Life-of-Mine Ventilation and Refrigeration Planning for Resolution Copper Mine

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ABSTRACT

Resolution Copper Mine in Arizona, USA, is planned to be a 2000 m deep panel cave mine with virgin rock temperatures exceeding 80°C in rock with high crystalline silica content, resulting in a very challenging ventilation and cooling system design. This is one of the largest copper orebodies ever found and, with a planned rock production rate of 120 kton/day. The project is currently in its prefeasibility phase and the paper discusses features of the ventilation and cooling system design which includes multiple ventilation shafts with total primary ventilation flow of about 3000 m^3/s and both surface and underground refrigeration plants producing more than 140 MW refrigeration capacity. The cooling system features large surface bulk air coolers chilling all downcast air supplemented by an underground secondary air cooler system and a chilled service water system. This will be a very challenging mine to ventilate and cool but this work has demonstrated that it will be technically achievable with the application of existing technology.

INTRODUCTION

The Resolution Copper project is located 110 km southeast of Phoenix, Arizona near the town of Superior and adjacent to the old Magma Mine. The project is run by Resolution Copper Mining (RCM) which is owned by Rio Tinto and BHP Billiton. The orebody is a large, deep, high-grade porphyry copper deposit located close to the historic Magma Vein (Pascoe, Oddie and Edgar, 2008).

The mine is planned to be a large, deep and hot, block cave operation. RCM is currently undertaking a prefeasibility study for the project life-of-mine. In the course of this prefeasibility work, ventilation and refrigeration studies have been carried out to establish:

- heat loads, cooling, ventilation and refrigeration requirements
- preliminary ventilation distribution layouts
- suitable refrigeration and ventilation strategies
- life-of-mine profiling of heat loads, refrigeration, ventilation, power and water needs
- engineering designs or equipment selection and specification
- capital estimation, construction scheduling and cash flow profiling.

Although the mine development phases are hugely important to the project feasibility, this paper concentrates more on the ventilation and refrigeration designs for the fully established life-of-mine scenarios.

The planned production rate is 120 kton/day and the mining method will be an advance undercut panel cave operation using single panels with one cave front. The mine will employ three hoisting and service shafts and three upcast shafts. Within the mining block, the basic levels will include undercut levels, production level, intake vent level, return vent level, haulage level and crusher conveyor level. Electrical loaders will be used for production but diesel equipment will be used for development and undercutting. There will be an electrical rail haulage system delivering rock from orepasses to the crushers from which a belt conveyor system will report to the hoisting shafts loading facilities. There will be midshaft skip discharge and, from that location, another conveyor system will deliver the ore to the surface plant. The dust control at the midshaft skip discharge zone will be particularly challenging. The shaft system will be as follows.

Downcast shafts:

- No 11 Shaft (hoisting shaft) 10.0 m Ø
- No 12 Shaft (hoisting shaft) 10.0 m Ø
- No 13 Shaft (service shaft) 11.0 m Ø.

Upcast shafts:

- No 9 Shaft 6.7 m Ø
- No 14 Shaft 8.5 m Ø
- No 10 Shaft 10.0 m Ø.

The rock will have high silica content which will create serious challenges for dust control. Also the mine will be deep in hot virgin rock temperature (>80°C). Thus dust and

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thermal issues dominate the design evaluations and DPM management will also be important. There is no indication of significant strata gas emission potential and the ventilation rates based on the dust and heat criteria will, under normal operating conditions, satisfy acceptable general standards. These and other relevant design considerations are first presented below and then the technical design descriptions of the systems follow.

DESIGN CONSIDERATIONS

Silica/quartzite levels

Analyses of rock samples indicate a range of quartz content of 20 - 50 per cent for the diabase formations and 40 - 80 per cent for other formations. The main mining activity will be in diabase with an average host rock quartz content of 37 per cent. Depending on how crystal grain boundaries fail during drilling, blasting, transport and crushing, it is possible that the respirable dust fraction will have free crystalline silica content up to 45 per cent of the host rock.

