legends in figures 20, 21 and 22 are reversed. A statement is added that run-up distance can decrease if turbulence intensifying obstructions are present such as cribs or cans. A statement is also added that steel reinforcement will also help prevent shear failure around the seal perimeter. Description of the theoretical curve shown on figure 6 is added in the report.

Regarding some of your questions and comments, we offer the following explanation. The possibility of direct detonation initiation via lightning is unknown. We will attempt to examine that question in an upcoming, longer-term research project. How the explosibility ranges for methane-air changes at higher pressure will also be examined in future research. Reflected blast waves can superimpose both constructively resulting in increased pressures and destructively resulting in decreased pressures. The simple gas explosion model calculations in figure 14 show that behavior, although the calculations are not very accurate due to the coarse grid size that cannot properly consider extremely high pressure waves of short duration.

Water traps and water-retaining bulkheads will continue to present problems. If the primary purpose of a seal is to provide explosion containment at 50, 120 or 640 psi, then water traps and float valves are incompatible with that purpose. A through seal pipe to a pump may be acceptable. We cannot offer an immediate solution to this serious problem.

An arching analysis may be inappropriate in many coal mines with soft roof and floor. However, structural calculations by another reviewer confirmed the validity of select calculations from WAC. While the analyses presented in the NIOSH report are not comprehensive, they are sufficiently accurate for the intended purpose. The primary purpose of the structural analyses presented in the NIOSH report is not to provide final design recommendations for seals to resist the three proposed explosion pressures, namely 640, 120 and 50 psi, but to provide approximate seal design thickness, so that engineers can judge the relative merits of alternative sealing strategies with typical construction material possibilities. With the new proposed explosion pressure design criteria, the mining industry faces choices of sealing with thicker seals and not monitoring or sealing with thinner seals and monitoring or not sealing and continuing to ventilate. To weigh these alternatives and decide on a strategy, we provided these approximate design charts that will provide engineers with approximate values for relative seal thickness using the different design pressures and a range of typical seal construction materials. These charts were developed following specific assumptions stated explicitly in our report and are only valid if these assumptions are met. Again, these design charts are not intended as a substitute for proper engineering design of seals with site investigation, structural analysis and quality control during construction. Furthermore, they should not be accepted as a substitute for the required structural engineering.

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Comments by MSHA, Technical Support, PS&HTC on the NIOSH draft report "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" and NIOSH Responses

Comments - General

The readers should be made aware of the atmospheric conditions that must exist to attain the pressures that are presented; that is, 10% CH4 and 90% air (which is ~21% O2 and 79% Nitrogen). As stated, physics reveals that these 640 and 120 psi overpressures are attainable, given ideal or worst case scenarios. In gobs and sealed areas, however, these worst case scenarios, involving that uniform, homogeneous concentration, would never occur. The NIOSH proposed design criteria for unmonitored seals are based on a worst-case scenario. For example, it is not practical or economical to design a civil structure for the maximum blast loading from a terrorist attack. The report should address the fact that it may be practical from a risk-based approach to design seals to a lower criteria than that presented in the report. NIOSH should assess the practical risk and provide a rational basis by using research and actual experiences from around the world for establishing overpressures and pressure-time curves.

NIOSH personnel have traveled to many countries throughout the world to obtain data on seals and their design requirements. The physics is the same and high attainable explosion pressures have been known for several decades by researchers and blasting experts throughout the world. Many of the references cited by the report state these high explosion pressures. However, no country in the world has adopted a law requiring a seal to resist an overpressure greater than 72 psi; with a safety factor of 2, the pressure would not exceed 144 psi. Could NIOSH explain this? Could it be that the atmospheric conditions that must exist to attain levels such as 640 psi (as suggested by NIOSH) are rarely found? In general, it is noted in the report that authorities in Poland and Australia recognized that higher pressures were possible but did not think it was practical to design to those standards. An explanation should be provided, perhaps in Section 5, to justify why the full 640 psi is being recommended for the United States.

The Introduction, Section 1.2, 3rd paragraph, states that; "When an area of an underground coal mine is mined out, operators will frequently choose to isolate the abandoned area with simple dam-like structures called seals rather than continue to ventilate the area." It should be stated here, that the reason for this trend was not solely economical. It was to reduce miners' exposure to fire and explosions. Accident history shows that there has been a significant reduction in fires and explosions as operators progressed to sealing techniques. Other risks of exposure for miners to bad roof conditions and poor air quality have been reduced or eliminated through sealing. The term "dam-like" is used to describe seals. MSHA treats underground water-retention structures differently than explosion-control structures. For this reason, MSHA would prefer that "seals" are not referred to as "dam-like." A suggestion is to use the term "barrier," as in: "Seals are barriers constructed in underground coal mines…" The term "dam-like" is also used on page 3.

The report indicates that in sealed areas, CH4 increases, and oxidation creates more CO2. This will in turn lower the O2 in the atmosphere. When these conditions exist, the explosive ranges that are presented in this paper can be drastically reduced. See, Section 1.4 page 6. Figure 6 shows comparisons of theoretical pressures (NASA) and "experimental pressures". Other than at the 10% CH4 range the discrepancy is significant. The experimental pressures are significantly lower than the theoretical pressures. At a percent or two above or below the optimum 10% CH4 range, the experimental pressures are 20 to 30% lower then theoretical.

The authors disagree with the inclusion of design charts as presented. Based on comparison with MSHA approved alternative seals, the NIOSH recommendations are not conservative. If the charts in the final report do not consider all failure modes and incorporate structural code, they should not be included. If this is the case, the title of the report should be changed to "Explosion Pressure Design Considerations for New Seals in U.S. Coal Mines".

NIOSH lists eleven mine explosions that have occurred in sealed areas from 1993 – 2006. NIOSH does not give any information about the explosive pressures that would have been generated by these explosions. The reader may incorrectly assume that the pressures were high and similar to those described in their report, however, MSHA records show that the pressures associated with these explosions are much lower than those being presented in this report.

If NIOSH is to focus in on the worst case scenario, then maybe the title should state "worst case scenario".

Response

The general comments provided by MSHA Technical Support focus on several important points that require consideration by MSHA and the industry as we strive to develop sensible design criteria for seals. Those points include 1) the likelihood of developing an explosive mix and high pressures in an explosion, 2) the risk associated with alternative sealing and ventilation strategies, 3) comparison of the NIOSH recommendations to practices in other countries, and 4) the design charts.

1) Developing and explosive mix and high pressure explosions

The explosion pressure derivations assume 10% methane and 90% air mix which is nearly stoichiometric and near the point of maximum energy release. This assumption is stated at the beginning of section 3 of the NIOSH report. While this is the worst case, it must be recognized that high explosion pressures develop over a considerable range of methane-air mixes. For example by figure 6, laboratory experimental data and theoretical calculations show that constant volume explosion pressure exceeds 690 kPa (100 psi) from 8 to 12% methane in air by volume. Furthermore by figure 10, the Chapman-Jouguet detonation pressure exceeds 1.38 MPa (200 psi) and the reflected detonation wave pressure exceeds 3.80 MPa (550 psi) over this same range. Non-homogeneous mixes will also develop high constant volume explosion pressure as long as the overall methane-air ratio for the volume is within the explosive range. Thus the possibility for achieving high pressure is not limited to a near stoichiometric, homogeneous mix.

As discussed in section 1.4 and shown in figure 3, whenever a mined out area is sealed, methane gas will accumulate and at some time, the sealed area atmosphere will cross through the explosive range. Depending on the methane emission rate, that atmosphere could become fuel-rich and inert within a few days, it could remain in the explosive range for many weeks or it may never become a fuel-rich and oxygen-low inert atmosphere.

Developing a homogeneous methane-air mix without layering is easily possible, since, in the absence of airflow, diffusion processes will lead to homogeneity within a matter of hours. The authors disagree with MSHA's statement the achieving the worst-case scenario would never occur. The explosion at the Blacksville #1 mine (MSHA Accident Investigation Report 1993), other recent mine explosions and experimental data show that high pressure methane explosions can occur.

As discussed earlier, high explosion pressures can develop over a considerable range of methane concentration. Between 8 and 12% methane, the constant volume explosion pressure exceeds 100 psi, both theoretically and experimentally. The discrepancy with theoretical pressures for these experiments arises due to heat loss in the laboratory-scale experiments conducted. In such small scale experiments, creating adiabatic conditions (no heat loss) is difficult; hence pressures measured in small scale experiments are lower. However, in large mine explosions, achieving near-adiabatic conditions is much more likely. The authors agree that maximum explosion pressure occurs within a narrow range of conditions. However, rather than design less substantial seals and hope that conditions will never result in high pressure explosions, the authors advocate the use of monitoring and inertization as necessary to keep the sealed area atmosphere out of the explosive range.

Of the 12 explosions reported in table 2 of the NIOSH report at least 8 of the MSHA reports indicated blown out seals. The Blacksville #1 explosion indicated pressures of around 1000 psi. Generally, it is not possible to accurately back-calculate explosion pressure, because access to the sealed area to collect the necessary forensic evidence is not possible. Recent LLEM experiments show that it is not possible to assess the explosion pressure within a sealed area from seal debris downstream of an explosion. The authors believe that the explosion pressures that can develop in sealed area explosions have been seriously underestimated.

2) Risk associated with alternative sealing and ventilation strategies

The authors agree with MSHA's recommendation to consider the practical risk of seal failure and to use that as a basis for pressure-time curves for seal design. NIOSH may employ risk assessment techniques in a future research project on seals. The present NIOSH report presents possible explosion pressures that are achievable. Correctly understanding the possible explosion pressures and their possible consequence is essential information for a proper risk assessment. A proper risk assessment should consider several possibilities, such as 1) not sealing and continuing to ventilate an area, 2) sealing with unmonitored seals designed to withstand high pressure events and 3) sealing while monitoring and, if needed, actively inerting the sealed atmosphere, and using seals designed for lower explosion pressures.

The present report recommendations are based on the worst case scenario. MSHA reviewers cite that it is not practical or economic to design buildings to withstand the maximum blast loading from a terrorist attack. However, many other engineering designs are based on worst case analysis. For example, emergency spillways for certain dams may be based on the probable maximum precipitation for an area. Earthquake loading for dam design always considers the largest magnitude event for an area seen in recorded history.

The authors acknowledge that the more widespread use of seals may have contributed toward a reduction in explosions in active mine areas and also a reduction in exposure to hazardous ground conditions. Section 1.2 of the report is changed to reflect this contention. However, other factors have also contributed to the reduction of explosions, such as improved methane drainage through horizontal boreholes and gob ventilation boreholes and better ventilation monitoring systems.

3) Comparison of the NIOSH recommendations to practices in other countries

The 4.4 MPa (640 psi) design criterion applies to unmonitored seals with no control of the atmosphere behind the seal. It is correct that other countries around the world use lower design pressures. In Europe, a 0.5 MPa (72 psi) criterion with a safety factor of 2 generally applies, and in Australia, a 138 kPa (20 psi) criterion applies. However, the Europeans and the Australians monitor and control the atmosphere behind seals especially immediately after sealing during the initial inertization phase. Because of their monitoring and inertization practices, the Europeans and the Australians can use lower design pressures for their seals. European seals are also fully ventilated during the curing phase of the concrete.

Other practices also contribute to the success of lower pressure seals in Europe and Australia. In order to control leakage through seals where high ventilation pressure differentials are expected, certain European mines will construct seals that are thicker than required by the design formula. This practice also results in a much stronger seal for possible explosion loads.

4) Design charts

The authors have re-checked the design charts and found their accuracy sufficient for their intended purpose and for the input parameters defined in this report. The design charts used WAC and a simple plug analysis. Two independent checks using structural modeling with the UDEC and FLAC3D programs verified select points on the charts and the overall concept of the charts.

The NIOSH charts do not consider all failure modes and other structural considerations; however, their intent is to show approximately the kind of seal necessary to resist the three design pressure-time curves. This approximate seal thickness information is important for a mine operator's decision to 1) seal with monitoring, 2) seal without monitoring or 3) continue ventilating an area. As stated in section 6 of the report, these design charts are for minimum seal thickness, and the design engineer must consider additional factors such as the foundation and interface with roof, floor and ribs, convergence loading and reinforcement in a proper structural analysis.

Comments on Executive Summary

1st paragraph: The term "dam-like" is used to describe seals. MSHA treats underground water-retention structures differently than explosion-control structures. For this reason, MSHA would prefer that "seals" are not referred to as "dam-like." A suggestion is to use the term "barrier," as in: "Seals are barriers constructed in underground coal mines…" The term "dam-like" is also used on page 3.

1st paragraph, 2nd Sentence: The report refers to the mine regulations requiring seals to withstand an "explosion" pressure. The 30CFR §75.335(a)(2) actually states a static horizontal pressure of 20 psi, not a 20-psi explosion pressure.

2nd Paragraph, 3rd Sentence: Terminology in the field of explosives and blast design is inconsistent at times and may lead to confusion. The recommendation is made to provide a glossary of terms so that the audience is fully cognizant of the use and meaning of the terms (4, pp. B-1'– B-4)1. The recommendation is made to use the term "pressure-time curve(s)" instead of "pressure pulse(s)" in this section and throughout the document. The term "pressure-time curve" is more commonly used in the structural design of blast-resistant structures (1, fig. 1-6; 4, p. 3-15; 5, p. 291). Pressure-time curves provided for structural design are always relative to the ambient pressure. A design total (absolute) pressure-time curve is provided in Figure 22 and is not consistent with the term total pressure, since the plot falls below ambient pressure. In addition, the subtitle of Figure 22 states overpressure, meaning pressures relative to the ambient pressure.

3rd Paragraph: One of the assumptions made during the NIOSH analyses is that the seals are infinitely rigid and may be decoupled from the CFD analyses. A flexible structure (one that deforms) will not create the ideal reflected pressures provided in the report; the reflected pressures will be less due to the interaction between the structure and blast wave (2, p. 222). A coupled code is required to properly address this interaction and determine the actual reflected pressures (this was discussed at the MSHA-NIOSH meeting on 18 January and the underwater explosion on a miter gate was presented as an example). In addition, the FLACS and AutoReaGas CFD codes are not capable of modeling the transition from deflagration to detonation (DDT). Other codes such a SAGE have this capability, and for a detonation, the reflected pressures on an infinitely rigid seal may be significantly higher due to reflected wave reinforcement.

3rd Paragraph: The 50- and 120-psi pulses noted in the report are not reflected pressures. NIOSH should address the case where the methane gas is ignited at the boundary of the assumed gas cloud (the farthest distance) rather than at the face of the seal.

4th Paragraph: The comment should be provided that seal thicknesses computed from arching action in WAC are based on the assumption of non-yielding support conditions and as a result, the seal thicknesses provided in the design charts may or may not be conservative, depending on the actual mine support conditions and the material and construction quality control measures employed, even with a safety factor equal to 2. Only a more rigorous analysis may determine the degree of conservativeness or un-conservativeness of the propose designs. In addition, WAC only considers failure in terms of user defined limits on support rotation and does not address other modes of failure, which may occur prior to the limit established for support rotation.

Response

Many of the clarifications suggested by the reviewers are included. For example, "dam-like structure" is changed to "barrier"; "20 psi explosion pressure" is changed to "static horizontal explosion pressure", and "pressure-time curve" instead of "pressure pulse" is now used throughout the text.

In the executive summary, the authors refrain from certain discussions such as the assumptions within WAC as suggested. Despite the simplicity and perceived shortcomings of our preliminary structural analyses, the results have been verified by several different methods. Details of these favorable verifications are provided later. Additional discussion of the need for coupled CFD-structural analysis for proper structural design and the need to include DDT in gas explosion model calculations is provided in the appropriate sections of the report. The authors offer the following explanations to points raised about the 800 and 345 kPa (120 and 50 psi) design pressure-time curves.

The 800 kPa (120 psi) pressure-time curve applies to an unmonitored sealed area where the run-up length is less than approximately 50 m (165 ft). As indicated in figure 19 and table 5, the mix is partially confined and vented because the expanding gases can vent in part into the broken rock of an inert gob. As shown by the gas explosion model calculations in figure 14, for a confined gas cloud less than 50-m-long (165 ft), the pressure rises relatively smoothly to the constant volume explosion pressure. In these calculations, the gas cloud is ignited at the opposing end from the seal as desired by the reviewer. With a gas cloud less than 50-m-long (165 ft), these calculations suggest that pressure amplifications due to reflections are small. Thus, for explosive gas clouds where the 800 kPa (120 psi) pressure-time curve applies, pressure wave reflections and amplifications appear small and are not considered. For explosive gas clouds larger than 50-m-long (165 ft), then the recommended pressure design criterion jumps to 4.4 MPa (640 psi) due to pressure wave reflections and the possibility of detonation.

