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METHODOLOGY FOR PREDICTING EXPLOSION RISK AROUND UNDERGROUND COAL MINE OPENINGS TOWARDS DEVELOPING EXCLUSION ZONES

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ABSTRACT: The risk of explosions in coal mines is an important subject that requires a comprehensive understanding of explosion dynamics, mining operations, and mining safety. A high level of knowledge is now available in the field of gas emissions, gas, and coal dust explosions in underground mines. However, not sufficient attention has been given to the potential risks associated with explosive forces expelled through the mine opening and resulting in injuries and fatalities to personnel (underground and at the mine portal) and catastrophic infrastructure damage in proximity to the mine opening on the surface. This paper presents a methodology for predicting explosion risk around the coal mine openings (drifts, shafts, boreholes, etc). The proposed methodology is based on establishing an empirical relationship between the parameters of blast overpressure waves emitting from mine entries and the radial distance at an azimuth angle for the various magnitude of methane or coal dust explosions. An Advanced Blast Simulator with the cross-sectional dimensions of 0.3 m x 0.3 m has been manufactured for this study to conduct a series of experiments simulating blast waves exiting a portal entry and propagating over an outside mine site terrain. An array of pressure sensors is placed along the centreline and at several azimuth angles of the blast simulator and along a surface representing a highwall to record the characteristics of blast overpressure waves. Computational Fluid Dynamics modelling of blast wave propagation outside of mine openings is used to correlate the experimental results and scale them up to full-scale dimensions of the coal mine infrastructure and mine sites. A procedure to estimate the lethal ranges of projectiles from mine entries using existing guidelines from a military ammunition storage reference manual is described. The outcome of this research will support the development of scientifically defined exclusion zones around surface mine openings that could be affected by an underground explosion event.

INTRODUCTION

Over the past century, the underground coal mining industry experienced a large number of explosions leading to a considerable loss of life and severe destruction of surface infrastructure. National Institute for Occupation Safety and Health (2019) recorded 503 cases of underground coal mine disasters caused by methane-air and/or coal dust explosions with a total of 12 thousand recorded casualties. While technological improvements and stricter safety regulations have reduced coal mining-related fatalities, accidents are still too common. Looking back as close as November 19th 2010, the Pike River coal mine located northeast of Greymouth in New Zealand exploded, trapping miners underground and ultimately claiming twenty-nine miners underground (Mine Accident and Disaster Database 2021b).

Significant research efforts worldwide have been directed at investigating the prevention and minimisation of the effects of explosions in underground coal mines. However, not sufficient attention has been given to the potential risks associated with explosive forces expelled through the mine opening

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and resulting in injuries and infrastructure damage in proximity to the mine opening on the surface. Although mine accidents have notably reduced due to the advancement of coal mining industry regulations and associated controls, the high-risk exclusion zone around mine entrances has been proven to be insufficient. After the Pike River explosion, Australian coal industry (Y2012) reassessed the applicability of the standards previously used in the industry to design explosion protection of coal mines. The review identified shortcomings with the current scientific knowledge on the basis and expectation to comply with the Reg 156 (Coal Mining Health and Safety Act of 1999) on various explosion panel ratings and informal guidance values of exclusion zones of up to 500 m. The review also resulted with proposals to carry out separate ACARP funded and industry coordinated research to address this shortcoming (B Belle, 2012, Personal Communication, Anglo American Coal). Although several operation guidelines and regulations are currently put in place to establish a high-risk zone around mine portals and ventilation shafts, there is an inadequate scientific basis to support the zone dimensions suggested in the Queensland Mines Rescue Services document (MIU-931 2019).

Past events such as the Raspadskaya mine and the West Wallsend mine disaster illustrated in **Figure 1** highlights significant infrastructure damage near the mine opening after the underground explosion (Australasian Mine Safety Journal 2020; Living Histories 2017; Mine Accident and Disaster Database). In addition to air blast propagation, further investigation reveals the hazardous effect of structural debris and projectiles on surface structures and personnel in the vicinity of the mine entrance. Historical records (**Figure 2**) such as Kainga No.1 Mine and Mount Mulligan Mine reveal large debris such as machinery, belt-rollers and even large rocks were blown out up to several hundred meters away from the mine entrance (Australasian Mine Safety Journal 2019; Loane and Queensland 1975).

(a) **(b)**

Figure 1: (a) The ventilation shaft of West Wallsend was thrown off by the explosion (Living Histories 2017), and (b) infrastructure facilities were damaged by the explosion in proximity to the Raspadskaya mine entrance (Mine Accident and Disaster Database 2021c)

(a) **(b)**

Figure 2: (a) A motor vehicle that was parked at the top of the incline of Kainga No. 1 mine entrance was found flipped and damaged beyond repair (Mine Accident and Disaster Database 2021a), and (b) several large cable drums were found 15 meters away from the Mount Mulligan mine entrance after the underground explosion (Rigby and Mounter 2016)

Several previous studies on determining the safe exclusion zones for underground ammunition storages have developed empirical relationships to estimate blast wave characteristics as a function of azimuth angle and distance from the tunnel exit as the blast wave propagates into an open space (Helseth 1985; Kingery 1989; Skjeltorp et al. 1977; Swisdak and Ward 2000). Although the environment and explosion sources can be different, some of the studies can be relevant to underground mine explosions. Blast parameters such as peak overpressures, duration and impulses estimated by the empirical formulas can be characterised into explosion risks by relating them to personnel injury and structural damage thresholds compiled by the NATO manual for safety principles of storage of military ammunition and explosives (AASTP-1 2010).

This paper proposes a methodology for predicting explosion risk around different types of mine entries to develop scientifically established exclusion zones that comprehensively consider the effects of blast waves and projectiles emanating from mine entries.

DEVELOPMENT OF METHODOLOGY TO DEFINE EXCLUSION ZONES FROM MINE ENTRIES

Physical Simulation of Blast Waves Emanating from Mine Openings

To investigate the propagation of blast waves exiting mine entrances and over an outside mine site terrain, an Advanced Blast Simulator (ABS) with the cross-sectional dimensions of 0.3 m x 0.3 m was fabricated (**Figure 3**). The simulator is based on the ABS concept which is specially designed to generate shock or overpressure waves that replicate the wave dynamics of an actual free-field explosive blast (Gan et al. 2020). The Driver of the ABS has a divergent wedge-shaped profile and operates by the detonation of the oxy-acetylene mixture to generate a propagating shock wave. The characteristic blast wave shape is created by the expansion of the gas out of the divergent Driver and through the initial divergent Transition Section; once formed, the wave is smoothly re-converged into the Test Section before eventually exiting the ABS into the open space as a propagating shock front.

