

Case study: Management of the risk of air blast at Carrapateena

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ABSTRACT

Air blast is a principal mining hazard in cave mining, and it is essential that this hazard is monitored and well understood by the mining operation. During propagation the Carrapateena cave back stalled and an air gap formed resulting in the potential for an air blast. The air gap was closely monitored, potential air blast velocities regularly calculated and mitigating strategies put into place. Using the Caving Air blast Simulation Tool in VentsimTM, the volume of air, mine design and vent network were used to assess the maximum potential air velocity in the event of an air blast event. Over time the understanding of the model inputs, outputs, sensitivity and mechanism were further investigated and reported. The volume of the air gap is the primary driver of air blast hazard magnitude and monitoring of the airgap is a critical control. Significant work was undertaken at Carrapateena using state of the art methods to measure the air gap volume, estimate the maximum air blast velocity and ensure it remained below trigger levels, allowing the mine to continue to operate safely. This methodology and lessons learnt may be applicable to air gap management at future cave mines.

1 GEOLOGICAL SETTING AND CAVE INITIATION

Carrapateena is a copper-gold underground sub level cave mine formally run by OZ Minerals. It is located over 400km north of Adelaide in South Australia and now forms part of BHP Copper SA. The project is located on Pernatty Pastoral Station and the Kokatha People are the traditional owners.

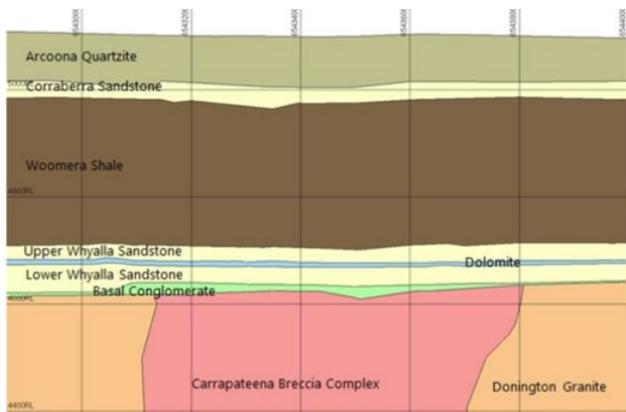


Figure 1 Carrapateena Geology.

The ore body is situated below 500m of barren sediments (Figure 1). Undercutting begun in 2019 and the cave initially propagated well. In late 2020 the cave rapidly propagated vertically into the highly laminated Woomera Shales, where it remained with no movement for five months until cave remediation activities begun. Over the next 20 months the cave void and potential air blast hazard were closely monitored and analysed, in addition various cave engineering strategies were implemented to promote cave propagation. This paper details the methodologies used by the team to measure, assess and manage the air blast hazard. The cave safely broke through to surface in late 2022 without any air blast events or evacuation necessary.

2 AIR BLAST CALCULATION METHODOLOGY

Initial air blast calculations at Carrapateena were conducted using simplistic nomograms. The nomograms assumed that the full volume of air

gap expelling to the mine network on one level. This method used Isentropic Compression;

$$P_1 = P_a \left(\frac{V_{ag} + V_{mp}}{V_{mp2}} \right)^\gamma$$

Where,

P_1 is the pressure after the collapse,

P_a is the ambient air pressure,

V_{ag} is the volume of the air gap,

V_{mp} is the air volume in the muckpile,

V_{mp2} is the air volume in the muckpile after the collapse,

γ is the adiabatic constant of air (1.4).

This method uses the pressure differential between the cave and the muckpile after collapse to determine peak airflow in the individual drives connected to the cave. This method had several limitations including, the method did not consider that drives connecting to the cave on different levels will have differential pressure and therefore differential air flows.

The software Ventsim Visual™, specifically the add on Caving Air blast Simulation Tool was utilized to represent the underground workings, vent network and potential air velocities in the event of an air blast. There were numerous model inputs necessary to achieve a realistic air blast hazard assessment. The following sections will discuss each of these variables and the sources of uncertainty.

