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**Subject:** Comments on the seal report

**Attachments:** NIOSH Seal report Review Form.pdf; NIOSH Feb 2007 Seal Design Comments on Report.pdf

NIOSH Seal report Review Form....  NIOSH Feb 2007 Seal Design Com...

Karl,

Thank you for the opportunity to comment on the draft seal report. Though well organized and very informative, I have listed several critical areas which I believe must be addressed before the report is finalized. If you have any questions concerning the comments, please feel free to contact me.

Dave

(See attached file: NIOSH Seal report Review Form.pdf)

(See attached file: NIOSH Feb 2007 Seal Design Comments on Report.pdf)

# Comments on the *NIOSH* Draft Report, "Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines"

By

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## 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.

## 2.0 Review

In the following sections, a point-by-point approach is taken to bring out what the reviewers thought as problem areas that require further research and elaboration.

### 2.1 The 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,

* Numbers in the square brackets indicate the references given at the end.

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 "worst-case" 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.

### *2.1.1 On the assumption of 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 in 1861, the noted differences between the values estimated based on adiabatic assumptions and measured values were ascribed to heat loss from the vessels [2]. To quote Bone and Townend [3], 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.[4] 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 Kpa to 870 Kpa, much less than that estimated by the *NIOSH* report.

### *2.1.2 On the homogeneous gas mixture filling the entire coal mine entry*

The density of methane is about 0.55 times that of air [5, 6]. 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 [5, 6]. 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 [5, 6]. 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.

#### *2.1.3 On the Existence of "Normal" 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 [7]. The data shown in Figure 1 was obtained from an abandoned room and pillar mine, which has not been retreat mined. Curves in 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.

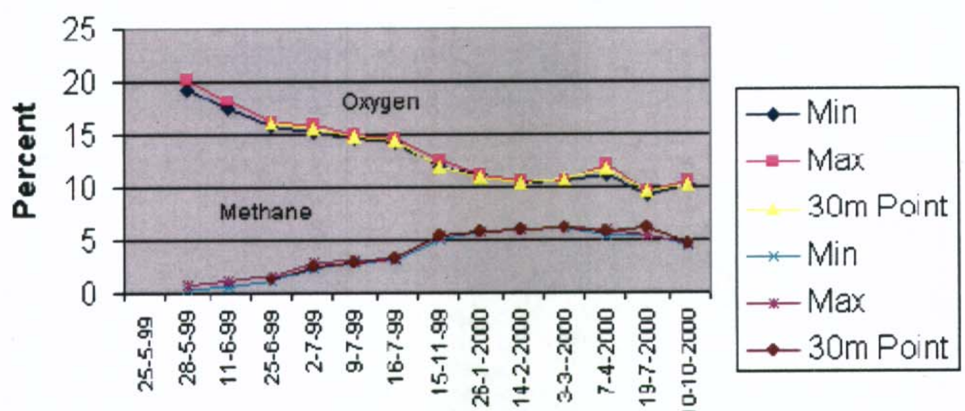


**Figure 1.** Change in the oxygen and methane content in gob air over time [7].

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' [3] 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 [3].

| 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 [3] 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.

### *2.1.4 Some General Remarks on the Constant Volume 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 [3]. 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 [3].

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.

## 2.2 Deflagration-to-Detonation Transition (DDT), CJ Detonation Pressure and Reflected Pressure

### *2.2.1 On 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 [8]. 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 [9]. Also, Li et.al. [10] 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 $\lambda$ value of 30 cm and a $D/\lambda$ 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. [11] shows that 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 [12].

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. [13], *'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 [13] 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 [13]. 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 [13].

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 [9,14,15] on the subject shows promise.

#### *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

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

Where $P_1$ and $P_2$ are the pressure ahead and behind the detonation wave; $\gamma_1$ and $\gamma_2$ 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 [16] gives the equation as

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

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 [17]. While the *USBM* version in equation (2) was not derived from the first principles, Landau and Lifshitz [17] give a step-by-step derivation of the equation. Their version reads as

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

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 [18], 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.

### 2.2.3 On the Reflected 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

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

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

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

Equation (5) is given in an example problem in Landau and Lifshitz's book [17]. 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. [19], the derivation of equation (5) was credited to Zel'dovich and Stanyukovich, who derived the equation in 1948 long before the publication of Landau and Lifshitz's book. Since Shepherd et.al. 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 ($\gamma_1$ and $\gamma_2$). 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.

## 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.*[20] in 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 3 strong 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[21] :

"*According to the current classification, a combustible mixture can be excited by three basic methods [1]:*

- *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 correspond 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.

## 2.4 Numerical Modeling of Gaseous 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.*[22] 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 [22]. 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.

## 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 potion 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.

## 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.* [22] 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.*[22];
- 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 $\sqrt{2}$ 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* [22] 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.

## 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.*[22].
- 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.

## 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.

## 5.0 References


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