The 345 kPa (50 psi) pressure-time curve applies to a monitored seal and as indicated in figure 19 and table 5, the maximum length of explosive mix behind the seal could be as much as 30 m (100 ft). As shown in figure 18, a 30-m-long (100 ft) gas cloud ignited at the seal would reach a peak pressure of about 276 kPa (40 psi). The same 30-m-long (100 ft) cloud ignited opposite the seal would necessarily reach a peak pressure less than 276 kPa (40 psi), since expanding gases could vent in a direction opposite the seal. Thus, by limiting the size of potentially explosive mix behind a seal to a small volume through effective monitoring, lower seal design pressures become possible.

Comments on Section 1

Section 1.2 - 1st Paragraph: The report may also discuss other hazards faced by the mining industry if mined-out areas are not sealed and abandoned, such as spontaneous combustion, exposure to roof falls during inspections, and methane explosions due to deteriorated ventilation controls and/or restricted ventilation.

Section 1.2 - 3rd Paragraph, 3rd Sentence: The number of existing seals is approximately 14,000. There is a reference to seals constructed of materials such as concrete, brick, or cinder block. Since brick and cinder block are not currently used in seal construction, a suggestion is to delete the reference to these materials.

Section 1.2 - 5th Paragraph, 1st Sentence: Mining companies may also only develop panels with three entries from the submains to minimize the number of seals. This may create a pressure focusing condition (converging blast waves), where multiple entries converge to three entries.

Section 1.3 - In general, is the focus of this work purely on explosions occurring in the worked out area? Since seals are supposed to be capable of withstanding an explosion from either direction, how would the potential for an explosion in the active portion of the mine affect the seal design recommendations in this report?

Section 1.3 - 2nd Paragraph, 1st Sentence: The explosion loading potential should include the initial blast pressure and the C-V pressure.

Section 1.3 - 2nd Paragraph, 4th Sentence: The statement may lead to the opinion that the larger the sealed area, the greater the blast pressures, and this is not necessarily true. The pressures will not exceed those for a detonation unless the blast wave is reinforced by additional reflected waves.

Section 1.4 - 3rd Paragraph: For figure 3A, the explanation may be provided that the seals will be subjected to an initial short-duration blast pressure followed by a long-term constant-volume pressure caused by the air heated to a high temperature as a result of the burning of the methane-air mixture. The C-V pressure is a long-term load and dissipates by the surrounding strata in the sealed area acting as a heat sink and gradually cools the temperature of the air and subsequently decreases the pressure until ambient pressure is re-established

Section 1.4 - 5th paragraph: It is stated that sealed areas continue to present explosion hazards even after inertization, oxygen depletion, etc. because air leakage around seals can create an explosive atmosphere around the perimeter of the sealed area. Do they mean to say around the area of the seal rather than the entire sealed area?

Section 1.5 - 1st paragraph: It is indicated that ten explosions have occurred in sealed areas since 1993, but Table 2 lists 11 cases. Also, Table 2 indicates that "more seals were destroyed" in the June 1996 explosion at Oasis Mine. Is this based on the MSHA accident report, or other information? The MSHA accident report did not indicate what damage was caused by the June

1996 explosion. The report should mention the likely detonation in the Blacksville mine shaft that killed several workers doing maintenance on the shaft cap.

Response

Sentences are added in section 1.2 to discuss additional benefits to sealing such as spontaneous combustion control, improved ventilation to active mining areas and decreased possibility of methane accumulation due to restricted or deteriorated ventilation paths. The number of seals is corrected to approximately 14,000. Reference to cinder block and brick as a seal construction material are deleted. Reference to concrete blocks, cementitious foams and other cement-like materials are added.

The possibility of pressure focusing as a panel necks down from multiple entries to three entries at the mouth where sealing occurs is acknowledged. The authors believe that the 4.4 MPA (640 psi) and in some cases the 800 kPa (120 psi) pressure time curve addresses this problem. If monitoring and inertization is employed such that the amount of potential explosive mix behind a seal is maintained limited in size, then the possibility of high pressures due to pressure focusing is eliminated.

This NIOSH report focuses on explosions within sealed areas only. The authors believe that seal design should consider explosions originating within the sealed area first and that seal design to withstand an explosion in the active area is a secondary consideration.

When introducing the explosion loading potential, the report states how this design load is defined. In one case it is the reflected detonation wave pressure followed by the CV pressure. In the second case it is just the CV pressure. However, for monitored seals with limited volume and length of explosive mix, the maximum explosion pressure is 345 kPa (50 psi).

Appended to the sentence in section 1.4 is "up to detonation pressures and reflected detonation wave pressures."

The authors agree with the reviewer's statement pertaining to the constant volume explosion pressure with reference to figure 3A; however, it would be premature to make this statement on the long term CV pressure. First the authors develop the nature of the explosive gas cloud and how it originates in section 1.4. Later the authors present the notions of CV, CJ and reflected wave pressures in section 3. Then the authors develop our recommended design pressure-time curves.

This sentence in section 1.4 is changed to read "because air leakage around seals can create an explosive atmosphere immediately behind the seals."

Table 2 now lists 12 cases of explosions within sealed areas. Reference to McClane Canyon is deleted because the authors were mistaken. The explosions at Big Ridge and Roadfork mines were added. With reference to the second Oasis mine explosion, the statement more seals destroyed is changed to unknown. Reference to the Blacksville #1 explosion is added because it was a detonation within a sealed atmosphere inside the shaft.

Comments on Section 2

Section 2.1 - On the origin and evolution of the 20 psi seal design criterion in the US, no mention is made of the possibility that Mitchell's recommended 20 psi "static" pressure was intended as a static loading in the structural engineering sense of the term rather than in the ventilation engineering sense of the term.

Mitchell believed that a seal that was designed to withstand an explosion of 20 psi static could withstand an explosion pressure of 50 psi, which was the previous 1921 Dept. of Commerce standard.

Section 2.2 - In general, it is noted in this section that authorities in Poland and Australia recognized that higher pressures were possible but did not think it was practical to design to those standards. An explanation should be provided, perhaps in Section 5, to justify why the full 640-psi is being recommended for the United States.

Section 2.2 - Paragraph 2: The strength of the gypsum was 1,700 to 2,000 psi after 24 hrs (6, p. 23). In addition, it should be noted that the minimum seal length permitted is 3 m. The failure of the unreinforced gypsum seal was quite violent and was completely blown out of the test site and into a nearby field.

Safety factor should be based on the maximum load-carry capacity (peak reflected pressure and impulse) of a structure and should not be based on a material property, such as shear strength. The reason is that for a pressure-time curve, the safety factor computed for shear may be 2; however, if the peak reflected overpressure is increased by only 40 percent, the seal will fail. This has been revealed through numerical analysis using FLAC3D and LS-Dyna 3D. Safety factor for a reinforced structure or steel structure may be reliably based on ductility.

Section 2.2 - Paragraph 10: In the discussion of the Australian seals design requirements, one would expect that the standards would also require the design strength of the seals to achieved when the sealed area transitions through the explosive range, where the transition time period would be based on a methane liberation study. This is an important consideration in the design of the seals.

Response

Section 2.1 paragraph 5 states Mitchell's conclusion for a seal to withstand a static load of 138 kPa (20 psi). The authors interpret this as 138 kPa (20 psi) in the structural sense and not as a side on static pressure in a ventilation sense. The authors acknowledge the reviewer's interpretation that Mitchell believed a seal designed to resist a 138 kPa (20 psi) static pressure in a structural sense could resist a 345 kPa (50 psi) explosion pressure. That may be possible depending on the character of the 345 kPa (50 psi) pressure-time curve.

Explanations are added in section 5 and elsewhere justifying the 4.4 MPa (640 psi) criterion with respect to European and Australian practice. This design criterion applies to unmonitored seals with no control over the atmosphere behind the seal.

Section 2.2 of the report now mentions that the required minimum thickness is 3 m (10 ft) and that the strength of gypsum (Hardstem) is about 4 MPa (600 psi) after 2 hours and 12 to 14 MPa (1,700 to 2,000 psi) after 24 hours.

NIOSH researchers used a load based safety factor as you suggested and not a strength based safety factor. With reference to the seal thickness formula based on Anderson in section 6.2 of the report, the authors increased required seal thickness by 41% which corresponds in effect to a doubling of the pressure load.

The authors agree that a critical time during sealing is during the initial inertization phase. The Australian seal design requirements seem to imply that the seal achieves design strength before entering service; however, The authors did not note any discussion of seal strength during its cure time.

Comments on Section 3

Section 3.1 - 1st Paragraph: The stoichiometric methane-air mixture is 9.5 percent. The definition for term stoichiometric fuel-air mix should be provided in the section or in the glossary for reference.

Section 3.3 - 1st Paragraph: The C-V pressure is the same for a deflagration versus a detonation. The resultant blast pressures (side-on and reflected) will be significantly different in magnitude, but the C-V pressures will be the same.

Section 3.3 - 2nd Paragraph: The mine entry roughness and debris causes significant turbulence during the combustion wave propagation. This in turn will be a significant factor on flame speed, the resultant pressures, and possible DDT.

Section 3.4 - 1st Paragraph: This section needs to be carefully presented and it is recommended that the terminology be clarified for internal explosions. Internal explosions are characterized by two phases of loading – the blast loading phase (pressure wave for deflagration or shock wave for detonation) and the gas or quasi-static loading phase. A seal may initially be subjected to the side-on pressure or reflected pressure, depending on its orientation with respect to the direction of the blast load. Following the blast pressure (side-on overpressure or reflected pressure), the structure would then be subject to the gas or quasi-static pressure.

Section 3.4 - 7th Paragraph: The 20 psi static pressure specified in 30CFR §75.335 is a time-independent pressure; it is not the quasi-static (side-on) pressure implied in this paragraph.

The second equation on page 18 is missing parentheses. In general, equations should be given reference numbers.

Section 3.5 - Chapman-Jouguet is never defined or explained.

Section 3.8 - 3rd paragraph: In Cybulski's research, please clarify if the 290 psi pressure was side-on or reflected.

Response

The authors considered and rejected the use of a glossary to define terms such as "stoichiometric." 9.5% is "about 10%" as stated in the report. The authors do not see a need for any more precision at this time.

The CV pressure is the same whether the reaction proceeds via deflagration or detonation. However, the transient blast pressures can differ significantly. A reflected detonation wave creates much higher pressure than a reflected non-detonation pressure wave.

Entry roughness and debris can cause turbulence which will affect flame speed, blast pressures and DDT. Sentences are added in section 3.3 to discuss turbulence and the causes of turbulence such as obstructions, wall roughness, machinery or debris.

The authors believe that section 3.4 adequately represents the notions you suggest. The authors disagree with dividing the explosion load into two phases, namely blast loading phase and the subsequent gas loading phase. The authors want to avoid confusing terms such as "side-on overpressure" and prefer to present the fundamentals such as dynamic pressure and quasi-static pressure with respect to the seal orientation.

A sentence in section 3.4, paragraph 7 is changed to reflect that CFR 75.335 means a static, time-independent pressure and not a quasi-static or side-on pressure.

Parentheses are added to the equation as requested. Equation numbers are also added throughout.

The detonation pressure is frequently referred to as the Chapman-Jouguet detonation pressure or CJ pressure in honor of the two scientists who first derived the theoretical relationships describing the thermodynamics of detonation.

In reviewing the instrument layout as described in the paper, the pressures reported by Cybulski et al. (1967) are quasi-static (side-on) pressures and not reflected pressures.

Comments on Section 4

Section 4.1 - Dr. Ingel may have conducted the first CFD study of the methane explosion tests conducted in the Kloppersbos 20 m and 200 m tunnels using FLACS and AutoReaGas. In addition, the U.S. Army Corps of Engineers under contract with MSHA is currently conducting a CFD study using SAGE (SAIC) of the Sago Mine accident. SAGE will handle DDT and detonations and may also be used to model methane-air-coal dust explosions.

Section 4.1 - 6th paragraph: It is stated that the models used are not correct but they will "indicate" the pressure build up. There is no explanation given why the models are not correct. Further, it seems that more information is necessary before difficult decisions can be made on "indications" rather than facts.

General comment. The report should fully explain the modeled methane/air mixture makeup (i.e., percentages of oxygen, methane, nitrogen, etc.). If an oxygen content of 20.6 percent was used, is this realistic? What would the effects of lower oxygen content be on the resultant maximum pressures?

Section 4.3: Similar to comment 11b. It is stated that the models used are not accurate, but the models are correct in "indicating that very high pressures have developed." Can the pressures presented in the document be trusted?

Response

The NIOSH report in section 4.1 states that the AutoReaGas and FLACS CFD codes do not consider detonation or the detonation-to-deflagration transition (DDT). The authors recognize that other codes from the Army Corps of Engineers or the U.S. National Laboratories can handle detonation and DDT; however, the authors chose to start with simple models despite their limitations and add complexity in future work.

The authors are aware of the work done by Christian-Michelson Research Institute using FLACS and Century-Dynamics using AutoReaGas for Dr. I.M.A. Gledhill at CSIR in South Africa. This CFD modeling reproduced test data at the Kloppersbos facility with good agreement. Their studies made no attempt to apply the model to a real mine geometry. The authors are aware of a Czech study that attempted to apply AutoReaGas to mine explosions, but no results were indicated. The authors are also aware that FLACS was used to investigate a mine explosion in Spain, but again the authors have no additional information. Finally, the authors look forward to studying the USACE SAGE models of the Sago explosion when they become publicly available.

The gas explosion modeling efforts described in the NIOSH report are the first known published effort to calculate pressures that can develop during a mine explosion using CFD codes and realistic mine geometries. Several key facts are known about mine explosions in a 10% methane-air mix from fundamental thermodynamics, namely, that for a completely filled volume the explosion pressures will equilibrate to the absolute CV explosion pressure of about 908 kPa (132 psi), that a detonation wave will propagate with a pressure of about 1.76 MPa (256 psi) and that detonation waves will reflect with a pressure of about 4.5 MPa (653 psi). The models The authors chose for these initial efforts, AutoReaGas and FLACS, are among the simplest ones available. These models handle the basic fluid mechanics well and are coupled to accepted turbulence and combustion models. These models also calculate pressure wave interactions such as constructive and destructive interference. As pointed out in the report, the physics and numerical algorithms behind these models are correct until pressures of several hundred psi develop. At these high pressures, other physical processes may become dominate. Shock waves may develop and the combustion process may transition from deflagration to detonation (DDT). Because the models do not consider DDT, they are not correct once detonation might have occurred and beyond. However, the calculations are fine up to that point and the calculations of detonation pressure and reflected detonation wave pressure based on thermodynamics still hold true.

The models provide two critical insights into methane explosions in coal mines. First, figure 14 shows that, beyond a run-up length of 100 m (330 ft), peak explosion pressures may exceed 1.38 MPa (200 psi) and DDT may occur. These calculations coupled to empirical observations lead to the NIOSH recommendation limiting run-up length to 50 m (165 ft) or less to decrease the likelihood of detonation. Second, the model calculations produced figure 18 that relates volume of explosive mix behind a seal to the explosion pressure. These calculations do not approach the possibility of DDT, so their accuracy and reliability is high. Furthermore, the extrapolation from actual LLEM tests is small as figure 18 indicates. This computed relationship is useful because it provides a tolerance for monitoring efforts to limit the amount of explosive mix behind a seal and hence the possible explosion pressure. Thus, although the computational models are limited because they do not consider DDT and detonation, they still provide reliable insights and solid guidance to future design of sealed areas of mines.

As explained in section 3, explosion pressure calculations based on thermodynamics consider a range of methane-air calculations as shown in figures 6 and 10. Significantly high pressures are obtained across a wide range of methane-air mixtures. Lower or higher than stoichiometric oxygen concentrations will lower the explosion pressures somewhat, but they are still high. The uncertainties associated with the composition of the sealed area atmosphere and their effects on explosion pressure amplify the necessity of monitoring the atmosphere behind seals and controlling it with inertization as needed. During initial inertization or through subsequent leakage through a seal, it is easy to develop a potentially explosive mix. Fortunately, through monitoring and inertization it is also easy to keep the sealed area atmosphere out of the potentially explosive range.