International standards for respirable dust and free crystalline silica vary, they are subject to continuous review and are continually reducing. Historically, typical values for eight hour time weighted average exposure concentrations for respirable dust were 5 mg/m^3 (not coal) and 0.2 mg/m^3 for free crystalline silica. The review of silica health effects (NIOSH, 2002) recommended a TWA limit of 0.05 mg/m^3 (ten hour day, 40 hour week). The Rio Tinto exposure limits (eight hour day, 40 hour week) are 5 mg/m^3 for general respirable dust (not coal) and 0.1 mg/m^3 for respirable crystalline silica.

However, with the highly mechanised nature of the mining method, most workers will not be in dusty environments for significant periods. It was recommended that the 0.1 mg/m^3 free crystalline silica limit is used (40 hour TWA over seven days) with a short-term exposure limit of 0.3 mg/m^3. In practice, this means that periodic sampling will be suitable for the main workforce but a more rigorous monitoring regime will be required for occupations such as crusher operators or conveyor belt inspectors.

It is noted (NTP, 2003) that free silica in the form of cristobalite and tridymite are considered more hazardous. These occur in igneous rocks and may be found at RCM. The NIOSH (2002) document also distinguishes between free crystalline silica, quartz, cristobalite and tridymite implying that the health hazard is dependent on how silica presents itself in the respirable dust fraction. In any event, worldwide limits for respirable dust will most likely continue to fall and a limit of 0.05 mg/m^3 may well be imposed on the project by the time it comes into production. This is similar to the situation with diesel particulate matter where an 'as low as technically achievable' position is being taken, ie when the industry demonstrates it can comply, the limits are reduced further.

Thus the control of respirable dust will be a very significant ventilation issue and the best practice in terms of dust control measures will be applied. This will include extensive use of water sprays (which will also assist in high dry bulb (db) temperature control) and relatively large quantities of ventilation exhausted from dusty areas direct to return (eg crushers, transfer points, skip loading, skip discharge, etc). Extensive use will be made of PPE and personnel will be trained in the control of exposure to respirable dust.

Temperature issues

Virgin rock

The general geothermal gradient will be 2.7°C per 100 m and the virgin rock temperatures will be high. For example, the following reference virgin rock temperatures apply:

- Undercut level 2030 mbc 78.84°C
- Crusher-to-conveyor level 2180 mbc 82.89°C.

Thermal conductivity will be relatively high particularly in quartz rich areas (4.8 - 6.6 W/m^2 °C).

Ambient weather data

Figure 1 gives some surface design ambient temperature data. After detailed statistical evaluation, the design conditions were taken as 21/37°C wb/db (wet bulb/dry bulb) (88 kPa barometric pressure).

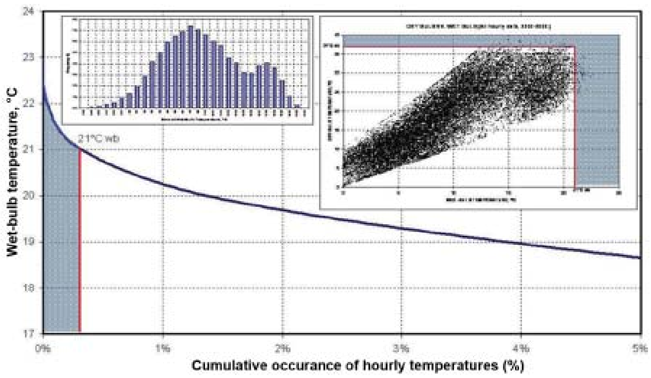

FIG 1 - Mine weather data.

Underground design temperatures and heat stress management

There are many decades of mining heat stress management experience and there a number of standards for heat stress evaluation. There is also a wide body of information supporting heat stress management plans for screening, training, symptoms, treatment, hydration, acclimatisation, protective equipment, action responses, etc. Arizona regulations and Rio Tinto standards do not insist on the use American Conference of Governmental Industrial Hygienists (ACGIH) work regimen charts and wet bulb globe temperatures and this project can select the optimal method for thermal environment monitoring.

Primarily, there is a need for clear values in decision-making that are safe, justifiable, operationally practicable and economically realistic. Normally a simple method is used for determining work place status as regards changing action levels. Wb temperature is used because it provides a clear simple indication and does not rely on sophisticated instruments or calculations. Then, for work above say 'Level 0', a more detailed heat stress index is used to account for air velocity, db and radiant temperatures. This heat stress index may then take precedent over the more simplistic initial wb 'trigger', see Table 1.

