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Pressure piling and the impacts of blast relief to protect primary fans in a highwall longwall operation

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ABSTRACT: A significant outcome from the Pike River coal mine disaster in New Zealand was reinforcing the importance of being able to re-establish primary ventilation as soon as possible after an underground explosion. This helps reduce the build-up of further explosive gas mixtures in the workings which potentially may have much more devastating impacts than the initial explosion. Two key factors that Australian regulators have subsequently identified as not having been sufficiently understood or considered in the past are the phenomenon of “pressure piling” and the design of blast relief at primary fans. This paper, which includes a case study, examines just what is meant by the term “pressure piling” and how it impacts on pressure spikes at surface fan installations in the event of an underground explosion. It describes modelling which found that in the case of an highwall-style retreating longwall operation where the portal for the surface conveyor drift also contains the surface primary exhaust fan for that longwall panel, provision of sufficient pressure relief (and hence volume flow relief) at the portal to protect the fans may result in such high velocity pressures within the conveyor drift, as the explosive over-pressures escape, that severe damage to the conveyor, and possibly plugging of the drift by conveyor debris, could result. In such a case, even if the primary fan is protected by the design of the pressure relief, the restart of the fan may not restore the primary ventilation circuit due to the total or partial blockage of the main exhaust circuit upwind of the fans. Potential implications and solutions to this problem are discussed.

1 INTRODUCTION

The report from the *Royal Commission on the Pike River Coal Mine Tragedy* (Royal Commission on the Pike River Coal Mine Tragedy, 2012) identified a number of major problems at that operation, some of which relate to the way the mine was ventilated.

To further understand the Australian mining Inspectorate’s concerns, the following (selective) extracts should be noted from the Pike River Commission’s report:

> “On Friday 19 November 2010, at 3:45pm, the mine exploded. Twenty-nine men underground died immediately, or shortly afterwards, from the blast or from the toxic atmosphere…
>
> “Over the next nine days the mine exploded three more times before it was sealed…
>
> “The commission is satisfied that the immediate cause of the first explosion was the ignition of a substantial volume of methane gas.…
>
> “The area most likely to contain a large volume of methane was a void (goaf) formed during mining of the first coal extraction panel in the mine. A roof fall in the goaf could have expelled sufficient methane into the mine roadways to fuel a major explosion. It is also possible that methane which had accumulated in the working areas of the mine fuelled the explosion, or at least contributed to it.
>
> “The original mine plan specified two main fans located on the mountainside next to a ventilation shaft. Two planning changes were made. Pike decided to relocate the fans underground in stone at the bottom of a ventilation shaft... Placing a main fan underground in a gassy coal mine was a world first. The decision was neither adequately risk assessed nor did it receive adequate board consideration. A ventilation consultant and some Pike staff voiced opposition, but the decision was not reviewed. Putting the fan underground was a major error.
>
> “The placement of the main fan underground and the damage caused to the back-up fan on the surface meant that the mine could not be reventilated quickly.…
>
> “The expert panel concluded that the size and duration of the explosion indicated it was fuelled by a large volume of methane, perhaps up to 2000 m^3. Methane

> accumulated in the hydro goaf following mining was estimated at up to 5000 m^3. Another roof fall like that which occurred on 30 October 2010 would have caused a large pressure wave bearing a substantial volume of methane.
>
> "The pressure wave would have flowed down the hydro panel roadways and entered the main mine roadways, with the potential to flow inbye, particularly if a temporary stopping failed and allowed the wave to enter the main intake roadway. Methane carried along the roadways by the pressure wave would be diluted by air into the explosive range.

Under "Proposals for Reform", the Enquiry made the following comments regarding ventilation (italics mine):

> *"Ventilation and gas monitoring*
>
> "Placing main ventilation fans underground in coal mines should be specifically prohibited. It is unlikely that a mining company would do so in the future, given the consequences at Pike River, but the matter should be put beyond all doubt. *Main fans should be required to be protected against explosion and other hazards, in accordance with appropriate international standards*.
>
> "In addition to requiring a ventilation officer, standards for ventilation control devices, such as stoppings that control airflow, need to be specified.
>
> "Minimum requirements for gas monitoring systems are needed so that the mine's atmosphere can be continually and comprehensively analysed."

In Australia, mining is regulated at the State not Federal level. To avoid the likelihood and/or reduce the consequences of a similar event occurring in Australian coal mines, state government regulators subsequently asked mine operators to review their ventilation systems and primary fan installations to ensure that if an underground explosion were to occur, the primary ventilation system could be restarted in the shortest practical period of time.

In this regard, two key factors that the regulators asked operators to consider are the impacts of:

- "Pressure piling", and
- Blast relief at primary fans to avoid any serious damage to the fans, i.e. damage that would prevent the fan being restarted quickly after a blast and the primary ventilation exhaust shaft returning to operational status.

