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The design of push-pull primary and secondary ventilation systems and a vertically-split intake-exhaust ventilation shaft

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ABSTRACT: The duty on mine ventilation shafts is usually either intake or exhaust; it is unusual to split the shaft vertically with one compartment an intake and the other an exhaust. Modern mines in Australia also rarely employ "push" or "push-pull" primary ventilation systems; they are almost always surface exhaust ("pull" or extracting) systems. Similarly, underground district (circuit) ventilation systems are almost always designed as exhaust-only. This paper describes an unusual set of circumstances that led to the selection of a conventionally-sunk, concrete-lined, vertically-split primary ventilation shaft with asymmetrical intake and exhaust compartments for a major mine expansion in Indonesia. Site power generation costs are high, so to provide a ventilation-on-demand system to deliver intake air directly to the new working levels as required, an unusual push-pull district ventilation system was also utilized. The split shaft design was also required to facilitate retro-fitting of surface refrigeration if the mining depth or level of activities required. A key issue was to ensure satisfactory safety including egress and entrapment design for underground workers. This paper describes the factors impacting on the choice of the ventilation design, the design itself and the management of the risks associated with the design, and the various implementation issues on the site.

1 Introduction

The Kencana mine at Gosowong on Halmahera Island in eastern Indonesia (Figure 1) is a high-grade, low-tonnage underground gold mine owned by PT Nusa Halmahera Minerals, a member of Newcrest Mining Limited, a major Australian gold producer. Until 2009, production came solely from the K1 orebody using undercut and cemented paste fill mining methods. Twin-boom jumbo drills and large diesel loaders and trucks are used for ore breakage and transport to surface. K1 is flat dipping (45°), approximately 350 to 400 m along strike, averages 10 m in thickness and extends from about 130 m to about 300 m below surface.

The mine is effectively on the equator only a few km from the ocean and is almost at sea level, so the climate is hot and humid all year around.

The requirement to almost double production would be achieved by including the nearby K2 orebody (and a linking ore lens called K Link) accessed underground and separated about 1 km laterally from the K1 orebody (Figures 2 and 3). K2 is similar style mineralisation to K1 but extends from about 200 m to about 400 m below surface. The mining method will be the same.

An interim ventilation upgrade was required for initial development across to the K2 orebody, followed by a final ventilation upgrade to enable production from K2 whilst maintaining production from K1 until its reserves were exhausted, at which point K2 would be required to meet the full expanded mine production.

A number of factors meant that a conventional approach to the design of the primary and secondary ventilation systems for K2 would not be practical, economic or timely, leading to investigation and then adoption of alternative methods.

2 Original (K1) Ventilation System

The primary ventilation system for the K1 orebody is effectively a single whole-of-mine series circuit with the principal mine intake being the surface ramp (also used for all trucking and support services) and a single exhaust shaft with surface fans connected to the ramp bottom (Figure 4). A minor auxiliary intake is the surface escapeway (with ladder). As the ramp is progressively deepened, a new vertical leg of the surface exhaust shaft is completed and any upper connection into the exhaust shaft is closed off.

The mine employs an undercut and fill mining method with resuing[1] in the wider orebodies. The width of each stope varies considerably along strike due to the variable width of the ore mineralisation. All stope development and production is ventilated using 180 kW 1.4 mØ fans hung in the ramp forcing air via flexible duct to the workplace, with the return air exhausting back to the ramp and then proceeding to the levels below and finally to the exhaust shaft.

Due to a combination of the hot, humid surface climate and the mine developing to greater depths (with more autocompression, diesel trucking and strata heat), conditions at the workplace were becoming oppressive.

[1] In a wide section of cut and fill stope, the ore is taken out by Jumbo drill and blast techniques to the maximum safe width initially, then paste filled, and then the remaining ore left in the "wall" is removed by Jumbo, and then also paste filled

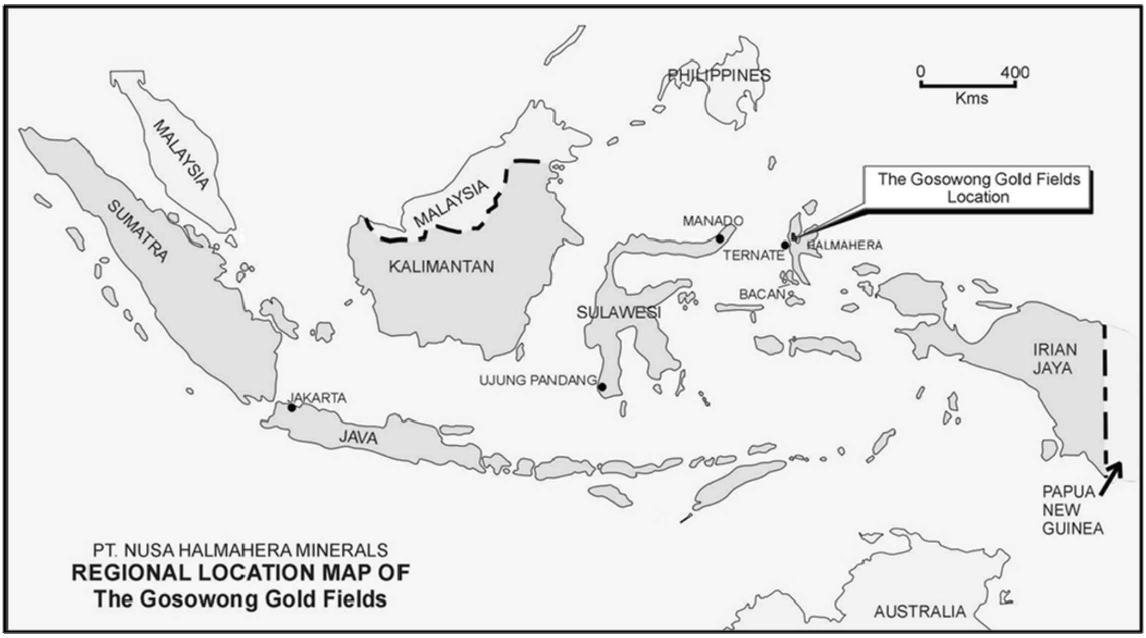

Figure 1 Locality map for Gosowong site (Kencana Mine)