Of the many heat stress indices, the three main ones are: effective temperature (Australia, Europe and historically South Africa), wb globe temperature (mainly North America) and air cooling power (South Africa and Australia). In addition, ISO 7933 (ISO, 2004) determines thermal stress using calculated sweat rates or predicted heat strain. Air cooling power (ACP) describes the ability of the environment

TABLE 1
Heat stress management levels.

Action level	Wet and dry bulb temperature (wb db °C)	Air cooling power (ACP W/m²)	Description	Occurrence	Principal controls in place
Level 0	wb <27 db <32	200< ACP	Negligible risk of excess heat related illness	At any time	• Generic training in heat stress management and health screening • Provision of adequate drinking water • Appropriate clothing • Heat stress zones marked on mine plan and communicated to workforce • Monitoring the thermal environment – screening using wb and db
Level 1	27< = wb <29 or 32< = db <37	200> = ACP >145	Potential risk of heat related illness during routine work periods	Likely in underground work places for most of the year. This is the design status of heat management systems for routine work outside air conditioned environments	Level 0 plus • Use ACP for confirmation of thermal environment status • Limited access to un-acclimatised persons • Un-acclimatised persons not to work alone • PPE, work practice and hydration protocols • Supervision, documentation and worker location monitoring
Level 2	29< = wb <32 or 37< = db	145> = ACP >115	Increased risk of heat related illness during routine work periods	Likely in the vicinity of operating mine development and production equipment	Level 1 plus • Workers to be in air conditioned environments other than for short durations • Persons not to work alone outside air conditioned environments for specified durations • Redeployment for persons outside air conditioned environments • Limits on type of work undertaken • Documented remedial actions to improve conditions for work outside air conditioned environments
Level 3	32< = wb	ACP < = 115	Unacceptable risk of heat related illness	Not designed for but many occur in the event of control system failure	Level 2 plus • Work under written permit with additional special precautions

Notes:

1. Wet bulb trigger levels rounded for clarity but assume the workplace to be adequately ventilated – used when air cooling power unknown.

2. Wet bulb is the aspirated wet bulb temperature with limits established from regulatory standards elsewhere.

3. Air cooling power method takes precedent when obtained and is calculated from wet bulb temperature, dry bulb temperature, air velocity, radiant temperature and barometric pressure. This can include assumptions regarding average barometric pressure and radiant temperatures.

4. Air cooling power limits established from ISO 7933 (Light activity = 115W/m², moderate activity 145W/m², high activity 200W/m²).

to cool a person carrying out various degrees of work in order to maintain a safe body core temperature. The ACP values are calculated from all five thermal environment factors and are as valid as the ISO 7933 approach, providing clothing parameter inputs are the same, and, for this project, an ACP approach, that is consistent with ISO 7933, was recommended.

It is important to distinguish between the heat stress management limits and air temperatures used for refrigeration design. The heat stress management plan determines the level of control; for example, the stop work level of 115 W/m² ACP means that, if other systems fail, a person can still safely walk out to a cooler location. The temperatures used for design of refrigeration systems are set so that, on average, specified work place return air temperatures are met. For example, if the reject temperature is set at 27.5°C wb, then return air temperatures may range 26 - 29°C wb due to the dynamic nature of the mining process.

The ACP limits were based on a classification of metabolic rate provided in ISO 7933 for which 115 W/m² provides for 'light activity' such as arm work (driving vehicle in normal conditions, operating foot switch or pedal); machining with low power tools; light strolling. The value of 145 W/m² provides for 'moderate activity' such as sustained hand and arm work (hammering in nails, filing); arm and leg work (offroad operation of lorries, tractors or construction equipment).

The amount of cooling required depends on the reject temperature and balancing the heat stress management needs with the cost of refrigeration. The recommended trigger levels are shown in table above with wb and db temperatures being used for rapid decision-making (in absence of ACP data). At this stage, the recommended design reject temperatures are 27.5/37.5°C wb/db in development faces when persons are outside air conditioned cabins and 30/40°C wb/db in production cross-cuts when equipment is operated remotely. That is, Level 1 conditions in development faces and Level 2 conditions in production cross-cuts.