These concerns were further expressed in a presentation by the Queensland government agency SIMTARS (Davies and Smith, 2013) in which the following general comments about blast protection in Queensland coal mines were made (italics are additional comments by this author):

> "It appears the (surface fan) enclosures were designed based on an explosion occurring in the enclosure itself *(i.e. not the potential for a much larger blast upwind of the fan within the mine)*
>
> "Explosion vents amount at best to 7 m^2 in total cross sectional area and are usually placed strategically around the fan housing
>
> "Ventilation shafts are typically around 20 to 25 m^2 in cross sectional area
>
> "No standards exist in Australia"

"Pressure piling" is discussed more fully later in this paper but effectively it refers to the following situation:

- An explosive gas mixture is simultaneously present in two (or more) interconnected volumes,
- An explosion is initiated in one volume (the first volume),
- For reasons discussed shortly, the peak explosive pressure reached in the other (second) volume is *higher than the peak reached in the first volume and is higher than the value that would otherwise be predicted for that volume from thermodynamic analysis*,

It can be seen from Figure 1 that the explosion panels for the surface backup fan installation at Pike River were small but probably typical for current practice in Australia.

Regarding the underground main primary fan (of which no post-blast photos are available, as the mine has not to date (January 2014) been re-entered), the report also states:

> "Pike did not install explosion proofing for the main underground fan, did not site the fans in rock and the blast panels on the surface fan proved inadequate during the explosion."

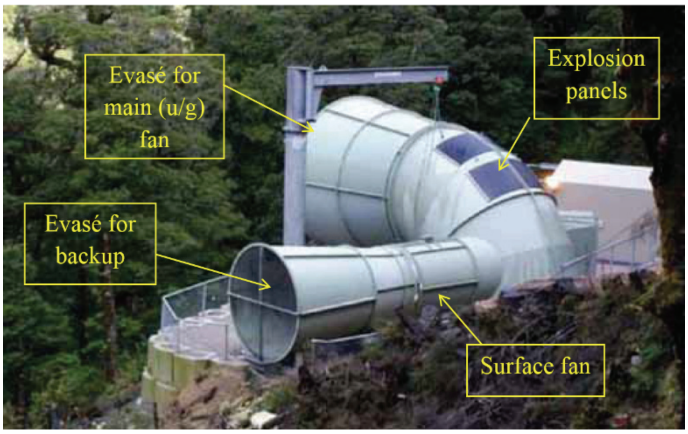

Figure 1. Surface backup fan at Pike River before the explosion. The dark panels on top of the elbow were the explosion panels. As the main fan was underground and the backup fan normally not operating, the exhaust shaft had a large evasé on surface as shown, allowing the underground fan to push air through to the surface. The main fan evasé outlet had louvres that could be closed to operate the backup fan (Photo: Pike River report).

In summary, the concern of the regulators was that:

- An initial methane explosion could so damage the surface fans that primary ventilation cannot be quickly re-established. However, at least

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some persons underground could possibly still be alive.

- The failure to be able to re-establish the primary ventilation leads to a more general methane accumulation issue underground, which prevents any search and rescue operations and then triggers a far more devastating methane or coal dust explosion which not only destroys much of the rest of the mine, but also proves fatal to any persons still alive.
- "Pressure piling" is one factor that can contribute to explosion relief on the primary fans being undersized, or in the wrong location, or of the wrong type.

2 OBJECTIVES

In this case study, four steps were identified as being required to address these concerns:

- Understand the theory of dynamic (time-dependent) overpressure propagation with respect to the factors in an underground mine (e.g. geometry of the mine and openings, etc)
- Understand the range of "credible" explosions that could occur in terms of near-instantaneous overpressures generated and locations
- Model the overpressures produced in the credible worst-case explosion scenario, including failure of ventilation controls
- Understand the potential solutions at the surface fan to protect it from these overpressures or to allow it to be restarted quickly.

The particular mine which was the subject of this study is a highwall operation using the longwall retreat technique. Each longwall block is effectively accessed via new mine entries driven off the highwall. The conveyor which removes the coal from the face exits the underground via one of these highwall entries (via a short concrete culvert). The same conveyor drift is also one of the mine exhausts, so has a primary surface fan off at 45^0 to the side of the culvert with a coffin seal at the end of the culvert to reduce short-circuiting of intake air directly into the fans. There were a total of 5 surface fan installations at this mine: four off highwall portals and one off a surface exhaust shaft (Fig 4).

It was decided to model potential longwall face/goaf explosions with the face position at 50%, 75%, and 100 % extraction. The 100% extraction location meant the face was closest to the highwall and therefore to the primary fans (about 150 m separation). An additional model for 0% extraction (i.e. at longwall start-up) was also examined.