The existing mine ventilation system was already at capacity (220 m^3/s) due to a combination of the limitations of the intake ramp (29.4 m^2), the small size of the sole surface exhaust shaft (3.5 mØ), the number of horizontal offsets in the shaft and the capability of the existing surface exhaust fans (2 x 400 kW twin axial fans in parallel).

3 Key Issues Impacting On The Ventilation Design For The Expansion Of The Mine

There are a number of important factors that any upgrade of the ventilation system at Kencana needed to take into account:

- Due to its high gold grades, there are security issues on-site, with the need for surface shafts to have security fencing and security staff. Effectively, this increases the operating costs of new surface shafts unless they can have their collars within the existing secure areas.
- The hot and humid climate and low elevation above sea level. There are few underground mines in the world as close to the equator and virtually at sea level.
- The difficulties, expense and timing of creating surface shafts in weak ground. Surface shafts at Kencana must be conventionally sunk and concrete lined as they proceed. For similar reasons, all underground ventilation raises and extensions to the surface exhaust shaft have also been developed by traditional shaft sinking methods. No raiseboring had ever been attempted at Kencana up to this time.
- The difficulties and timing constraints of mobilizing contractors to the site. This was particularly a concern if the mine schedule did not allow new surface ventilation shafts to be completed consecutively, as it would be impractical to find, mobilize and support two specialized shaft-sinking contractors to perform two conventional shaft sinks (intake and exhaust) at the same time.
- The labour-intensive nature of the mining method meaning that workers were immediately impacted by sub-standard ventilation conditions.
- The high dependency on auxiliary ventilation for the operation and the difficulties of maintaining good ducted ventilation due to the drill blast muck nature of the mining method, which does not use any flow through ventilation.
- The need to complete the expansion with some urgency to increase gold output to meet corporate objectives.
- The high airflow requirement for diesel equipment in Indonesia (3 m^3/min/HP rated diesel engine power, which is equivalent to 0.067 m^3/s/kW. This is 33% more airflow than is required under the current Western Australian regulations (0.05 m^3/s/kW) and 67% more airflow than required under the old Queensland regulations (0.04 m^3/s/kW)).