Diesel particulate matter exposure management

Another important design issue, along with heat and dust, will be that of DPM management (NIOSH, 2011). Controlling employee DPM exposure to less than the current tolerance level values and potential future values will be addressed by management plans including:

- underground diesel equipment will use modern tier three or four engines and all units will be purchased under tight specifications

- high quality, low sulfur fuel will be used with options to use alternatives like biodiesel
- exhaust conditioning, over and above that provided normally on engines will be applied (this technology is available)
- operators of a large portion of diesel equipment will be in air conditioned cabins with filtered air conditioned intake
- series ventilation of work places employing diesel equipment will have to be minimised or avoided altogether due to heat considerations
- all diesel vehicles will be operated according to a site specific, risk assessed DPM control plan as well as an emissions-based maintenance program, incorporating regular exhaust testing to identify problems proactively.

As will be seen, the life-of-mine ventilation capacity is about three times that required to operate the diesel fleet at 100 per cent load. However, there will be times during the development phase where control over diesel locations will have to be exercised to ensure appropriate ventilation rates at point of operation. This control will include monitoring of DPM concentrations and ventilation rates.

Features of a fully established mine

The design snapshot scenario in the life-of-mine is shown in Figure 2, this scenario was selected as the critical design year for sizing the ultimate ventilation and refrigeration needs and this is the basis of the detailed VUMA mine modelling, see later. The modelling work examined the working sections in detail and some of the activities are addressed in Table 2.

The basic statistics for the underground equipment and vehicles are:

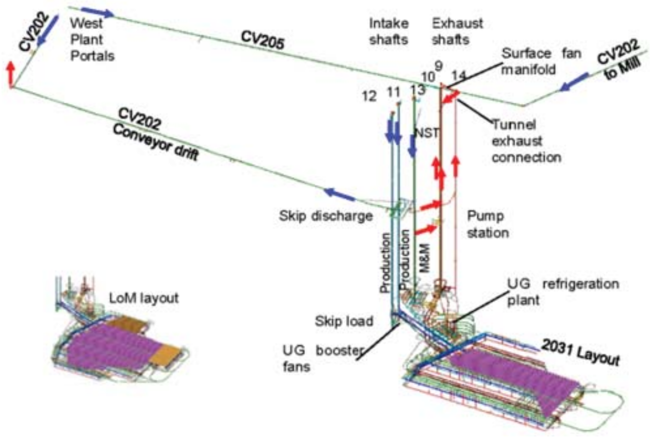

FIG 2 - Snapshot at critical design condition.

- Diesel auxiliary and service vehicles 8.0 MW*
- Diesel loaders and diesel rock breakers 4.2 MW*
- Electrical loaders on the extraction level 4.6 MW*
- Drill rigs (blind borers, raise borers) 4.1 MW*~

*total MW rating; ~(1.9 MW diesel).

The total heat load related to vehicle and mobile equipment will be about 16 MW on a general overall average basis.

Apart from the active zones in the mining block, the following other general 'infrastructure' zones are accounted for in the modelling: workshops, warehouses, batch plant, pump stations, refrigeration plant chamber, conveyor belt system to hoisting shaft facilities, crusher station, electrical substations, etc.

TABLE 2

Production activities.

Undercut levels	
Undercut headings (retreating)	• 11 off retreating using two diesel load-haul-dumps (LHDs) • broken rock from development and surrounding rock heat • other heat: auxiliary vehicles, auxiliary fans, drill rigs, lights
Undercut development and rim tunnel development headings	• five off in undercut development plus two off in rim tunnel development using two diesel LHDs • broken rock and surrounding rock heat • other heat: auxiliary vehicles, auxiliary fans, drill rigs, lights
Production extraction level	
Production cross-cut zone	• 70 off active 150 m production cross-cuts using 30 electric LHDs • broken rock and surrounding rock heat • other heat: auxiliary vehicles, drill rigs, lights
Production cross-cuts in drawpoint construction	• two off cross-cuts with through flow vent using two diesel LHDs • broken rock and surrounding rock heat • other heat: auxiliary vehicles, drill rigs, lights
Production cross-cut development and rim tunnel development headings	• one off in cross-cut development, two off in rim tunnel development using one diesel LHD • broken rock and surrounding rock heat • other heat: auxiliary vehicles, auxiliary fans, dust sprays, raise bore rigs, drill rigs, lights
Intake vent level (haul trucks, development drives and 'background' activities)	• two off developing drives using one diesel LHD • broken rock and surrounding rock heat • other heat: haul trucks auxiliary vehicles, auxiliary fans, drill rigs, lights
Rail haulage level (development drives and 'background' activities)	• four off developing drives using one diesel LHD • broken rock and surrounding rock heat • other heat: auxiliary vehicles, auxiliary fans, drill rigs, lights, electrical (trolley) locomotives, dust sprays, dust control equipment
Return vent level (development drives and 'background' activities)	• two off developing drives using one diesel LHD • broken rock and surrounding rock heat • other heat: auxiliary vehicles, auxiliary fans, drill rigs, lights

