Australian Sealing Practice and use of Risk Assessment Criteria - ACARP Project C17015

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ABSTRACT

The US Sago mine disaster in 2006 caused mine seals to be destroyed by an atmospheric explosion. Investigations into the appropriateness of seal strength requirements to withstand a pressure event followed. New designs have been developed and various changes in US regulations implemented. Australian reviews of coal mine safety in the mid 1990s after the Moura Number 2 explosion in a similar way directly resulted in changes to management of hazards in Queensland.

An Australian Coal Association Research Project (ACARP) funded research project has been undertaken with one of the main objectives being to examine views of Australian operating mines on the industry's approach to the use of seals; also the new US approaches to sealing and their possible application to Australian conditions. The research is current and results interim. While in many ways approaches to underground coal mining in Australia and the US are similar, Australian approaches to the management of hazardous mine atmospheres differ significantly. Australian risk management approach to handling hazardous situations implies adoption of international industry best practices. There has been a move for Australia to consider and possibly adopt new US standards for seal pressure rating codes. The Australian industry has gone through a debate on how the new US information on seal behaviour and new regulations should be incorporated, if at all, into Australian practice. However the industry as a whole, including mines' management, state inspectorates and mining unions have decided not to adopt the principal dictates of the 2008 US seal regulations.

The second part of the ACARP research project being led by SIMTARS is undertaking further physical testing study of the risk of explosions in sealed areas. This propagation tube study of the consequences of explosions is being conducted to both determine the nature of the explosion overpressures that a structure can be subjected to and also the nature of the pressure pulses that will impact on the structure. During the tube studies an analysis of a number possible mine scenarios where a methane explosion could occur is being made.

INTRODUCTION

The 2006 US Sago mine destroyed mine goaf seals. Following the disaster investigations were launched into the appropriateness of seal strength requirements. Various studies have subsequently been undertaken, new seal designs have been developed and various changes in US regulations implemented. It is recognized that the US studies have advanced understanding of issues. The key US changes to US Mine Safety and Health Administration (MSHA) federal regulations has been to increase the pressure rating of seals installed in coal mines from 140 kPa to 840 kPa (or to 350 kPa if the goaf being sealed is being monitored under real time gas analysis and inertisation facilities are available to control a hazardous event).

Similar Australian reviews of the safety of coal mining operations in the mid 1990s after the Moura Number 2 mine explosion resulted in changes to hazard management in Queensland. Australian approaches are formulated on a risk assessment basis under which hazards must be identified and appropriate "world's best practice" systems adopted. The principal approach in Australia to goaf management is early prevention of hazardous situations through use of real time gas monitoring from the goaf periphery to ensure the maintenance of goaf inert atmospheric conditions. Another line of defence is having inert gas systems on hand (most commonly jet or diesel engine exhaust, nitrogen or CO_2) to proactively ensure potentially explosible gas concentrations cannot form or are handled appropriately. The final approach is through use of well engineered seal structures constructed to segregate all worked out areas where there is any likelihood of explosible gas concentrations occurring. Seals on gassy goafs most commonly are designed to meet a 140kPa rating.

INDUSTRY QUESTIONARIOUS SURVEYS

A comprehensive and representative survey of a large number of Australian mines has been undertaken during 2008 to establish how mine managers are handling seal design and implementation. Fourteen mines were included in the survey, seven from each of Queensland and New South Wales and the basis of the survey was an interview questionnaire completed at site. In brief the following information was sought.

1. Ventilation network details such as main fans, underground monitoring systems, types and numbers of sensors installed, seam gas type and quantity, gas drainage system, gas concentration in air and possibility of spontaneous combustion.
2. Specific questions asked on whether sealed areas pass through the explosive range, final goaf atmospheric conditions in sealed area, records on behaviour after sealing, permeability and pressure issues, consideration of induced inertisation, and use of panel bleeders and their arrangements.
3. Specific questions on possible dimensions for explosion propagation, propensity for propagating explosion and probability of explosion.
4. Information on current approach to installing Ventilation Control Devices (VCDs) and seals such as Mains separating intake from belt air, Mains separating intake or belt air from return, panel gate roads separating intake from return, final panel seals providing separation from adjacent panel air, final panel seals providing separation from Mains air and other air.
5. Information on ground stress relationships and seal integrity, structural properties of seals and stress time dependent relationship through life of seals.
6. Views were sought in the final section on the following issues:
   - i) Sources of explosion, pressure disturbance or air blast,
   - ii) Should a seal be designed to as an impervious membrane or an explosion barrier or both?
   - iii) How seals, stopping and VCDs should be designed and tested and opinions on Queensland 14/35/70/140/350 kPa rating codes.
   - iv) Should design be by structural analysis or physical destruction testing?
   - v) Pressure balancing of a sealed area and how to achieve, barometric pressure influence and intake air passing a sealed area.
   - vi) Contractors vs company labour installing VCDs.