2.1 Muckpile Resistance Coefficient

The muckpile resistance coefficient was measured through the Carrapateena muckpile and was recorded to be $0.0491 \text{ N s}^2 \text{ m}^{-8} / \text{vertical m}$ per $10,000 \text{ m}^2$ in December 2020. At the time of the measurement, the cave was in the initial stages of propagation and thus had a lower void ratio, a more mature cave leads to a higher muckpile resistance (Vejrazka 2016). This combined with the expectation that the property of the muckpile is strongly heterogenous led to a more conservative muckpile resistance of $0.0203 \text{ N s}^2 \text{ m}^{-8} / \text{vertical m}$ per $10,000 \text{ m}^2$ being applied for the simulations. This value aligns

with industry standards and historical back analysis.

2.2 Air Gap Volume - Cave Shape

The cave shape was estimated by analysing several geotechnical monitoring data sources, as detailed in ‘Geotechnical monitoring of the Carrapateena Cave, Poulter et al 2022’ and summarised in Figure 2.

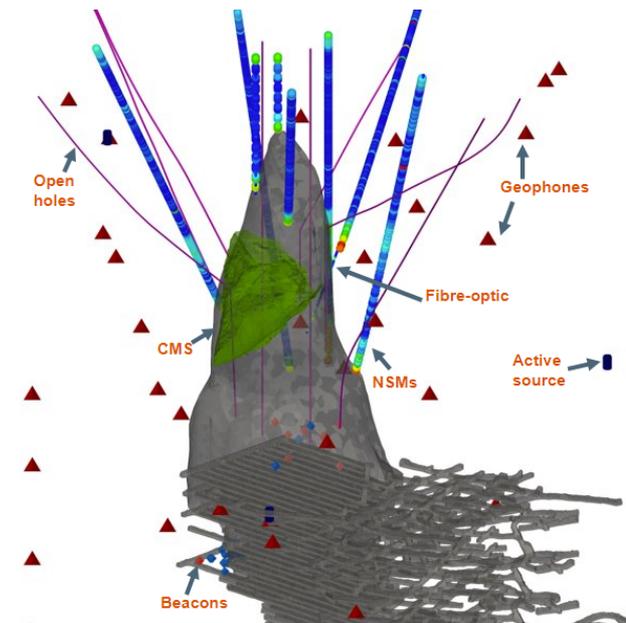


Figure 2 Carrapateena cave monitoring.

Each data source had a range of uncertainty and spatial precision, the typical distance between monitoring points ranged between 30m and 100m. As such, the process for estimating the shape was subjective and depended on interpretation by the engineer. The cave shape was reanalysed on a minimum monthly frequency, using the software package Leapfrog Geo to generate the cave shape, muckpile shape and estimated volume of air.

Despite the regular monitoring and dense array of instrumentation, significant uncertainty in the cave and muckpile shape still existed. In the early stage of the air gap management the uncertainty was managed by creating a single cave shape interpretation and then applying an arbitrary factor of safety, by scaling up the air gap volume to 125%.

Later in the project a more sophisticated method of air gap volume was developed whereby numerous shapes were created in each analysis;

maximum, likely and minimum. The maximum and minimum shapes represent the largest or smallest shape respectively that could be realistically supported by the data, or lack of. These shapes were used in a sensitivity analysis rather than attempting to specifically define an uncertainty factor. This process provided a more dynamic and comprehensive approach to managing the range of potential scenarios. Furthermore, it provided a systematic method for evaluating the value of additional drilling and monitoring to further define the cave back. This was a key step in ensuring the cave void was safely managed until it broke through to surface with no air blast event recorded.

2.3 Air Gap Volume - Muckpile Height

To determine the volume of the airgap it is necessary to define both the shape of the cave back as well as the muckpile. The primary method for estimating the top of the muckpile was from open hole dipping with a wireline camera. Mass balance and height of draw calculations were used as a sense check; however, these calculations were not employed as the primary estimation method due to their indirect nature.

Initially the monitoring density for the top of muck was low with only three open holes to measure a cave footprint of approximately 40,000m². Given the limited data the surface of the muckpile was assumed to be planar and near horizontal. To reduce the potential uncertainty in the top of muck measurement, the team developed a novel method for scanning the airgap.