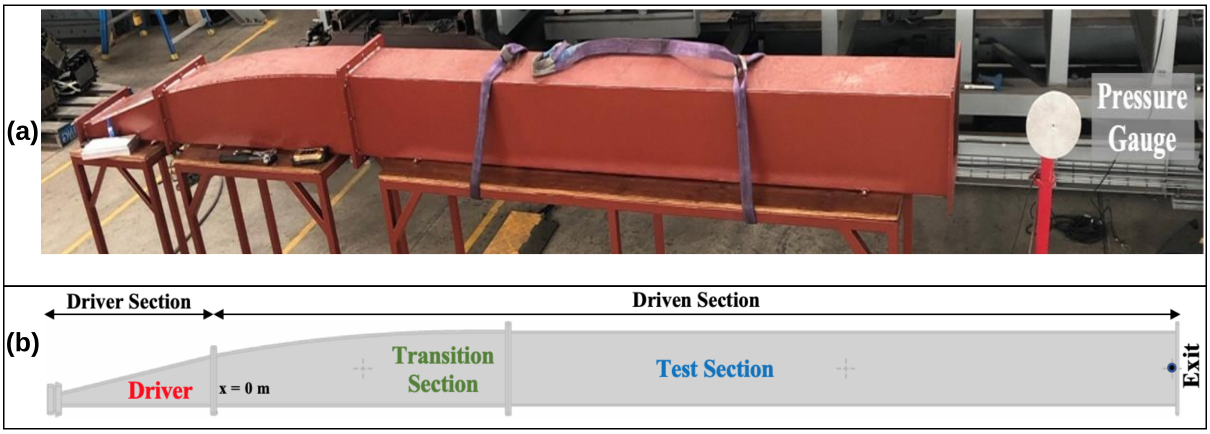


Figure 3: (a) 0.3 m x 0.3 m Advanced Blast Simulator (ABS); (b) main components of the ABS

For this study, the ABS was set-up with three configurations to represent different types of mine entries: portal into highwall, standalone portal, and a mine shaft (**Figure 4**). In addition to measurements of blast pressures at the ABS exit, pressure transducers were mounted outside on baffle plates (for measuring static overpressures) and pitot-static probes (to determine dynamic pressures) as an array along the centreline and on the vertical flange (surrounding the ABS exit) at 1 m intervals from the ABS exit. The ABS was rotated (i.e., 0˚, 30˚, and 60˚) to characterise the outside blast environment at different azimuths. A high-speed data acquisition system (Synergy P Portable; Hi-Techniques, Inc.) was used to record data at a sampling rate of 500 kHz.

A sample of eight experimental tests performed with the ABS with either 1.75 L or 7 L of oxy-acetylene filled in the Driver of the ABS (see **Figure 3**) to vary the blast wave strength were used for analyses. These tests simulated the effect of blast waves propagating out of the portal into highwall (**Figure 5**). When the results were divided with the ABS exit pressure and ABS diameter, a consistent trend of pressure ratio P/P_{portal} vs. distance ratio R/D_{portal} is observed for all results regardless of differences with the blast wave strengths (see **Figure 6**). P is peak overpressure determined, P_{portal} is the peak overpressure at the portal, R is the outside distance from the ABS exit, D_{portal} is the diameter of the ABS exit.

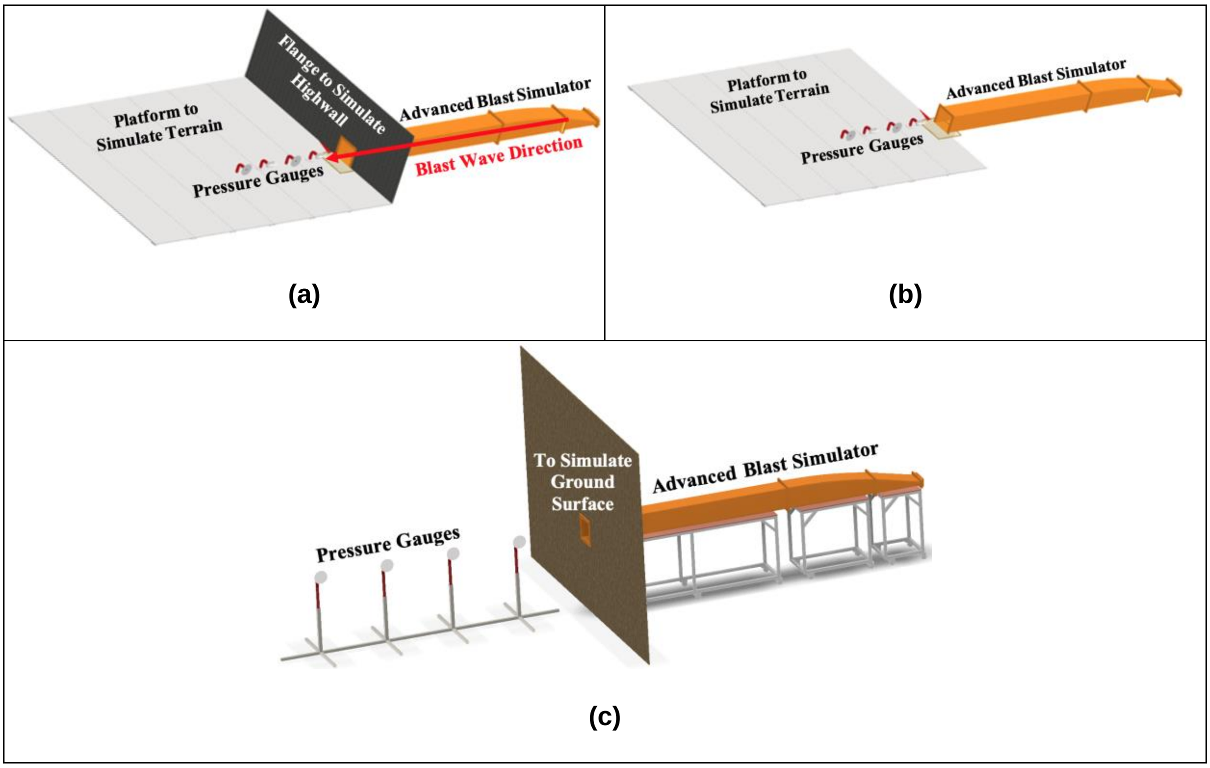


Figure 4: Experimental setups for physical simulation of blast propagation from different mine openings: (a) portal into highwall; (b) standalone portal; (c) shaft