RELEVANT US DIFFERENCES WITH AUSTRALIAN MINES

Some of relevant differences of US underground coal mines compared with Australian mines are as follows. In the US:

- Most (about 80 percent) US Longwall Gate roads have three Headings. The middle Heading when within the goaf can be expected with a gas initiation to lead to an explosion disturbance characterized by a long run-up distance. This compares with Australian practice of normal use of two Headings.

- Significantly lower take up of electronic monitoring
- Only one mine makes use of "Tube bundle" gas monitoring
- Little proactive use of inertisation
- Limited use of ventilation network programs
- Limited usage of trained Ventilation Officers
- Extraction in US of thinner seams common; these mines leave less coal in goaf
- Seals placed along Mains but generally not along chain pillars separating panels

Figure 1 shows a typical longwall district (series of longwalls) and panel sealing practices in US longwall mines. Multiple seals may be constructed against the Mains or Submains at the mouth and bleeder ends of the panel after a longwall is mined out and the tailgate is no longer needed. A mined-out longwall panel district may then be closed off by constructing seals across Mains, Submains, and bleeders at the proper location. This type of sealing is referred to as "delayed panel sealing" and is common where there is low risk of spontaneous combustion as shown in Figure 1.

Where spontaneous combustion is a potential problem as occurs in some Western US states, longwalls may undertake "immediate panel sealing" with seals constructed in every crosscut nearest the goaf down the Headgate entries immediately behind the longwall face. The newly formed mined-out area is substantially isolated from oxygen soon after mining, thereby decreasing the risk of spontaneous combustion problems. Depending on the length of the longwall panel, 50 to 100 seals might be constructed as the panel is mined.

In Australia, "immediate panel sealing" is used in the majority of mines especially in Queensland. Use of bleeder roads is not as prevalent as in the US. Figure 2 shows typical district (series) and panel sealing practices in Australian longwall mines.

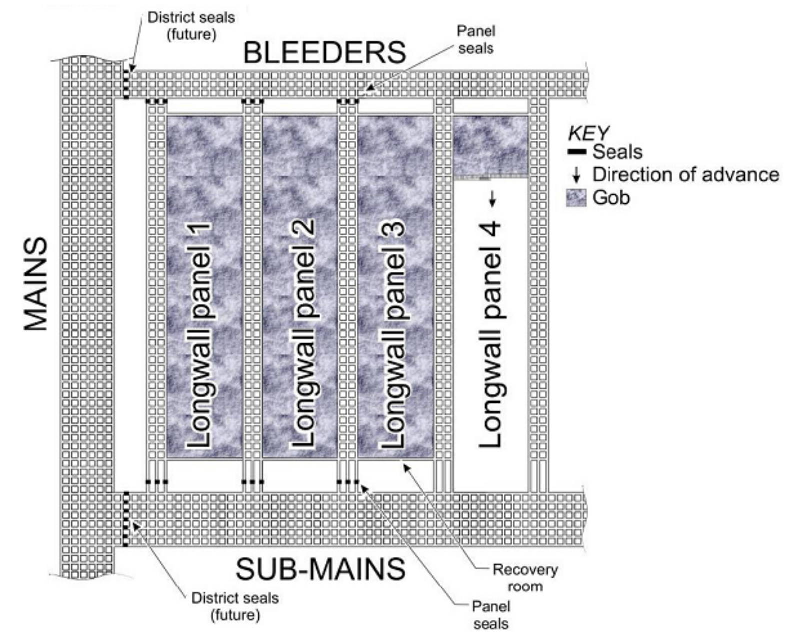

Figure 1 Typical district (series) and panel sealing practices in US longwall mines (after Zipf, Sapko and Brune, 2007)[1].

1 Zipf, Jr. RK, Sapko, MJ. and Brune, JF. 2007 Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines, IC 9500, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Pittsburgh, PA.

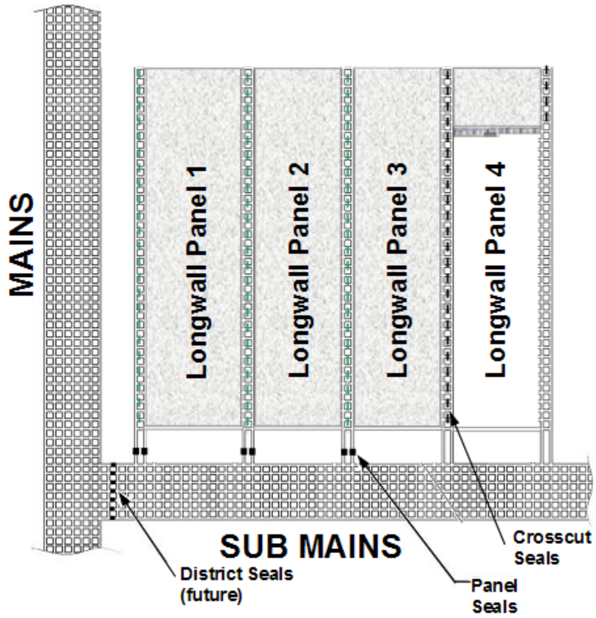

Figure 2 Typical district (series) and panel sealing practices on Australian longwalls