The model calculations are trustworthy. As shown in figure 14, the model calculations equilibrate to the CV pressure as expected. As shown in figure 18, the computed peak pressures from the models extrapolate well from measured LLEM experimental explosions. These two observations demonstrate good model reliability and trustworthiness of conclusions. Furthermore, calculations such as these based on sound science, provide essential information from which to better judge alternatives as opposed to reliance on opinion and conjecture.

Comments on Section 5

Section 5 - 1st Paragraph: The term "pressure-time curves" is more consistent with the terminology used in the design of structures for blast loads. This isn't to imply the use of "pulse" is incorrect, but "pressure-time curve" and "pressure-time history" is predominantly used.

Section 5 - 2nd Paragraph: The recommendation is made to label the y-axes for figures 20 through 22 "Reflected Overpressure and Quasi-Static Pressure".

Section 5 - 3rd Paragraph: Figure 21 should provide the ignition source location. This figure appears to be an ignition at the face of the seal and not 41 m away from the seal. For a blast wave propagating to the seal, one would expect to observe a reflected wave, not a gradual buildup to the C-V pressure. The pressure wave shown in figure 21 does not resemble the pressure waves propagating in C-drift for the LLEM tests, especially the rise time to peak pressure.

The section presents the design pulses that should be used for seal design. However, it seems that Figure 22 is overstating the design pressure when compared to Figures 20 and 21. The plateau shown on the first two figures is plus and minus the model prediction while the Figure 22 plateau is about 25 percent greater than the peak shown. The basis for the 50 psi design criteria should be clarified.

Some consideration should be given to determine if it is possible to develop a method for minimizing the run-up distance that would allow the lower pressure seal criteria to be applied. Some thoughts include breaching parts of an entry, placing gob plugs, placing stoppings, etc. This may be more economical than designing all seals for 640 psi.

In the designation of the limit of the size of the zone in which an explosive mixture can be allowed to develop adjacent to a seal, Table 5 and page 30 cite 5 meters as the distance to be monitored. The basis for this distance should be better explained – with reference to the pressures shown in Figure 18. Presumably, the 5-meter value is based on consideration of the reflected wave pressure. Does it also include a factor of safety?

Response

The authors have changed terminology in the report to "pressure-time curves" and removed the use of "pulse." The labels on figures 20 through 22 were incorrect: "Total explosion pressure" is now "explosion overpressure."

The computed pressure-time histories at the seal shown in figure 21 are for the 41-m-long (135 ft) cloud shown in figure 14. Ignition is opposite the seal 41 m (135 ft) distant. The entire volume is filled with explosive mix. This numerical calculation is unlike any experiment ever conducted at LLEM so a direct comparison is not possible. The numerical calculations show numerous pressure waves reflecting back and forth off the seal and other walls such as crosscuts.

At this time, the authors do not have computed pressure-time histories for the 345 kPa (50 psi) design curve that match our exact intentions. The simplest application of a 345 kPa (50 psi) seal is a panel or district seal with unlimited expansion room into inert gas. A leaking seal could tolerate an explosion from a 45 m (148 ft) gas cloud behind the seal according to figure 18. The authors rounded this downward to 30 m (100 ft). The nearest calculation the authors have to compare with this situation is the 30 m (100 ft) cloud as shown.

For cross-cut seals, the authors apply two design limits – the maximum length of explosive mix behind the seal must be less than 5 m (16 feet), and the volume behind the seal must be no more than 40% full of explosive mix. A typical distance from a cross-cut seal into the gob is about 12 m (40 feet). A 5-m-long (15 ft) explosive mix in a 12-m-long (40 ft) volume would reach a CV overpressure of 5/12*800 kPa = 333 kPa say 345 kPa (50 psi). This 345 kPa (50 psi) pressure may partially bleed off into the gob, but the authors assume no such leakage which is conservative.

The authors appreciate this comment, and such studies may become part of a future NIOSH research project. It may be possible to shield seals from the transient 4.4 MPa (640 psi) reflected detonation wave pressure using a variety of protective techniques. Even with the proper protection is in place, the seal must still withstand the 800 kPa (120 psi) CV explosion pressure. The authors plan to collaborate with the U.S. National Laboratories and other groups to further understand these possibilities.

The authors repeat an explanation given above. For cross-cut seals, two design limits are applied – the maximum length of explosive mix behind the seal must be less than 5 m (16 ft), and the volume behind the seal must be no more than 40% full of explosive mix. A typical distance from a cross-cut seal into the gob is about 13 m (40 ft). A 5-m-long (15 ft) explosive mix in a 12-m-long (40 ft) volume would reach a CV overpressure of 5/12*800 kPa = 333 kPa say 345 kPa (50 psi). This 345 kPa (50 psi) pressure would bleed of into the gob, but the authors assume no leakage which is conservative. These pressures do not consider a reflected wave pressure, because the explosive clouds are small and ignition is located close to the seal.

Comments on Section 6

Section 6 - In general, please clarify if a seal needs to be designed for pressures from both directions. If an inby explosion is 640 psi, what should the seal be able to take from the other direction? That is, on the outby (active) side? This is an important point when selecting the locations for flexural reinforcement in concrete.

Section 6 - 3rd Paragraph: It should be stated that the proposed conceptual design may or may not be conservative, since all failure modes are not considered. In addition, one-way arching action may not be appropriate without proper consideration of the stiffness of the strata in comparison to the stiffness of the structure.

WAC is an analysis tool for predicting structural response. Although unreinforced structures may be analyzed for blast loads, the program is really not meant to design these types of structures for blast loads. There are a number of other design checks that must be made to assure structural integrity and this has not been done from a structural engineering point of view.

Section 6 - 4th Paragraph: This document should not refer to the design charts as "recommended design charts" as in the last sentence of this paragraph. Unless, of course, NIOSH is recommending use of the charts alone for design.

Section 6 - 4th paragraph: It is stated that a quasi-static approximation is used for the plug and arching analysis. The authors should detail why no dynamic magnification factor is applied. In particular, a discussion should be made of the period of vibration of the structure verses the time of load. This same comment would apply to Section 6.2.

Section 6 - 5th Paragraph: In the referenced Table 6, the shear strength values appear to be a higher percentage of the compressive strength than is typically expected or assumed. Can the basis for these shear strength values be given?

Section 6 - 7th Paragraph: Seal designs should be based on a pressure-time curve, not a "quasi-static pressure." The loading and reactions are not the same, since the designer needs to evaluate the support reactions at peak response for the SDOF approach, and this is dependent on structural resistance and the pressure time curve (5, p. 213-214). For example, the WAC reaction results for the reinforced concrete seal (2-way or 1-way slab) would not correspond to the reactions obtained by assuming a uniformly distributed load about the perimeter of the seal using a static pressure equal to 300 psi.

Section 6 - 8th paragraph: Since a detonation basically has no rise time and the assumed decay time is approximately 100 milliseconds, the ratio of load duration to period of the structure is large. This would imply that the affect on the structure is double, not cut in half as stated by the authors who are using 300 psi.

Response

The premise of the NIOSH seals report and the three-tiered pressure design criteria is an explosion within the sealed area. The authors envision the seals loaded from the gob side only. In the active side of the mine, extensive monitoring of methane is conducted in the routine fireboss examinations while adequate ventilation is provided to dilute accumulations of methane. Ignitions of flammable methane-air mixtures are therefore limited in size and unlikely to produce significant overpressures that may breach seals.

A sentence is added in section 6 to the effect that these preliminary structural analyses may not be conservative, since not all possible failure modes are considered. An additional statement is added on the necessity to consider the mechanical properties, of the foundation, e.g. stiffness, to make sure that one way arching can develop. A statement is added to clarify that the old 138 kPa (20 psi) criterion was a true structural static load and not an explosive or quasi-static load.

The authors clearly state our intent for using WAC as a preliminary design tool to demonstrate potential seal designs to resist the recommended design pressure-time curves. These simple analyses are required so engineers can estimate approximate seal designs for the explosion pressure-time curves and choose between monitored or unmonitored sealing approaches.

The phrase "and confidence in the recommended design charts" has been eliminated. The authors intend to present these charts for demonstration only and want to make clear that more detailed structural analyses are required that properly account for all failure modes, the seal foundation and other structural loads.

The authors agree that a coupled CFD-structural code is a better determine the reflected wave pressures. However, the authors started with simple analyses based on a decoupled analysis. Later, the authors intend to refine their analyses with a proper coupled analysis.

In the preface to section 6, the authors mention the rise time for the 50 and 120 psi pressure-time curves as 0.1 and 0.25 seconds, respectively, and that these times are much greater than the transit time for a stress wave across a seal. The authors stop with this simple transit time consideration to justify a static approximation to these two pressure-time curves. The authors do not believe that a dynamic magnification factor is required for the static approximation to these two curves.

The 300 psi static approximation to the 640 psi pressure time curve is withdrawn from the report as it is no longer necessary.

Comments on Section 6.1

Section 6.1 - 2nd Paragraph: WAC should not be used for structures where the thickness to span (height) ratio is greater than 1/5 to 1/4. Thickness to span greater than these ratios should be verified with FEM. The magnitude of the mobilized in-plane thrust forces for the force-couple will also depend on the compressive strengths and stiffnesses of the floor and roof rock. In addition, the unconservative assumption is made that the seal, following construction, will be in perfect contact with the mine roof. This assumption and many others are not justified, considering the mine conditions and the construction methods employed.

Section 6.1 - 5th Paragraph: The guidelines referencing proposed ductility and support rotation limits for various types of structures were developed for the Facility and Component Explosive Damage Assessment Program (FACEDAP) and may be used in the analysis and design (TM 5-1300) of structures.

Safety Factor: Safety factor in blast design may be used differently, depending on the circumstance and type of structure. For reinforced structures, the safety factor may be based on the reserve of strength in terms of ductility or support rotation. For an unreinforced structure (plug), the safety factor in reference to the maximum load-carry capacity (energy) should be evaluated using FEM or other appropriate analytical methods. It would seem more appropriate to raise the peak pressure of the pressure-time curve by a factor of two to determine the required thickness.

Response

As stated in the report, the authors recognize that WAC applies best when the seal thickness-to-height ratio of the wall is less than1/4 whereas plug analysis applies best when that ratio exceeds 1. According, NIOSH engineers selected the WAC analysis when the ratio was less than 1/2 and plug analysis when the ratio exceeded 1/2. The transition between these two completely different analysis methods is seamless leading to a high degree of confidence in the results for the intended purpose. The authors agree that these charts need verification with FEM or another analysis method, and such verification studies will become part of a future NIOSH project on seals.

The authors recognize that an arching analysis assumes perfect contact between the seal and roof. The authors disagree with the assertion that this assumption is not justified. Many seals constructed with pumped or sprayed products achieve good contact when proper care is taken. In order to account for possible poor construction practices, the authors recommend a safety factor of at least two.

NIOSH researchers used a load based safety factor as you suggested and not a strength based safety factor. With reference to the seal thickness formula based on Anderson in section 6.2 of the report, the authors increased required seal thickness by 41% which corresponds in effect to a doubling of the pressure load.

Comments on Section 6.2

Section 6.2 - 1st and 2nd Paragraph: The plug equation and the safety factor only evaluates shear strength or interlock strength and is not representative of the true strength of the seal in terms of peak reflected pressure and impulse. The plug equation used to size the seals for dynamic loading may not be appropriate for plug design and its use needs to be validated through numerical analysis. NIOSH, in introducing this equation, is validating its use and will make it extremely difficult for MSHA to refute its use in the future. NIOSH should refrain from using this equation until it is validated for dynamic loading.

Section 6.2 - 1st and 2nd Paragraph: The safety factor equal to two is misleading, since the seal will most likely not be able to carry twice the peak reflected pressure. This concept was introduced to a design engineer and the engineer verified the concept using FLAC 3D. For cellular concrete structures, shear strength is not the only factor that needs to be considered.

The internal shear strength of 100 psi for the lightweight cement foam presented in table 6 and used in the quasi-static plug formula may be reasonable for material with a compressive strength of 400 psi; however, the design should also consider the shear strength at the boundary between the seal and host rock. In materials with higher internal shear strengths such as concrete, the possibility of shear failure through the coal ribs, floor, or roof become an increasing concern. In limited direct shear strength test data from Minova, an interface shear strength (between the Tekseal and coal samples) of 36 psi was found for Tekseal material with a compressive strength of 400 psi.

Section 6.2 - 4th Paragraph: A word of caution needs to be expressed concerning the NIOSH tests. The seals were subjected to a pressure wave (side-on pressure) traveling at roughly 1,850 ft/sec. The seals were not subjected to a direct blast pressure (reflected pressure). As a result, the magnitude of the leading and trailing peak pressures is different and the response of the structure will be different for the traveling pressure wave (side-on) versus a reflected pressure wave.

Response

The authors use the plug equation for the 345 kPa (50 psi) and 800 kPa (120 psi) pressure-time curves where a quasi-static approximation is shown to be valid. The authors changed the report and do not use the plug equation with the 4.4 MPa (640 psi) pressure-time curve. The authors also add a few sentences in section 6.2 stating that the plug analysis formula applies to static analysis only and should not be used for a dynamic analysis without verification.

The authors agree that for plug analysis the proper shear strength to consider is the lesser of 1) the seal construction material, 2) the seal-rock interface or 3) the surrounding rock. The authors agree that a proper structural analysis for a seal must consider the seal structure itself and the surrounding rock.

In table 6, the need for an assumed relationship between unconfined compressive strength and shear strength is eliminated. Analyses using WAC consider a range of "high and medium" unconfined compressive strength materials. The plug analyses for "low" strength materials consider three typical shear strengths directly.

The authors agree with the reviewer's remarks regarding tests at LLEM and their applicability to structural design of seals. These full-scale tests do not replicate the loading conditions expected from an explosion within a sealed area.

Comments on Section 6.3

General Comment: A comparison of seal thicknesses found using the charts in the report to the thickness of seals approved by MSHA indicates that the charts are unconservative. See table 1.

Table 1. Comparison of NIOSH Recommended Thickness Versus MSHA Approved

Type of Seal (20 feet wide unless noted)	Height (inches)	Approximate NIOSH Thickness Recommendation (inches)	MSHA Thickness Approval (inches)	Additional details from MSHA Plan
Concrete	96	12	20	6,000 psi concrete 2 row dowels flexural reinforcement stirrups for shear
Minova Tekseal	96	35	78 *	
Minova Tekseal (22 feet wide) (design pres. 100 psi)	120	95 (chart for 120 psi, 20 feet wide)	96 – 120	2 row dowels all sides
Minova Tekseal	90	31	109	
Minova Tekseal	120	41	112	

Minova Tekseal	156	55	131	
Minova Tekseal	48	19	55 to 67	Lower value for gob isolation seal; Upper value for main seal.
Minova Tekseal	72	26	77 to 92	Lower value for gob isolation seal; Upper value for main seal.
Minova Tekseal	96	35	95 * to 114	Lower value for gob isolation seal; Upper value for main seal.
Minova Tekseal	144	50	125 to 150	Lower value for gob isolation seal; Upper value for main seal.

* Reason MSHA approvals may differ for same height: For the seal with a 78-inch thickness, a more in-depth structural analysis was conducted by the designer. The 95-inch thickness was simply taken off Minova's design charts for plug-type seal.

Section 6.3 - 1st paragraph: The criteria for using the wall analysis versus the plug analysis is stated. Then the last sentence states that this was determined based on a factor of safety of one, not two. If there are ramifications for not considering a factor of safety of two, they should be stated.

Section 6.3 - 1st Paragraph: The safety factors may really not be realized considering the assumptions made in the analyses. The minimum seal thicknesses may not be conservative and this should be discussed in the report. Using WAC for a t/h ratio greater than 1/4 may be unconservative and potentially violates the basic assumption of arch-action and the kinematics that are required to occur. Again, when the safety factor equal to two is emphasized throughout the report, it portrays a degree of safety and confidence that may not be realized and justified, considering the assumptions made.

Section 6.3 - 2nd paragraph: A 48-inch-thick masonry wall probably would not be able to withstand 640 psi. There isn't any shear resistance at the roof line if only the ribs and floor are hitched.

Section 6.3 - 2nd Paragraph: The 300-psi static pressure for the 640-psi reflected pressure (fig. 20) is not justified.

This section presents design charts for minimum seal thickness. These charts are very misleading. Here are five points that demonstrate this.