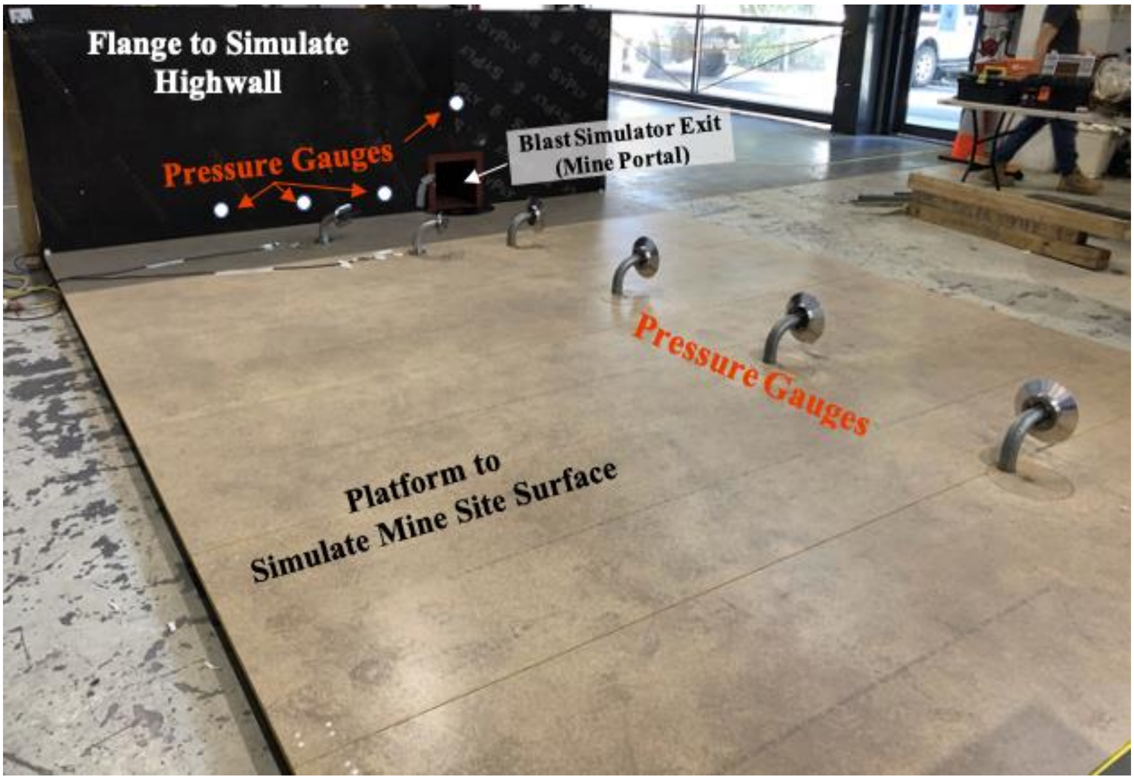


Figure 5: Blast simulator setup for characterising blast wave propagation from mine portal

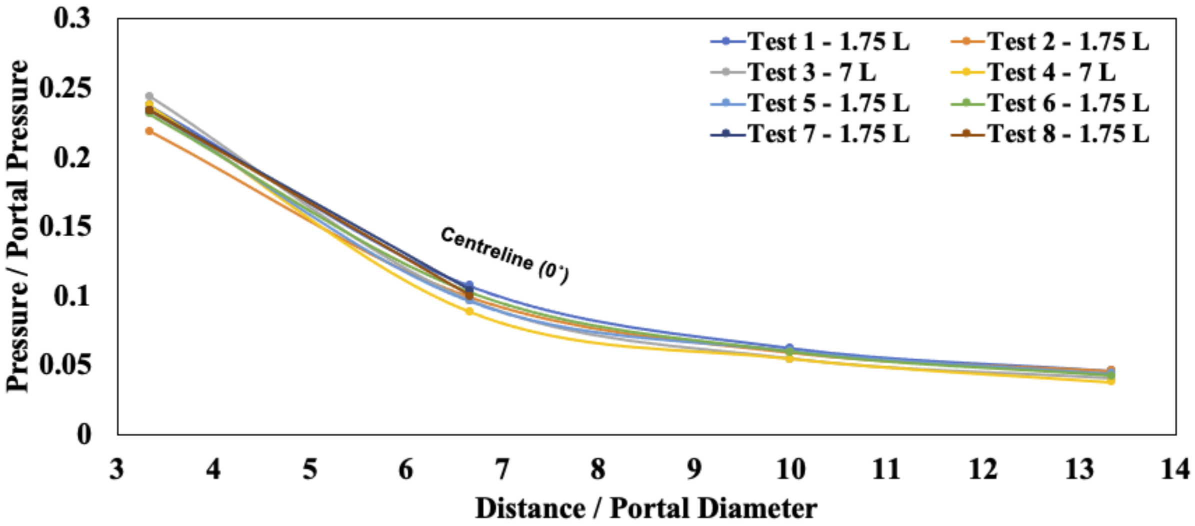


Figure 6: Several experimental tests superimposed. Consistent trend along the ABS centreline (i.e., 0˚) generated regardless of the volume of gas mixtures in the Driver of the ABS (i.e., detonation chamber)

Figure 7 presents examples of blast wave records for the laboratory ABS exit pressures of 70 kPa (**Figure 7a**) and 170 kPa (**Figure 7b**) at varying distances from the ABS exit along the centreline. The records illustrate that peak static overpressure reduces considerably as blast wave propagates away from the ABS exit.

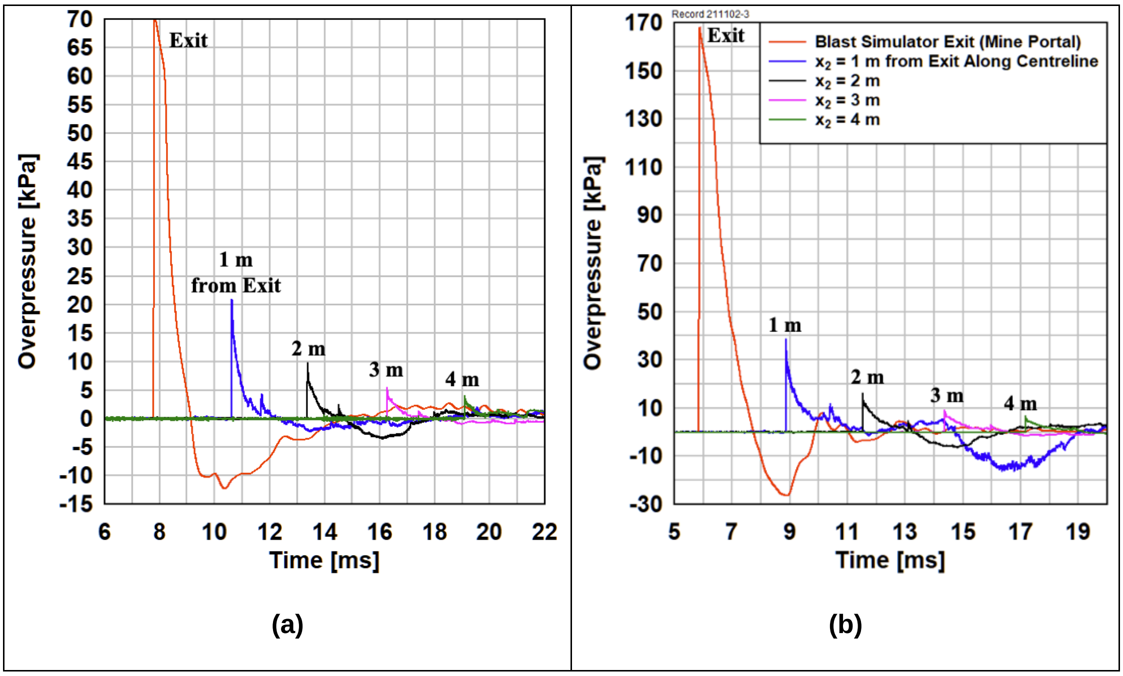


Figure 7: Experimental records recorded at the ABS exit and several locations away from the exit along the centreline: (a) 1.75 L Driver; 70 kPa portal; (b) 7 L Driver; 170 kPa portal