In early 2022 a Geosight NX150 CMS Scanner tool was lowered down one of the open holes, from this a partial scan of the cave void was obtained. As shown in Figure 3 and Figure 4 the observed slope of the muckpile was significantly steeper than what had previously been estimated. While this did not significantly change the estimate of the total volume of air and muck, it revealed a significant change in the assumed conditions in the muckpile and the expected slope of the rill. While the entire muckpile surface was not captured, the lowest point of the scanned muckpile was above the

area of the SLC with the *least* total draw. It is hypothesized that, at the time of the scan, more cave growth had occurred in the areas with higher draw, adding to the muckpile height. The slope of the muckpile was as expected for the rill angle of the material, measured to be between 35° to 40°.

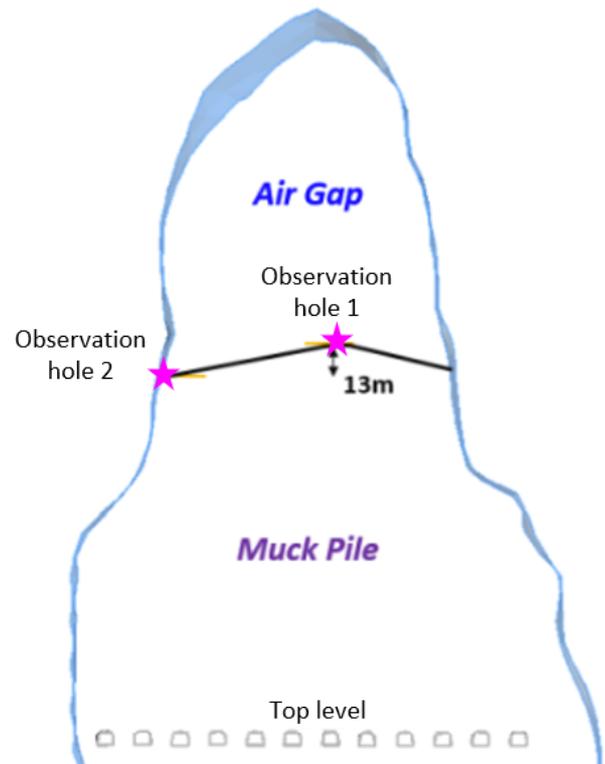


Figure 3 Early muckpile measurement estimation prior to the CALS scan.

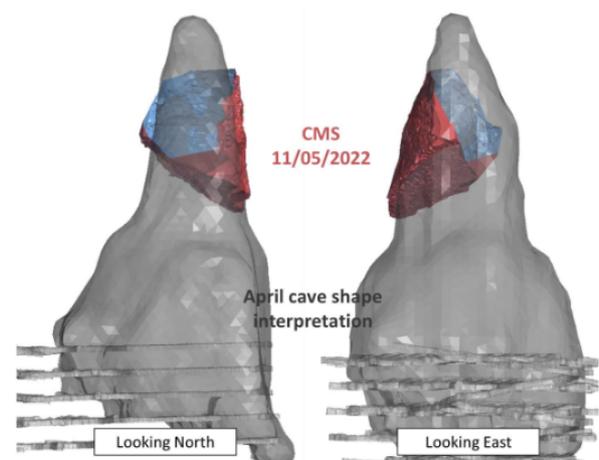


Figure 4 CALS scan of muckpile.

This demonstrates how the understanding in the cave void can change significantly. A large volume and area was being monitored by a few

points of data, hence there was significant uncertainty. It should be assumed there is limited understanding in the cave void until a higher density of data is obtained to increase the level of confidence.

During the early stages when the muck height was estimated using open hole dips, the muck height input for Ventsim was assumed to be the average height of all the dips, minus an arbitrary safety factor of 30m to account for variability and uncertainty in the muck height.

Following the CALs scan, the muckpile height was assumed to be the lowest point of the scan. The scans represented a point in time and uncertainty increased with time as they could not always be completed. Over time this 30m adjustment was re-applied when scans were unable to be completed.

3 VENTSIM MODELLING

The Caving Air blast Simulation Tool in Ventsim VisualTM is based on a representative build of the underground mine network to simulate air flows and other contaminants and influences for the underground ventilation network. This also includes restrictions to underground vent flows such as vent doors and other ventilation infrastructure. In the Carrapateena air blast assessment the normal ventilation model was expanded to include the following:

- Strength rating for all ventilation infrastructure that may be impacted by an air blast,
- Airway connections to the simulated cave,
- Virtual monitoring points throughout the mine network to record changes in velocity and pressure over the course of the air blast event. These were selected on two criteria:
 - Locations where multiple airflows combine, which leads to overall higher air velocities. This will usually be level accesses, declines, return airways and similar.
 - Locations where air blast walls are to be installed to determine required pressure design criteria.