1) The second paragraph in Section 6.5 states that convergence and water pressure must also be considered in the structural analysis. The charts have not considered all loads that will be acting on the seal.
2) The seal material shear strengths listed in Table 6 are high. Table 6 shows the shear strength to be 25 percent of the compressive strength. While shear strength can only be

accurately determined with testing, the accepted rule-of-thumb for estimating the shear strength for standard concrete is 20 percent [ASTM STP 169C, 1994]. It is difficult to say if this relationship is appropriate for low density and low strength material since this property is not typically used in design. In any event, the estimated shear strengths of the seal materials appear to be high.

3) There are two curves on the design charts for unreinforced standard and high-early-strength concrete. The charts assume that the concrete will act as a monolithic structure with the strength as designed. The use of concrete requires that steel reinforcement be used. As a minimum, reinforcement is necessary to control shrinkage and thermal cracking. Concrete will crack and the reinforcement is necessary to control the cracking and maintain the concrete as a monolithic structure. The reinforcement also has to be adequate to take any flexural and shear loads since concrete is only strong in compression.
4) The design charts show concrete block and specify that the strength is 2,500 psi. The charts and the report need to clarify that this is the masonry compressive strength and not the compressive strength of the concrete block. A masonry strength of 2,500 psi will require that the block be a higher strength and will require the use of an appropriate mortar to achieve that strength.
5) The design charts show low strength and low density materials being analyzed as walls and not plugs. This is inappropriate. The low density and low strength materials are only appropriate for use as plug material and should not be treated as a structural material. The Corps of Engineers may be able to provide guidance on this, but the limit should be at least 1200 psi. Any material with a compressive strength of 1200 psi or less should only be analyzed as a plug.

The plug seal design curves presented in figure 25 (640 psi design pulse) were based on shear strengths for lightweight foam cement, 1 day fly ash/cement, and sprayed gypsum presented in table 6. The shear strengths used to create the design curves may not represent more critical shear design conditions at the seal-boundary interface or through the host rock itself. Using a relatively conservative boundary interface shear strength of 36 psi (which is used by Minova in the design of their Tekseal plugs) in the plug formula presented in the draft, a seal would need to be 31.6 feet thick for an opening 2 meters in height and 20 feet in width. The corresponding thickness presented in the NIOSH draft document for a seal of equal dimensions is 14.8 feet. This thickness is considerably less than what the material manufacturer is using.

There appears to be discrepancies between calculated thicknesses for plug seals constructed of fly ash/cement and sprayed gypsum and the design curves presented on figure 25. For example, using the plug formula with the shear strength presented in table 6 for the fly ash/cement mix, a required thickness of 16.8 feet was calculated for a seal height of 2 meters. The corresponding thickness using the design curve is only 7.9 feet. Similarly, when analyzing a 2-meter-high seal constructed of sprayed gypsum with the plug formula, a required thickness of 25.3 feet was calculated. The corresponding thickness from the design curve yields a thickness of 11.5 feet. The appropriate corrections to the design curves need to be made. The calculations for figures 26 and 27 appeared to be consistent with the design curves.

For the design curves presented in figures 25 through 27, it should be indicated if the curves can be extended for seal heights exceeding those on the diagram and required thicknesses extrapolated.

Response

Table 1 in the MSHA comments uses 400 psi as the UCS for this cementitious foam material in question. The authors altered the design charts to consider a range of low shear strength materials for seal construction. Using the design curve for 0.25 MPA (36 psi) shear strength material on the 345 kPa (50 psi) chart gives the following minimum recommended thicknesses shown in the table below. By inspection, the comparison with the MSHA approved thicknesses is good. The authors use a safety factor of 2 in our chart. The safety factor within the MSHA approved seal designs may be higher.

Type of seal	height - inches	NIOSH 345 kPa (50 psi) chart minimum thickness - inches	MSHA approved thickness - inches
3500 psi concrete	96	12	20
cementitious foam – shear strength = 0.25 MPa (36 psi)	96	90	78
cementitious foam – shear strength = 0.25 MPa (36 psi)	120	110	96 – 120
cementitious foam – shear strength = 0.25 MPa (36 psi)	90	90	109
cementitious foam – shear strength = 0.25 MPa (36 psi)	120	110	112
cementitious foam – shear strength = 0.25 MPa (36 psi)	156	130	131
cementitious foam – shear strength = 0.25 MPa (36 psi)	48	60	55 to 67
cementitious foam – shear strength = 0.25 MPa (36 psi)	72	75	77 to 92
cementitious foam – shear strength = 0.25 MPa (36 psi)	96	90	95 to 114
cementitious foam – shear strength = 0.25 MPa (36 psi)	144	125	125 to 150

A clarification is added. The choice between analysis methods based on t/H ratio was done at a safety factor of 1. Next, the design curves are scaled to include a safety factor of 2.

The authors disagree with the reviewer's opinion that the simple structural analyses presented in the NIOSH report are not conservative because the authors may violate the basic arching action kinematics by exceeding the preferred t/H ratio. As discussed above, the NIOSH 345 kPa (50 psi) charts produce minimum seal thicknesses that are close to MSHA approved seal thicknesses. In addition, independent calculations provided verification of the charts at select points. A review by Esterhuizen verified a few points using high UCS materials. His analysis used UDEC. The authors are aware of the critical assumptions within these charts and the problems associated with real seals. An adequate foundation is required; the seal construction materials must meet the minimum required strength, and good construction technique must be employed to assure good contact with the surrounding rock. However, these problems will continue to exist with even the most sophisticated analysis methods. The authors believe it is better to start with a simple estimate of minimum seal thickness and add complexity to the analysis as the particular situation demands.

For a 4.4 MPa (640 psi) static pressure on the 6.1-m-wide (20 ft) by 2-m-high (80 in) seal, the average shear stress around the perimeter is 3.3 MPa (480 psi) for the 1-m-thick (40 in) concrete wall and 2.76 MPa (400 psi) for the 1.2-m-thick (48 in) concrete block wall. The authors agree that a proper structural analysis should compute all stresses and develop designs to resist them.

The authors acknowledge that the design charts do not consider possible convergence loads or water pressure or a weakening of seal materials due to standing water. These site specific conditions require site specific analyses. The intent of these charts is to present approximate seal thicknesses required to resist the proposed pressure time-histories. That approximate information is required by seal designers to evaluate choices between seal and monitor with 345 kPa (50 psi) seals or seal with unmonitored seals using 4.4 MPa (640 psi) seals.

The authors recognize the importance of this detail pertaining to the use of concrete blocks and mortar. The authors agree that detailed structural design using concrete blocks must properly consider the mortar strength. However, such details are beyond the scope of the present report. The authors will consider such detailed specifications in a future NIOSH research project if required.

The authors have complied with the reviewer's suggestion to use plug analysis for low density and low strength materials. The 4.4 MPa (640 psi) design chart considers only stronger, higher density materials and only uses WAC analyses. The 800 kPa (120 psi) and 345 kPa (50 psi) design charts use plug analysis for the low density, low strength materials and WAC analyses for all other materials considered.

Because an equivalent static pressure for the 4.4 MPa (640 psi) pressure-time curve is not available at this time, the authors eliminated plug-analysis curves in the 4.4 MPa (640 psi) design chart. The authors have removed the 2 MPa (300 psi) static equivalent which appeared in the draft report. This approximation in the draft report appears to be the source of the discrepancy described in one comment.

The authors are comfortable extrapolating these design charts to seal heights up to 6 m (20 ft) high, which corresponds to the assumed width of the seal. Beyond that height, a different analysis is recommended. The design charts presently go to 4.5 m (15 feet) which should encompass most coal mines in the U.S.

Comments on Section 6.4

Section 6.4 - 1st paragraph: Clarification should be provided regarding the installation of steel reinforcing bars within the seal. Would a continuous (spliced) section of rebar anchored to the roof and floor constitute 2 points of reinforcement? Additionally, the use of continuous rebar through the seal would greatly increase the flexural capacity of the seal.

In the equation for the number of reinforcing bars, should the strength of the bars used in the equation be the shear strength of the bars instead of the yield strength?

Section 6.4 - 1st Paragraph: The structural design of reinforced concrete seals requires the use of yield-line theory, ACI 318, and TM 5-1300.

Section 6.4 - 2nd Paragraph: The anchorage requirements for the seals cannot be resolved. For instance, assuming the anchorage acts as shear-friction steel and using the maximum coefficient permitted for concrete cast against hardened concrete intentionally roughened (ACI 318-02, Sec 11.7.4.3), the total number of dowels required for a seal 20 ft by 6.6 ft high subjected to a 300-psi static pressure is 190 for No. 6 dowels with 40-ksi yield strength (300 psi x 20 ft x 6.6 ft x 144 in2/ft2 / [0.75 in2 x 40,000 psi]). Note that this does not include a "safety factor". It is not clear how a total number of No. 6 dowels equal to 160 was derived. Shear of the concrete and punching shear due to the dowels also needs to be addressed. Shear, not flexure may dominate the design of the reinforced concrete seals and this needs to be a consideration in the design of proposed seal thicknesses.

Section 6.4 - 2nd paragraph: Rebar shear strength using LRFD is = .9 x .6 x Fy (i.e. = .54Fy). Generally the bars should be at least 60 psi for yield strength in order to cut down on the amount required.

Section 6.4 - 2nd paragraph: The floor hitch should be into competent floor. If the 4 inches is all fireclay and the mine makes water, then the floor material will turn to soft mud. The mines may not be able to rely on the hitches due to long-term weathering and water effects if the mine makes water, therefore the bars should be sized to take all of the shear loading.

Section 6.4 - 2nd paragraph: The report should clarify the intention for how far the reinforcing bars need to extend into the seal.

Section 6.4 - 3rd Paragraph: An electrical engineer would need to address the hazards associated with a pump connected to piping extending through a seal, but this does not appear to be a safe recommendation for dewatering. There may be valves (blow-out prevention) to eliminate this hazard.

Section 6.4 - 3rd paragraph: Would it be acceptable to put a drain pipe in a 50 psi seal since the loading is less severe than 640 psi? What about the 120 psi?

Section 6.4 - 3rd paragraph: Unless the sump is accessible through a borehole to the surface, the system would not be serviceable. More consideration is required for controlling water accumulation.

Response

The equation for anchorage reinforcement and the associated design chart are removed from the final report. In section 6.4 and 6.5 of the report, the authors recommend proper hitching and anchorage to the roof and floor. The authors also recognize the necessity of steel reinforcement for both flexural reinforcement and anchorage to the surrounding rock and recommend the use of such steel reinforcement where necessary.

The NIOSH report states that hitching should extend at least 4 inches into the floor. If the floor is weak, prone to moisture degradation, or wet, then these foundation conditions must be addressed in a proper design. The authors acknowledge the reviewer's good point.

This is an excellent point about electrical safety. An electrical expert should address this important issue.

345 kPa (50 psi) is the equivalent of 35 m (115 ft) of water head; 800 kPa (120 psi) is the equivalent of 85 m (279 ft) of head, and 4.4 MPa (640 psi) is the equivalent of 450 m (1477 ft) of head. Even for 345 kPa (50 psi) seals, water traps less than 35 m (115 ft) deep are not compatible with one of the primary purposes of a seal, which is to prevent toxic gases and blast pressure from an explosion from entering the active area of the mine. Drain pipes with minimum strengths of 345, 800 and 4400 kPa (50, 120 and 640 psi), respectively, that are hooked into a pumping system are the recommended method to remove water from a sealed area if necessary.

The authors disagree with the statement that a pump system would not be serviceable, because that depends on the location of the pump. Seals in a remote, topographically low section of a mine could be problematic; however, solutions are available. The authors agree that more engineering consideration is required for addressing water accumulation behind seals, but the authors stand by our recommendation for the discontinuance of water traps since they conflict with the primary purpose of seals.

Comments on Section 6.5

Section 6.5 - 1st Paragraph: The first paragraph implies that the proposed seal dimensions and reinforcement is conservative and safe and this may not be true, considering the assumptions made, the limited number of failure modes considered, and the lack of quality control in construction employed in the mines.

Section 6.5 - 2nd Paragraph: A safety factor equal to 2.0 is not warranted for reinforced concrete and steel structures, due to ductility.

Section 6.5 - 2nd Paragraph: It is stated that structural analyses should consider all likely failure modes including flexural, compressive or shear failure through the seal material along with the shear failure through the rock or at the rock-seal interface. The presentation of design curves based solely on the use of approximated internal shear strength of the seal material may be misleading since a shear failure along the interface or through the host rock may actually govern the plug seal design. The shear strength in the latter scenarios may be considerably less than the internal shear strength of the material. As such, companies should be strongly cautioned when using the presented design curves.

Response

The authors agree that proper seal design should consider all the possible failure modes and that quality-control in seal construction is a problem. However, the authors stand by our design charts for their intended purpose, which is to enable engineers to examine the approximate structure requirements of 345, 800 and 4,400 kPa (50, 120 and 640 psi) seals in order to decide on a sealing strategy that may or may not involve monitoring and inertization.

The authors acknowledge the reviewer's point about our recommendation of a safety factor of 2.0. The authors await suggestions from MSHA and the industry regarding a better-suited safety factor for seals.

In discussions of the design charts, the authors have added cautionary statements that these charts do not consider all possible seal failure modes and that the user should also check for shear failure through the surrounding rock and along the seal-rock interface.

Comments on Section 7

The document should discuss that the monitoring of a mine atmosphere may be inconclusive for the reasons below:

1) The interpretation of gob gases requires expertise be available.
2) Effective monitoring may require that the complete atmosphere of the sealed area be monitored. Monitoring of methane content only can be misleading if ethane, butane, and other hydrocarbons are present in the atmosphere.
3) A monitoring system needs to consider the gases that will be present. Heavy hydrocarbons will be at the bottom and methane will be at the roof. Monitoring can be inconclusive because of the layering of the gases.

Section 7.1 - 4th paragraph: Scenario 2, Part F (from figure 19) is explicitly outlined, but Parts D and E are not summarized. Design summaries should also be provided for Parts D and E.

Section 7.2 - In general, it is important to include that the professional engineer must stamp the information, design, and construction record. This should be included as a bullet item under Items 1, 2 and 3. Second bullet item under Item 4, it should be clarified that the repairs must be "structural repairs". It is important to emphasize the difference between a structural repair versus eliminating air leakage.

Section 7.3 - It would be beneficial if NIOSH could research explosion barriers in front of seals, such as stacked sand bags, etc.

Response

The authors disagree with the reviewer's opinion that monitoring may be inconclusive for the reasons stated. In fire or spontaneous combustion situations, the interpretation of gas analysis data does require expertise; however, routine monitoring of a sealed area atmosphere can be done by technical mine personnel with appropriate training. Understanding Coward's triangle or better yet an Ellicott diagram is something that all mine personnel involved with mine seals should and must become familiar. Understanding how a sealed area atmosphere is changing with time an understanding whether it is moving toward or away from the explosive zone are not difficult concepts to master. Appropriate monitoring software tools are currently available for mine operators to implement a monitoring system together with actions to be initiated at appropriate trigger levels. The authors, and in particular NIOSH, should make such material readily available to all and educate the industry.

By monitoring the complete atmosphere of the sealed area, if the reviewer means monitoring various points in the middle of an inaccessible gob, the authors disagree. Monitoring at points around the perimeter is sufficient particularly in high gas emission mines. The authors agree that analyzing for higher hydrocarbons in addition to methane can provide useful information; however, for keeping most sealed area atmospheres out of the explosive range, monitoring for methane concentration is of foremost importance. As pointed out in our description of monitoring practices in Australia in section 2.2, they typically analyze for CH_4, CO, CO_2, and O_2.

The authors disagree with our reviewer's statements on layering and that heavy hydrocarbons will settle to the mine floor whereas methane will rise to the roof. In a still atmosphere without any air movement due to ventilation, molecular diffusion will mix the air and methane molecules into a homogeneous mixture within a few hours.

Figure 19 and table 5 have been revised significantly. Detailed discussions on each seal scenario are provided.

The recommendations in section 7.2 are modified to require a PE stamp on the information, design and construction record. The PE stamp requirement appears as a bullet under items 1, 2 and 3 as suggested.

Item 4 bullet point 2 refers to "conduct structural repairs as necessary." Bullet point 3 refers to "eliminate leaks as necessary."

In a future research project, NIOSH plans to collaborate with the U.S. National Laboratories and other research groups to develop techniques to protect seals from certain high transient pressures. At the very least, a seal must withstand the design pressure; however, there may be simple means available to protect the seal from reflected detonation waves, reflected blast waves and other transient pressures.