In these zones, the heat loads (and ventilation requirements) will be due to the surrounding rock as well as the equipment/activities such as fans, lights, diesels, welding, pumps, refrigerant compressors, apron and vibratory feeders, belt conveyor sections, gyratory crushers, dust collection, fans, transformers, belts, etc.

The heat load due to all the equipment in these infrastructure zones will be about 6 MW on a general overall average basis.

Heat from broken rock

The broken rock flow of 120 kton/day or 1389 kg/s (average) is high, the rock will be hot and the heat load from the broken rock flow will be very significant. The 'worst case' heat load relates to the hypothetical situation where all rock enters draw points at the virgin rock temperature and leaves the mine close to the ambient underground intake db. The virgin rock temperature will vary as the cave moves down and the ambient underground intake db temperatures will range from 25 - 35°C. Assuming a representative value for this ΔT of about 50°C, this 'worst case' potential heat flow will be of the order of 60 MW ($m^* \times C_p \times \Delta T$).

This simple analysis cannot indicate how the heat load will be distributed. It does however provide an indication of the order-of-magnitude involved and the potential effect of mitigation, for example reduced residence times in intake airways or separation of haulage route and crusher ventilation circuits from other main intake airways. In addition, if rock leaves the mine at a temperature above ambient db then the heat load to the mine reduces. This means that it is important to estimate the rate at which rock will transfer heat to ventilation as it passes through the ore transport system, Figure 3. This involved the fundamental assessment of issues such as: residence time of broken rock in various sections of the ore transport system; rock sizes and shapes; transient cooling in broken rock masses, etc. This required many simplifying assumptions but, nevertheless, it did supply order of magnitude level guidance. In summary, the application of this logic in the mine wide heat load model was that the order of magnitude of full potential will be about 60 MW and of this:

- 30 MW will manifest itself as heat load on the underground mine
- 2 MW will manifest itself as heat load at skip discharge/bin and feeders
- 4 MW will manifest itself as heat load in the surface conveyor system
- 24 MW remaining leaves the entire mine in a 'still hot' condition.

The heat from broken rock flow in the underground mine is assumed as follows, and this was input to VUMA network in the relevant branches:

- Loading level horizon 12 MW
- Rail level and shaft 18 MW
  - Characterisation level up to crusher 6 MW
  - Transfer to crusher and belt 5 MW
  - Conveyor belt system 2 MW
  - Loading station to hoisting shafts 3 MW
  - In shaft No 11 and No 12 Shafts 2 MW

18 MW total.

It is emphasised that this assessment is an approximation but the main outcome of this is:

- Underground heat load from broken rock will be very significant and will require appropriate design of the haulage route ventilation and cooling circuits.
- Rock piles in draw points between loading cycles will emit heat which will generate unacceptable air temperatures if ventilation is reduced during these times ie this could limit opportunities for a ventilation-on-demand approach to control.