In comparing US and Australia some other issues of relevance are that in the US:

- Currently many changes are occurring in the handling of mine atmospheres and potential flammability conditions as a result of the Sago Mine disaster.
- There are a large number of small mines.
- MSHA adopts a system of "prescriptive regulations" and in general there is lower acceptance of risk assessment approaches.
- There is a perceived lack of trust between managers and inspectors and less working together of the two groups; the role of unions is less.
- US underground industry is diverse and larger; as a result the industry is less cohesive and there is less availability of data, less sharing of information and less frequent industry forums.

SURVEY RESULTS ANALYSIS

Of the 14 mines surveyed 13 used longwall extraction while one uses room and pillar method only. Of the longwall mines, five mines have Run of Mine coal production of more than 4 mtpa, three mines have 3 to 4 mtpa, two mines have 2 to 3 mtpa and the rest of mines have less than 2 mtpa. Production from these surveyed mines represents about 46% (43 mt) of total Australian longwall production of 92 mt in 2007. For the final Chain Pillar seals providing separation from adjacent panel air, it was found that

- The one Room and pillar mine uses no seals.
- Eight mines use 140kPa rating.
- One mine uses 70kPa rating.
- One mine uses 35kPa rating.
- Two mines use Nitrogen balance chambers with a cross-cut space formed with one seal rated at 35kPa and the other at 140kPa.
- Two mines use cementitious seals or plaster board stoppings with sealed joints meeting no rating standard.

For the final panel seals providing panel separation from Mains air, it was found that

- Five mines use 350kPa rating.
- Four mines use 140kPa rating.

- Two mines use 35kPa rating.
- One mine uses 140kPa but may move to 350kPa in the future.
- Two mines use Nitrogen balance chambers with seal ratings as above.

In summary all mines were receptive and positive to sharing information. goaf management is proactive with universal use of risk assessment methodologies. goaf atmospheres are complex and changing; gas concentrations vary across the goaf and some move in and out of explosibility ranges. There is a good understanding of

- sealing purpose (stated as to separate the goaf atmosphere from adjacent ventilation network air),
- diurnal atmospheric changes, pressure effects and seal limitations and leakage.
- geomechanics issues related to the key structural member – the roof, ribs and walls, floor and the seal itself.

Almost all mines mentioned that they have had seals that became defective over life. It is recognized that chain pillars crush out leading to atmosphere connectivity. All mines (including those with only two Heading Gate roads) have voids within sealed goafs of longer than 50m. More information is needed on gas concentration data across the extent of goafs; it cannot be assumed that gas composition is the same along the length and breadth of individual goafs. Many of the goafs record significant CO_2 that occurs in mines either as a seam gas or as a product of oxidation and it is considered that as CO_2 is an inerting gas and reduces the likelihood of an explosion its existence should be taken into account in determining risk of a goaf ignition.

VIEWS ON US CHANGING APPROACHES

When asked about the US changing approaches on seals and adoption of new MSHA regulations it was found that majority of mines agreed that the Australian industry should stick with what appears to work best for the conditions for Australian industry. Industry should use appropriate risk levels for seal design. The proposed new 840kPa seals design in the US are considered excessive and the US move to this rating an overreaction. Regardless of application of seal pressure rating requirements it is impossible to contain some explosions in the highly variable mine environment. The introduction of prescriptive US seal pressure ratings does not appear to have been formulated on any risk assessment basis. There are impressions that US (in almost all cases without realtime monitoring systems in place and relying on periodic “bag” sampling) is coming from a lower standard to current Australian practices. There is a perception that the US appears to have a different approach to the way Australian mines manage goafs. It is considered that US should move to use of gas monitoring and prevention of situations in which a goaf atmosphere can ignite.

Australian approaches to health and safety management are formulated on a risk assessment basis under which hazards must be identified and appropriate “world’s best practice” systems adopted. The principal approach in Australia to goaf management is early prevention of hazardous situations through use of real time gas monitoring from the goaf periphery to ensure the maintenance of goaf inert atmospheric conditions. Another line of defence is having inert gas systems on hand (most commonly jet or diesel engine exhaust, nitrogen, CO_2 or CH_4) to proactively ensure potentially explosible gas concentrations cannot form or are handled appropriately. The final approach is through use of well engineered seal structures constructed to segregate all worked out areas where there is any likelihood explosible gas concentrations occurring.