The cave itself is represented by a circular piston as discussed below. The model was set up using a specific interface with the following inputs:

- Equivalent cave diameter – the equivalent diameter of a cylindrical cave with the same area as the undercut area.
- Highest Point – height of the cave back.
- Lowest Point – level of the lowest connection to the cave, i.e. base of muckpile.
- Muckpile height
- Muckpile resistance, as discussed above.
- Time step – time between each simulation reiteration
- Vertical group interval – drives that connect to the cave within the interval are assumed to connect to the cave at the same height to reduce model complexity.

The accuracy of the results of the simulations are influenced mostly by:

- The accuracy of the input Ventsim model,
- The muckpile resistance,
- And the total air gap volume when compared to reality.

The mine ventilation network used as the basis for the air blast modelling needs to be calibrated against the real life mine network. Air blast model results and the location of the highest velocities are more accurate when there is a small or no difference between the model and reality. It is therefore important that all ventilation infrastructure in the mine has a realistic failure criteria. For example, if a vent wall fails due to an air blast the air might suddenly travel through the decline to surface rather than the return network therefore putting people at risk.

The muckpile resistance within the model determines how fast or slow the air passes through the muckpile, the lower the resistance the quicker the air passes through and the higher the peak velocity in the mine network will be. It should be noted that resistance decreases as caves mature and the void ratio increases (Vejrazka 2016). Air blast modelling should therefore always use a conservative resistance

value to allow for cave stall and muckpiles maturing without being replenished.

3.1 Piston mechanism

To assess the event of rapid cave propagation leading to an air blast, a range of possible failure mechanisms were considered. The worst-case scenario was assumed to be a crown pillar failure.

The Ventsim model assumes a sealed piston which forces all the air gap volume into the mine workings, this was accepted to be a conservative assumption as it is expected air would also flow out through the crater to the surface. The actual path of air flow is dependent on several factors, including:

- How quickly the rock mass unravels when falling,
- The total mass of the falling rock mass, which determines the maximum pressure the rock mass can assert downwards before it will disintegrate and release air upwards.

However, given the uncertainties surrounding the above and the lack of a more accurate methodology, the sealed piston was used in all calculations with the rock mass falling under gravitational acceleration, i.e. 9.81m/s^2 which aligned with industry best practice.

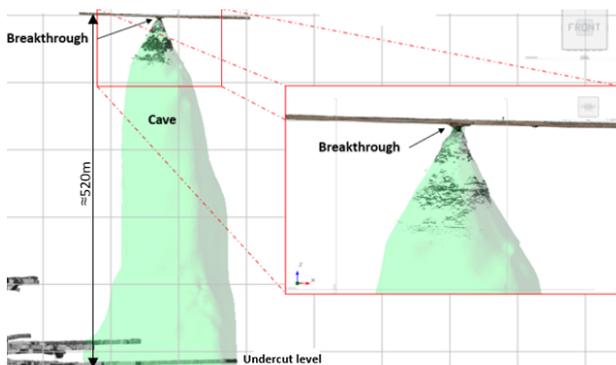


Figure 5 Carrapateena cave breakthrough shape.

A range of possible failure mechanisms including leaky piston, crown pillar buckling, large scale wall failure and progressive unravelling were considered. Given the laminated nature of the shale, the team considered “progressive crown pillar

unravelling” as the most likely mechanism. However, the under broken conical shape of the cave void at the apex was not expected. The initial break through expression was also much smaller than expected, at approximately 5m in diameter, Figure 5. As the cave matured over the following months the surface expression increased to approximately 50m in diameter.

3.2 Piston geometry

The VentSim modelling package is only capable of simulating a cylindrical piston, however the Carrapateena cave shape was an irregular arch shape. Cave monitoring data showed that the cave was widest at the extraction level and then narrowed at the apex.