Note that this paper reports only the modelling aspect of the work completed; *other important aspects of this work such as a review of ventilation controls and a review of the fan/conveyor drift geometry/layout are not reported here.*

3 DEFINITIONS AND GLOSSARY

There is frequently inconsistent use of important explosive and pressure piling terms in the various literature. For the purposes of this paper, the following definitions, largely taken from Bjerketvedt et al (1997) and Zipf et al (2007), are used:

Table 1. Glossary of terms

Blast wave	The air wave physically set in motion by an explosion
Burning rate	The amount of fuel consumed by the combustion process per second
Flame speed	The absolute velocity of a flame front relative to a *stationary observer*
Burning velocity	The relative velocity of the flame front *with respect to the velocity of the unburnt fuel immediately in front of the flame front*
CJ pressure	The Chapman-Jouguet detonation pressure
CV	Constant volume (an explosion which occurs within a fixed volume vessel)
CV pressure	The "ending" pressure produced when an explosion occurs in a fixed volume
Deflagration	A rapid combustion (explosion) with burning velocity (note: not flame speed) less than the speed of sound (1193 kph or 331 m/s)
Detonation	A rapid combustion (explosion) with burning velocity (note: not flame speed) greater than the speed of sound (1193 kph or 331 m/s)
Dynamic pressure	The pressure of a moving fluid (e.g. air) if were to be stopped against a wall
Overpressure	The peak value of pressure (e.g. the pressure wave) above the normal value of pressure at that location, i.e. the increase in pressure rather than the absolute pressure. For example, an overpressure of 800 kPa from a pre-blast absolute pressure of 100 kPa (about sea level pressure) would create an absolute blast peak pressure of 900 kPa.
Reflected wave	When a shock wave strikes a solid surface, part of the energy of the shock wave induces a reflected wave, which can result in very high pressures at that location, but with lesser energy and pressures in the continuing shock wave
Shock wave	A fully developed pressure wave of large amplitude, across which the density, pressure and particle velocity change dramatically
Stoichiometric composition/ mixture	The ratio of fuel and air which results in no excess fuel or excess air being left at the end of the reaction. For methane at standard temperature and pressure, this is 9.5% CH_4 by volume, or 67.8 grams CH_4 per m^3 mixture. In most cases, the peak pressures from an explosion are obtained when the mixture starts at the stoichiometric value.

4 FUNDAMENTAL THEORY AND REVIEW OF CURRENT WORK

4.1 *Consequences of an explosive gas release or presence*

When there is a flammable gas release or presence, the consequences can be (Bjerketvedt et al, 1997):

- *Nothing*, if there is no ignition source and the gas dilutes away.
- *Fire*, if the gas immediately catches fire on exposure to the air. In this case, the fuel and the oxygen are mixed *during* the combustion process.
- *Explosion*, if the gas/air mixture builds up to a flammable cloud, and is then ignited. In this case, the fuel and oxygen are mixed *before* the combustion process starts.

For a stoichiometric mixture of methane and air at 25°C and 101 kPa, the increase in pressure at constant volume is 8.94 times starting pressure and the increase in volume at constant pressure is 7.72 times starting volume (Zipf et al, 2007). See Fig 2.

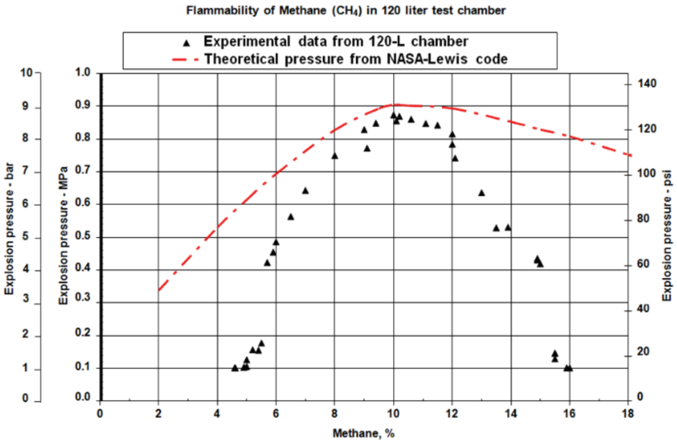

Figure 2. Peak (over)pressures from a methane-air mixture occur at the stoichiometric mixture of 9.6% CH_4. Experimental data is influenced by the limited size of the test vessels. (Zipf, 2007).

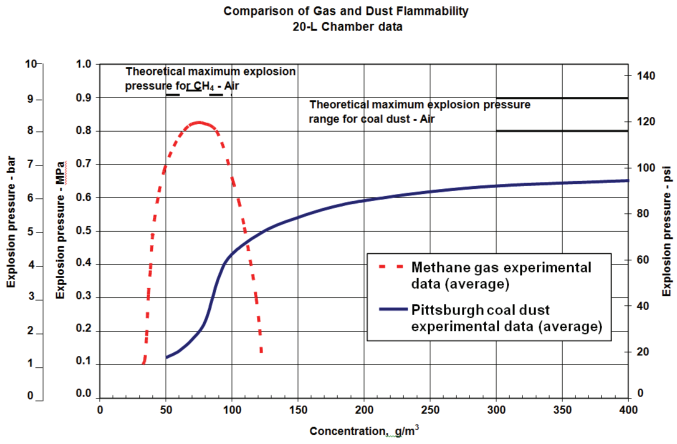

Figure 3. Explosion pressures from methane and coal dust explosions (Zipf, 2007)

4.2 *Potential pressures from a combination of methane and coal dust explosions in closed vessels*

Unlike methane, coal dust does not have a similar "rich" or upper concentration limit beyond which the mixture becomes non-explosive. Coal dust reaches a maximum explosive pressure at concentrations of about 200–300 g/m^3 (Fig 3). The energy release from a coal dust explosion is only limited by the available oxygen in the reaction vessel or the sealed area of a coal mine, if enough dust is available.