Figure 8 compares the blast wave records taken at various angles with respect to the ABS centreline 1 m from the ABS exit. The 90˚ record is taken from a pressure transducer mounted on the vertical flange which represents a highwall. The plots indicate that the most severe conditions are generated along the centreline axis (i.e., 0˚) with peak overpressure reducing according to the azimuth angle. Interestingly, while the least severe conditions were generated at the 90˚ angle, the blast or explosion overpressure wave appears to arrive soonest at the 90˚ and latest along the centreline (i.e., 0˚).

The preliminary experimental results presented in this section will be correlated with the numerical models in the next sections.

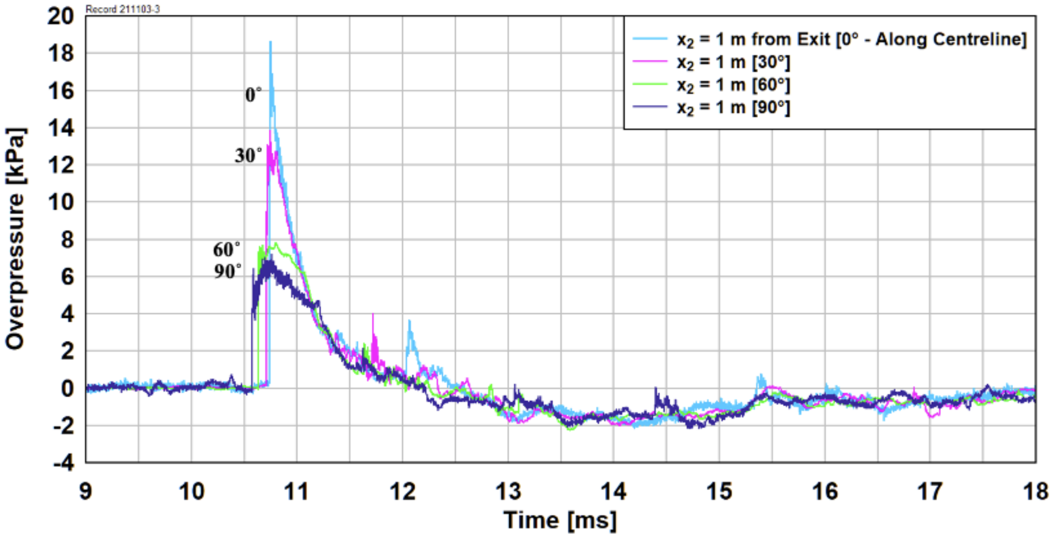


Figure 8: Comparison of blast wave records generated with a 1.75 L Driver and measured at different azimuth angles from the ABS centreline. All angles are at 1 m from the exit

Numerical Simulation of Blast Waves Emanating from Mine Openings

Numerical models based on Computational Fluid Dynamics (CFD) were developed with the Viper::Blast software (Stirling Simulation Services Limited 2020) (**Figure 9**). The models were based on the laboratory ABS described in the previous section and were employed to correlate the experimental results, validate the scalability of the results to full-scale dimensions of coal mine infrastructure, and develop visualisations of blast pressure contour maps for characterising the blast environment outside different mine openings and configurations (**Table 1**).

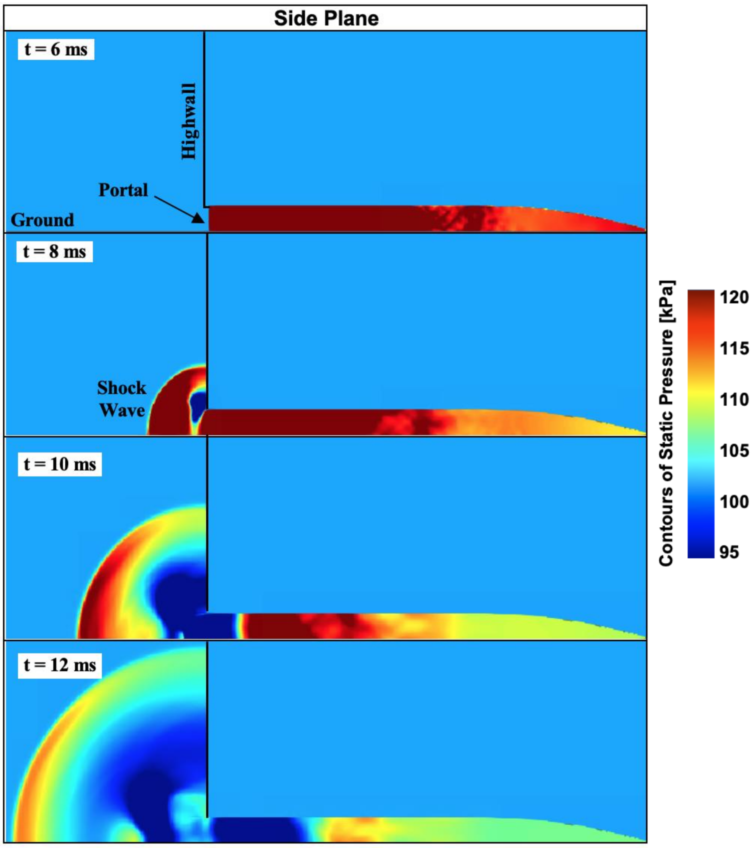


Figure 9: Pressure contours from CFD model showing blast wave propagation from ABS exit (representing mine portal) at snapshots up to 12 ms after detonation

Table 1: Configurations tested to evaluate external blast environment from different openings

Mine Opening Type	Configuration	Applicable For:
Square Portal	Portal into highwall	Drifts, slopes, etc
Rectangular Portal		
Round Portal		
Square Portal	Standalone portal	
Shaft	Shaft without ventilation infrastructure	Shafts, boreholes, etc

The CFD results were validated with small-scale laboratory experimental testing and existing empirical relationships of blast wave parameters given as a function of azimuth angle and distance from the tunnel exit taken from previous research on underground munition storage explosions from the open literature and military documents. **Figure 10** compares results for pressure ratio P/P_{portal} vs. distance ratio R/D_{portal} generated with the CFD model for standalone square portal with existing empirical equations (Helseth 1985; Kingery 1989; Skjeltorp et al. 1977; Swisdak and Ward 2000) along the centreline of the tunnel (0˚). This figure demonstrates that the CFD model correlates well with other existing equations and the experimental results in this paper.