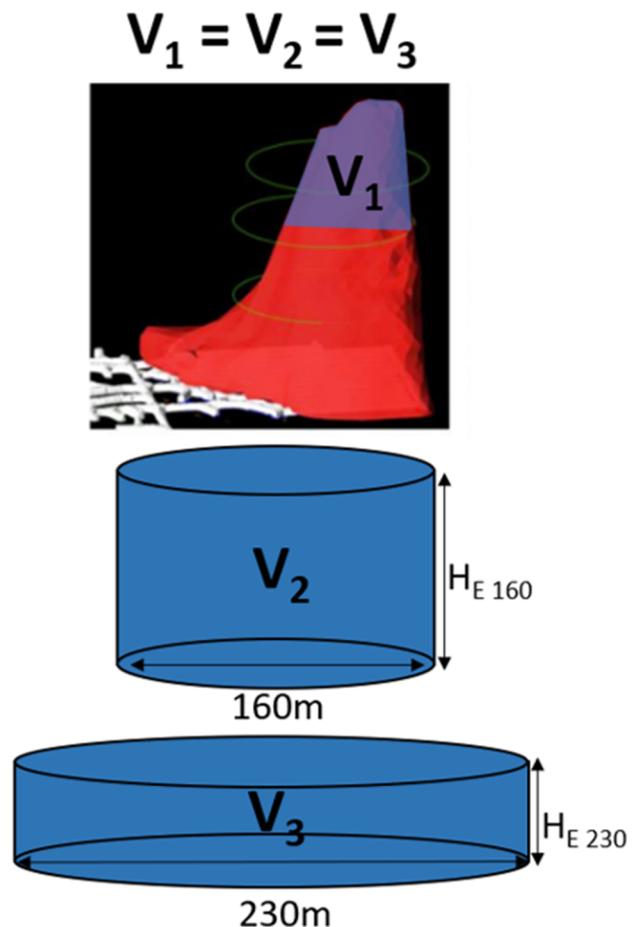


Figure 6 Air gap volume estimation.

The VentSim piston was represented as a cylinder with a 230m span with an equivalent height (H_E) such that the volume of simulated air was equivalent to the actual air gap (Figure 6). The 230m span has a horizontal surface area that is equivalent to that of the undercut level. It is

acknowledged that this “equivalent piston” does not match reality however, it was considered that this is the most conservative practical method of modelling the scenario. By reducing the height of the air gap in the model, the total event time is slightly reduced, and the air is expelled faster resulting in a slight over estimation of reality. Alternatively, if the total real height was used for the same undercut area the air gap volume would be overestimated and would result in a gross overestimation of the air velocities.

3.3 Vent Network Resistance and Geometry

The VentSim software can achieve a detailed simulation of airflow through the mine workings. Each model assumes a specific vent network scenario (resistance and geometry). Using a process of detailed mine monitoring the model will be calibrated to ensure it is representative of the actual mining environment.

However, in reality the actual vent network is constantly changing with the addition of new development, opening and closing of vent devices, fan operation and drive blockages. It is important to note that minor changes in the geometry of the mine ventilation network can potentially result in a significant change in the air blast velocity predicted by the model. It is essential to identify a range of possible scenarios, what the consequences of those scenarios are and implement management strategies to prevent unwanted events. Examples to consider include:

- Critical vent doors left open.
- Vent network changes.
- Primary fans on/off.
- Blocking of raises.

4 MANAGEMENT STRATEGY

The overarching strategy conservatively assumed that 100% of the air blast volume would be forced into the mine workings. The laws of fluid dynamics dictate that the overpressure created by the falling rock will flow along the path of least resistance towards the point of lowest pressure, i.e. the surface. The precise pressure, velocity and rate of the airflow in the underground workings is determined by

the resistance and geometry of the workings. For example, if a shaft and decline had the same cross-sectional area, the air would initially flow solely up the shaft until the increase of resistance due to the higher air velocity is equal to that of the decline. After that point the air will distribute evenly between the two paths.

Conventional air blast management best practice dictates that wherever possible connections between the active workings and the cave should be monitored or eliminated. This control is particularly important where there is a direct connection between the cave without the damping effect of the muck cover.