4.3 *Potential pressures from a methane/coal dust explosion in tunnels*

Zipf et al (2007) describe the potential development of an explosion in a tunnel initially completely filled with an explosive mixture, from a slow deflagration to a rapid deflagration to a detonation including the potential for very damaging reflected waves. The four possible stages are: "slow deflagration, fast deflagration, detonation and reflection of a detonation wave from head-on impact with the closed vessel".

> "Above each stage of combustion is a pressure profile along the tunnel. Upon ignition, the initial laminar flame speed is only 3 m/s; however, a slow deflagration accelerates, and the turbulent flame speed might increase to about 300 m/s *(the "run up")*. The pressure in the burned gas behind the flame front increases to the 908-kPa CV explosion pressure. The combustion front acts as a piston, compressing the unburned gas in front of it. The leading edge of this acoustic wave propagates at the local sound speed of about 341 m/s. In between this wave front and the flame front, the unburned gas acquires velocity and the static pressure inside this region will increase. This pressure increase ahead of the flame front is termed 'pressure piling.' (italics mine).

Zipf et al (2007) goes on to note that the peak pressures due to pressure piling will be higher than the CV value, that peak pressures in a detonation can be up to about 1.76 MPa (the CJ (Chapman-Jouguet) detonation pressure) and reflected overpressures could be 4.1 Mpa or higher. However, in all cases, "these transient pressures will quickly equilibrate to the 908-kPa CV explosion pressure as before".

The important point for explosion modelling in this study is that the explosion in the portion of the mine that initially contains the explosive gas mixture could reach catastrophically destructive transient pressures, but as soon as the blast has run out of fuel, the pressures within this zone will revert to 908 kPa overpressure.

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4.4 *Pressure piling: what is it?*

There has been some use of the term "pressure piling" already in the above discussion. However, this is not the only (or even most common) way in which the term is used. There are at least three contexts in which the term "pressure piling" is used.

4.4.1 *"Pressure piling": Classical definition*

Di Benedetto et al (2005) define pressure piling in this way: "The phenomenon of explosion of flammable hydrocarbon-air mixtures in two or more interconnected compartments is commonly defined as 'pressure piling' and it is characterized by a pressure peak higher than the thermodynamic value".

This is a similar definition to that used in AS2380.2 (1991) which defines pressure piling as "a condition resulting from ignition of pre-compressed gases in compartments or sub-divisions other than those in which ignition was initiated".

There are major differences between the classical pressure piling situation in closed vessels and the sense in which the term has more recently been used in coal mine airways:

- At the time of ignition in a coal mine, only the "initial vessel" (e.g. an open longwall goaf or the longwall face itself) has explosive gas in it. All other "vessels" have non-explosive mixtures in them (although the initial explosion could partially push an explosive mixture into some of them, although this is not a major mechanism given the speed of the flame front)
- In a conventional pressure piling situation, there are no additional "vents" except for the two interconnected and gas-filled vessels: the first vessel can only vent into the second, and the second vessel must vent back into the first (unless the vessels themselves fail or the vessels are vented to elsewhere). In an operating mine, there are many points at which the "vessels" (airways) can vent into other "vessels" (airways) and also more than one vent to atmosphere via the shafts or portals.
- In a coal mine, there is the risk of a gas explosion proceeding to a coal dust explosion, a different scenario to pressure piling which is based on gas explosions only.
- The term *pressure piling* is not used, in this sense, with respect to detonation-type (CJ) explosions only constant volume (CV) explosions.

4.4.2 *"Pressure piling" in a long duct*

As used by Zipf (2007), the term "pressure piling" can indicate the increase in pressure as an explosive mixture in (say) a tunnel is ignited at one end of the tunnel, and the flame front accelerates along the tunnel pre-compressing the explosive gas in front of it and hence increasing the pressures from the initial starting values at the site of the ignition. There is no need for "two vessels" in this sense of the term, merely one long vessel.

4.4.3 *"Pressure piling" in non-explosive venting*

The term "pressure piling" has also been used to describe the short-term pressure increase in a duct system well away from an actual explosion and in a region where there is no explosive gas. In this situation, the pressure piling is not due to an explosion at the pressure piling point itself but is due to the increase in pressure *away from the explosion site* where the high pressures in the shock wave meet obstructions in the escape paths resulting in a high-pressure reflected shock wave and pressure concentration. It is important to remember that each time a shock wave produces a reflected wave, the energy of the original shock wave is divided into the continuing shock wave and the reflected shock wave, so that the energy of the continuing shock wave reduces.