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Comment

Further to our brief discussion at the SME and after listening to your very comprehensive and well-presented lecture, I have the following comments on the paper, which I downloaded off your web site as you requested:

- I cannot comment on the analytical/modeling approach as I have not been involved in such work for many years. On the face of it however it all appears logical (and what would be expected from a very small seismic event).
- The two options investigated also make sense (i.e. monitored and unmonitored seals) and as we discussed the Australians in particular have considerable experience and success in using monitored seals. The main potential downside of monitoring seals is that action must be taken when indicated and without delay.
- Under an effective "monitoring and action" scenario I can see no reason why most current seals (50 psi and possibly even 20 psi) should not be adequate.
- The design charts (Figures 25 to 27 on pages 114 to 116) giving minimum seal thickness do not take into account the "keying into" the rock walls and the need for some minimum seal thickness (site dependent due to local geology) such that the explosion pulse cannot by-pass the seal and travel around it through the immediate surrounding rock.
- I do however believe that the design charts are missing the most technically and cost effective solution. This involves the use of "yielding support" – the same way as tunnel support is designed in seismically active areas. The most effective way of handling dynamic loading is by systems that absorb energy. In the case of seals this would be mainly low strength foams (say only 50 to 150 psi compressive strengths). The optimum properties could be established using a numerical code with dynamic loading ability (UDEC, 3DEC or PFC I guess could work). These systems would have numerous important benefits such as:
    - Existing products and proven experience and placement.
    - Energy absorption by "yielding/deformation" is the most effective and proven method to overcome dynamic loads (common in nature).
    - Ease of placement.
    - Relatively low cost.
    - Ease of rehabilitation after an explosion.
    - The seals would need to be wide and thus the mechanical key with the rock would be good possibly avoiding the need to "key it into the rock".
- It would seem that a weak foam would only have to be deformed/compressed by a couple of feet to absorb a 640 psi dynamic pulse. At Vaal Reefs Gold Mine in South Africa we used a foam around a tunnel that intersected a major seismically active fault and it sustained several rockbursts (>2 on the Richter Scale) with little damage.

Based on this very brief review therefore I don't share the industry's concern that creating unmonitored seals to withstand a pulse of 640 psi will be a huge cost although it will clearly increase the costs. The most logical approach however would still seem to be a monitored seal, but here again I still believe that a yielding/compressible material is the optimum approach.

Response

I'm genuinely pleased that you fundamentally agree with the report's approach, the options presented (monitored or unmonitored seals) and the general conclusions.

We agree with your assessment about the potential down-side to monitoring. If an explosive mix is detected, appropriate action must be taken and without delay. We also agree that, with an appropriate monitoring and action program, 50 psi seals are adequate. If proper monitoring becomes a common practice in the U.S., it may be possible to re-consider this design strength.

We agree that design work is needed for the anchorage of seals to account for site specific conditions of the surrounding strata. The primary purpose of the structural analyses presented in the NIOSH report is not to provide final design recommendations for seals to resist the three proposed explosion pressures, namely 640, 120 and 50 psi, but to provide approximate seal design thickness, so that engineers can judge the relative merits of alternative sealing and monitoring strategies with typical construction material possibilities. With the new proposed explosion pressure design criteria, the mining industry faces choices of sealing with thicker seals and not monitoring or sealing with thinner seals and monitoring or not sealing and continuing to ventilate. To weigh these alternatives and decide on a strategy, we provided these approximate design charts that will provide engineers with approximate values for relative seal thickness using the different design pressures and a range of typical seal construction materials. These charts were developed following specific assumptions stated explicitly in our report and are only valid if these assumptions are met. Again, these design charts are not intended as a substitute for proper engineering design of seals with site investigation, structural analysis and quality control during construction. Furthermore, they should not be accepted as a substitute for the required structural engineering.

We agree that "yielding structures" such as low strength cementitious foams may provide the most cost effective solution to resist explosion pressures. We did not include such materials in the 640 psi design curve, because our analysis method (WAC) was not appropriate with such materials. I believe these foams were originally developed to protect structures from nuclear blast, so they should have application to lower pressure-time curves as well.

We appreciate your encouragement regarding the reception of this controversial report by the industry. Construction of unmonitored 640 psi seals will clearly cost more, but the problems are not insurmountable. Through better ventilation planning, we can minimize the number of seals required and control costs that way. We continue to advocate the monitored approach tha can utilize lower strength seals.

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Comment

Typographical Errors

Section 1.2, 1st paragraph – In 5th line change "mined-out <u>area</u> still" to "mined-out <u>areas</u> still".

Section 1.2, 7th paragraph – In 2nd line change "mouth and bleeder <u>end</u> of the panel" to "mouth and bleeder <u>ends</u> of the panel".

Section 3.9, 8th paragraph – In 1st line change "mix <u>will develop</u> vary" to "mix <u>will</u> vary".

Section 4.3, 4th paragraph – In 4th line change "<u>C-J</u> detonation" to "<u>CJ</u> detonation" for consistency.

Section 6, 1st paragraph – In 1st line change "explosion <u>pressure design</u> pressure" to "explosion <u>design</u> pressure".

Section 6.1, last paragraph – Correct the square root symbol, the top bar is not showing.

Section 6.3, 1st paragraph – Correct the square root symbol; the top bar is not showing.

Editorial Comments

General – Where equations and formulas are shown, the units for the terms in the equations should be shown.

General – Conversion units are shown for some metric values but not all. It is recommended that the English conversions be shown throughout.

Section 1.2, 5th paragraph – The term "cross-cuts" is introduced in the 2nd line. It is recommended that this term be defined with "mains" and "submains" in the previous paragraph.

Section 1.2, 5th, 6th and 7th paragraph – Several terms are introduced in these paragraphs. It is recommended that the following features be labeled on Figures 2A and 2B – gateroads, tailgate, headgate, and mouth.

Section 1.3C – In the 3rd line it is recommended that "constructed <u>behind</u> the retreating longwall" be changed to "constructed <u>with</u> the retreating longwall". In reality the cross-cut seals are constructed ahead of the retreating face, so "ahead of" would also be appropriate.

Section 3.3, 2nd paragraph – The term "combustion front" is used in the text, but Figure 8 refers to the "pressure wave front". If this is the same thing, the term should be standardized. Otherwise the difference should be explained.

Section 5 - Figure 19 is referenced after Figures 20, 21 and 22 are referenced in the text. Recommend renumbering the figures so they appear in order as referenced.

Section 7.2 – It is recommended that a flowchart be added to show the decision tree for determining the seal criteria that should be used.

Table 4 – It would be informative to show the peak pressures that the seal was subjected to and the distance from the ignition point.

Response

Thank you for you editorial review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." Without going into detail, we have made all the suggested typographical and editorial changes.

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Comment

I appreciate sending me the NIOSH draft report, concerning the mine seals, with you Michael and Jurgen being the authors.
I am being busy lately; everything is getting behind because of my injury. I am on the crouches; I broke my hip six weeks ago. Therefore, it took me few days to get through your report.
I have to give you credit for the good report. I like how you organized, outline the problems concerning the mine seal design issues:

1. Classification of the methane-air mixture explosions in the coal mine openings based on a free space (volume) for explosion to develop to the detonation stage,
2. Validate the existing codes for numerical simulations of the methane-air explosion phenomena, using explosions data from the laboratory scale tests, to asses the pressures (load) developed during such a explosions for the different mining scenario, and
3. Based on these two above mentioned steps, you were able to perform computer modeling to determine the thickness of the mine seals to resist these pressure loads.

As could be seen, and I agree with you, the numbers concerning the seal thickness are in the reasonable range. I still believe that more design work is needed concerning anchoring (keying) of the seals based on the local (site) characteristics of the strata (rock and coal property).
Today I was able to discuss your work with Braden Lusk, your former student. Now, Braden is the faculty member in our department. As you probably know Braden is already involved in the mine seals construction and design study.
Both of us, him being the explosive man and me ventilation one, we plan to work together doing research associated with mine seal design. Because of my area of interest, I know the role of seals in the mine ventilation systems. I am familiar with the work done in Poland by Prof. Cybulski, Pawel Krzystolik and Kazimierz Lebecki at the Experimental Mine "Barbara" and works done in Australia. During my six months Sabbatical Leave in Australia 2002, attending and presenting the paper at the Queensland Mining Industry Health and Safety Conference 2002, I was able to discuss with Jan Oberholzer the procedures needed to test performance of the mine seals being exposed to certain pressure load.
Finishing this short letter, I would like to ask you if you (NIOSH) will be interested to see a proposal regards to the research on mine seals construction and design, from Braden and myself.

Response

Thank you for your review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." This NIOSH report has stirred much discussion in the U.S. coal mining community, because the high pressures that can develop from a methane-air explosion are not widely known to mining engineers. The subject of seals remains controversial, and we hope our report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines.

We are pleased that you found the seal thicknesses in the reasonable range, and we agree that much design work is needed for the anchorage of seals to account for site specific conditions of the surrounding strata. The primary purpose of the structural analyses presented in the NIOSH report is not to provide final design recommendations for seals to resist the three proposed explosion pressures, namely 640, 120 and 50 psi, but to provide approximate seal design thickness, so they engineer can judge the relative merits of alternative sealing strategies with typical construction material possibilities. With the new proposed explosion pressure design criteria, the mining industry faces choices of sealing with thicker seals and not monitoring or sealing with thinner seals and monitoring or not sealing and continuing to ventilate. To weigh these alternatives and decide on a strategy, we provided these approximate design charts that will provide engineers with approximate values for relative seal thickness using the different design pressures and a range of typical seal construction materials. These charts were developed following specific assumptions stated explicitly in our report and are only valid if these assumptions are met. Again, these design charts are not intended as a substitute for proper engineering design of seals with site investigation, structural analysis and quality control during construction. Furthermore, they should not be accepted as a substitute for the required structural engineering.

Mr. Bruce Watzman
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Comments from National Mining Association Packer Engineering and Baker Engineering and Risk Consultants on the NIOSH draft report "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines" and NIOSH Responses

The authors would like to thank the National Mining Association, Packer Engineering and Baker Engineering and Risk Consultants their excellent technical review of NIOSH's report entitled "Explosion Design Criteria for New Seals in U.S. Coal Mines". We will strive to address your comments and rectify any deficiencies in our draft report.

Packer's Review Summary

Comment: The NIOSH Report relies upon four basic assumptions in its attempts to justify its proposed design criteria. These assumptions are highly idealized and are based on theoretical calculations and experimental conditions that do not accurately reflect the actual conditions in coal mines. These assumptions are:

1. Combustion of stoichiometric (~10%) methane-air in a closed volume raises the pressure from 101 kPa to 908 kPa (14.7 psi to 132 psi).
2. Combustion of fuel-rich coal dust and air mix in a closed volume raises the absolute pressure from 101 kPa to about 790 to 890 kPa (115 to 129 psi) which is only slightly less than combustion of methane-air mix.
3. If a detonation occurs in an ideal methane-[dry] air mix at 1 standard atmosphere, the detonation pressure developed is 1.76 MPa or 256 psi (CJ detonation pressure).
4. A methane-air detonation wave reflects from a solid surface at a pressure of 4.50 MPa (653 psi).

The pressures stated in the above assumptions are total pressures, atmospheric pressure + pressure rise form an explosion.

The methane concentration throughout a mine varies temporally and spatially thus, assuming a constant stoichiometric homogeneous mixture as the basis for a design criteria is inappropriate. The assumptions used by NIOSH and the corresponding recommendation derived from those assumptions failed to include highly relevant information that can greatly impact the calculations of constant volume overpressures. The issues include:

- Flammable cloud size potential;
- Methane-air mixing based on known methane-air behavior;
- Realistic vapor cloud concentration gradients within sealed volumes based on mixing characteristics;

- Accounting for the effects of moisture in the air on combustion;
- Effects of geometry on mixing, potential flammable volumes, and combustion characteristics; and
- Effect of existing explosion mitigation mechanisms in place in coal mines.

The NIOSH Report also presents design criteria for high overpressures from methane-air detonations. This assumption of a methane-air detonation does not take into account a large body of research that questions the ability of a methane-air mixture to detonate. In addition, the conditions required for any potentially detonatable gas mixtures to transition from a low speed deflagration to a detonation are not addressed in appropriate detail in the NIOSH analysis. The requirement set in the NIOSH Report for seal designs to protect from a detonation in a sealed area of a coal mine is not justified given the superficial level of analysis the NIOSH Report provides and the referenced literature in this review. Finally the NIOSH Report does not adequately outline the input parameters used in the Computational Fluid Dynamics (CFD) models and incorrectly assumes that the calibration of the model that was necessary to achieve agreement with the experiments is generally applicable to larger scale scenarios with alternative geometries, concentration profiles, and blockage ratios.

Response: We agree with the reviewers that the methane concentration throughout the sealed gob varies temporally and spatially. We disagree with the reviewers' comment that the worst-case analysis as presented in the NIOSH report which assumes a 10% homogeneous methane-air mixture as the basis for design criteria as inappropriate. Without monitoring and control of gas exchanges within the gob, no one can foretell the size of the potential flammable volume and the changing concentration gradients. Therefore the authors recommend a conservative value of 131 psia as per Fact 1 of our report for 10% methane-air mixture where the maximum energy release occurs. The explosion pressure derivations assume a 10% methane-air mixture which is near stoichiometric proportions and near the point of maximum energy release. This assumption is stated clearly in the beginning of section 3 of NIOSH's report. While this is considered the worst case, it must be recognized that high explosion pressures can develop over a considerable range of methane-air mixtures. For example, the data in figure 6, laboratory experimental data, and theoretical calculations show that constant volume explosion pressure exceeds a 100 psig from 8 to 12% methane-air volume percent. Furthermore as shown in figure 10, the CJ detonation pressure exceeds 200 psia and the reflected detonation wave pressure exceeds 550 psi over this same range. Non-homogeneous mixtures will also develop high constant volume explosion pressures as long as the overall methane-air ratio for the volume is within the explosive range. Thus the possibility for achieving high pressure is not limited to the near stoichiometric, homogeneous mixture.

The authors did not include the effect of water vapor saturation at 13 °C (55°F) on the combustion of the methane-air system. The reduction in the Cv and Cj pressure with 1.5% added water vapor reduces the Cv pressure Cj pressure ~1%.

We agree with the reviewers' comment that there exists a large body of research that questions the ability for methane-air to detonate. Most of these questions come from experiments conducted in small diameter tubes where the diameter is less than or equal to the detonation cell size of 30 cm for methane-air. For example, included in the review from Baker Engineering and

Rick Consultants, Inc., this topic is succinctly discussed in Section 2.2 v. which states "... *that the bulk of the technical literature on this topic would support that a stable detonation can occur in a pipe with a diameter equal to about 3 times the detonation cell width; in the case of methane, this would imply a diameter of less than 1 meter. Furthermore, unstable detonations can occur in a pipe with a diameter equivalent to roughly one cell width.*"

We disagree with the reviewers comment that "Historical experience in coal mines does not lend support that an underground coal mine environment can develop a detonation.

The most relevant documented U.S. mine explosion where the "worst case" or near worst case detonation scenario occurred was the Blacksville No. 1 Mine on March 19, 1992. On March 13, a cap was placed on the production shaft thereby reducing the amount of intake air entering the shaft. As a result, ventilation within the shaft had been curtailed to an extent which allowed methane to accumulate beneath the cap. The methane was ignited by welding activities conducted on top of the cap. MSHA, using structural failure analysis, concluded that the pressures at the top of the shaft were approximately 1000 psig. Their calculated failure pressures ranged from a low of 782 psi to a high of 3016 psi. These values correlate to the destruction of the reinforced 5 foot thick reinforced 3000 psi concrete shaft lining. MSHA report indicates this detonation of coal dust/methane accumulations of such high proportions has never been previously recorded in the coal mining industry. This explosion at the Blackville shaft, other recent mine explosions and experimental data show clearly that high-pressure methane explosions, even detonations, can and do occur.

<u>Reference-</u> MSHA Report of Investigation in paper:
Underground Coal Mine Explosion Blacksville N0.1 mine-I.D. NO.46-01867, Consolidation Coal Company, Blacksville, Monongalia County, West Virginia, March 19, 1992. 247 pages

REVIEW OF KNOWN MINE SEALED AREA EXPLOSIONS

<u>Comment:</u> There is no analysis in the NIOSH Report of the past explosion incidents and how seal type, their location in the mine and geometry of the area affected the development of the explosion. Faulty construction leading to seal failure in explosions has also been sited by the Mine Safety and Health Administration. From a damage prevention and safety analysis perspective, an analysis of data provided by the past incidents is essential because it is necessary to consider all variables of this problem in order to develop an analysis that correctly addresses it in the most effective manner. The Report fails to do this.