In undertaking risk assessments a number of Australian companies have expressed that they do not consider US new approaches are "world's best practice". The comment has been made that the US approach of principally and almost exclusively considering "seal rating" is one of "guarding against failure rather than adopting an approach of prevention". There appears to be a consensus among mine operators, inspectorates and union leaders that Australia should not blindly go down the path of copying US current and post Sago sealing practices.

SIMTARS PROPAGATION TUBE TEST WORK

The Queensland group SIMTARS is examining consequences of explosions through testing being conducted in a propagation tube as part of the effort to determine the risk of explosions in sealed off areas. This is being investigated not only to determine the nature of the explosion overpressures that a structure can be subjected to but also the nature of the pressure pulses impacting on the structure.

An analysis of possible scenarios in a mine was made and indicated that there were nine different situations where a methane explosion could occur in a mine. The most probable of these scenarios was a high length to diameter ratio roadway that would be full or partially filled with an explosive mixture. If an explosion occurred in the workings of the mine the roadway would not be enclosed and in the case of an explosion occurring behind a seal the roadway would be enclosed. Tests in the propagation tube (as shown in Figure 3) were designed so that varying parts of the tube were filled with an explosive mixture and the tube was left open or closed off with structure that withstood or failed under the pressure.

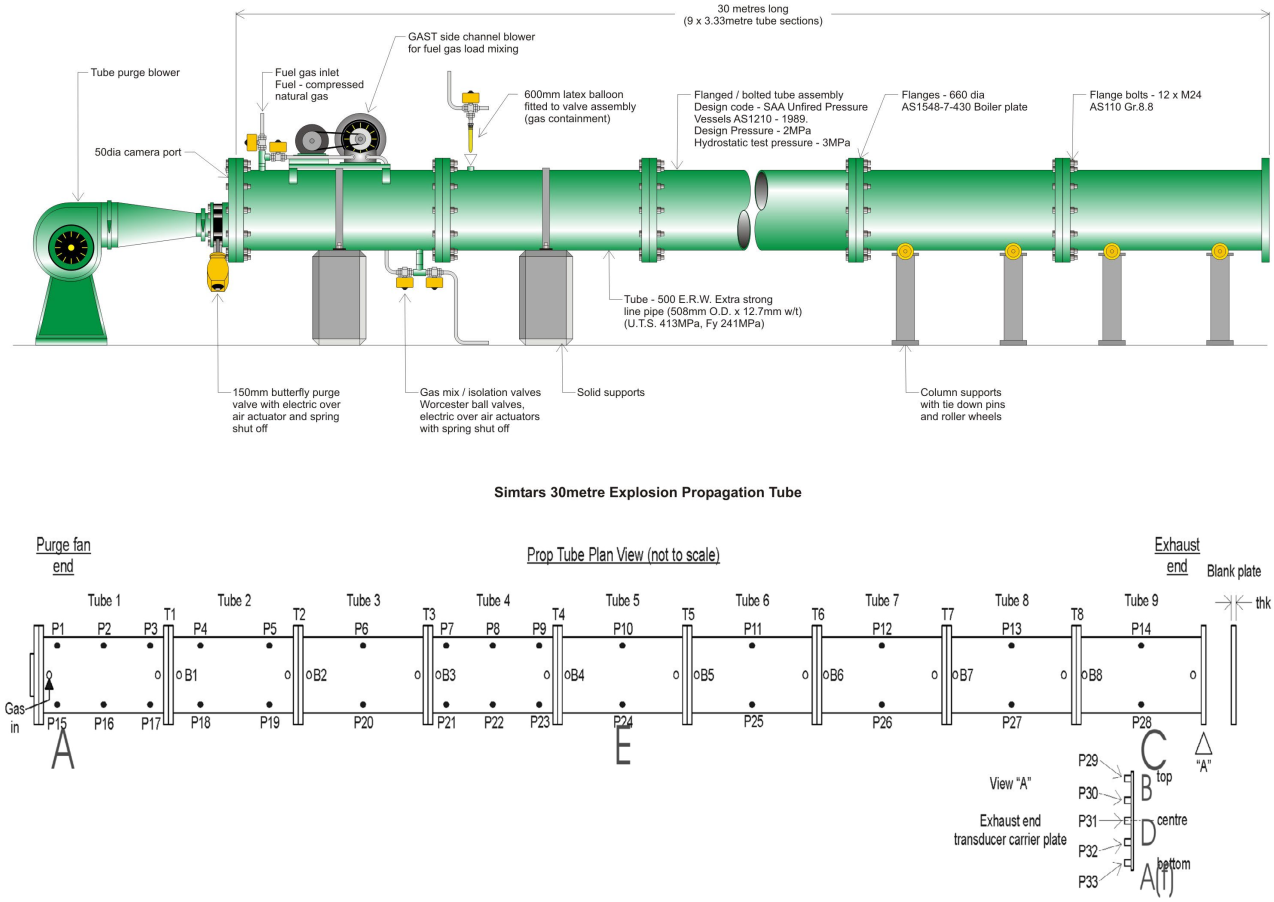

Figure 3 Layout of the explosion propagation tube at SIMTARS

Even though it could be argued that mine scale larger galleries with greater volume are more suitable for this type of study the propagation tube is nevertheless deemed appropriate for the following reasons.