4.5 *Overpressures and pressure piling*

Whether the overpressure produced at the surface fan location from the blast is due to the dissipation through the workings of the explosion overpressure at the original blast site, or due to the pressure concentration due to shock wave reflections in the airway at the fan location (or a combination of both), if this overpressure cannot be relieved ahead of the fans (e.g. by blast doors), then the overpressure will destroy the fan elbow as well as catastrophically damaging the main fans and rendering the primary ventilation system inoperable for some time. If the blast panels "do their job", then the elbow and fan will survive and the blast panels should be able to be easily replaced allowing the fan to restart very quickly.

4.6 *Implications for explosion modelling in coal mines to protect primary fans*

With regard to understanding overpressures near the primary fans, the objective of this exercise is not to try to estimate the damage to the area of the mine originally filled with explosive gas (e.g. longwall face) or even to other production-related underground infrastructure (conveyors, regulators, overcasts, etc). Rather the issue is to estimate the potential overpressure spike ("pile") at the exhaust shaft collar or shaft portal where surface primary ventilation fans are located and to assess what mitigation strategies are required to ensure the primary fans can re-establish the primary ventilation immediately (or in a very short time) after a blast, to prevent further more damaging blasts and/or to facilitate self-rescue from those who survived the blast and/or to facilitate safe aided rescue by mine rescue teams.

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5 BLAST RELIEF TO PROTECT PRIMARY FANS

Unfortunately, the research and standards for pressure piling and pressure relief applicable for industrial facilities are limited to situations where the length of the enclosure is not more than about 20 times the diameter of the enclosure. This makes most of this theory of little value for mines at least within the zone originally filled with explosive gas, as this can be subject to detonation as well as pressure piling.

The MSHA (USA) requirements for blast relief on primary fans are set out in MSHA CFR 75.310 and further discussed by Conn and Verakis (1993).

They note that the fan can sustain explosion damage by:

- Explosion damage from an explosion wind,
- Debris propelled by the wind or
- A shock/detonation front.

The important thing here is that it is not only the "pressure piling" effect that can damage the fan; in particular flying debris is an important potential source of damage.

6 EXPLOSION MODELLING SOFTWARE

The two gas explosion models used by NIOSH in the Zipf et al (2007) report were AutoReaGas, available from Century Dynamics in the United Kingdom and FLACS (Flame Acceleration Simulator) available from GexCon of the Christian Michelson Research Institute in Norway (of which Bjerketvedt, the lead author of the Gas Explosion Handbook (Bjerketvedt et al, 2009), was an employee). AutoReaGas and FLACS are specialized computational fluid dynamics (CFD) models for numerically solving the partial differential equations governing a gas explosion. These models are used extensively in the oil, gas, and chemical industries to assess risks, consequences, and mitigation measures for various gas explosion scenarios. In particular, they have seen application to offshore oil and gas production facilities since the Piper-Alpha oil platform disaster that occurred in the North Sea, UK, in 1988. A few European research groups have made attempts to use these models to study gas explosions in mines, but to date such work is very limited.

Zipf et al (2007) performed comprehensive modelling but this was to examine local pressures on seals using relatively simple geometries and was not to model the "dissipation" of the high pressures through to surface, or the "domino effect" as ventilation controls such as regulators and overcasts fail.

The complexity of most underground mines, along with their ever-changing geometry, means that the use of such special purpose CFD programs for explosion modelling in operating mines is not practical. The following case study uses an explosion modelling feature within the ventilation modelling software Ventsim™, key details of which are described below.

7 CASE STUDY

7.1 *Credible scenario for explosion*

There are no doubt a large number of potentially credible explosion scenarios for any coal mine. However, the mine which is the subject of this case study adopted the following credible scenario:

- Gas explosion on the longwall face and/or in an open goaf behind the longwall face
- At the time of ignition, there are no other explosive gas mixtures in the mine. This would be typical of a well-operated mine before any secondary explosions occur.
- Whether the explosion is a deflagration or a detonation is not relevant in that this only determines the local transient peak pressures within the zone of explosive gases (or somewhat further along the flame path, i.e. the longwall face). Immediately after the explosion, gas pressures return to the CV values and it is this value that must then be dissipated through the rest of the mine, and eventually to the surface.
- In addition, since a detonation does not disturb the air mass in front of it and moves at 1800 m/s (Mach 5.3) (Zipf et al, 2007), if explosives gases were to extend through the entire mine to the surface and this mixture was to detonate, then blast relief panels would be useless as there is no local pressure increase at the fans to activate the blast relief panels, until the detonation itself arrives with its catastrophically destructive overpressures.
- The gas explosion occurs on the longwall face, so that the overpressure is produced at this location. Modelling can therefore be considered to assume an instantaneous high pressure and volume on the longwall face, attenuating as this overpressure moves rapidly through to mine to all lower-pressure regions, causing seals to fail, and the pressure-relief path through the mine to then change (continuously as seals continue to fail), etc.