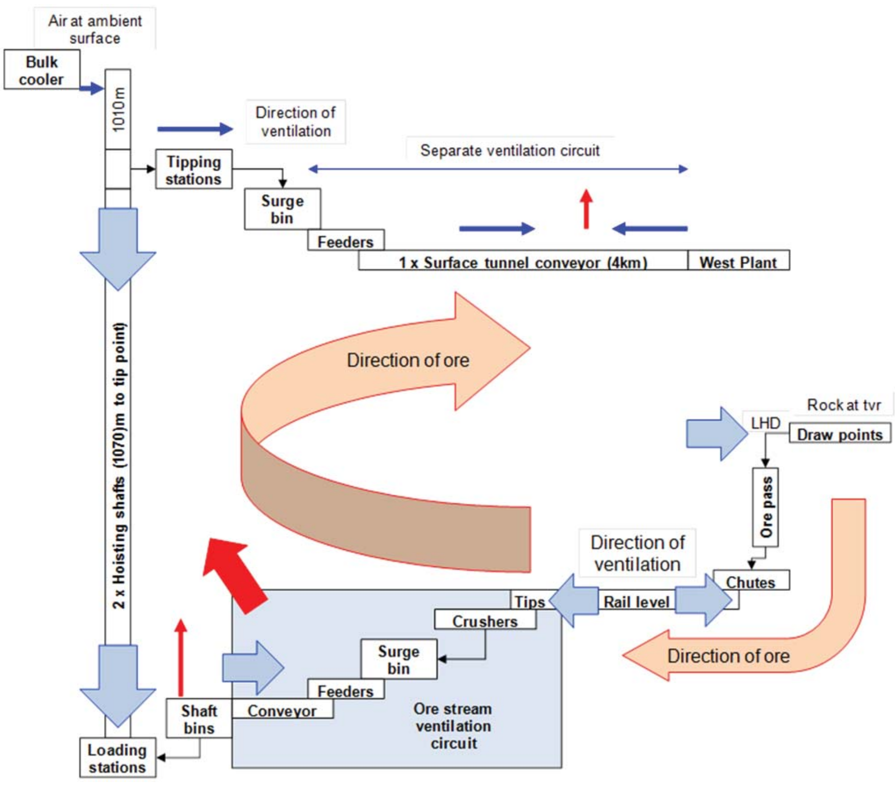

FIG 3 - Schematic basic ore transport flow chart.

PRIMARY VENTILATION SYSTEM

Primary ventilation flow rates

The density of air will vary significantly through the mine and, in general terms, the overall primary ventilation distribution is 2760 kg/s (or 2345 m^3/s) to the underground workings. The total flow from surface will be 3120 kg/s with the difference being that used on midshaft skip discharge level. During full production, the needs will be dominated by the number of extraction drives with about 70 off individual locations at 12 kg/s each with 35 regulated exhaust raises (24 kg/s each). Some of the specific considerations included:

- Development crew allocations are based on two separate active faces per crew with exhaust vent raises installed to limit force duct lengths to <500 m.
- Undercut and drawbell levels involve both development and mucking of swell.
- Extraction drive allocation is for remotely controlled electric loaders only and will not change for standing (secondary) work in terms of heat management.
- The potential for high db temperatures will be most prevalent on the production level. Liberal amounts of water will be used at drawpoints and orepasses for controlling temperature and dust. The models indicate that, with reasonable amounts of moisture, the db temperatures can be practically kept below 35°C db (without water sprays this could exceed 42°C db).
- Ventilation for fuel/tyre bays will report directly to return airways but other workshop ventilation will be reused elsewhere.
- Raise bore location ventilation will be reused and this allocation is therefore not an additional load.
- Dust management will be based on capture velocities of about 2.5 m/s applied to cross sectional area of capture point.
- Midshaft skip discharge points require a robust dust capture strategy to avoid contaminating No 11 and No 12 Shaft intake and a return connection to No 14 Shaft exhaust will be provided for this purpose.

The subsystem related to the underground conveyor ramp is an important feature of the overall design. The crusher station and rock handling systems will generate significant heat and dust loads and these facilities will be located such that they can be encompassed in this subsystem. There are benefits in isolating this subsystem in its own ventilation district thus ensuring that these heat and dust loads are prevented from entering the main mine workings. This isolation strategy is also sound fire engineering practice.

Comparison with other block cave mines

The comparison between the planned ventilation requirements for this project and those of some other block cave mines are shown in Figure 4. Considering the need at RCM to manage high heat loads with refrigeration and to allocate relatively large flow rates for controlling dust (including midshaft skip discharge), this somewhat subjective comparison indicates that the planned ventilation rates are consistent with those employed at other block cave mines (it is assumed that ventilation rates reported for other block cave mines are at surface density).