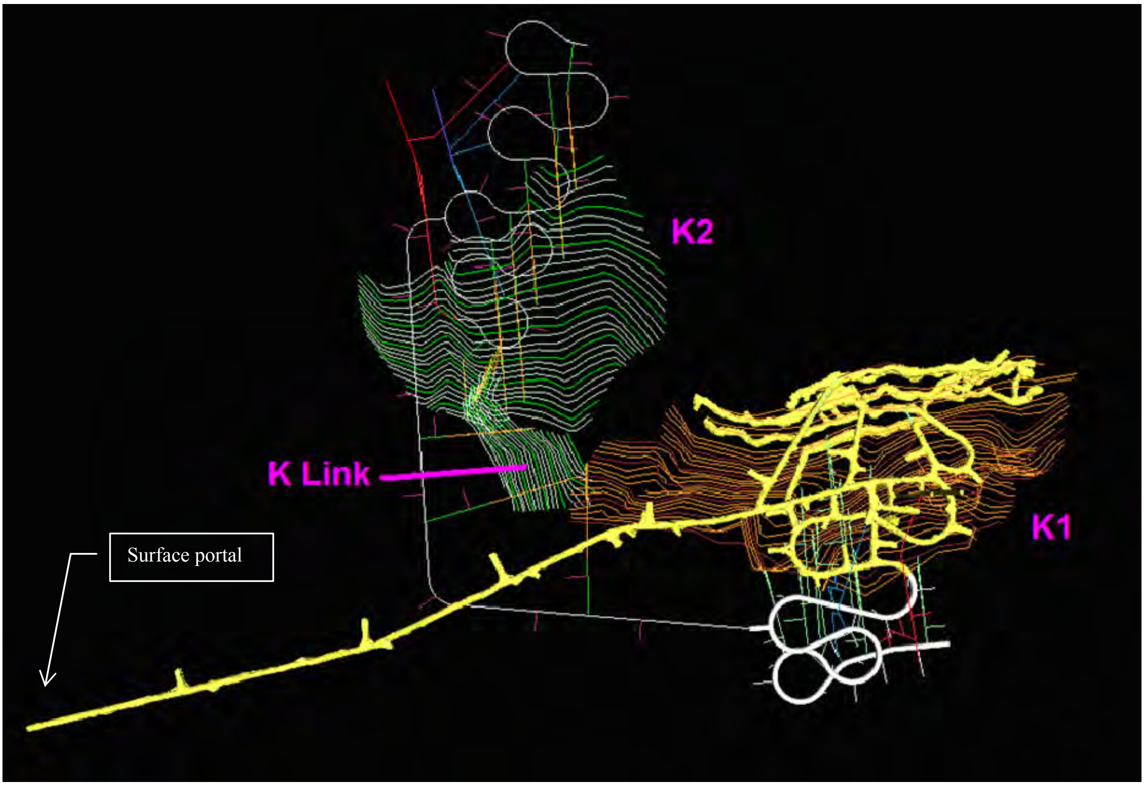

Figure 2Plan view of K1 (existing), K2 and K Link (under development) orebodies

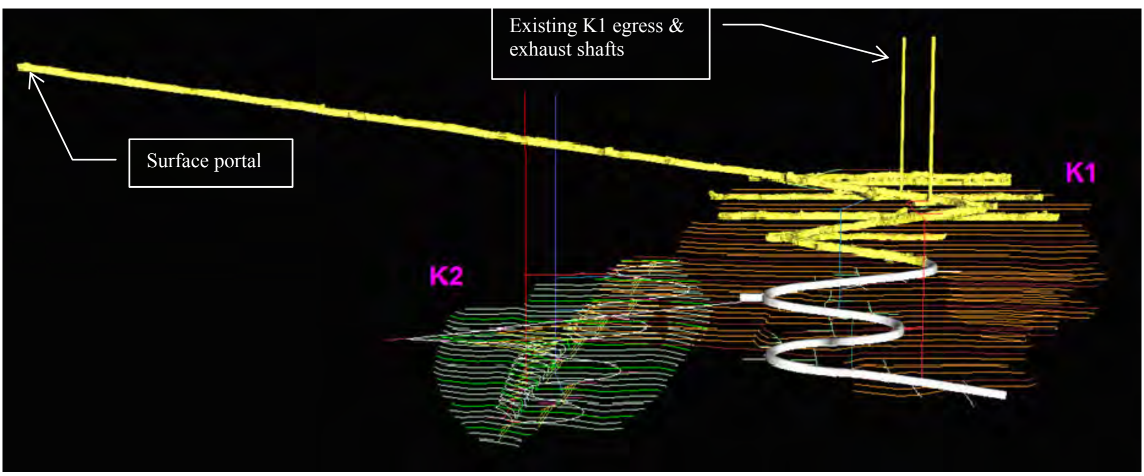

Figure 3 Section view of K1 (existing) and K2 (under development) orebodies. K Link is mid-way between K1 and K2

4 Final Ventilation Design

4.1 Split Ventilation Shaft

An initial conceptual study examined a wide range of options for K2 ventilation which was reduced to the following five for the pre-feasibility study (PFS):

- Two new surface ventilation shafts at K2 (intake and exhaust).
- One new surface shaft at K2 (intake) with a separate lateral dedicated return airway back to K1.

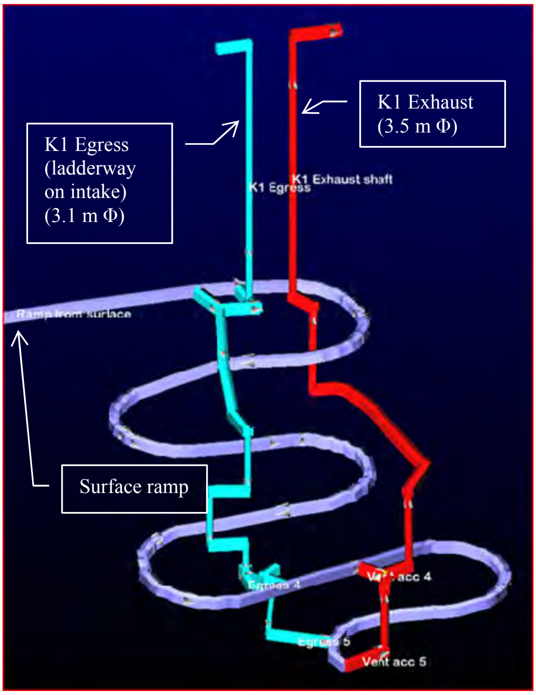

Figure 4 Existing K1 simple whole-of-mine series ventilation circuit

- One new surface shaft at K2 (exhaust) with a separate lateral dedicated intake airway from K1.
- No new surface shafts at K2, with intake and exhaust coming from K1 via twin dedicated lateral developments (one being the access ramp).
- A divided ventilation shaft at K2 (intake and exhaust).

Key findings from the subsequent pre-feasibility study (PFS) were:

- The total mine airflow needed to be increased from its existing 220 m^3/s to about 520 m^3/s for the expanded production.
- The development program for K2 needed to be accelerated and this, combined with the other reasons above, meant only one surface ventilation shaft would be constructed for K2.
- Provision should tentatively be made for some form of mine cooling, probably on surface.
- An interim ventilation upgrade would be essential to maintain production from K1 whilst developing across to K2. Two 200 m long small diameter raisebores (reamed 2.4 mØ and then shotcreted to 2.2 mØ), named RB1 and RB2, would be established from surface bottoming near the underground break-off to K2 to facilitate this development (Figure 5). However, concerns were raised as to whether these could be kept open long enough to complete the shotcreting. The design was therefore changed so that both raises could top out on the main ramp near the surface portal, avoiding the very poorest ground near the surface. The portal could then feed one raise as an intake, and the other raise would duct exhaust air out of the mine through the portal via twin 1.2 mØ steel ducts.
- These two small raisebores were also important in the long-term as the stopes in the K Link area were too distant from K2 shaft to be fed fresh air from K2, and the best source of intake air for K Link production would be one or both of these small raisebores.