7.2 *Assumptions of the initial gas volume and concentration and initial pressure for explosion modelling*

Given the above and the fact that it is overpressures at surface ventilation connections that are the object of this case study, the following key assumptions were adopted:

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- The Pike River Enquiry notes that the initial explosion was perhaps up to 2000 m^3 of methane. This was taken as meaning pure CH_4 volume plus associated diluting air. In the case study, the longwall face was about 330 m long and about 3.5 m high, and assuming the depth available for an explosive gas mixture is 10 m, the total volume of explosive gas mixture along the face would be in the vicinity of 11550 m^3. If the mixture was 10% CH_4, this would be a volume of CH_4 of about 1155 m^3 or a little over 50% of the estimated Pike River event.
- Peak pressures after the blast were set at the CV value of 8.96 times the starting pressure or 900 kPa absolute (assuming the underground workings are approximately at sea level). This pressure will exist along the longwall face and then be dissipated throughout the mine blowing out ventilation controls as the overpressure expands outwards from the original blast site.
- This value of 900 kPa is high compared to the known or estimated peak values from other historical coal mine explosions, but is not incredible (Zipf et al, 2007).

7.3 *Modelling technique used for the Case Study*

As noted above, there has been no “whole of mine” explosion modelling package developed for any type of complex underground facility such as a coal mine, to date. Any explosion modelling has used CFD techniques and been strictly limited in application. For this exercise, a new module within Ventsim (“ExplosionSim”) has been used for the modelling. However, it is important to understand that some simplifications have been made in the modelling technique. Ventsim has taken the following approach in the explosion module:

- Ventsim injects air at the user-defined fixed (explosion) overpressure into the zone of airways in which the user has designated the explosive mixture will be present. In the case of the case study, this is the entire length of the longwall face.
- Ventsim performs a simulation to determine the effective resistance from the explosion site through to surface.
- The program then loops through every 1/1000th second, feeding a portion of the overpressure volume (1/1000) into the model through pathways leading from the blast zone. The remaining volume allows the next overpressure to be calculated.
- During each loop, the overpressure expansion radiates in all available directions such that pressure can be calculated at any location based on the ratio of expanded gas pressure to the original overpressure at the time the pressure wave reaches that location.
- A ventilation control “fails” when the overpressure on the control exceeds the user-nominated failure pressure, e.g. a “35 kPa” seal will fail at 35 kPa overpressure on either side of the control, assuming the user sets up the control to fail at this overpressure. Requiring the control to fail when the overpressure on either side of the control reaches the failure pressure is more realistic and conservative than attempting to use a “modelled” differential pressure across each control, given the blast wave moves so quickly.
- Effectively, this means new resistances of the blast dissipation through to surface can then be re-calculated minus the failed control.
- The blast dissipation routine is then restarted assuming the control will no longer be in place and the algorithm repeatedly progressively expands the blast overpressure volume further until no further controls will fail
- The total time of blast dissipation occurs when the remaining blast overpressure fall below 10 Pa (0.01 kPa residual overpressure). This is reported in the message box.

As noted earlier, peak pressures within the initial explosive gas-filled zone can reach as high as 1.8 to 4.5 Mpa. However, even in the event of a detonation, the peak pressure within (or outside) the initial zone filled with explosive gas, a very short time after the flammable gas is consumed, will not exceed 9 times the initial local underground absolute pressure, or about 900 kPa. “Pressure piling” due to the obstructions in the airways including at the fan location can still occur, but it will only “pile” on top of the already dissipated pressures reaching the collar. Ventsim does not attempt to calculate the potential local pressure spikes due to reflected shock waves.

7.4 *Results of modelling at the Case study*

As with any modelling exercise, it is important to understand the objectives of the model as this governs whether it is “fit for purpose”.

The two critical issues for the case study mine were to understand:

- Which primary fans could “fail” in the event of a gas explosion on the longwall face, and
- For those fans, what measures could be taken to protect the fans or to ensure they can be restarted as soon as possible.

In addition to the potential for the ventilation controls in the mine to fail and the primary fans to fail if there is insufficient blast relief, a highwall operation such as the case study also has the potential for any structures projecting from the portals to fail. For example, at the case study mine, a concrete culvert (containing the conveyor and associated coffin seal) projects from the mine entry and also provides a suitable mating point for the main fans.

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Predicted peak overpressures at the five primary fan locations are summarised in Table 2. To estimate *potential* peak overpressure at each fan location, column B in Table 2 assumes that the fan portals have not failed (coffin seals are intact) and blast relief doors have not operated, i.e. while other seals in the mine fail are allowed to fail at their nominal pressure rating (e.g. 14, 35 and 140 kPa), the fan portal "seals" are assumed to not fail in this modelling. This is to estimate the potential peak overpressure value at the fan location *without pressure relief*.

The number and location of seals within the mine workings that fail is complex, determined by how fast the original blast overpressure can dissipate through to surface, and the amount of "expanding volume" available for pressure relief as the various seals fail, as well as by the strength of individual seals.

In the case of portal fan MG8, peak wind speeds (and hence velocity pressures) will occur if the structure or blast relief doors at the fan do "blow out" (fail). To estimate the potential upper severity of the wind blast at the fan portal, modelling of values in column B was performed where it is assumed the portal structure has "blown out", i.e. failed. This is quite different to the situation in column A where to estimate the potential peak overpressure at the fans, it is assumed the structure around the fans has not failed.