Shafts and primary ventilation infrastructure

The life-of-mine primary ventilation circuit is that shown in Figure 5. The plan is to downcast No 11, No 12 and No 13 Shafts, upcast No 9, No 10 and No 14 Shafts together with

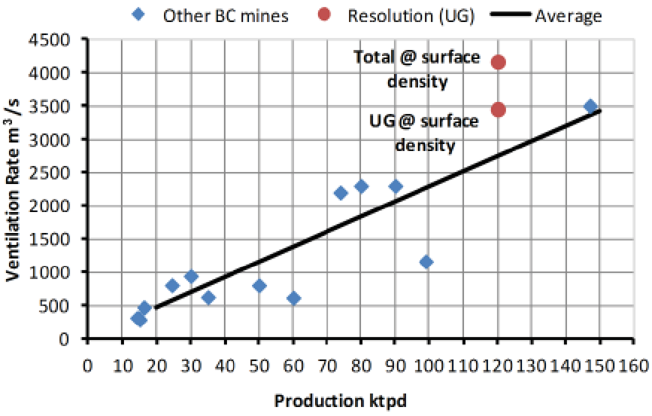

FIG 4 - Resolution ventilation rate benchmarking.

exhaust via the conveyor drift. Provision is also made for a return connection between the skip discharge horizon in No 11 and 12 Shafts to the No 14 exhaust shaft, midshaft pump station and conveyor tunnel to surface.

The ventilation distribution in each airway, with the exception of the conveyor and regulated returns, is based on free splitting at the bottom of shafts and through the workings. Thus, it is based on airway resistance and connections that will fully load main intake and return airways. The return ventilation from the mining block will join the return air from the ore handling system and flow in the main return system to the upcast shafts. The underground return airways will operate near limiting air velocities for occasional vehicle or pedestrian access.

The main fan stations will be installed on surface and will operate in exhaust mode drawing ventilation through the mine. To allow for phased increase in ventilation capacity, available surface space during sinking and long-term security of production, it is planned to connect all exhaust shafts together in a manifold configuration (all fans connected to all shafts).

With respect to water management, all upcast shafts will be maintained well above 12 m/s during the various phases even if this requires some underground regulation. This means that water droplets will be carried up the shaft to collars and manifold take off points.

High speed intake airways with booster fans

The primary intake infrastructure will include two large airways (each >60 m^2) which will be used as high speed dedicated intakes. These airways will be no-go zones with limited or no pedestrian or vehicle access. These airways will each be operated at >11 m/s air speed for 700 m^3/s and will carry more than 60 per cent of all underground ventilation (below skip discharge level). There will be booster fans installed in each of the high speed intake airways. The objective will be to optimise the carrying capacity of these large airways as well as to control air velocity in other trafficable airways. Each of these two underground fan stations will comprise four fan motor sets (each 250 kW) installed in parallel in bulkheads.

Note that the rationale for the intake booster fans was not for the purpose of pressure balancing the cave for control of leakage. This was not deemed necessary because of the depth of the cave and the fact that the orebody does not extend to surface, ie workings are not beneath an opencast pit. Furthermore the buoyancy or natural ventilation pressure effect could cause the cave pile to leak out from the mine rather than in.