In the Sub Level Caving method it is not possible to isolate active draw points from the cave while in production. Sealing individual draw points after production is completed is costly, time consuming and difficult to ensure that the seal is competent and capable of withstanding the necessary load. Given the top-down approach of sublevel caving, any seal installed on the top level would have to be constructed in a manner to be able to withstand higher pressures than subsequent levels. If cave growth stalls and the muckpile is drawn below what was originally anticipated, the pressure will further increase potentially requiring further costly works on the respective walls, or unintended air blast risk if not identified. Furthermore, sealing the completed draw points can have the unintended consequence of forcing a greater proportion of the potential air blast into the active workings.

The air blast management strategy employed at Carrapateena aimed to redirect the potential air blast away from personnel, rather than attempting to contain the airflow by fully isolating the source of the air blast from the active workings. The strategy aimed to ensure that the airflow pathway between the cave and the surface was significantly lower resistance along the return airway than for the access way. As a result, the majority of the air blast would flow through the return airway where personnel exposure was removed, up to the surface. Where the predicted air flow velocity exceeds the safe exposure limit, return airways could be closed to personal access without significant impact to the

operation of the mine.

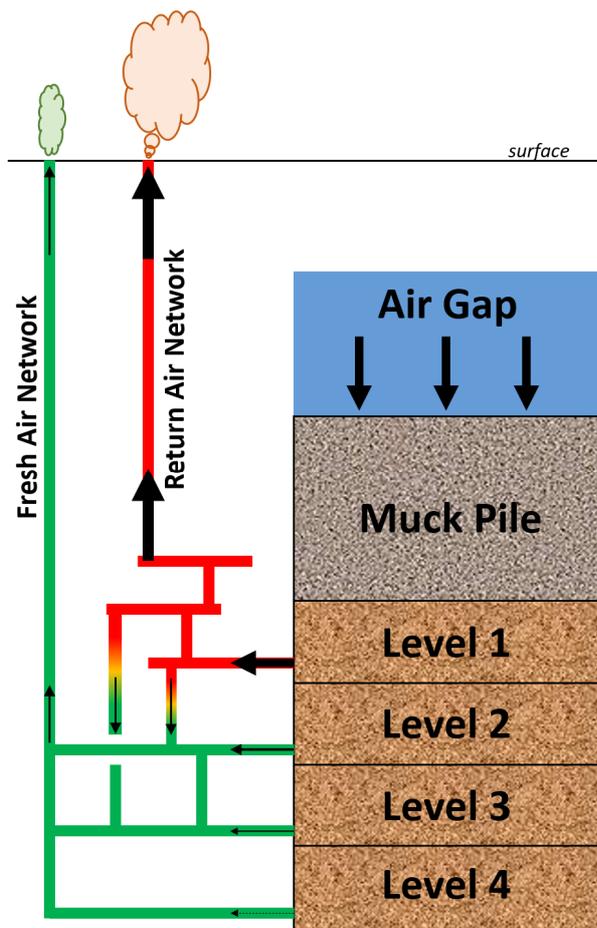


Figure 7 Carrapateena simplified vent network diagram.

Rather than attempting to seal off individual draw points after production was completed the entire production level was partially isolated. This was achieved by isolating all connections to the level other than the return airways and the draw points (access drives, fresh airways, ore passes were left open) using a structurally competent brattice wall designed and constructed to withstand a possible air blast event. The production levels at the top of the ore body were the first to close and were used to intercept the majority of the air blast flow. This is because the top levels have the least muck cover and least air flow resistance. Once the air blast reached the top level there were two relief pathways for the airflow; up the return airway to the surface, or down the return airway into the mine workings and to surface through other pathways such as declines and fresh air intakes. The path up is a significantly shorter distance with lower air resistance, and as such most of the

air reports to this route, this is summarised in Figure 7.

It is important to note that this strategy of directing the flow path does not eliminate the underlying hazard to the underground workforce, it merely reduces the impact severity of a potential event by limiting personnel exposure. Once an air gap has been formed and the cave back is stalled, the only way to eliminate the air blast hazard is to break the cave through to surface. Increasing the span of the cave back through continued draw in conjunction with cave engineering works (hydrofracturing) were the strategies that ultimately resulted in the surface break-through of the cave. The air blast mitigation strategies enabled the mine to safely continue production until breakthrough occurred.

Colour	Trigger level	Impact to access
Blue	12-15m/s	No restrictions
Green	15-17m/s	No restrictions
Yellow	17-20m/s	PPE required (foam back glasses) Remove loose objects
Orange	20-30m/s	Vehicle access only
Red	>30m/s	No access

Figure 8 Carrapateena air blast velocity TARP.