It is critical to note that these wind speeds assume the entire conveyor drift cross-sectional area is available for flow, which is not the case. Likely wind speeds are possibly up to twice those modelled.

For comparative purposes, the "equivalent" cyclone/hurricane wind speed is also shown in the table. Wind speeds cannot be directly compared to "cyclone ratings" as the air density in a mine explosion overpressure situation is much higher (and therefore more damaging) than air density in a cyclone. However, comparisons between velocity pressures of cyclones and explosive overpressure releases should be more comparable in terms of damage.

7.5 *Potential controls*

It is important to note that the risk control strategy recommended for this operation, and required by the regulators, assumes the primary ventilation circuit can be re-established very quickly after the primary explosion, so that any secondary explosions are avoided, or the fuel content of any secondary explosion is kept low by dilution with fresh air so that they do not (as in the case of Pike River) create more damaging secondary explosions than the original primary explosion.

One complication that makes this highwall operation unusual is that the exhaust (portal) in which the fan is located is also the conveyor drift, and any major explosion underground will produce not only high overpressures in this drift, but (unlike most other coal mine exhausts (shafts) which are "empty") is also likely to result in damage or destruction of the conveyor and/or "piling up" of the destroyed conveyor belt and its steelwork potentially near the portal (particularly in the scenario where the longwall is fully retreated). This drift with all its infrastructure would also provide an ample supply of flying debris, some of which will be at very high speeds.

The issues here are that the damaged conveyor partially blocking the drift could produce even higher overpressures at the portal than predicted (by "bottling up" the pressures) and also provide ample projectiles that could easily pass through the fan and destroy it.

Possible controls to help ameliorate this issue included:

- Design pressure relief blow-out panels at the portal to keep overpressures and wind speeds "as low as reasonably achievable" (ALARA) and comply with MSHA CFR 75.310.
- Being able to safely close off the conveyor portal irrespective of its condition
- Using a combination of other fans in the mine to provide a temporary ventilation circuit that ventilates as much of the mine as possible.

Table 2. Predicted peak pressures at all five surface fan locations and peak wind speeds MG8. Note that there are significant changes to the primary ventilation circuit (including primary fan relocations) between LW8 at 0% and the other three scenarios.

A: Assumes blast relief does not operate								B: Assumes blast relief has operated
LW8 % extraction	Blast dissipates (seconds)	Number of failed seals	Peak overpressure at each fan location, kPa					Peak velocity pressure, Pa, MG8 fan and equiv category cyclone
			MG8 fan	MG10 fan	MG11 fan	MG3 fan	Surf fan	
0%	20	24	7.4	n/a	n/a	6.2	6.9	2300 Pa (category 3)
50%	11	24	13.7	0.0	0.0	n/a	n/a	9400 Pa (>>category 5)
75%	5	38	23.5	0.0	0.0	n/a	n/a	12500 Pa (>>category 5)
100%	6	25	52.5	0.0	0.0	n/a	n/a	34000 Pa (>>category 5)

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Each of these strategies requires a plan to be developed and risk assessed to ensure the work can be carried out even with a potential explosive mixture of unknown volume present underground.

Note that even if the pressure relief panels do operate, the portal will still experience high overpressures due to the finite rate at which the blow-panels can relieve the oncoming pressure wave from the explosion. The purpose of the blow-out panels is not to eliminate the potential for overpressures, but to:

- *Reduce* the peak overpressures, and
- Where the blow-out panels are located in the direct line of the blast (the normal situation), to *allow flying debris to escape* without being forced into the fan inlet and fan impeller

Assuming the fan is undamaged in the explosion or can be rapidly recommissioned, provision must be made to allow the blast relief panels to be reinstalled assuming an explosive mixture remains underground without creating excessive risk for the repair crew.

8 SUMMARY AND CONCLUSIONS

The explosion scenario examined in this case study is for a blast igniting a flammable gas mixture filling the entire longwall face, but not elsewhere in the mine. It assumes no secondary gas explosions and no triggered coal dust explosion.

Peak pressures reached when a volume of gas explodes in a coal mine can reach up to 4.5 MPa due to a combination of: the explosion pressure itself, the “enhanced” effects of pressure piling, potential detonation (for supersonic explosions) and shock wave reflections.

These “enhanced” pressures, except for reflected shock waves, only occur within the volume originally containing the explosive mixture.

These “enhanced” pressures are transient, i.e. as soon as the explosion is over, the peak pressures within the volume originally containing the flammable mixture reduce to about 900 kPa.

Extreme destruction can therefore occur within the volume originally containing the explosive mixture.

Outside of the volume containing the explosive mixture, the peak non-transient pressure reached will be 900 kPa and will reduce as the now exploded gases expand into the remainder of the mine workings, including via failed ventilation controls.

A primary ventilation fan can sustain explosion damage by:

- Explosion damage from the airblast (wind) produced by the blast,
- Debris propelled by (carried along with) the wind, or
- A shock/detonation front.

The impact of reflected shock waves is to increase the pressure at the location of the obstruction, but reduce the energy and pressure of the continuing wave.