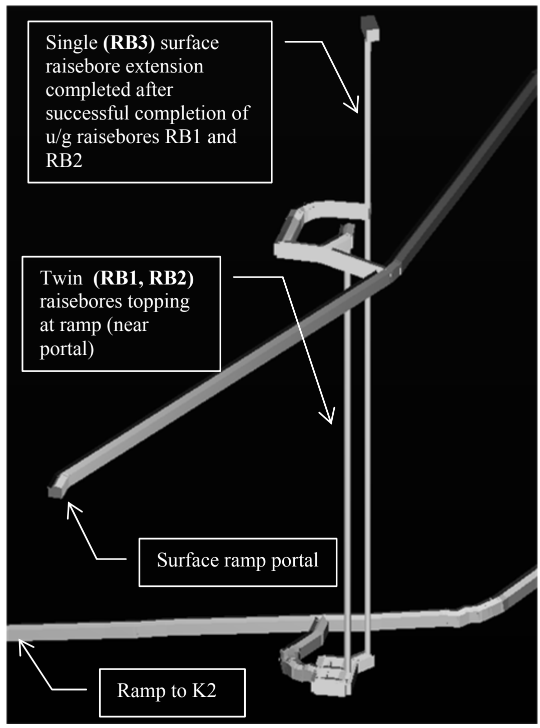

Figure 5 Twin raisebores for initial K2 development (and longer-term ventilation of K Link production)

A feasibility study (FS) was immediately commenced. This study was required to evaluate three primary ventilation configurations for the 300 m deep K2 shaft:

- Divided K2 shaft with two small raisebores as per above for K2 development (one intake, one exhaust). These would top out adjacent to the surface ramp near the portal.
- Divided K2 shaft with no surface raisebores for K2 development (effectively a worst case, assuming neither raisebore could be kept open at all).
- Undivided K2 shaft downcasting fresh air with a lateral return air connection back to K1.

For a variety of practical and timing reasons, the first of these options was the final choice.

Investigations confirmed that conventionally-sunk shafts of 4 mØ or less must be manually hand-mucked into kibbles. Shafts of 4.5 mØ or larger can be mechanically mucked. From a safety and productivity point of view, mechanical mucking is preferable. After a trade-off study into the upper practical shaft limit for the site, a finished size of 5.5 mØ was selected based in part on a final intake airflow requirement for K2 of about 250 m^3/s.

This style of split ventilation shaft arrangement is not common but has been employed successfully at other mines, in particular, in South Africa. For example, one of the AngloGold Ashanti operations in South Africa (*Moab Khotsong*) employs such a system. In common with other similar installations in South Africa, this type of shaft is called a "rock/vent" shaft or RV shaft. It is called this because the intake compartment is also used for hoisting ore, which will not be the case at K2.

Mines using these RV shafts usually operate them with very high wind speeds in the upcast portion (25 to 30 m/s) and much lower speeds in the downcast portion, so the shaft is not evenly divided into two sections. The downcast portion uses a lower wind speed as it contains all the shaft equipment and conveyances. It needs lower wind speeds for safe travel, and also to perform inspections and maintenance in that compartment.

Characteristics of this style of ventilation shaft include:

- The entire shaft is first developed and lined, and includes a slot cast into the walls (Figures 7 and 8) in the correct place for the subsequent brattices to be placed.
- All shaft plats (intake or exhaust) are cut in about 20 to 30 m during the sinking process so they can be connected to the workings later on without damaging the shaft.
- As the downcast compartment is larger than the exhaust, it contains all the services, skips, etc.
- The upcast compartment is basically empty.
- The concrete brattice is heavily reinforced pre-cast concrete to a particular precise shape with sling holes.
- Each brattice section is about 10 m long, weighs about 11 tonnes and is installed from the bottom up.
- The bottom edge of each brattice is "bull nosed" and designed to dovetail into the top edge of the brattice below (which is concave cup shaped to accept the bull nose). See Figure 6.
- After each brattice section is lowered, a very sticky bitumen is poured into the "cup" of the brattice below. The same sticky bitumen is also placed on the sides of each brattice.
- After installation, special tight-tolerance plugs are hammered into all of the sling holes to seal them.

Particular features of using a split ventilation shaft at K2 included:

Figure 6 Moulds for concrete brattice sections

Figure 7 Looking up from shaft sink showing brattice slot cast into wall, pipe rack on wall and kibble

- Since K2 will continue trucking ore to surface, the shaft will not be used for ore hoisting. However, it will be required as a second means of egress and will use a winder for this purpose as well as for shaft maintenance of pipes and cables in the intake compartment.
- Since K1 and K2 are connected via underground ramp, and the ramp must have an airflow, the K2 shaft intake/exhaust must be "out of balance".
- Supply of intake air to K2 from the K2 shaft will be much better quality, and cooler, than air coming across to K2 from the K1 ramp.
- To maximise the amount of fresh air that can be brought down the K2 shaft, the ramp from K1 would be upcasted. This allows a smaller exhaust compartment in the K2 shaft (and therefore larger intake compartment) and/or lower wind speeds in the K2 intake compartment (important for the shaft conveyance). Upcasting the ramp back to K1 also allowed a longer-term use of the ventilation infrastructure at K1 than would otherwise be the