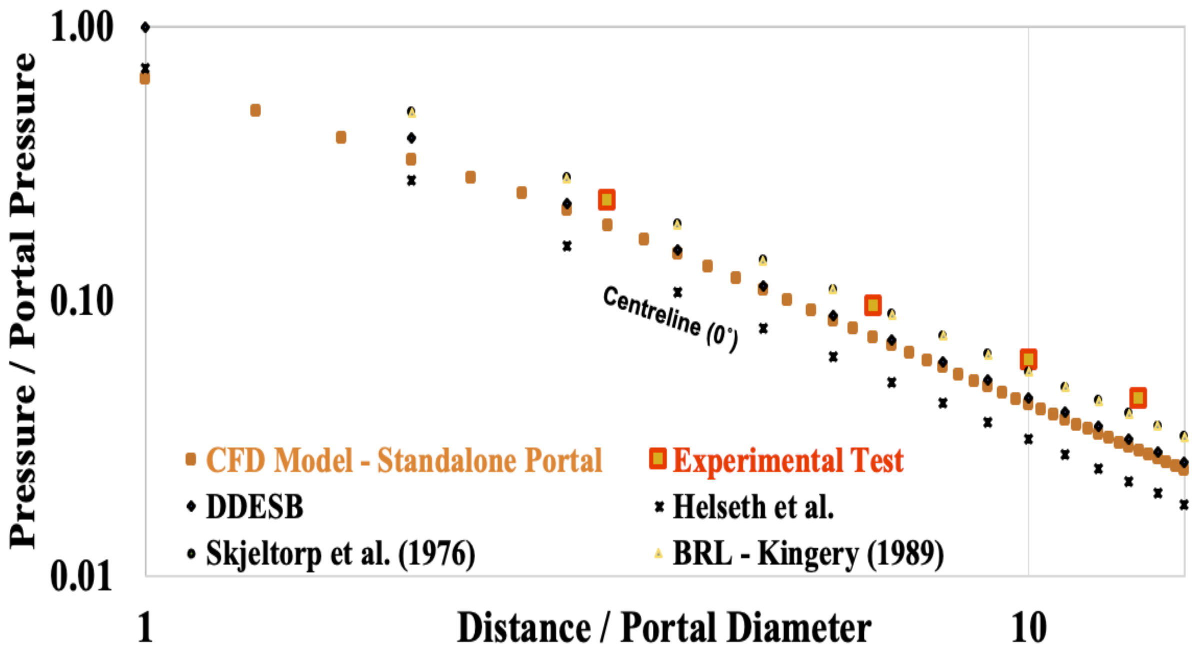


Figure 10: Comparison of CFD model and experimental results in this study with empirical equations from previous studies of blast propagation from ammunition storage tunnels

The scalability of the results generated by the 0.3 m x 0.3 m ABS was also confirmed and validated. CFD models with an adit cross-section of 0.3 m x 0.3 m and 3 m x 3 m to represent small-scale and full-scale dimensions of mines, respectively were used to generate contours of peak static overpressure. When the results were divided with the portal exit pressure and effective portal diameters, all differences resulting from the length scales become cancelled out and identical contours are generated. This confirms that the results generated from the 0.3 m x 0.3 m ABS model are valid and applicable for characterising the blast environment of full-scale mine openings.

Generation of External Blast Environments in Proximity to Different Mine Openings

This section investigates the external blast environment in proximity to different types of common mine openings generated with the CFD models. Where applicable, the results in this paper are provided as ratios of effective portal diameters (R/D_{portal}) and ratios of portal pressures (P/P_{portal}). This enables external blast environments to be characterised for a wide range of mine openings of different diameters, shapes, and portal conditions. Results can then be calculated and read in meters and kPa (pressure) by multiplying lengths with effective portal diameters and portal pressures.

Figures 11 to **14** present contours of blast overpressures that characterise the blast environment outside of different mine opening types and scenarios. In these figures, it can be observed that blast pressures dissipate with distance away from the mine opening. The contours visualise the effect of directionality with the most severe blast environment occurring along the centreline of the opening and decreasing in severity with azimuth angle at the same distance.

Portal into Highwall (Plan View) vs. Shaft (Side View)

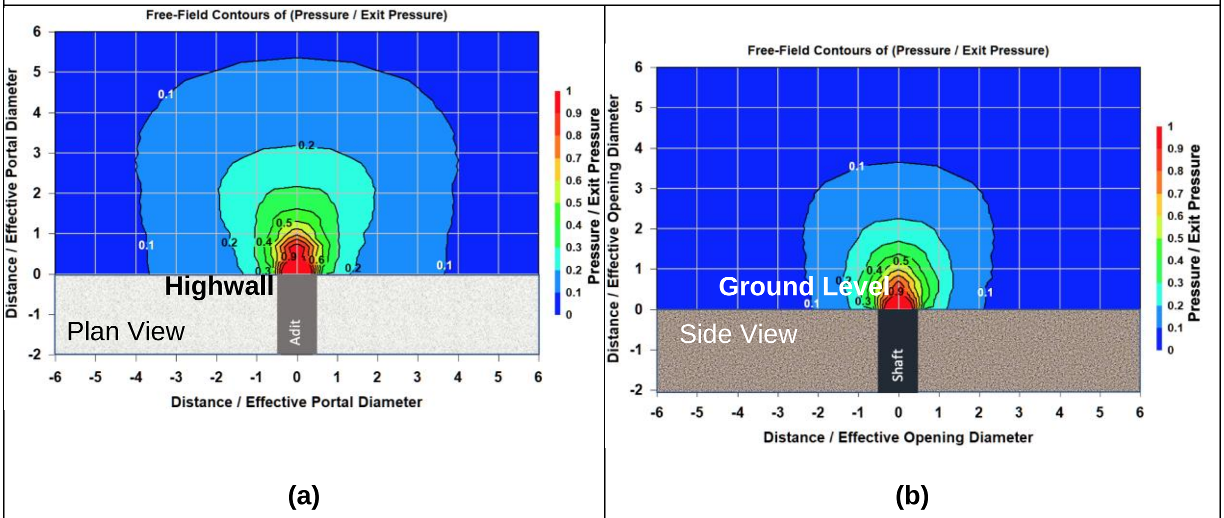


Figure 11: Comparison of peak static overpressure contours for (a) portal into highwall (plan view) and (b) vertical shaft without infrastructure (side view)

The blast pressure contours of portals differ from shafts in terms of the orientation of the opening. Portals are typically oriented along the horizontal ground surface while shafts are oriented vertically. Their distinctions can be best visualised by comparing the contours in **Figure 11**. As the most hazardous blast environments are most critical along the centreline of the opening, shafts generate a smaller danger zone as compared to portals. This is because the most severe blast conditions occur along the centreline of the mine opening. The centreline of a shaft opening is directed upwards away from the ground level. Blast pressures dissipate quickly away along horizontal (ground) distance from shafts, where it would only take 2 to 3 shaft diameters to dissipate blast pressures to 10% from the conditions at the exit. In contrast with portals, about 5 portal diameters are required to dissipate blast waves to 10% of portal conditions. Note that the present study conservatively considers exhaust shafts without the ventilation infrastructure (e.g., elbows, collars, connections, etc) and simply as a vertical opening in the ground) due to complexity and unknowns to the connection strengths. Several CFD modelling studies have been carried out by the coal mining operators for the shaft exhaust fan infrastructure to qualitatively understand the likely impact of blast overpressures on the main fans and the applicability of the 70 kPa recommendations (B Belle, 2012, Personal Communication, Anglo American Coal).