5 RISK COMMUNICATION

Trigger Action Response Plans (TARPs) were utilized at Carrapateena to categorise the level of risk of an air blast and outline mitigation controls. Clearly defined air velocity triggers, the associated controls and actions were documented and approved prior to the potential for an air blast risk. The TARP shown below in Figure 8 shows the air speed personnel exposure trigger levels used at Carrapateena. The TARP below only highlights the velocity levels for personnel exposure, a more detailed TARP based on these levels was developed to specify what cave stimulation activities (draw specifications, undercut expansion, hydrofracturing) as well as area isolation and wall building activities were required to reduce the air blast hazard and eventually eliminate the risk with the successful breakthrough to surface.

5.1 Forward planning

Multiple scenarios were modelled to forecast how the hazard may change over time. This was key for forward planning for blast wall construction and production scheduling to assess which areas would have changed access conditions. However, it was not known exactly how the cave would perform in the future, therefore, to communicate the potential future risk three scenarios were presented describing different levels of production draw down vs cave growth:

- Scenario 1: Ongoing cave growth and muckpile draw down.
- Scenario 2: Larger than current airgap volume, reduced cave growth and higher muckpile draw down.
- Scenario 3: Ongoing cave growth and reduced muckpile draw down.

For each of these scenarios, the resultant maximum velocities were calculated to assess how the hazard was developing and at what point the level of hazard would become unacceptable. Figure 10 below shows an example of how this was communicated. This was a key step in the assessment and communication of the risk of air blast, as it was unknown exactly how the cave would respond to cave stimulation activities. It also provided mine management with clear communication on the expected response when assessing which remediation activities to pursue and how aggressively to target them. This approach was key in managing the evolving air blast risk until the surface breakthrough, which occurred without any air blast event.

The muckpile draw down rate was based on a review of the mass balance and measured muckpile depletion over the previous 6-12 months, particularly when there was no recorded cave growth or evidence of caving activity (Figure 9). This was assumed to be the rate at which the muckpile would continue to reduce given a similar production rate and no cave growth. It was checked against a mass balance review using back calculated bulking factors and

the scheduled production. It should be noted, the cave was wider at the bottom than the top and therefore it was anticipated the draw down rate of the muckpile would reduce if it was gradually depleted. Despite this, the forecast draw down rate was maintained as part of a more conservative approach.

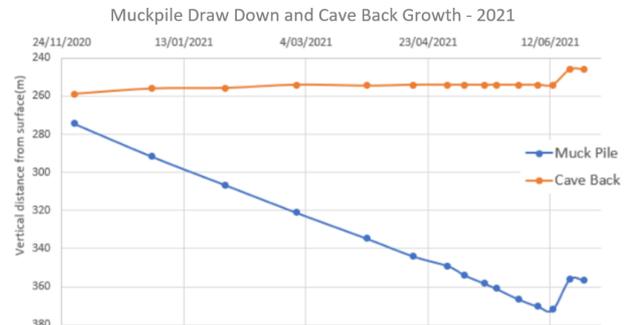


Figure 9 Carrapateena muckpile draw down measurements over time.

Communication of the air blast risk was presented in both a summary page and detailed air blast review in a monthly geotechnical report (increased to weekly as required), an example of the summary page is shown in Figure 11.

Both the safety risk to personnel and business risk were communicated in the form of:

- The date at which there is no access to any underground workings.
- The date at which bogging of swell only would be required (and the associated reduction in total production)

5.2 Cave Review Boards

A key step in this evaluation of risk and communication cycle was a review by external experts. Cave review boards were conducted yearly, but more frequently as issues emerged. The purpose was to minimise group think, confirm levels of conservatism and risk by inviting external industry experts to review the hazard management strategies as well as the current data, risk, and assumptions. This was undertaken specifically for the air blast simulation work as well as the cave in general. They were an invaluable step in the safe management of the Carrapateena cave.