- It has been proven that the maximum constant volume pressure is determined by the temperature of the burning gases in the container and not by its volume. The nature of the volume or space in the container might however influence the temperature that can be reached.
- The level of instrumentation on the tube allows significant information with regard to the pressures to be gathered.
- The tube allows a high rate of testing and multiple daily firings to be conducted.
- The tube has a design strength of 2MPa and can be closed with a strong structure to allow a contained constant volume explosion with a stoichiometric mixture.
- The tube at 30m long and 0.5m diameter has high length to diameter ratio. This allows simulation of compression of unburned gases before the explosion front. Due to availability, natural gas it is being used as the fuel in preference to pure methane.

The structures used within the tube during testing consist of plywood of varying thicknesses firmly bolted to the end of the tube. Just inside these structures there is a set of pressure and force transducers. The force transducer measures the dynamic pressure of the pressure wave and also gives a very good indication of when the air started moving after the structure failed. As the pressure transducer at the end of the tube is directed into the incoming pressure wave it reads the total pressure whereas the pressure transducers that are at right angles to the pressure wave and placed in the walls of the tube read the static or omni-directional pressure. In the testing process to date no attempt was made to generate a detonation even though obstructions can be placed in the tube to cause increased turbulence.

Explosion Tube Testing undertaken

Initial tests were carried out with gas mixtures occupying varying numbers of sections with a maximum of six out of the nine sections being ultimately filled with an explosive mixture. For any gas mixture filling more than one section, the extent of the flame is beyond the end of the tube. The strength of the structures was increased with each series of tests using a constant number of sections until the explosion was contained in the tube by the structure.

Characteristics considered to be of importance notwithstanding variance caused by changes in explosive energy and structure strength are as follows.

- The maximum pressure generated by constant volume explosions was less than the theoretical or calculated pressures for the test conditions. In the absence of any evidence of significant leakage the opinion was reached that the temperature has a significant effect on the pressure reached by the explosion. Efforts are presently directed at confirming the temperature effect.
- There is a very close correlation between the total pressure that is measured at the end of the tube and the sum of the dynamic pressure at the tube end and the omni-directional pressure in the last tube. This supports the theory that the total pressure is comprised of the dynamic and omni-directional pressures. It also indicates that there is no measurable reflected pressure generated by the explosive pulse. It was also evident that the structures failed due to being subjected to an increasing pressure caused by compression of gas due to deflagration rather than being subjected to the impact of a blast wave.
- The pressures that were measured when structures were broken indicated that during the period of the explosion and directly after, there were significantly larger total pressures measured after the structure had broken than at the time the structure broke (the point of failure). The point of failure can be determined from the pressure traces as there is no flow of gases as measured on the dynamic sensor until failure occurs. This increased total pressure is caused by the increase in dynamic pressure at the tube end caused by a rapid increase in the outflow of gases. The work in the tube has indicated that the flow of gas through a breach in the structure and the original pressure is related but not necessarily proportional to each other.

- The omni-directional pressure measured when the tube is not closed off does not seem to be influenced significantly by the volume of gas used in the explosion. This pressure would be a function of the friction in the tube as well as the inertia of the unburned gas column. When the tube is closed off the pressure measured on the total and omni-directional pressure sensors for a specific volume of explosive gas is proportional to the strength of the installed structure. In the event that the structure does not fail the total pressure is proportional to the volume of flammable mixture in the constant volume formed by the enclosed tube.
- The increase in total pressure that occurs after the release of gas following the failure of the structure is caused by the unburned portion of the gas mixture burning after being compressed by the reflection of the pressure wave back from the structure in the tube. This "pressure piling" effect occurs after the structure has failed and thus causes a significant increase of gas flow in the opening.

Some Results of Explosion Tube Testing

Tests with three sections filled with gas

Results from seven firings are shown in Figure 4. Two resulted in the explosion being contained within the tube resulting in total and static pressures being similar in value. Plywood structures were gradually increased in thickness from 3.6mm up to 12mm. Maximum total pressure developed with explosion was contained was 231kPa. Higher total pressure values were obtained when the structures broke with maximum recorded of 430kPa.