A portal could be a standalone structure or surrounded by a surface. **Figure 12** evaluates the influence of the surrounding surface around a portal on the resulting static blast pressure contours. The surrounding surface appears to influence only the distribution of pressures in the direction perpendicular to the portal and in close proximity from the portal. The results generated along the centreline of the portal are unaffected by the surrounding surface.

The effects of different portal shapes on the blast environment are also evaluated in **Figure 13**. Nearly identical blast pressure contours are produced when the distances are divided with the effective portal diameters. This validates the use of the effective diameter of portal openings as a single parameter to characterise other portal shapes. For example, the effective diameter for a rectangular portal of 4 m x 6 m cross-section would be 5 m. While the variation between the contours is insignificant, the square portals generate the most conservative results overall while the circular portals generate the least severe blast pressure conditions.

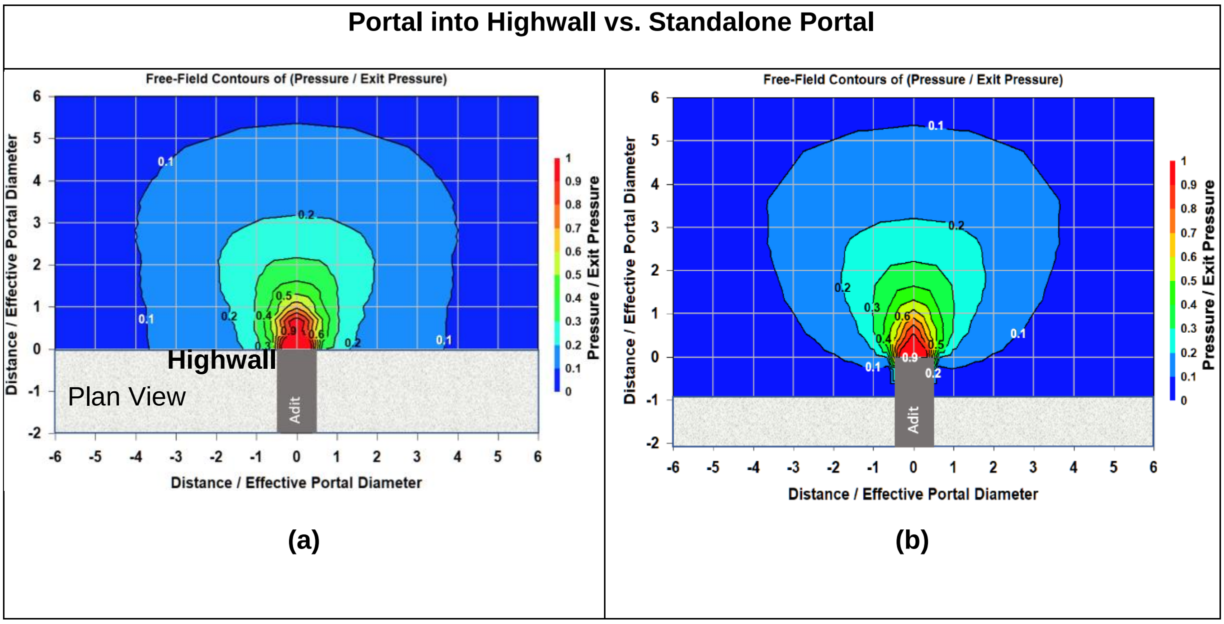


Figure 12: Comparison of peak static overpressure contours for (a) portal into highwall and (b) standalone portal

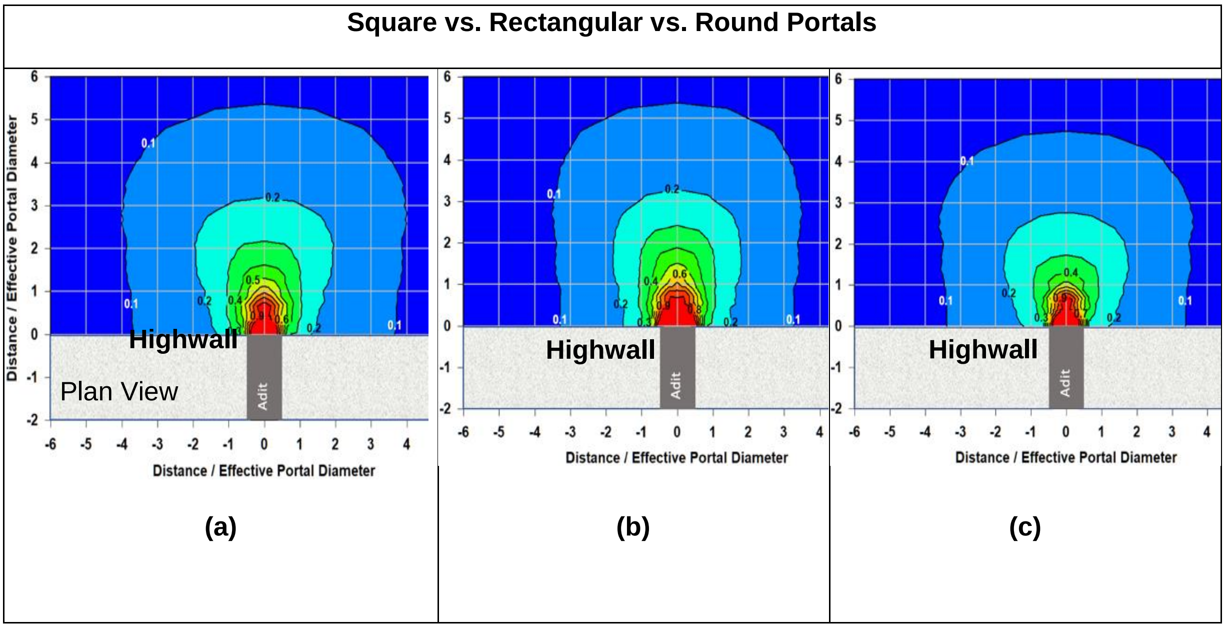
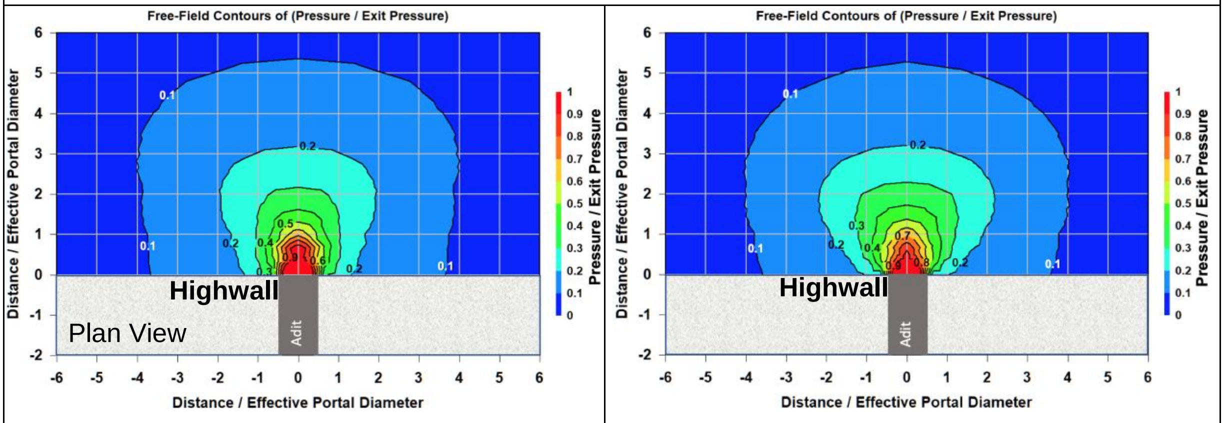