Only the potential for airblast overpressures and debris damage have been considered for this case study modelling.

The number and location of seals that fail is complex, determined by how fast the original blast overpressure can dissipate through to surface, and the amount of “expanding volume” available for pressure relief as the various seals fail, as well as by the strength of individual seals.

Table 2 provides estimated peak (worst case) overpressures in the case study operation and Figure 5 provides the expected ventilation control failures.

Table 2 also provides estimated peak velocity pressures at MG8 assuming an “open” drift (i.e. without any deduction of cross-sectional area for the conveyor). This is an indication of the potential destructive force of the wind on the conveyor structure in this region. A comparison with cyclone “ratings” is also provided.

Potential solutions to this issue at this mine include having a contingency plan to recreate a viable primary ventilation circuit without the highwall fans on this maingate, and, in the medium term, to not put highwall fans servicing future longwall panels in the conveyor drift for that panel.

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Figure 4. Case study mine plan of operations

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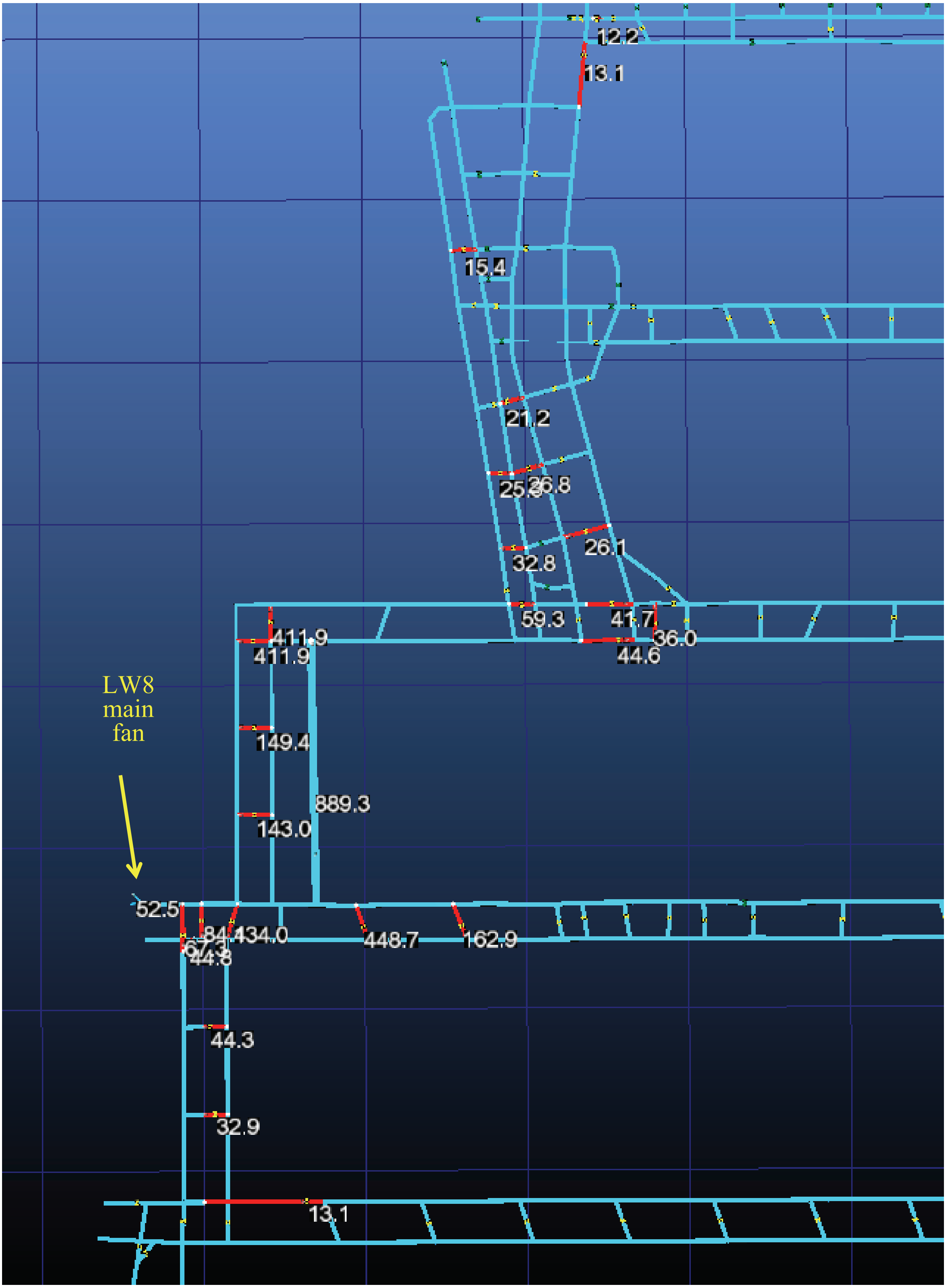

Figure 5. LW8 at 100% (scenario D in Table 2): 25 seals fail (red). Numbers are peak explosion overpressure kPa

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