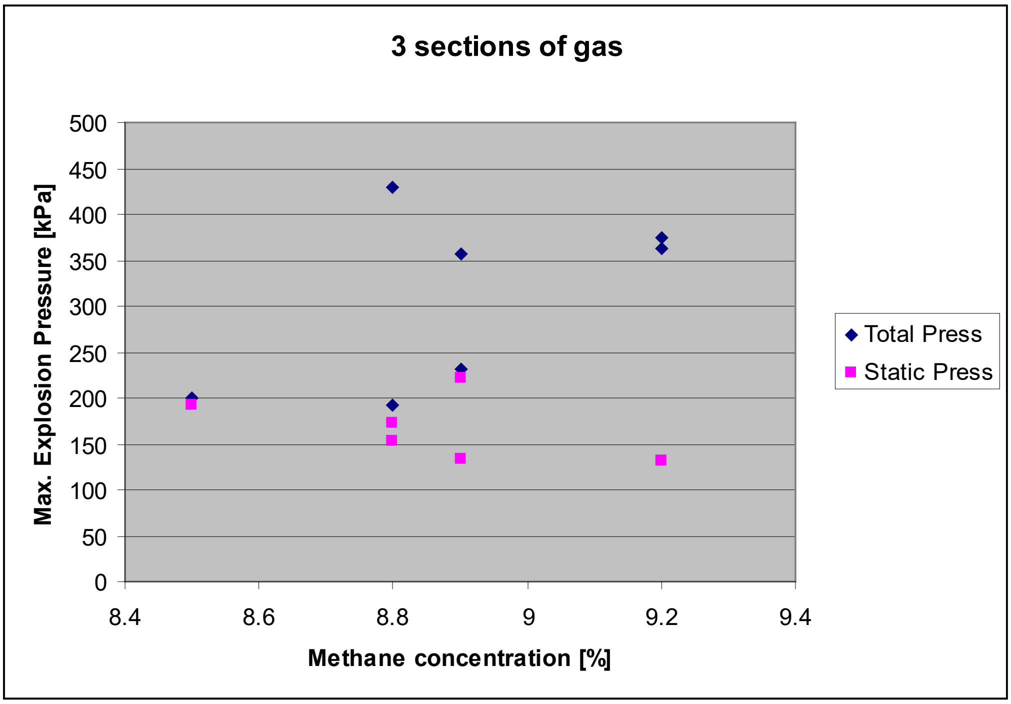

Figure 4 Tube explosion pressures against methane concentrations with three gas filled sections (basically one third full of gas)

Tests with four sections filled with gas

Results from four tests conducted are shown in Figure 5. Two of these resulted in the explosion being contained in the tube with total and static pressures being similar in value. Plywood structures were gradually increased in thickness from 9.6mm to 12.6mm. Maximum pressure developed when contained was 265kPa. Higher total pressure values were obtained when the structures broke (maximum recorded was 400kPa)

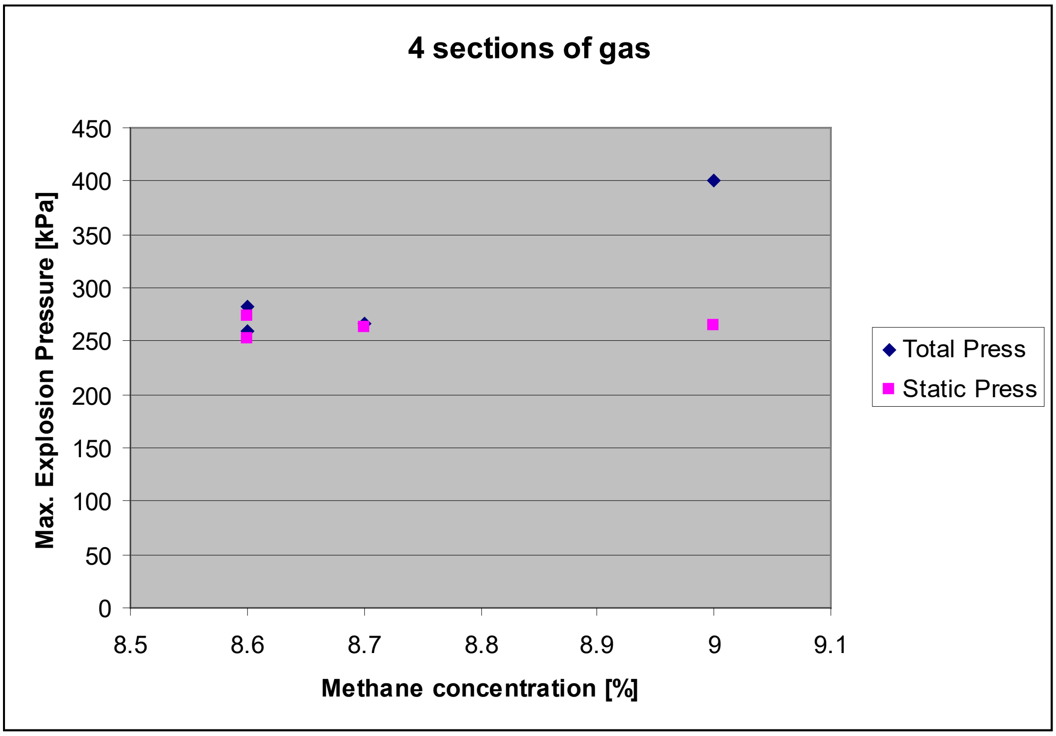

Figure 5 Tube explosion pressures against methane concentrations with four gas filled sections