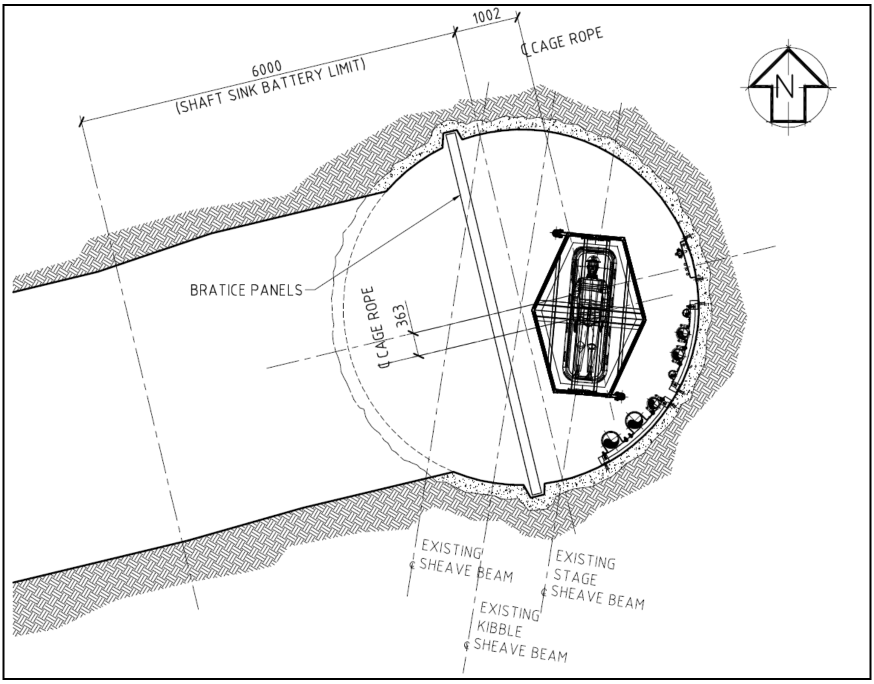

Figure 8 K2 shaft internal layout (note 60/40 split and 2 guide ropes only for cage)

Figure 9 4 x 2 x 55 kW (110 kW) 1.250 mØ fans blowing into RB3 single 2.2 mØ intake raise on surface

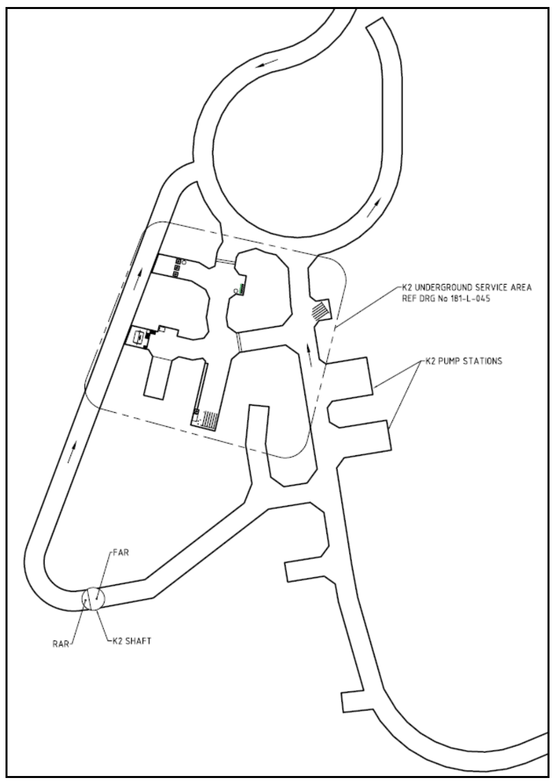

Figure 10 K2 shaft bottom services layout

case and significantly reduces the hazard to workers in K2 in the event of a vehicle fire in the ramp.

4.2 Balancing K1 And K2 Airflows

Once intake air reaches the bottom of the K2 intake shaft compartment, it needs to be distributed to the working places (development faces or stopes). It was recognised that the "series" style of ventilation used at K1 (where air is taken off the ramp into the working place on a level and then returns to the ramp) was sub-optimal for a number of reasons. Therefore an internal fresh air raise (FAR) system was designed for K2. This meant that air will be taken from the K2 intake compartment and distributed to each working level via a dedicated, secure and isolated fresh air raise system. The FAR system will be sealed on all levels via secure brick walls, and air will then be drawn out of the FAR by fans installed in those walls, and then ducted to each work place. The air will return to the bottom of K2 via the K2 ramp and then to surface via the K2 exhaust compartment and the surface ramp, effectively creating a push-pull system.

This strategy also overcomes two other problems with the split shaft design:

- Because the intake compartment will be operating at high wind speeds, it will have a high pressure loss compared to drawing air down the surface ramp. Modelling showed the downcast compartment would not naturally downcast sufficient air for K2 requirements.
- It was determined that provision must be made to fit (or retro-fit) a surface bulk air cooler to the K2 intake compartment. A conveyance also had to be able to exit the intake compartment on surface. A surface blowing fan to push air down the K2 intake compartment would therefore be very difficult to achieve.

In addition to much improved safety in the event of a fire, and the delivery of cleaner and cooler air during normal operations, a further advantage of this system is that it delivers air to only those work places that are operating, and that the more work places that are operating (via more auxiliary fans being turned on), the more air is pulled down the K2 shaft intake compartment, and vice versa. The system was designed to allow up to 7 levels (14 working places) to be ventilated at any time, drawing up to 250 m^3/s down the K2 intake compartment.

However, the volume drawn down the shaft would be changing potentially throughout each shift. To ensure the "balancing" flow in the K1 to K2 ramp remains at reasonable levels, and in the right direction, it will be essential to have the ability to continuously vary the flow up the exhaust compartment in K2. The surface fans at K2 (and K1) are therefore being fitted with VVVF (variable speed) drives and wind speed and direction monitoring will be required in K Link ramp.

4.3 The Interim Ventilation Upgrade

The PFS had recognised that the 1000 m of single-heading development from K1 to K2 could not be completed without an interim upgrade of 100 m^3/s to the K1 ventilation system, taking the K1 ventilation capacity from 220 m^3/s to about 320 m^3/s.