<u>Response:</u> The reports reviewed in the NIOSH report were those investigated and documented by MSHA. NIOSH does not participate directly in MSHA's on site accident investigations. Only recently, NIOSH was asked by MSHA and the State of West Virginia for assistance with their investigation of the Sago disaster. NIOSH conducted 6 large scale explosion tests at the direction of the investigators at our Lake Lynn Experimental Mine (LLEM).

Of the 11 explosions reported in table 1 of the NIOSH report, at least eight of the MSHA reports indicated blown out seals. The Blacksville explosion indicated pressures of around 1000 psi. Sago investigations, other than the MSHA investigation indicate pressure more than 100 psi. It appears that most of the prior MSHA explosion investigations did not conduct back-calculations of the explosion pressure. Generally, this could not be done, because access to the sealed area to collect the necessary forensic evidence was not possible. Recent LLEM experiments relevant to the Sago investigation showed that it is not possible to assess the explosion pressure within a sealed area from seal debris and damage downstream of an explosion.

We believe that until now, explosion pressures that can and have developed in sealed area explosions have been seriously underestimated.

SEAL DESIGN PRACTICES IN THE U.S., EUROPE AND AUSTRALA

Comment: The conclusion of Section 2.1 of the NIOSH Report is that the 20 psi (140 kPa) requirement does not originate in the need to make a seal explosion proof, but more to avoid leakage. This is based on the work of Mitchell that is referenced in the NIOSH Report; nevertheless this conclusion is not consistent with the rest of the text.

Response: The reviewers will include the following change in section 2.1 to help clarify.

Text change: In summary, the original 140 kPa (20 psi) design criterion for seals is not based on containment of an explosion within the sealed area but based on an explosion occurring in the active workings and compromising the containment of methane and toxic gases within the sealed area. The criterion apparently stems from the belief that the atmosphere within the sealed area was not explosive and that the real hazard from sealed areas arise from leakage of methane or toxic gases from sealed areas into the ventilation system.

Comment: The NIOSH Report provides a review of the standards established by a few countries when sealing abandoned areas of mines. The standards in the United Kingdom, Germany, Poland and Australia are summarized in Table 3 of the NIOSH Report. The United Kingdom, Germany and Poland all require a 72 psi rated seal. These three countries are reported as never having recorded a seal destroyed in an explosion. All four countries have at least some requirements on inerting and monitoring of the sealed areas under some circumstances.

Response: Correct - The United Kingdom, Germany and Poland all require a 72 psi rated seal. These three countries are reported as never having recorded a seal destroyed in an explosion. All four countries have at least some requirements on inerting and monitoring of the sealed areas under some circumstances. Of critical importance is the fact that Europeans and the Australians monitor and control the atmosphere behind the seals during the initial inertization process, especially immediately after sealing. Because of their control, monitoring and inertization practices, the Europeans and the Australians can use lower design pressures for their seals.

COMBUSTION AND EXPLOSION ASSUMPTIONS DEVELOPED IN THE NIOSH REPORT

Comment: The second explosion scenario consists of a flammable mixture being formed directly behind or in front of the mine seal as a result of leakage through the seal. In this scenario, it is unclear how much flammable volume would be created due to seal leakage. [Baker Risk, 2007].

Response: Generally all seals and strata seal strata interface leak gases to some degree. The amount of leakage is proportional to the differential pressure across the gob primarily produced by the mine ventilation system. In addition to leakage produced by fan ventilation pressure, the gob also exchanges gases as a result of barometric pressure changes. When the barometer falls, methane and other gases vent out through the seal and surrounding strata. When the barometer rises air is taken in through the seal. NIOSH recommends limiting the flammable volume directly behind the seal by regular monitoring and control of this flammable volume to ≤ 5 meters. Some mines have successfully used a pressure balancing technique by adjusting or adding mine ventilation regulators to help minimize the differential pressure across the gob and therefore reduce the exchange of gases.

Comment: The NIOSH Report in Figure 3 presents three different potential explosive volumes to be considered when designing seals. This description of methane volumes assumes that the filling volume is uniform and creates a homogenous methane-air mixture. Methane is lighter than air and has mixing characteristics that would lead to concentration gradients within the mixture. Concentration gradients would create different combustion characteristics of the methane-air mixture and affect the magnitude of pressures created in the confined space. Thus, it is inappropriate to assume that the response mechanisms envisioned by the Report's authors, even if one were to accept them, could be applied universally throughout the underground coal mining industry given the range of potential applications

Response: As discussed in section 1.4 and shown in figure 3, whenever a mined-out area is sealed, methane gas will accumulate and at some time, the sealed area atmosphere will pass through the explosive range. The time period will depend on the methane emission rate for the sealed area. The atmosphere could become fuel-rich and inert within the few days. However, with lower methane emission rates, the atmosphere could remain in the explosive range for many weeks or it may never become a fuel-rich or oxygen-low inert atmosphere. Developing a homogeneous methane-air mixture without layering is very easy, especially in mines with lower emission rates, since diffusion processes will lead to homogeneity within a matter of hours in the absence of airflow. When a component of a gas mixture is present in non-uniform concentration, at uniform and constant temperature and pressure and in the absence of external fields, that component diffuses in such a way as to tend to render its concentration uniform. The mixing process is described by Fick's first law of diffusion. The diffusion coefficient for methane-air system is 0.157 cm^2/s.

The authors believe that each gob should be considered on a case by case basis and Figure 3 in the NIOSH report provides three different potential explosion scenarios to serve as examples and to be considered when designing seals. The general concept is to reduce and control the size of explosive volume to a level that the seal design can contain should ignition occur. Without monitoring and controlling of gob gas exchanges, especially after initial sealing when people are working nearby, one needs to consider designs for the "worst case" scenario. Also the seal cure time should be considered when the sealed area transitions through the explosive range. In fact, some countries require materials that develop full design strength within 24 hours of construction.

Review of NIOSH Report assumptions:

Comment: The chemical equation presented by NIOSH for methane combustion is a simplistic approximation; methane combustion is a very complex phenomenon which has many intermediate steps [Glassman, 1987]. An example of issues from an over simplified approximation is the statement in the Report "the [chemical] energy content of 1 m^3 of ideal methane-air mix is about the same as 0.75 kg of TNT." This statement is offered by NIOSH to design engineers as guidance when evaluating hazards. However, in application vapor clouds convert a small amount of the chemical energy to kinetic energy during an explosion. Therefore, factors like confinement and obstructions are far more important influences on explosion magnitude more than fuel values in the cloud [CCPS, 1994]. This is one example of why understanding the entire system when evaluating explosion hazards is important.

Response: The authors agree methane combustion is a very complex phenomenon which has many intermediate steps. The NASA-Lewis code that was used for calculating Cv and Cj conditions considers all of the complex chemical reactions. The ideal gas equation shown in section 3.1 of report is just a simplified summary to demonstrate concepts. The detailed NASA-LEWIS input and output data is attached at the end of these comments.

We discussed confinement and obstructions issues in the report. The reference to TNT was used to show the equivalence of blast effects but just equivalence of energy. We also used the TNT example for illustration only, i.e. for relating these concepts to subjects which mining engineers and miners would be more familiar. TNT chemical energy was not used in the pressure design pulses. The design pulses were based on thermodynamic equilibrium calculations for methane air combustion.

Comment: Both carbon dioxide and water vapor will considerably narrow the flammability and detonability limits [Zabetakis, 1965] and additionally, may significantly reduce the probability for mixtures to transition from deflagrations to detonations. In addition, experiments with atmospheres containing both water and carbon dioxide need to be conducted. The addition of these species on deflagration and detonation characteristics needs to be verified before a tight three tiered prescriptive regulation can be considered.

Response: Zabetakis (Bulletin 627-1965) and others have published flammability limits of combustible vapors in various oxidant-inert atmospheres for defining inerting and extinguishing requirements for methane-air mixtures. The more common inert gases and vapors for methane-air mixtures are water vapor, carbon dioxide and nitrogen. As expected the flammability range is progressively narrowed by addition of inert, particularly on the fuel-rich side, until propagation is not possible at some inert concentration. Carbon dioxide is more effective than water vapor which is in turn, more effective than nitrogen. Carbon dioxide requires ~24 % by volume, water vapor ~ 27% and nitrogen ~37%. To obtain the 27 % inerting limit for water vapor the methane-air mixture was heated to 67 C (152.6F) to produce the vapor pressure of 205 mm of HG. 9205/760*100 = 27%. Considering the average mine temperature of ~ 13°C (55F) the seal atmosphere could contain a maximum water vapor saturation is ~1.5 %. The authors did not include the effect of water vapor on the combustion of the methane-air system. The reduction is minimal. The Cv and Cj pressure with 1.5% added water vapor reduces the Cv pressure Cj pressure ~1%.

Ambient air also contains about 0.025% of carbon dioxide. At this small level there is no significant narrowing of the flammability or detonable limits. However, if one injects carbon dioxide or carbon dioxide is produced via oxidation reactions with reactive coal then according to Zabetakis 1975 figure 28 ~ 24% by volume percent of added carbon dioxide ~8.9% methane and 85.1% air the mixture would be non-flammable. On the other hand if the atmosphere only contains ~ 6% carbon dioxide ~8.9% methane and ~85.1% air the approximate explosion over pressure would drop from 120 psi to ~108 psi.

The effect of added rock dust for reducing methane-air explosion over pressures has been studied by Hertzberg et al (RI 8708). and shown to have little effect on reducing the maximum explosion over pressure. Rock dust, which is known to be effective against preventing coal dust explosion, was found to be almost entirely ineffective against methane air explosions. Their constant volume studies show ~1% reduction in peak chamber explosion pressure with a nominal concentration of ~500 g/m^3. At a concentration of ~1000 g/m^3 data show about 6% reduction in peak pressure.

<u>Reference: Bureau of mines RI 8708 Inhibition and Extinction of Coal Dust and Methane Explosions by Martin Hertzberg, Kenneth L. Cashdollar, Charles P. Lazzara and Alex C. Smith-1982</u>

<u>Comment:</u> The NIOSH Report assumes that the methane filling process is homogenous throughout the entire sealed area. This assumption is not valid as methane is less dense than air and will stratify in stagnant conditions, thus creating a vertical gradient within the sealed area.

<u>Response:</u> An unfortunate misconception exists that methane layering will develop in a quiescent sealed area. This misconception likely arises because it is common knowledge that methane tends to collect along the roof, especially in pockets, and that we measure methane concentration in a coal mine about 1 foot from the roof in the presence of air flow. The density of methane is about 0.55 times that of air, so buoyancy effects do exist. However, as discussed above, in still air within a sealed area, diffusion processes will dominate buoyancy effects according to Fick's first law of diffusion. The diffusion process will lead to a near homogeneous mixture within a matter of hours.

<u>Comment:</u> The Nagy, 1981 Explosion Hazard in Mining report that the NIOSH Report references, reports on experiments that indicate methane layering lowers the overpressures realized during an explosion. The assumption that stoichiometric conditions will prevail is also incorrect as the filling process is temporal and spatial in nature. There is only one segment in time during which stoichiometric conditions will exist at any given location throughout the mine. If ignition occurs before or after time the pressures will decay quickly. Extensive literature exists on methane filling and the pressure variation resulting from ignition of various mixtures. [Eltschlager, 2001, Cashdollar, 2000, Cote].

Response: Page 55 of the Nagy, 1981 Explosion Hazard in Mining report discusses experiments that indicate that methane layering lowers the overpressures realized during an explosion. One must consider the experimental setup and test zone relevant to the sealed gob scenario. Experimentally, a fixed quantity of methane was liberated just below the roof line along the length of the 25 foot test zone (1350 ft^3). The methane liberated for all experiments was sufficient, if mixed, to generate ~10% methane-air uniform mixture within the test zone. Immediately after the liberation of a fixed quantity of methane, the layer was ignited producing an explosion overpressure 4 psig. The explosion pressure increased with increased injection distance below the roof line. With the methane outlet located 5 inches above the floor the explosion pressure was 17psig. When the same amount of methane was well mixed and ignited the recorded overpressure was 33 psig. In all of these experiments, except for the homogeneous mixture test, the researchers ignited the gas immediately after release and before significant diffusion mixing of the gases had occurred. This is a key step in conducting these experiments. Had the researchers waited for ~ 5 to 6 hours before igniting, the explosion pressures would approach the maximum of 33 psig for this small test zone. Considering the sealed gob scenario, diffusion mixing will play a key role in mixing the gases. When methane enters via the roof line, diffusion will control the gas mixing process. If methane enters the sealed volume via the floor and ribs, the mixing by diffusion is augmented by additional convective mass transport processes.

Comment: It has been well documented that gradients will exist in a quiescent environment in which a gas is introduced based on its relative density in comparison to air. This implies that it is unrealistic to expect a homogeneous mixture to exist within the sealed area. Thus the location of the ignition source relative to the mixture is important.

Response: The timing of ignition and the location of the ignition source relative to the mixture are important considerations. These factors are especially important during the critical period shortly after sealing when potentially large volumes of explosive gas mixtures will exist, such as at Sago. Until the sealed area initially passes through this explosive range on its own or sped up with inert gas injection as done in Australia or Europe, the conditions for a DDT event such as reported at Blackville No. 1 mine is more likely should ignition occur.

There are a virtually limitless number of unknown conditions that one could envision that might exist to help justify moving off the proposed design criteria. However, without knowing the particular gob conditions that exist when an ignition occurs, the authors chose the maximum thermodynamic pressure for design considerations.

Comment: A more valid approach to this problem would be to generate risk curves based on the volume of the space and a range of liberation rates to determine estimates of overpressure as a function of time (based on the mixture fraction in the space). This could further be refined by introducing stratification and horizontal gradients.

Response: We agree with the reviewer recommendation to generate risk curves based on several key factors that consider the practical risk of seal failure and to use that as a basis for pressure-time curves for seal design. NIOSH may employ risk assessment techniques in a future research project on seals. The present NIOSH report presents possible explosion pressures that are achievable. Correctly understanding the possible explosion pressures and their consequences is essential information for a proper risk assessment. A proper risk assessment should consider several possibilities, such as 1) not sealing and continuing to ventilate an area, 2) sealing with unmonitored seals designed to withstand high-pressure events and 3) sealing with monitored seals designed for lower explosion pressures. However, caution must be used when conducting a risk assessment for which requisite data may not exist. We appreciate the difficult economic choices required to properly manage abandoned areas of coal mines and agree that proper risk analysis must consider these factors. We plan to carry out additional research on the sealing strategies as outlined above. This future research may provide a basis to modify seal regulations that must be in place by the end of 2007.

Comment: Some uncertainty exists whether methane can in fact detonate in air [Glassman, 1987]. The NIOSH Report references literature that a methane-air detonation was realized in an experimental mine during a set of experiments [Cybulski, 1967]. The methods for determining the maximum pressures observed are in most of the cited cases back-calculated from observations and empirical correlations that may or may not be realistic or applicable. Few of the tests showed pressures and velocities representative of a detonation and those that claimed to have shown a detonation were not based on values obtained with measurement devices, but rather were determined based on damage done to objects that were then further extrapolated to infer a specific pressure.

Response: Again as discussed above and as indicated by your attached Baker Engineering and Rick Consultants Inc., attachment -Section 2.2 v. which states "*...that the bulk of the technical literature on this topic would support and stable detonation can occur in a pipe with a diameter equal to about 3 times the detonation cell width; in the case of methane, this would imply a diameter of less than 1 meter. Furthermore, unstable detonations can occur in a pipe with a diameter equivalent to roughly one cell width*".

Unfortunately there are no black box recorders available with pressure transducers that investigators could use to document the precise explosion overpressures at different location that caused a particular level of devastation. The methods used by Cybulski, 1967 are still common among forensic accident investigators today. Such investigators use structural, dynamic and static failure-analysis utilizing analytical techniques and formulae whose accuracy is commensurate with the accuracy of the available investigative structural data. Because of the devastation, pressures are back calculated from damage observations and empirical correlations to ascertain the magnitude of the pressures needed to cause such devastation. A good example to illustrate such a process is the MSHA accident investigation of the Blacksville No. 1 Mine on March 19, 1992. MSHA, using elementary structural failure analysis, provided a range of back calculated pressures that were quite large and therefore concluded that a detonation occurred and that the pressure at the top of the shaft was ~ 1000 psig. These examples illustrate that the potential destructive overpressures can and have been quite high and the potential for detonation should be considered when designing seals to protect workers from potential blast effects and toxic gas exposure.