Figure 13: Comparison of peak static overpressure contours for (a) square portal, (b) rectangular portal, and (c) round portal

Figure 14 compares the influence of different portal pressures (i.e., 70 kPa vs. 170 kPa) on the blast pressure contours. As the blast pressure contours have been divided with the pressures at the portal, the resulting contours become nearly identical. This demonstrates that, as a technical guidance, it is appropriate to employ these scaled contours to determine outside blast environments of mine openings with other pressures (i.e., by multiplying with new mine opening pressures).

The presented results validate the robustness of the methodology of using scaled blast pressure contours given as ratios as they can be scaled for different shapes, dimensions, and portal exit pressures. A case study will be provided later to demonstrate the application of the scaled blast pressure contours for developing safety distances.

70 kPa Portal vs. 170 kPa Portal



(a) **(b)**

Figure 14: Comparison of peak static overpressure contours for (a) 70 kPa portal and (b) 170 kPa portal

Development of Exclusion Zones for Projectiles and Debris Throw from Mine Opening

In addition to hazards associated with the effects of blast waves as discussed in the previous sections, an underground mine explosion could also cause lethal debris and fragments to be propelled over a significant distance from a mine opening.

Guidelines to develop exclusion zones for lethal debris projectiles from an opening of an underground facility can be found in the NATO manual for safety principles of storage of military ammunition and explosives in Part III, Chapter 3, Section IV-2 (AASTP-1 2010). The debris defined by NATO consists of parts of ammunition and its packaging, technical installations such as ventilation equipment, doors and firefighting installations, chamber and adit lining and other reinforced concrete construction elements as well as of rock rubble produced by the explosion effects. In the absence of any previous mining specific methane or coal dust explosion references, these military ammunition storage guidelines could be credibly adopted in the interim for underground mine facilities due to similarities in the adit/portal configuration and type of debris.

The NATO manual provides empirical equations which consider the magnitude of the explosion, length of the adit, and average adit diameter to determine the spread of lethal fragments as a clover leaf-shaped contour line. The contour line describes a range containing 1 hazardous fragment (≥ 80 J) per 56 m^2 (see **Figure 15**). By combining the clover-shaped contour line plotted using NATO's methodology for debris throw with the blast pressure contours provided in the previous sections, a comprehensive exclusion zone from a mine opening that considers both the effects of blast waves and projectiles/ejecta could be developed. This will be discussed in the next section.

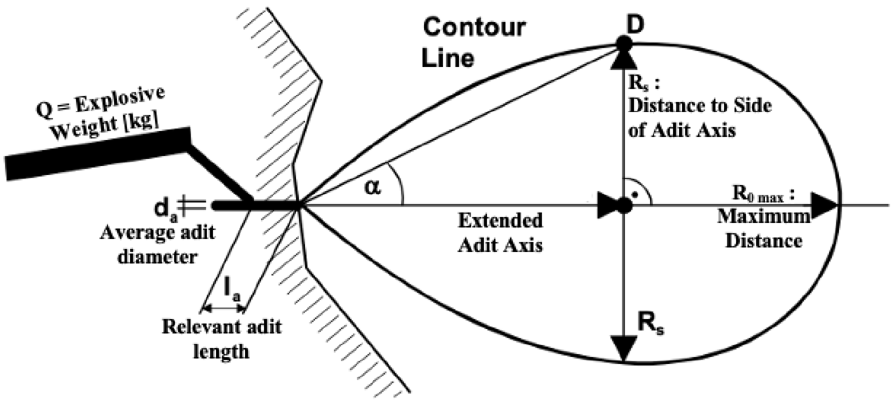


Figure 15: Clover-shaped contour line describing the range of lethal fragments from a portal. Adapted from AASTP-1 (2010)

Methodology for Developing Exclusion Zones Around Mine Opening

This section aims to consolidate the lessons of the previous sections and introduce a step-by-step methodology for developing exclusion zones from mine openings which accounts for both the effects of blast and projectiles/ejecta of material, debris and objects.

In summary, the steps to generate appropriate guidance on safety distances from underground mine openings are as follows:

1) Select realistic scenario and appropriate blast pressure contour for scenario (i.e., for a portal into highwall or standalone portal) (see **Figures 11** to **14**). Multiply x and y axes (i.e., Distance / Effective Portal Diameter) by effective portal diameter. Multiply shaded contour area with portal pressure;
2) Develop clover-leaf shaped contour line to determine lethal fragment/projectile range using NATO manual (AASTP-1 2010) (see **Figure 15**);
3) Combine contours of blast wave effects and lethal fragment/projectile range;
4) Estimate possible damage and injury according to determined blast overpressure levels and industry-approved guidelines or standards for evaluating explosion hazards;
5) Develop exclusion zone according to explosion risk and damage/injury criteria.

A case study for a 70 kPa blast pressure at the portal with a 1 km long adit with a 3 m x 3 m cross-section is used as an example. For plotting the lethal fragment range, a 100 kg TNT was used as input to generate a 70 kPa portal pressure 1 km away from the charge. The charge size was estimated with a CFD model of a 1 km long square tunnel with a 3 m x 3 m cross-section to generate a 70 kPa portal pressure. **Figure 16** illustrates the exclusion zone developed for this case based on the physics of blast propagation and projectile throw predictions. Straight lines were used for the conservative definition of the exclusion zone to identify zones of blast and projectile risks.