During the FS, a wide variety of options were examined to provide the interim increase in K1 airflow for K2 development. All options were modelled and examined in some detail. Two options were short-listed based on safety, operating or practical reasons:

- An upgrade of the K1 surface exhaust fans (installing a third fan in parallel, or purchasing an entirely new replacement fan installation).
- Installing booster fans at the bottom of the K1 shaft.

The option chosen was to replace the existing K1 surface fan with a completely new installation that would take total K1 mine airflow to about 300 m^3/s (about 31 m/s in the 3.5 mØ K1 exhaust shaft). This provided the most flexibility and best chance of successful development to K2, given the uncertainty about the RB1 and RB2 small diameter raisebores. Another factor was that the existing fan on K1 exhaust could successfully be relocated to be used as the exhaust fan on K2 shaft.

After approval of the overall K2 expansion project, the two small raisebores were commenced. It transpired that these did remain open and were successfully shotcreted. The added confidence meant that a short single surface raisebore (RB3) was then installed above one of these, which meant that the K2 development did not need to exhaust out of the portal via duct, which was recognised as a significant risk.

4.4 K Link Final Ventilation Design

The success of the small diameter raisebores confirmed the potential for these to be used in the long-term ventilation design to provide fresh air for the K Link production activities.

5 K2 Shaft Design

The K2 shaft has a maximum design flow of 250 m^3/s (18.6 m/s) in the intake and 190 m^3/s (21.2 m/s) in the exhaust compartments.

The design can be divided into three regions:

- The internal layout of shaft itself.
- The surface layout.
- The shaft bottom including the adjacent services area.

5.1 The Internal Layout Of The Shaft Itself

The shaft consists of the two compartments (intake and exhaust) with a conveyance in the otherwise nearly open

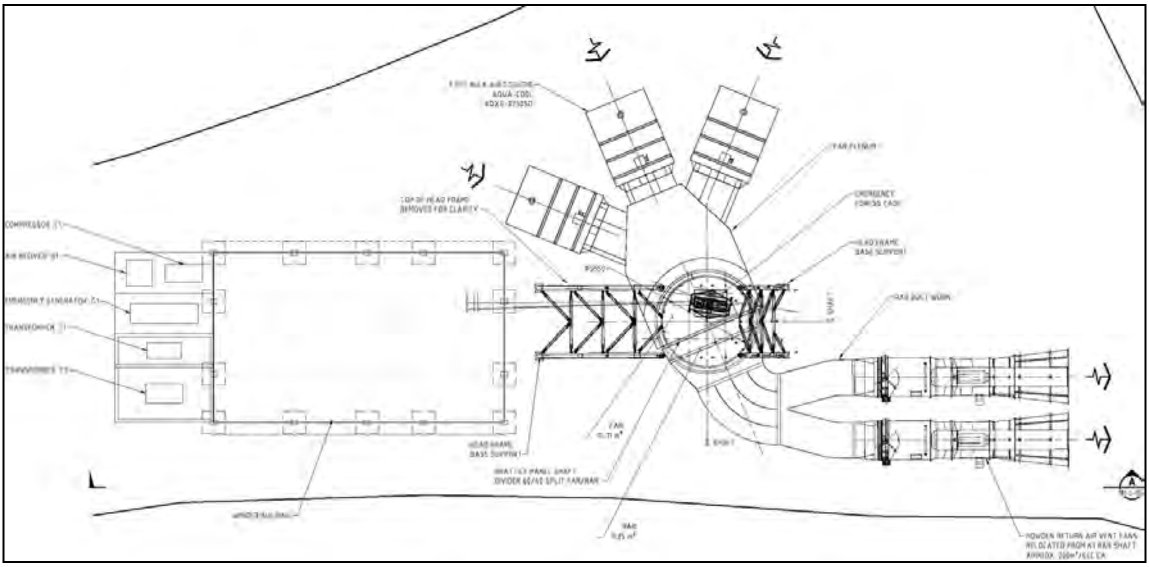

Figure 11 K2 shaft surface (plan view)

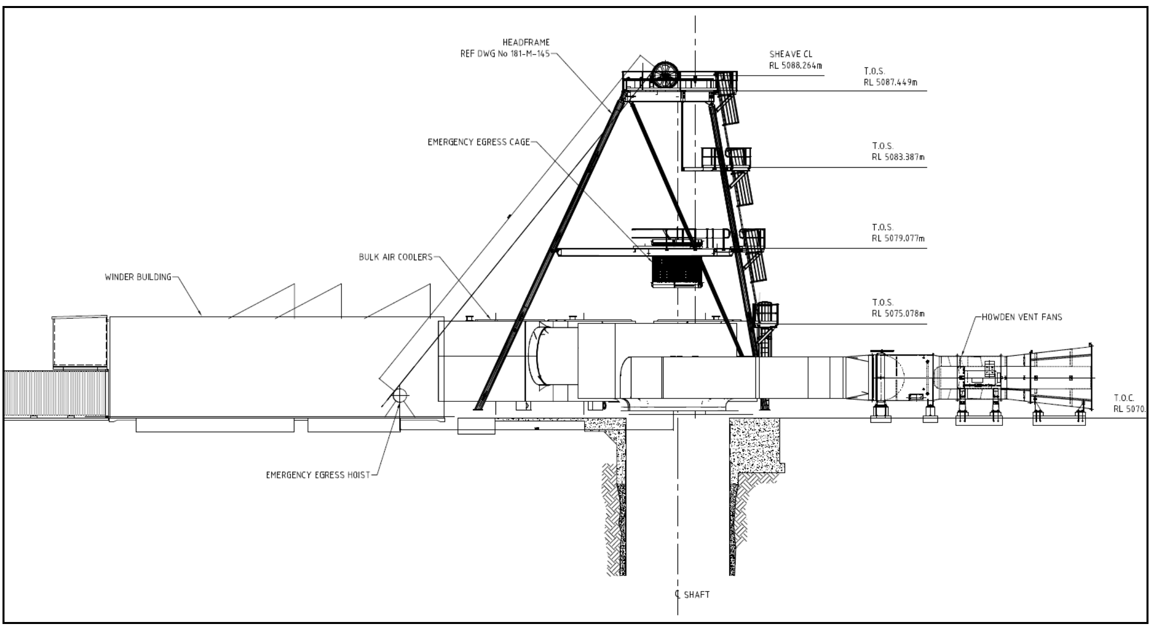

Figure 12 K2 shaft surface (elevation)