Comment: Cybulski's use of electric blasting caps, black powder and dynamite as ignition sources is unrealistic in its relation to most underground coal mining. Cybulski concludes that differences exist between the tests conditions and the assumed amounts of methane accumulations expected in actual operation regarding both flammable volume and methane layering. A more in depth analysis should be undertaken to ascertain if or when detonations can arise in a mine scenario.

Response: Cybulski's studies used various ignition sources according to the test scenario and variables under study. Most of the stronger igniters were not used to ignite methane but to generate a pressure profile with minimal methane to disperse and ignite mixtures of coal dust and rock dust. Also used for evaluating the suppression effectiveness of passive and trigger barriers against weak through strong deflagrations.

The NIOSH report utilizes these Polish experiments to verify, in part, our contention that reflected detonation wave pressures can reach a theoretical pressure of 653 psi as per fact 4 of our report. While the two tests described in Cybulski (1967) only reached pressures of 450 psi with flame speeds of 1200 m/s, which is short of 653 psi at a flame speed of 1800 m/s, that shortfall is insufficient reason to dismiss our contention for high reflected wave pressure. Additional tests in Poland also described in the NIOSH report, showed pressures of 595 psi at a flame speed of 1600 to 2000 m/s (Cybulski, 1975). In smaller tests, Genthe (1968) measured flame speeds up to 1200 m/s that correlated to static pressures (not reflected pressures) in excess of 270 psi.

The Blacksville No. 1 mine explosion documented by MSHA could serve as an example to answer your "if" question about a mine detonation scenario. The question of when depends on many factors coming into play at the same time and this does require additional research. One critical time is just after the initial gob sealing when the atmosphere is crossing from the explosive range into the inert non-flammable range. After the initial gassing out period, re-formation of explosive volumes near the seals depends on the degree of seal and strata leakage and the gob's interaction with the mine ventilation system. If high seal and strata leakage are coupled with large pressure differentials, a gob flow through condition could exist which could generate large volumes of explosive mixtures along the flow paths sufficient to support DDT events.

Comment: The issues of distance and flammable volume are not clearly separated in some portions of the NIOSH Report. Although the Report does classify and identify the potential of methane detonations, the use of distance can be misleading with regards to implementing distance as a safety factor or criteria. The explosion energy is determined by the flammable gas mixture volume and concentration, rather than by the length of the flammable gas column. The rate at which this energy is released, for a given fuel mixture, is controlled by boundary conditions and geometry (degree of congestion and level of confinement). Severe confinement and or congestion can lead to detonations. [Baker Risk, 2007].

In the case of tunnels, a one dimensional (1D) analysis is justified since the length to diameter ratio (or equivalent hydraulic diameter) is normally large (i.e., an L/D ratio of 30 or more). This 1D approach can utilize a "run-up" distance concept to determine the potential for a DDT. The tunnel lengths that the flammable mixture is present in impacts both the explosion strength and the potential to "run-up" or DDT.

To categorize the explosion scenarios by lengths alone can be misleading, as there are optimum situations which promote DDT. For example, some tunnels may be more congested than others or have more favorable boundary conditions that would promote a DDT. The "run-up" distances are dependent on the boundary condition in congested environments. A better criteria for explosion strength categorization may be the tunnel L/D ratio. [Baker Risk, 2007]

Response: The authors agree that the Baker Risk comment is most appropriate. We should specify the L/D ratio using the hydraulic diameter as a better criterion than just specifying length. Since the explosion energy is defined by flammable gas mixture volume and concentration rather than by the length. The NIOSH report indicated 50 meters run-up distance which was based on a nominal entry of 6.1 m (20ft) wide by 2.12m (7ft) high. Such an entry would have a hydraulic diameter of 1.58 m or L/D = ~32 for DDT which is consistent with Bakers Risk L/D≥ 30.

Comment: No known work exists examining detonations in rectangular geometries. The applicability of tunnel geometry for the analysis of mine geometry needs to be examined. The sealed areas of mines represent complex geometries consisting of linked tunnels and cross cuts. These areas can span several miles. How one dimensional analysis relates to this geometry should be analyzed.

Response: One study examining detonations in rectangular geometries was highlighted in your attached review from Baker Risk 2007. Results were compared between experiments carried out at McGill University by Chao, J., Kolbe, M., and Lee, J.H.S., in a rectangular tube of square cross section with previous experiments carried out at McGill University by Knystautas, R., and Lee, J.H.S., in tubes of round cross section. The results of these tests showed that the steady state flame velocities for the circular tube were all below the speed of sound, whereas significant portion of the velocities for the square tube achieved a state of "quasi-detonation". We agree additional mine scale controlled research should be conducted to better understand the key variables that influence DDT phenomena and identify techniques to prevent or mitigate such DDT events.

Comment: The energy required for ignition of a deflagration is on the order of 10^{-4} Joules. The energy required to ignite a detonation is on the order of 10^{6} Joules [CCPS, 1994]. The ignition sources in sealed areas are limited by the active removal of known, man made ignition sources. Rock falls may be the most credible source of sparking that could provide the minimum ignition energy required for the ignition of a deflagration in a methane-air system. Some research in this general area has been done for machine tools contacting rock [Blickensderfer, 1975, Ward, 2000] and frictional contact [Ward, 2005].

Response: We agree the energy to directly initiate a fuel-air detonation is quite large compared to that needed to ignite a deflagration (~0.3 millijoule). In fact, the immediate direct ignition (no-run up) of a fuel-air detonation of methane usually requires the high pressure, high temperature shock wave produced by the detonation of a solid high explosive in semi-confined tunnel conditions. The proposed NIOSH scenario does not involve high explosives for direct ignition but considers the deflagration-detonation transition (DDT) run-up mechanism for producing the high temperature and shock for starting the methane-air detonation.

In addition to lightning, roof falls are also a credible source of frictional heating that could provide the minimum ignition energy required for the ignition of a methane-air deflagration. There have been seven documented gob explosions, without fatalities, where the timing of local lightning by the National Lightning Detection Network coincided closely with gob explosions. Some preliminary reports on the Sago disaster indicate lightning may have been the ignition source.

Comment: Some of the explosions in the incident summary provided in the NISOH Report stated that lightning was the ignition source. Lightning as an ignition source in an actively isolated sealed area of a mine is not a greatly researched area. One study stated that lightning could be transferred to an underground sealed area and act as an ignition source for methane [Novak, 2001]. The implication of the report was that the energy transfer was not at a high energy level when transferred through rock strata. This issue requires more research to develop a better understanding of the hazard.

Response: We agree there is much work that needs to be done to understand how lightning can couple into a mine and ignite methane-air mixtures, especially in those cases where a direct metallic conductor cannot be found. Until the Sago event, most of the previous events could be associated with a metallic conductor penetrating into the sealed area. NIOSH is supporting research in this area to help better understand the coupling phenomena and ways to prevent the same.

Comment: An important concept the NIOSH Report used in establishing the seal design criteria for a detonation is the cell size required for detonation. NIOSH uses the cell size to create the parameter referred to in the NIOSH Report as the run-up length to a detonation. Cell size is a characteristic for a detonation of a given gas mixture and is based on the equilibration velocity of the wave and the corresponding cell size needed to complete chemical reactions. The minimum cell sizes for a given gas system usually exist at the most detonatable mixture of the gases and are representative of the sensitivity of a mixture. The NIOSH Report gives a methane detonation cell size of 300 mm which is consistent with other references [Glassman, 1987, Knystautas, 1986].

Response: The authors respectfully disagree; the authors did not use the detonation cell size for establishing the seal design criteria. The authors (section 3.1) used the validated NASA LEWIS and CHEETAH Thermodynamic Equilibrium Computer codes to calculate the Chapman-Jouguet detonation pressure and the Cv constant volume over pressure.

Comment: Methane is particularly insensitive to detonation compared to a corresponding cell size of ~ 535 mm for other alkanes (ethane, propane, etc.) [Glassman, 1987, Lee, 1984].

Response: Relevant to DDT phenomena, all other conditions the same, one can say that based on detonation cell size methane(~300 mm) is less sensitive to detonation than hydrogen (~15 mm) or propane(~50 mm). (Shepard et al, 1991; Lee et al 1984).

Comment: A literature search conducted as part of this review was not able to find experiments where a successful methane-air detonation was established. Two projects were found that conducted experiments in semi-confined spaces where no methane-air detonations were achieved [Bull, 1979, Inaba, 2004]. It is important to note that these two tests were not performed in tunnels and had only partial confinement of the explosive mixture, but the studies do provide some insight into the difficulty of achieving a methane detonation. One paper reported that based on the model developed from the experimental data, 22 kg of tetryl (a highly explosive compound) would be needed to initiate a methane-air detonation [Bull, 1979].

Response: In addition to experimental explosions highlighted in NIOSH's report, the Blacksville No. 1 Mine on March 19, 1992 best illustrates that a detonation can and unfortunately has occurred in a U.S. coal mine. With a sufficiently powerful ignition source, detonation occurs almost immediately upon ignition, even in the open. Secondary high explosives such as trinitrophenylmethylnitramine (tetryl) and many other high explosives are efficient for rapid initiation of fuel-air detonations with very minimal run-up. The ignition process that the authors are suggesting is not the immediate ignition by the shock pressure from the detonation of high explosives but rather as a result of the DDT process. As discussed in the report, the DDT process occurs as a result of shock formation or pressure piling produced by turbulent flame acceleration in tunnels. The DDT concept is generally discussed in Section 3.5 of the report shown in figure 8 and 9. The ignition source that resulted in the DDT at Blackville No.1 mine shaft was reported from welding.

Comment: Experiments that examined methane in air were carried out by Bartknecht in 1971 and reported in the Gas Explosion Handbook [Bjerketvedt, 1992]. These tests were done at 1 atmosphere pressure in a 1.4 meter diameter 40 meter long pipe with test conditions of one end closed and both ends closed. Two ignition point scenarios were used, one at the closed end and one at the open end of the pipe. Test were done with the pipe open at one end and closed at both ends, a case similar to the scenarios pictured in Figure 8 of the NIOSH Report. The experiment found that the highest flame speed was achieved when the ignition was at the closed end of the pipe and the other end was open. When the pipe was closed at both ends, the flame accelerated at first, but after 15-20 meters started to decelerate. This testing did not have obstructions in place in the pipe.

Response: The authors are familiar with these experiments conducted by Bartknecht in 1971. These tests were done with the pipe open at one end and closed at both ends, a case somewhat similar to the scenarios pictured in Figure 8 of the NIOSH Report. Bartkneckt shows a deflagration in a smooth wall pipe without DDT. In a deflagration, the flame speed slows as it approaches the closed end where the gases are pre-compressed. Unfortunately, Bartkneckt did not include the corresponding sharp increase in the pressure at the closed end as the mixture burns the pre-compressed unburned gases. For example, at 1 atmosphere pressure the pressure rise due to combustion is ~9 atms. Subsequently, if the gases at the end of the tube are pre-compressed to ~ 2 atmospheres before flame reaches and ignites, then local, short lived side-on overpressure would approach ~18 atmospheres. (2 X 9 atm =18atm).

Comment: Obstructions in the flow field of the explosion gases are very important because the methane-air (or any fuel-air) mixture interacts with the obstructions to create turbulence which accelerates the flame fronts during the propagation along the length of the geometry. Knystautas did not get methane-air mixtures to detonate and found that the flame speeds propagated in the obstruction fields for all tests were below the Chapman-Jouget (C-J) predictions. In short, the Knystautas research indicates that a high degree of obstruction is required in a closed tube (on the order of 0.43 fraction of the diameter) to propagate any of the tested hydrocarbons to a DDT. At no time during these tests was methane accelerated to near DDT velocities at the blockage ratio of ≤ 0.43.

Response: This statement is true for round cross sectional tubes however as noted in your attached review provided by Baker Risk, when similar experiments with same blockage ratios were conducted in rectangular (square) tubes "quasi-detonation" occurred for a significant portion of the velocities.

Comment: NIOSH states that any seal with a tunnel run-up of 50 meters or more requires a seal capable of withstanding an explosion overpressure load of 640 psi. The idea of an explosion containment system designed to withstand a detonation that is made of a single element, such as one big mine seal, may not be a very effective strategy. A detonation overpressure containment seal would have to be built to standards that may not be attainable, reliable or a cost effective use of safety resources given the real risk presented by a methane-air detonation in a mine.

Response: We disagree with the allegation that designing seals to resist the 640 psi explosion pressure design criterion is neither practical nor cost effective. Based on preliminary structural analysis, the NIOSH seals report provides one example for a 20-foot wide entry in a 7 foot high seal where a 40 inch-thick concrete seal is required for the 640 psi criterion. Granted, this simplistic structural analysis does not consider the seal foundation or convergence loading; however, it does indicate that practical and economically feasible solutions are available. Given the devastating consequences that can and have occurred, the authors are confident the U.S. coal industry and its contractors will devise clever solutions to this issue that are both safe and affordable.

Comment: Inherently, gas explosions are not the same as condensed phase explosions (e.g. TNT). A good discussion of the differences is found in Baker, W.E. et al. Explosion Hazards and Evaluation, Elsevier, New York, (1983) [Baker, 1983]. Baker discusses several significant factors that are not considered in the Report. First, the difference between constant pressure energy addition and constant volume-isentropic expansion is discussed in detail including how the combustion wave spreads.

Response: We chose the constant volume approach because we are dealing with a closed system. Constant pressure assumes tunnel expansion.

Comment: The transition from a three dimensional source wave to one with reflected pressures is a complex issue. Baker, 1983, makes clear that reflected pressures are extremely geometry dependent and the effects from a non-spherical explosive source that is not a high explosive need to be evaluated. The simple formula presented in section 3.6 (line 793) gives only one such limit.

Using a single equation to estimate the pressure of a reflected wave is extremely misleading. Rather, as Baker et al. point out, the effects of the specific impulse from an explosion need to be considered. Using a single equation to express reflected wave characteristics implies that Fact 4 (lines 801, 802) may not, in fact be valid.

Response: The authors agree that the reflected pressures and their interaction with structures represent a very complex process. Most of the research cited and Baker 1983 are from the point type open air detonation of high explosives and the subsequent interaction of hemispherical blast waves with surface structures. Such processes force the need to examine 3D blast wave interactions with surface structures especially from the detonation of large bombs, including nuclear. As indicated under section 2.1 of your attached BakerRisk review "in the case of tunnel, a one dimensional (1D) analysis is justified..." The authors chose a 1D approach for our analysis and assumed a head-on or normal seal impact to be justified given all the unknown possibilities. The authors agree, if the angle of impact of the blast wave with the seal is not normal the effective seal loading would be lower than 640 psi. However, on the other hand, non-normal blast wave reflections can coalesce, reinforce each other and significantly increase the loading pressures well above the 640 criterion.

Comment: The NIOSH Report uses explosion pressure and explosion pulse, not the terms used in the bulk of explosion literature, i.e. peak side-on overpressure and impulse. The NIOSH Report should make it clear what is being calculated or measured. For example, Figures 20-22 are given with explosion pressures on the axes. This term "explosion pressure" is not clearly defined in the NIOSH Report. Explosion pressure (see Lines 1817, 1823, and 1829) is not a term normally found in the literature and this complicates analysis of the Report.

Response: NIOSH will change the text and figures to clarify terms?

MODELING OF EXPLOSIONS

Comment: The NIOSH Report provides a summary of the different model packages that are available to analyze explosions. The model runs that simulate the Lake Lynn Experimental Mine provide a degree of validation to both model codes and their application to understanding overpressures in mine configurations.

These models can provide valuable information if used appropriately in designed studies to develop configuration and scenario specific seal evaluations. Different design concepts can be evaluated using these programs to help understand the mine and sealed area specific configuration elements that govern the potential overpressures.

The practice of calibrating a model based on small scale experiments and applying the same baseline conditions for different scenarios can be problematic. The calibration process typically involves adjusting various properties and model parameters that will affect turbulence, temperatures, pressures, and speed of the flame front. These adjustments are valid for a specific set of conditions but may not be generally applicable. Thus, the results predicted by the models that are not supported by any experimental/literature values must be treated extremely cautiously if they are based on calibrated baseline conditions.