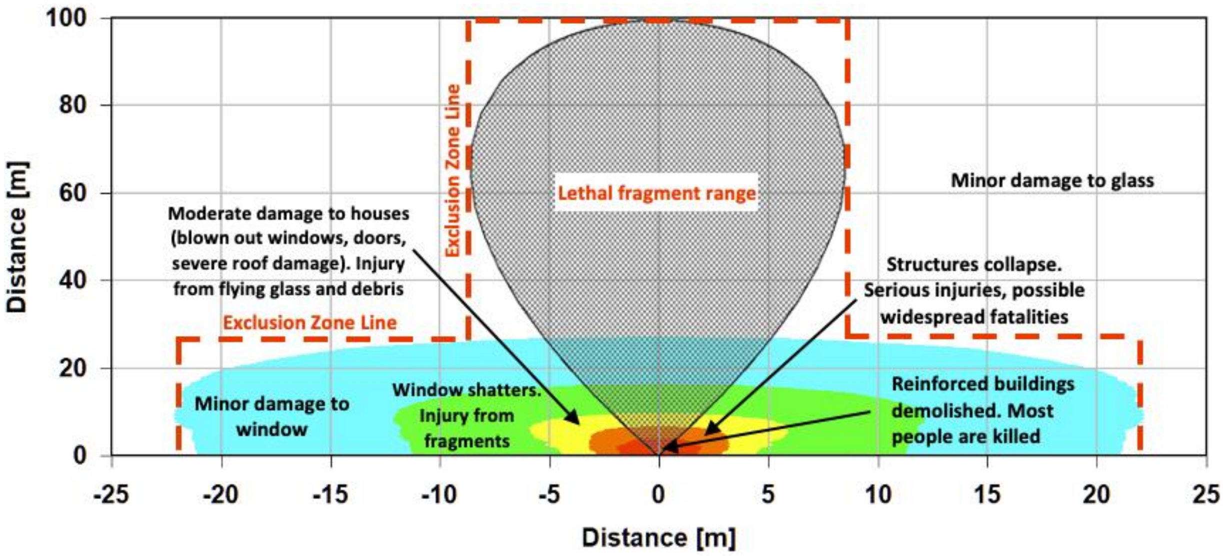


Figure 16: Proposed science-based exclusion zone for a portal with 70 kPa exit pressure

As a comparison to the proposed exclusion zone illustrated in **Figure 16**, **Figure 17** presents the current QMRS-established High Risk Zone defined around mine portals and shafts in the QMRS Inertisation (MIU) Operational Procedure (MIU-931 2019). The High Risk Zone is defined to be:

1) The area at 90 degrees from the portal entrance, for 250 m, extending out 1000m;
2) 150 m in all directions for vertical shafts greater than 2 m in diameter and 500 m upward;
3) 50 m in all directions for vertical boreholes/shafts from 0.5 m up to 2 m in diameter and 250 m upward unless a blast shield is fitted;
4) 5 m in all directions for vertical boreholes under 0.5 m in diameter and 250 m upward.

It should be noted that this exclusion zone recommendation is only implemented for GAG operations and does not extend to other cases even when an explosion risk is likely present before the commencement of the GAG operations. Parcell (2014) provided a review of the high-risk zone illustrated in **Figure 17** with the main criticism given for misleading and confusing dimensions and that the width of the portal being excessive; however, still recommending the adoption of this standard in the interim considering a current lack of a scientifically established high risk zone. The methodology for scientifically determining exclusion zones around mine openings proposed in this paper aims to be employed as a scientific evidence based approach to develop appropriate exclusion zones for future mine safety guidelines around mine openings.

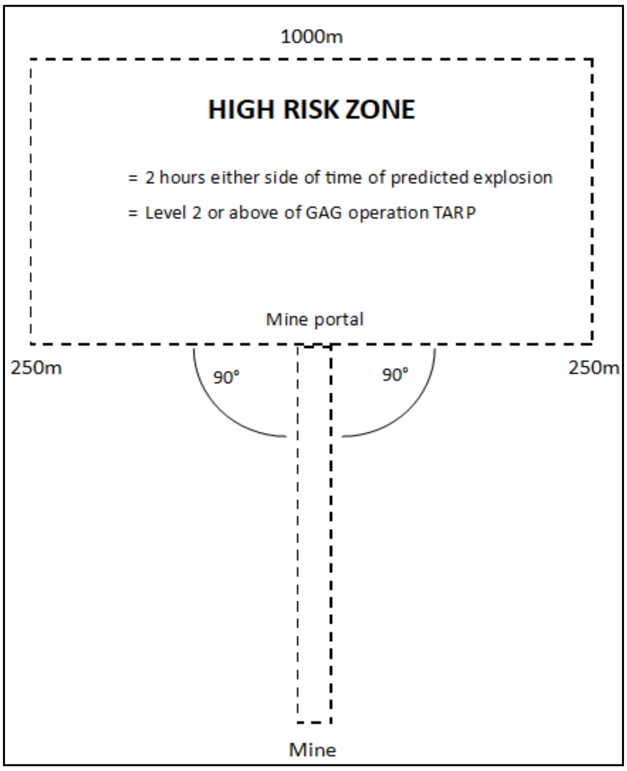


Figure 17: High risk zones as presented in the QMRS Inertisation (MIU) Operational Procedure (MIU-931 2019)

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CONCLUSION

There exists a significant gap in existing mining safety standards resulting in the usage of highly conservative safety distances/exclusion zones due to a lack of understanding or scientific-driven guidelines. This study aims to address this with the development of a methodology to predict explosion risk and appropriate exclusion zones from different mine entries (i.e., a portal into highwall, standalone portals, and shafts). A 0.3 m x 0.3 m Advanced Blast Simulator was fabricated and employed to conduct experiments of blast overpressure wave propagating from different types of mine openings into the open space. The results collected from pressure gauges were used to calibrate Computational Fluid Dynamics models developed for correlating the experimental results, validating that the results could be scaled up to full-scale dimensions of actual coal mine infrastructure, and develop blast contour maps to visualise the outside blast environment beyond the mine openings. It was demonstrated that when the results were given in the form of ratios of effective mine opening diameters and ratios of mine opening pressures, the scaled contours could represent and predict outside blast environments of different opening shapes, dimensions, and pressures at the mine opening. The models indicate that the most severe outside blast environment would be generated from square portals into highwall while the least severe would be from mine shafts. The findings from the study were consolidated with steps given to generate exclusion zones from mine openings from the risk of blast waves and projectiles as a result of underground mine gas or coal dust explosions. A case study was provided towards the end of the paper as an example.

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