intake compartment along with pipes and cables. The layout is shown in Figure 8. The conveyance has only two guide ropes, will normally be parked above the shaft collar and when in use only travels very slowly (1 m/s up, 1.5 m/s down), consequently it only has a small impact on friction (“k”) factor and can tolerate higher than normal wind speeds.

5.2 The Surface Layout

The design on the surface is heavily constrained by topography, with a deep gully on one side (West) and a steep mountain slope on the other. This together with the need to provide for surface bulk air cooling (if required) and the need for a winder in the intake compartment with the associated headframe, requires a complex multiple bend at the shaft collar feeding the exhaust fans. The layout is shown in Figures 11 and 12. If a BAC is required, it will be of the modular type, over-chilling only a fraction of the total intake air, so that the intake can be open to atmosphere on surface and can accommodate the potentially wide range of intake flows down the shaft required by the on-demand, push-pull system.

5.3 The Shaft Bottom Including Nearby Services Area

The shaft bottom (Figures 10 and 13) needs to keep the intake and exhaust air separate. The layout of the services area/workshop at the shaft bottom had to be carefully designed as:

- The K2 ramp will form the exhaust circuit from the working levels back to K2 but the adjacent services and workshop area needs to be fed with intake air.
- The services area must discharge into the K2 exhaust (due to the potential for fire in the refuelling facility).
- It also needs to provide at least one open access between workshop and ramp for operational reasons.

6 Friction Factors, Shock Losses And Brattice Leakage

6.1 Shaft Friction Factors

A "base" friction factor for an open concrete-lined slip-formed shaft of 0.005 Ns^2/m^4 was selected, which should be conservative. The exhaust compartment is fully open, and so its friction factor is estimated at 0.005 Ns^2/m^4 (however, its adverse shape affects its overall resistance). The intake compartment is almost fully open with minor loss of area for pipes and cables and no fixed guides. The conveyance has a speed of 1 m/s up and 1.5 m/s down. As McPherson (1993) notes, longitudinal fittings such as guide ropes may actually reduce the friction factor of a shaft. The apparent friction factor for the intake compartment (based on the open finished shaft area without adjustments for shaft furniture or equipment) is estimated at 0.00725 Ns^2/m^4 excluding shock losses top and bottom.

6.2 Shaft Shock Losses

There are no horizontal levels or cut-outs between shaft surface and bottom. The only shock losses are therefore at the top and bottom of the shaft. At the top of the shaft, any losses above the collar in bends etc would normally be taken into account in the fan curve. However, in the case of K2, the fan is being relocated from K1. The shock losses (using the velocity pressure associated with the respective compartment open area) were estimated as:

- Intake (1.0 at bottom, 1.0 at collar)
- Exhaust (1.0 at bottom, 2.5 from collar to fan inlets)

6.3 Shaft Brattice Leakage

Shaft brattice leakage was not considered a critical design parameter in this instance for several reasons:

- The short (300 m) length of the shaft.
- The relatively low pressure across the shaft brattice due in part to the push-pull system of operation.
- The high quality of the brattice design and sealing.

Based on limited data available from South Africa for this type of installation, a brattice leakage resistance of 8 Ns^2/m^8 was chosen, which was simulated in the Ventsim™ modelling as being a leakage path across the brattice at mid-shaft. Sensitivity studies using various leakage factors showed the absolute volumetric leakage to be small. Note that as the shaft is effectively using a push-pull system, there is the potential for the absolute pressures in the intake compartment to be higher than in the exhaust compartment, so that leakage could result in recirculation.

7 Push Pull System On Interim Ventilation Design

The standard mine development fans are 180 kW 1.4 mØ axial fans. Due to the limited height of the surface ramp at the portal, four 110 kW 1.25 mØ axial fans were purchased in case the K2 initial raisebores (RB1 and RB2) had to exhaust out of the mine portal using two small ducts. With the successful completion of the small surface raisebore (RB3), exhausting out of the portal was no longer required.

The K2 development was to proceed with up to three 180 kW fans in parallel on the bottom of RB1 and RB2 feeding three 1.4 mØ ducts. Once the resistance of the small raises was combined with the resistance of the long development ducts to reach K2, modelling indicated the 180 kW fans could potentially enter stall.

A system was therefore designed to push air into the RB3 raisebore from surface using the four available 110 kW fans (see Figure 9) which would operate in push-pull configuration with the three 180 kW fans pulling air out of the bottom of the raisebores to feed the three development ducts.

Modelling showed that if surface power is lost or the 110 kW fans trip for any reason, the 180 kW fans at the bottom of the raise would go into stall. To avoid this, a system of 1.6 mØ self-closing dampers (SCDs) was installed between the ramp and the top of the RB1-RB2 raisebores. In the event of the surface 110 kW fans being off, the SCDs would automatically open allowing ramp air to enter the system ensuring the 180 kW fans never went into stall.