Tests with six sections filled with gas

All three test results as shown in Figure 6 caused plywood structures to break with thicknesses gradually from 12 to 21.6mm. Maximum total pressure developed was 886kPa. Maximum static pressure obtained was 418kPa. Further testing is being undertaken to determine plywood structure thickness to contain this gas explosion pressure is currently being undertaken.

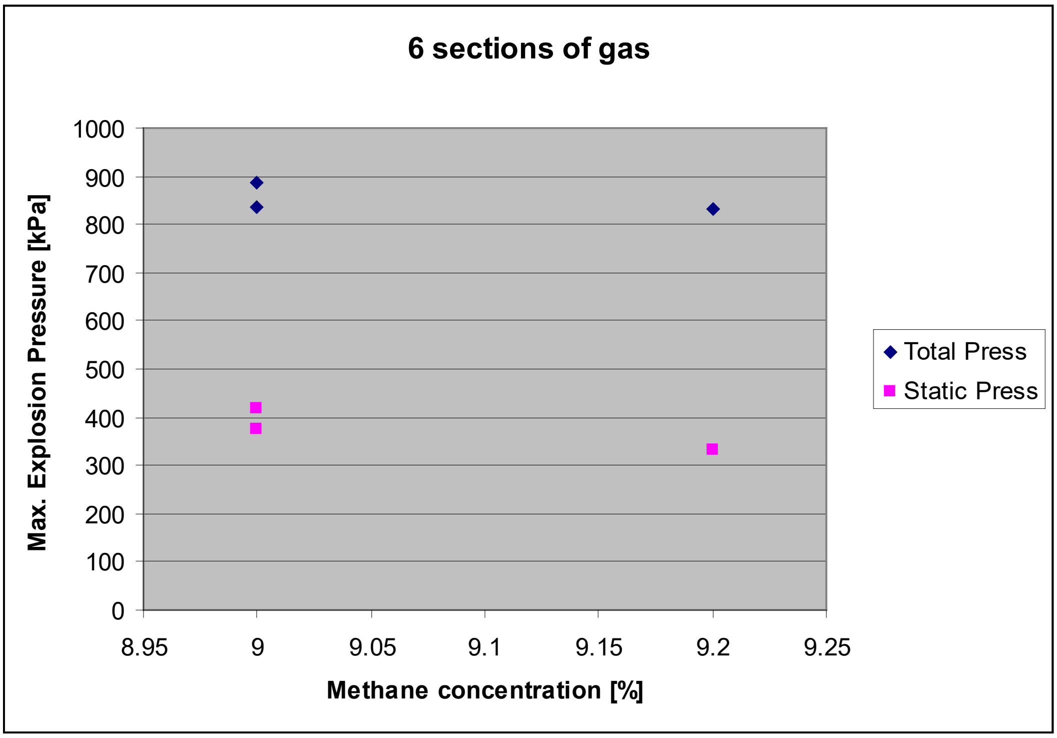

Figure 6 Tube explosion pressures against methane concentrations with six gas filled sections

Full Tube Testing undertaken

Closed volume tests are currently being carried out with the tube full of an explosive gas mixture. With the tube closed off with plywood sheeting the gas concentration in the tube was gradually increased from 6 percent in air to in excess of the stoichiometric or most explosible mixture. As plywood structures failed they were replaced with stronger ones. This was done for safety reasons and to ensure that the design strength of the tube was not compromised due to sudden pressure piling effects. The plywood structure was seen as the weak link and hence always the point of failure.

Tests with full nine sections filled with gas

Only one of the eight tests undertaken as shown in Figure 7 resulted in the structure breaking. Plywood structures were increased in thickness from 34mm (normal ply) to 36mm (structural ply). The maximum total pressure obtained was 907kPa was at 8.0 percent methane which is slightly less than the stoichiometric concentration of 9.5 percent. The maximum static pressure of 472kPa was also obtained at this concentration. This suggests there may be some variations in the way the gas is presented in the tube and the mixture is probably not completely homogeneous. This testing is continuing.