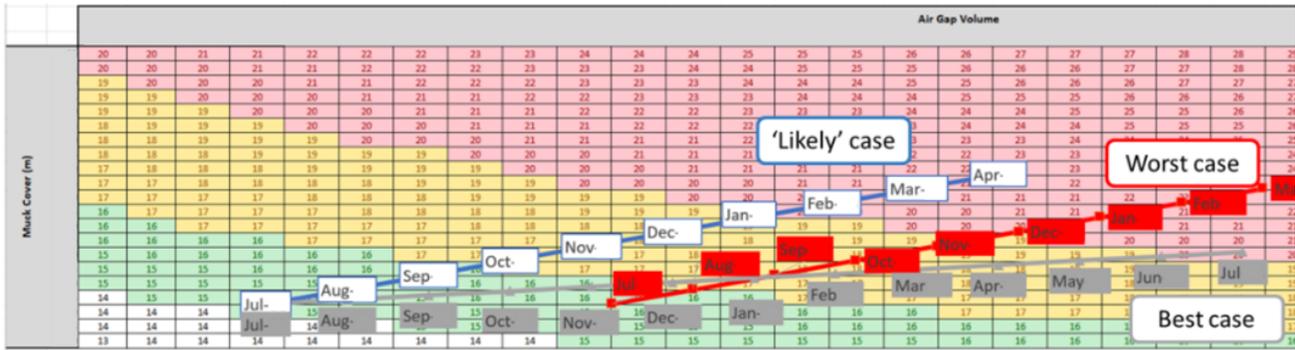


Figure 10 Air blast Hazard forward planning.

Overview:

MHMP overview	Status	Comment
Caving (CHMP)	Actions required	
Seismic (TARP)	On track	
Inrush; Water and mud	On track	
Inrush; Air	Actions required	

	NO ACCESS TO UNDERGROUND PAST 4580	
	Date	Months
Scenario 1 - Likely case Ongoing cave growth and muck draw down		
Scenario 2 - Worst case Larger current air gap volume, reduced caving and higher muck draw down		
Scenario 3 - Best case Ongoing cave growth and reduced muck draw down		

Business Risk

"No Access to Underground Past 4580"

This is the point at which, to ensure personnel are not exposed to dangerous air velocities, draw from the SLC must be significantly reduced.

- Bogging of swell only (30% of fired tonnes) from all rings in SLC.
- (Average planned draw for SLC is ~90%. This will mean a **reduction in total production** from the mine) with potential negative longer-term impacts to cave flow.

Cave growth activities are required to reduce the material business risk.

Figure 11 Hazard level summary page.

6 CONCLUSION

Managing the evolving air blast risk at Carrapateena was a detailed and complicated task. The Carrapateena air blast hazard was effectively managed and closely reviewed for three years until the cave broke through to the surface with no recorded air blast event. The following points were key in the safe operation of Carrapateena with its significant air gap and cave stall issues and are recommended for consideration in the design and operation of future caves:

- The Carrapateena cave had a high level of monitoring through the cave column, including direct and high confidence muckpile observations. The geotechnical

team were constantly reviewing the cave back and muckpile which were key inputs into the velocity modelling.

- The risk and uncertainty states were regularly reviewed. As the air blast risk evolved it was crucial to understand the current and future uncertainties, as the cave may propagate into areas of reduced monitoring density and additional monitoring may be necessary.
- The vent network was utilized to create a path of least resistance for a potential air blast, reducing the level of hazard to the rest of the mine.
- Use of the VentSim Caving Air blast Simulation tool with dedicated and experienced personnel to build and

regularly update this model. The confidence in the model was underpinned by an intimate understanding of the vent network and how minor changes could impact the potential flow of air.

- Understanding the model sensitivities and uncertainties of inputs into the model. There is the potential for large levels of unknowns when considering a cave back as well as the inputs and mechanisms required for an air blast model. These must be identified, understood and accounted for. Technology was used at Carrapateena to reduce uncertainty when it came to the muckpile and air gap volumes.
- Clearly defined air velocities TARPS to categorise the level of risk in the event of an air blast and the specific mitigation controls for each level.
- Review of the methodology and assumptions by multiple external experts. These cave review boards (CRB) were crucial in reviewing the hazard management strategies, data and risk levels through the multiple phases of the Carrapateena execution.

These key factors allowed the Carrapateena mine to continue to operate while the cave back propagated through to surface and the air blast risk was all but eliminated.

ACKNOWLEDGEMENT

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