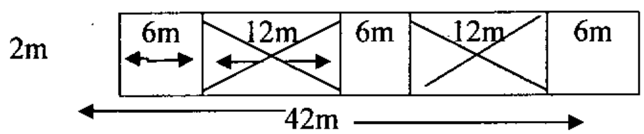
The simulation codes are continuously under development as new information is found and better representations of physics and chemistry is included in them. FLACS, AutoReaGas, NASA-Lewis, and the Wall Analysis Code all have version numbers and dates of release. These need to be included in the report as an appendix. As the Report presently reads, there is no means of comparing results with any additional information about geometry, temperature and concentration gradients, etc. For each code the version and date needs to be specified. For each application run for comparison purposes, the full initial decisions, assumptions, and conditions need to be provided. If new information is obtained, no comparison with the results from these simulations can be obtained. This is the bare minimum needed for each simulation. Detailed output from each case simulated would be a part of any proper and careful analysis.

Response: Thank you for comments regarding the numerical modeling efforts of gas explosions. First the FLACS code was not "calibrated" rather the supplier was asked to run combustion simulations of a 10% methane air explosion spark ignited in simulating different Lake Lynn test geometries. The simulations were conducted "cold turkey" without any input from NIOSH. After the simulation was completed the results were compared with NIOSH's actual measurements in the same geometries. The agreement was within 10%.

NIOSH's used the FLACS and AutoReaGas CFD programs to predict pressure development beyond the range of experimental data available from full-scale Lake Lynn Experimental Mine (LLEM) explosions. The CFD codes were not used to determine the Cv of Cj designs pressure. These CFD simulations used to help characterize the rate of pressure build up with increasing gas volumes that were ignited near the seal followed by flame propagation away from the seal deeper into the large inert gas volume. Such data was helpful for establishing 50 psi design criteria for identifying reasonable gas sampling locations for detecting dangerous explosive gas volumes. The authors know that the FLAX or AutoReaGas CFD model cannot handle DDT nor predict accurate reflected pressures and we did not use them for that purpose. The authors used the well validated CHEETAH and NASA Lewis code (thermodynamic equilibrium codes) to calculate Cv and Cj pressures for methane-air combustion. For the detonation reflected wave, the classical work by Zeldovich and Stanyukovich which was equation 4 in NIOSH report line 793. (~ (2.55)* (Cj)). ~ 640 psi was used.

The authors will make available outputs from the AutoRegas and FLACS simulations on NIOSH's mining web site (site...).

Comment: The models assumed for the AutoReaGas and FLACS trials are based on the Lake Lynn layout. This layout, if we assume a 2 meter tunnel height, has a blockage ratio of about 0.57 and essentially consists of a rectangular cross section with three venting shafts and two pillars (see figure below). [Baker Risk, 2007]



Tunnel designs and layouts illustrated in Figures 1A and 1B of the NIOSH report contains more obstacles and a blockage ratio of about 0.44. The differences between these arrangements can have a significant impact on the potential for a DDT.

Response: Figures 1A and 1B in NIOSH report were not drawn to scale. Baker Risk in their review incorrectly assumed that both entry and support pillar had the same width of 2 meters. With Baker's assumption the blockage ratio would be 0.44 (16 m^3/36 m^3 = 0.44). This ratio would indicate it is less likely for detonation based on work cited by Knystautas, R., and Lee, J.H.S., in round cross-sectional tubes using a blockage ratio of 0.43. However figures 1A and 1B illustrate 6 entry panel seals and 7 entry district seals. The open entries are 6 m wide while the support pillar between entries is 12 m wide same as those simulated at the Lake Lynn Laboratory with a blockage ratio of 0.57. Therefore, district panel seals would consist of 7 parallel entries 6 meters wide separated by 6 coal pillars 12 meters wide with a height of ~2 meters would give a calculated blockage ratio of 0.63 (144 m^3/228 m^3 = 0.63). Knystautas et al. show that a high degree of obstruction is required in a closed tube (on the order of ≥ 0.43 fraction of the diameter-blockage ratio) to propagate any of the tested hydrocarbons to a DDT. All other factors the same, a blockage ratio of ~0.6 is sufficient for detonation. The NIOSH calculations are also consistent with the data that support the possibility of DDT.

Comment: Conclusion: This review provides an analysis of the NIOSH Report and raises questions about each of the design assumptions that NIOSH used to justify the pressure requirement for the seals. The NIOSH Report does not present a convincing argument for providing a prescriptive seal standard that is many times in excess of successful standards in other countries throughout the world. It uses a theoretical homogeneous methane-air (dry) combustion conditions to represent the stratified methane combustion in the moist conditions in coal mines. This assumption is used in spite of data indicating that both of these conditions will significantly reduce the flammable mass and severity of combustion. Furthermore, the NIOSH Report uses the pressure obtained in ideal explosion conditions in narrow tube geometries to approximate the conditions in mine tunnels and entries. This method of developing design criteria is not appropriate for this application. Before a prescriptive regulation that is so much greater than the international standards is applied more analysis and data is needed.

Response: The NIOSH authors respectfully disagree with the reviewers. The questions raised by the Packer and Baker reviewers do not provide compelling technical arguments for the authors to deviate from their proposed criteria. The authors put forth technical arguments to support their position on point by point bases.

As detailed previously the authors respectfully disagree with the reviewers that moist conditions and stratified methane will significantly reduce the severity of combustion. Unfortunately, developing a homogeneous methane-air mix without layering is relatively easy, especially with low methane emission rates, since diffusion processes will lead to homogeneity within a matter of hours in the absence of airflow. The rate upon which this occurs under most conditions is proportional to the concentration gradient times the diffusion constant otherwise known as "Fick's" first law of diffusion. Again, the authors have also shown that assuming, at most water vapor saturation at mine temperature of 13C (55F), and 1 atmosphere pressure would at most contain ~1.5 volume % water. The presence of 1.5 % water only reduces the thermodynamic Cv and Cj pressures by less than 1 %.

The authors disagree that NIOSH report uses the pressure obtained in narrow tube geometries to approximate the conditions in mine entries. The Cv and Cj pressure are determined strictly by thermodynamic analysis and are independent of entry size.

It is certainly true that the proposed standard is many times higher than the standard in other countries. The fundamental difference from the U.S. is that the Europeans and the Australians monitor and controls the atmosphere behind seals especially immediately after sealing during the initial inertization phase. Because of these monitoring and inertization practices, the Europeans and the Australians can use lower design pressures for their seals. We advocate the creation of inert gob atmospheres that are fuel-rich and oxygen-low, specifically one which is more than 20% CH_4 and less than 10% O_2. More importantly, we also advocate the creation of an inert gob atmosphere as quickly as possible, either through self-inertization if the methane emission rate is sufficiently high or through artificial inertization. The 640 psi design criterion applies to unmonitored seals with no control whatsoever of the atmosphere behind the seal as is the current practice in the United States.

The explosion at Blacksville shaft, other recent mine explosions and experimental data show clearly that high pressure methane explosions can and do occur. Such possibilities must be considered by regulating authorities in the development of new regulations and strategies for sealing. In future research projects, NIOSH plans to collaborate with the U.S. National Laboratories and other research groups to develop simple techniques to protect seals from certain high transient pressures.

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Comment

Remarks and Computations Related to NIOSH Seals Report
Mike Wieland, UNCERTAINTY INK
Revision Date, April 24, 2007

The draft report, *Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines by R.K. Zipf, M.J. Sapko and J.F. Brune,* was released in 2007 for outside comments. This report represents considerable innovation that rests upon relevant well-supported scientific findings. Upon recognizing the complex and transitory nature of the phenomena involved, none of those findings differ significantly from work-principle and other theoretical model results, for reaction-gas mixtures close to stoichiometry. The overpressure 4.4 MPa design criterion relates to the upper-limit of the total (absolute) normally reflected detonation pressure, 4.55 MPa for methane/air. The second design overpressure criterion of 0.80 MPa is a logical round-off to NIOSH closed bomb-calorimeter or the upper-limit work-principle results, 0.88 MPa. The chosen criteria are justifiable, considering how hard it is to design retention structures for such harsh circumstances.

The experimental work encompasses nature's complexity or non-ideality that is not readily accounted for with theoretical restrictions. The modeling utilized contains no transfer coefficient effects, tends to over-estimate and fails to recognize the role of reaction extinction, unlike the test data. The unrealistic non-zero information in the wide-tails of the graphical curves outside the journal reported extinction limits should be disregarded, though near stoichiometry, the theoretical results only slightly overestimate results found experimentally. Four different theoretical circumstances were compared graphically, some of which were resolved with fewer points in the seals report: the work-principle explosion (refer to recent ISEE publications and references therein), the constant volume explosion, the Zeldovich von-Neumann Doering (ZND) detonation at the Chapman Jouguet (CJ) condition and the 'rigid-wall' normally reflected wave for that circumstance. The four maximum pressures, which represent the highest point resolved in constructing the graphical traces, occur slightly to the rich side of their stoichiometric methane concentration.

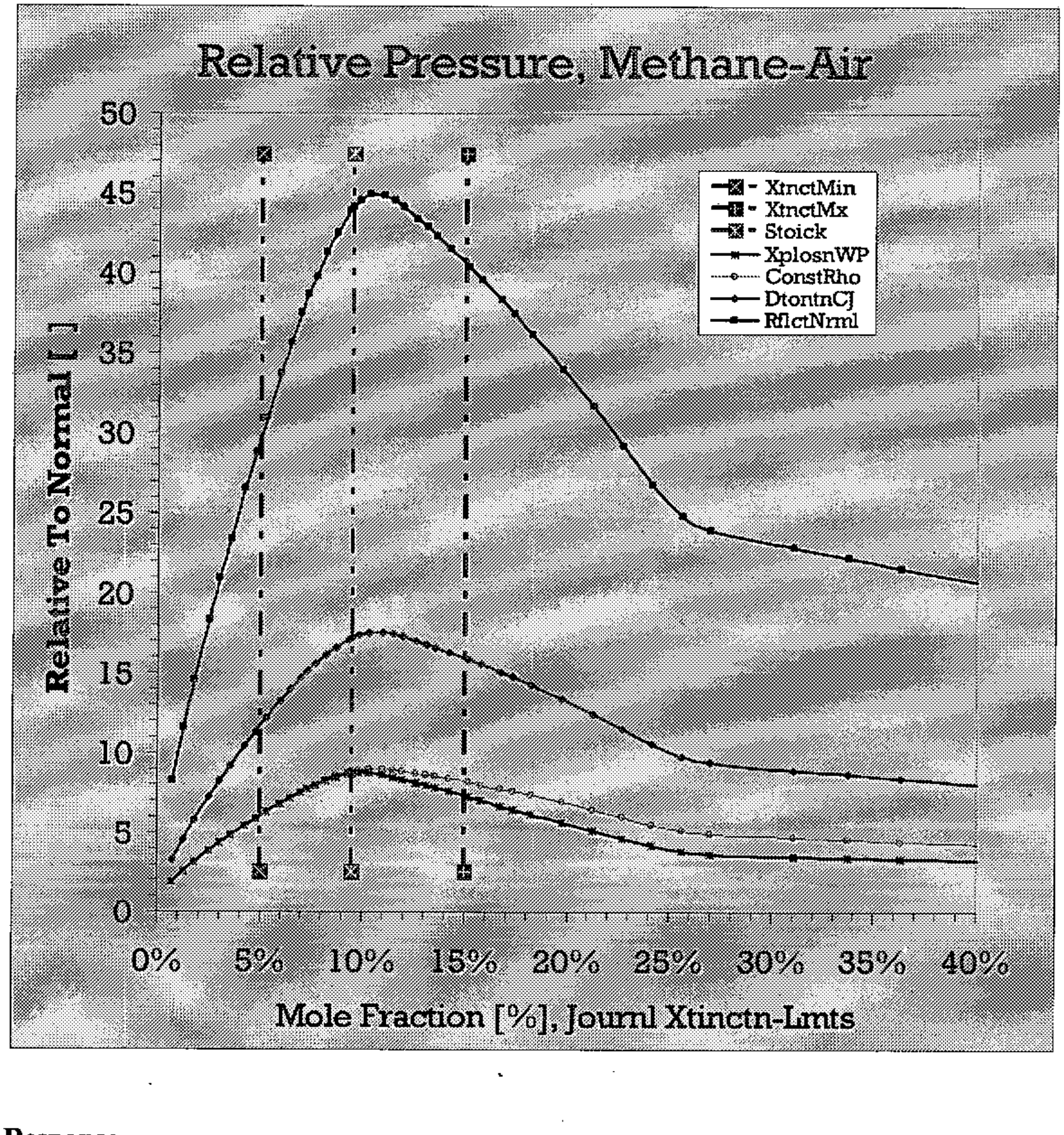
While the detonation modeling includes kinetic energy and is post run-up, the two explosion results are without relative motion and therefore ignore dynamic pressure. Wave-humping or the reality of impure methane or rough wall influences require the additional considerations that were noted in the report. Other naturally-occurring gases can occur in minor (though nontrivial) proportions, usually ethane or rarely propane. Worst-case near stoichiometry, these two reactant gases individually yield slightly higher explosion pressures than methane, so natural gas mixtures represent a worrisome prospect, not wholly (or readily) addressed. The second design criteria mentioned in the seals report therefore could underestimate some worst-case possibilities; the methane/air remains the logical typical guideline circumstance.

TABULATED/GRAPHICAL RESULTS

Relevant explosions occur within journal reported methane extinction limits: 5 mol% to 15 mol%. Graphed work-principle Z-state (fireball) explosion results are denoted "XplosnWP". Graphed constant density explosion results are denoted "ConstRho". The ZND-CJ detonation results are denoted "DtontnCJ". The ZND-CJ detonation normally reflected results for rigid wall with zero particle velocity are denoted "RflctNrml". [Normal pressure = 1 atmosphere ≡ 1 atm = 1.01325 bar = 0.101325 MPa = 101.325 kPa ≈ 14.7 psi, whereas

1 bar ≈ 14.5 psi. When compared to the report overpressure guidelines, it is necessary to subtract off unity form the relative (total/normal) pressures in the graph traces.] The highest resolved points in the graph traces were rounded-off when rendered in other units to a reduced number of significant figures:

Normally reflected detonation: high pt. 44.91 atm = 45.5 bar = 4.55 MPa;
ZND-CJ detonation: high pt. = 17.52 atm = 17.8 bar = 1.78 MPa;
Constant density: high pt. = 8.954 atm = 9.1 bar = 0.91 MPa;
Work-principle Z-state explosion: high pt. = 8.726 atm = 8.8 bar = 0.88 MPa.



Response

Your independent confirmation of the 120 psi constant volume explosion pressure based on your work-principle Z-state method is greatly appreciated and is important for the advancement of good science. We also appreciate your independent verification on the ZND-CJ detonation pressure and the reflected detonation pressure as a function of methane in air concentration. These calculations show very high pressure over a large range of methane concentration. Unfortunately, high pressure is not restricted to at or near stoichiometric conditions.

Finally, your remarks that the presence of minor gases in natural gas can raise explosion pressure about 10% are noted. Our report considers just methane-air; however, the effect that you mention could become important in certain situations.

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Comment

In the document above, the tube bundle monitoring system is discussed on page 25 with some figures (photographs) on page 88. The analytical equipment is incorrectly called a "gas chromatograph"
The wall mounted gas analyzer is a SICK-Maihak Model 715 which incorporates a UNOR optical bench to measure Carbon Monoxide (CO) at a ranges of 0-100 and 0-1000 ppm,. This unit operates under the principle of a non-dispersive infrared analyzer (NDIR) and is a continuous gas analyzer. The S715 shown also incorporates a MULTOR optical bench for the simultaneous measurement of Methane (CH4) and Carbon Dioxide (CO2) at ranges of 0-10 and 0-100%. The MULTOR optical bench is also a NDIR principle unit. Also included is an OXOR-P paramagnetic oxygen analyzer that measures oxygen at ranges of 0-10% and 0-25%. All of these units are within the single gas analyzer and are continuous gas analyzers.

Gas chromatographs are intermittent in their analysis and require a cycle time of probably 3 – 5 minutes for the analysis of these gases. A gas chromatograph is not capable of continuous analysis.

The Tube Bundle System was supplied by Gas Analysis Systems (G.A.S.), which is now a part of Sick Maihak Australia.

Product info attached

Response

Thank you for your review of the NIOSH report "Explosion pressure design criteria for new seals in U.S. coal mines." This NIOSH report has stirred much discussion in the U.S. coal mining community, because the high pressures that can develop from a methane-air explosion are not widely known to mining engineers. The subject of seals remains controversial, and we hope our report spurs intelligent discussion, new research, better engineering of sealed areas and safer mines.

In the draft report, we incorrectly call your analytical equipment a "gas chromatograph." This misnomer has been corrected to "gas analyzer" in the final report.