Similarly, if the 180 kW fans went off, the 110 kW fans on surface would go into stall as they could not overcome the combined resistance of the raises, fans and ducts at the bottom. To prevent this happening, SCDs were also set up at the bottom of RB1-RB2 in parallel with the 180 kW fans so that if the 180 kW fans went off, the

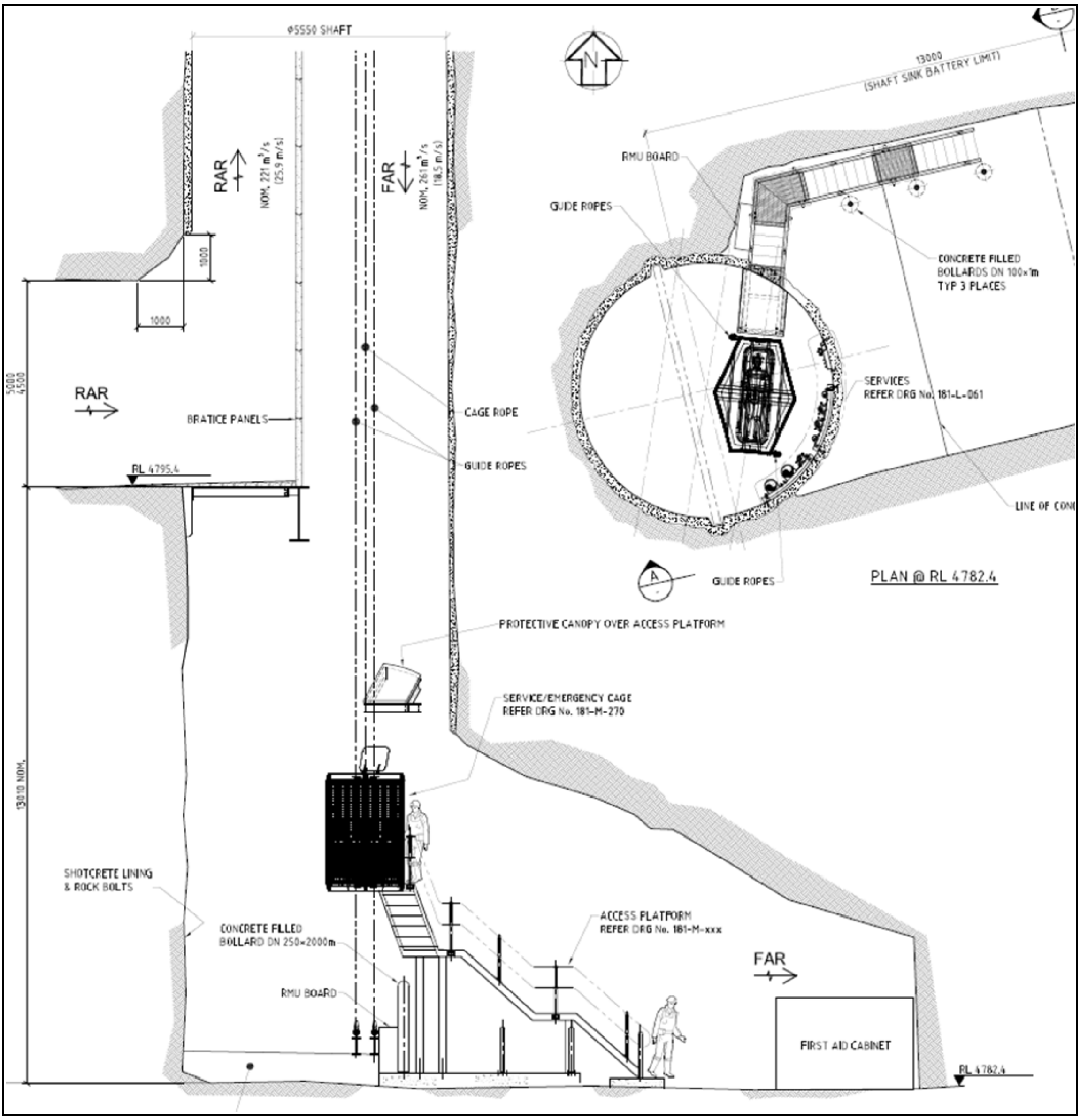

Figure 13 K2 shaft bottom

adjacent SCDs would automatically open ensuring the surface 110 kW fans did not enter stall.

8 Safety Aspects Of The Design

Key safety aspects associated with this design included:

- All persons underground wear minimum 30 minute self-contained self-rescuers at all times.
- Overall compliance with the various Australia mine fixed and mobile plant fire suppression codes and in particular the Western Australian approved guideline *Refuge chambers in underground metalliferous mines (2005)* including the requirements for maximum spacing of refuge chambers.
- Ramp in the K2 orebody forms the return (rather than using it as the intake as in K1).
- Dedicated, isolated and secure intake system from surface to each K2 working level, with the fresh air raise isolated on each working level effectively providing fresh air bases on each level.

- Each workplace fed with air ducted directly from the fresh air system with each FAR fan sealed to the FAR by a self-closing damper so that products of combustion from a fire cannot re-enter the FAR system.
- Internal ladderway/escapeway in K2 in fresh air.
- Simulation studies completed for each possible failure mode of the surface and underground fans (and combinations) including power failures to examine circumstances in which ramp reversals etc. can occur.
- Refuelling stations and magazines fed with fresh air and exhausted direct to a return.
- Winder in the K2 intake compartment that can evacuate all persons from the mine.

Acknowledgements

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