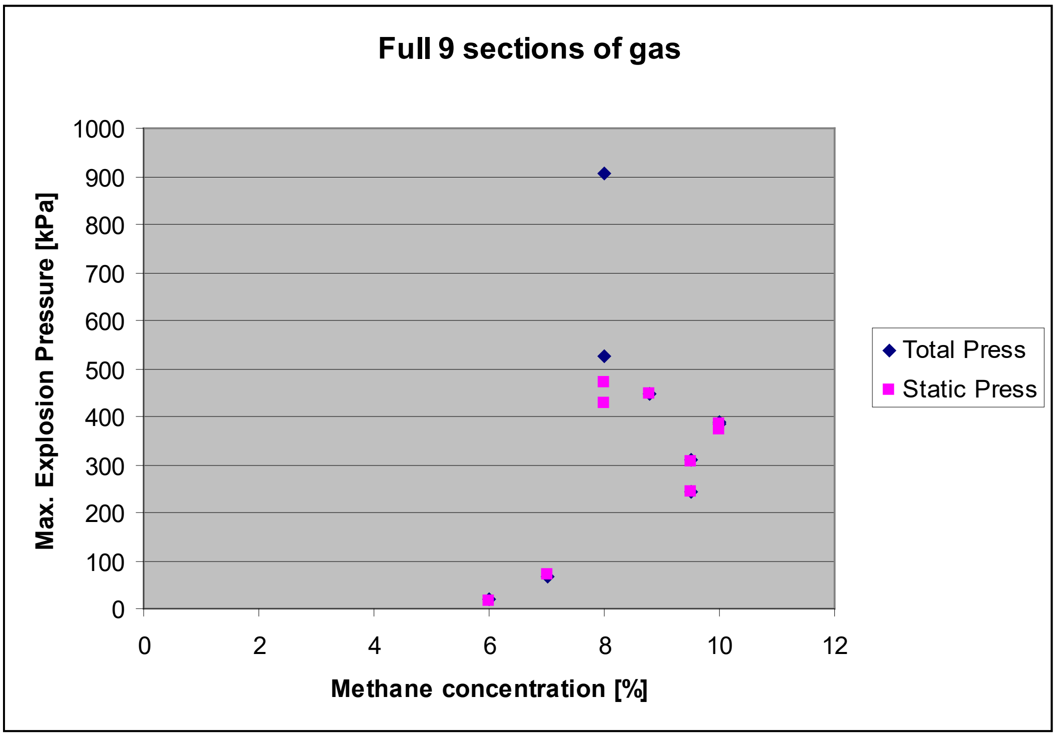

Figure 7 Tube explosion pressures against methane concentrations with nine gas filled sections (tube full of gas)

SUMMARY CONCLUSIONS AND FURTHER WORK

From survey results analysis and recent Australian debate on the topic it is concluded that seal design should start from premise that it is impossible to build a perfect seal.

- Seal designs must be determined using priorities from risk assessment of particular situations. Risk levels should meet ALARA (as low as reasonably achievable) with health and safety conditions expectations of less than
  - 1 death per million miner days of work

    - Less than 10 deaths per 10 million miner days of work
    - Never more than 10 miner deaths
- There is no known evidence of a mine atmosphere explosion detonations; every mine explosion has remained within the limits of a deflagrations.
- Seal should be rated to "seal" and not on structural applied pressure loading (to keep goaf gases out of ventilation air and oxygen out of goafs).
- Monitoring of goaf atmosphere and requirements for inert gases is critical.
- Mines with low gas levels should not face onerous conditions. Mines with potentially explosible gases need to monitor, respond and control. It is believed that "one rule is not appropriate for all situations".
- Seals must be competent engineered structures that normally meet 140kPa pressure rating.
- More understanding of mine strata geomechanics is needed; structural analysis should take account of the properties and behaviour of the strata surrounding the seal and maintain a low leak interface with coal seam and surrounding strata.
- More understanding of goaf gases ignition potential is needed. More information is needed on the variability of gas concentration data across the extent of a goaf; it cannot be assumed that gas composition is the same along the length and breadth of individual goafs.

The initial findings of the SIMTARS propagation tube test work have given a new understanding to the complex ways deflagrations can act on structures. Testing to date has resulted in a maximum static pressure of 472kPa and a total shut in or closed pressure of 524kPa. This is well below the explosion pressures expected for a closed volume. There appears to be no evidence of pressure piling at this stage. Sufficient evidence exists to warrant further in depth investigations. These fundamental characteristics will assist in drawing up measures that will assist in mitigating the effects of explosion pressures on seals.

As part of this ACARP project a generic risk assessment for 140kPa or 350 kPa rated seal designs will be developed based on the findings from the mine surveys and SIMTARS tests. This generic risk assessment will serve as a guide for the Australian mining industry when undertaking their own site specific risk assessments on 140kPa or 350 kPa seals.

ACKNOWLEDGEMENTS

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