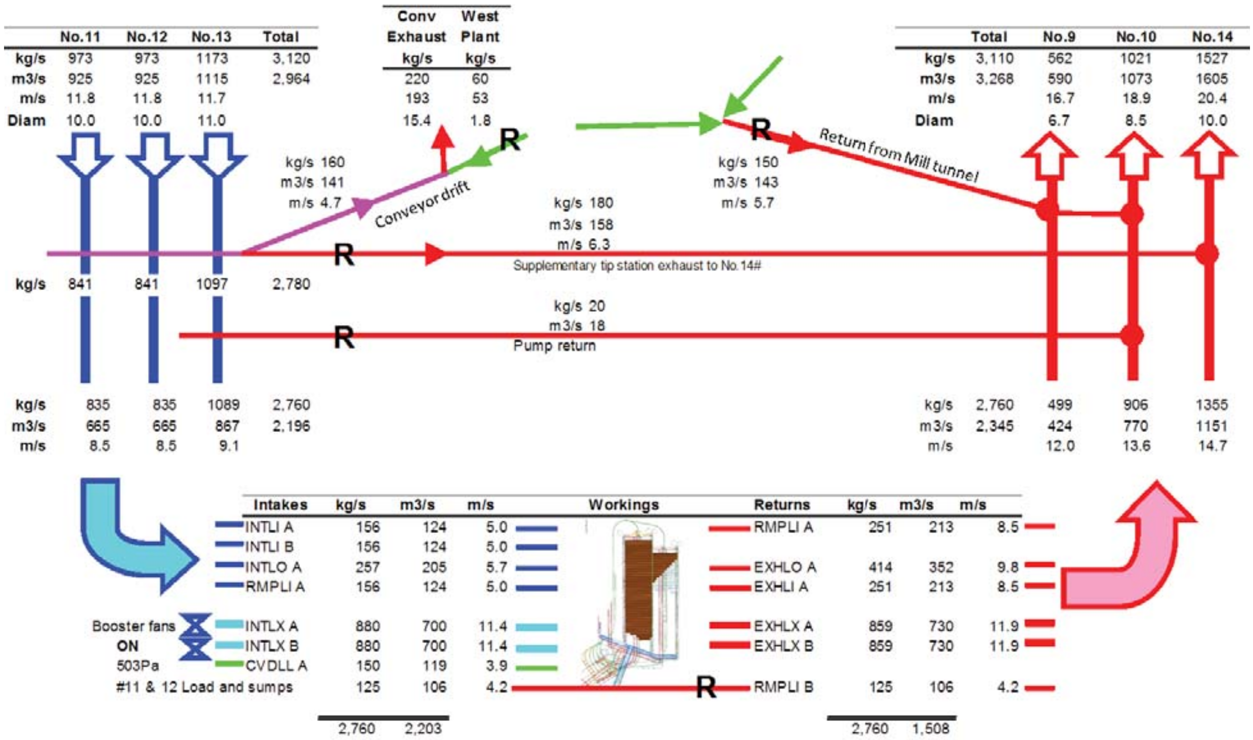

FIG 5 - Distribution of ventilation (booster fans on).

Undercut levels

There will be two undercut level (spaced at 20 m) in order to achieve the required wide inclined undercut for cave initiation. The undercut levels are generally challenging from the ventilation perspective and they were examined in particular detail and stand alone VUMA models were developed. In the modelling, provision was made for dead end swell mucking, rim tunnel and cross-cut development and cubbies for swell muck dump every 200 m.

Production level

Once steady production has been achieved, there will be up to 70 off open, 150 m long production cross-cuts. Of these, it has been assumed that 35 production cross-cuts will be active (35 electric loaders will be available for mucking) and 35 production cross-cuts will be available for operation. The airflow required for dust and heat dilution has been determined as 12 kg/s per production cross-cut. The air will be distributed to open production cross-cuts by regulators or secondary fans in the return raises, controlled from the central control station. This is a relatively low air allocation and the ventilation distribution will present a challenge in terms of equal distribution and leakage and this subset of the VUMA model was scrutinised in some detail, Figure 6. This 'per production cross-cut' allocation alone gives a total ventilation commitment of 840 kg/s. However, on the production level there will be additional ventilation in terms of that being used for rim tunnel development, extraction drive development, construction work and leakage.

DUST MANAGEMENT

The management of respirable dust will be very important because of the presence of high levels of silica in the orebody and host rocks. Additional exhaust raises to surface dedicated to dust extraction were ruled out due to depth of workings and, therefore, all dust will have to be suppressed, captured or report to return airways.

The main strategy will be to direct contaminated air to return airways and, for this, significant ventilation capacity has been allocated. With respect to control of respirable dust in general, the following assumptions are made:

- Provision will be made for industry standard/best practice dust controls such as:
  - Dedicated exhaust ventilation systems for crushers and transfer points.
  - Remote loading of extraction level with operator location on the intake side.
  - Water suppression sprays in all roadways for routine and controlled wetting.
  - Wetting broken rock for at least two per cent moisture in ore. Water consumption will be 70 L/s if five per cent is achieved (provision is made for 150 L/s of chilled service water).
  - Road base maintenance and dust suppression.
  - Limited access to return airways.
- Overall system geometry will minimise the need for filtration and reuse of contaminated air. However, there may be the need for some filtration in locations remote from return airways such as transfer points to main conveyor from secondary belts.
- Employees will be trained in the control of exposure to respirable dust, including PPE.
- Respirable dust sampling (personal by task and area gravimetric) regime will be setup to monitor employee exposure and samples will be analysed for composition, including respirable free silica in its various forms.

The dust generation and ore transfer points that have been accounted for in the design include:

- extraction level loader transport and tipping
- rail loading level

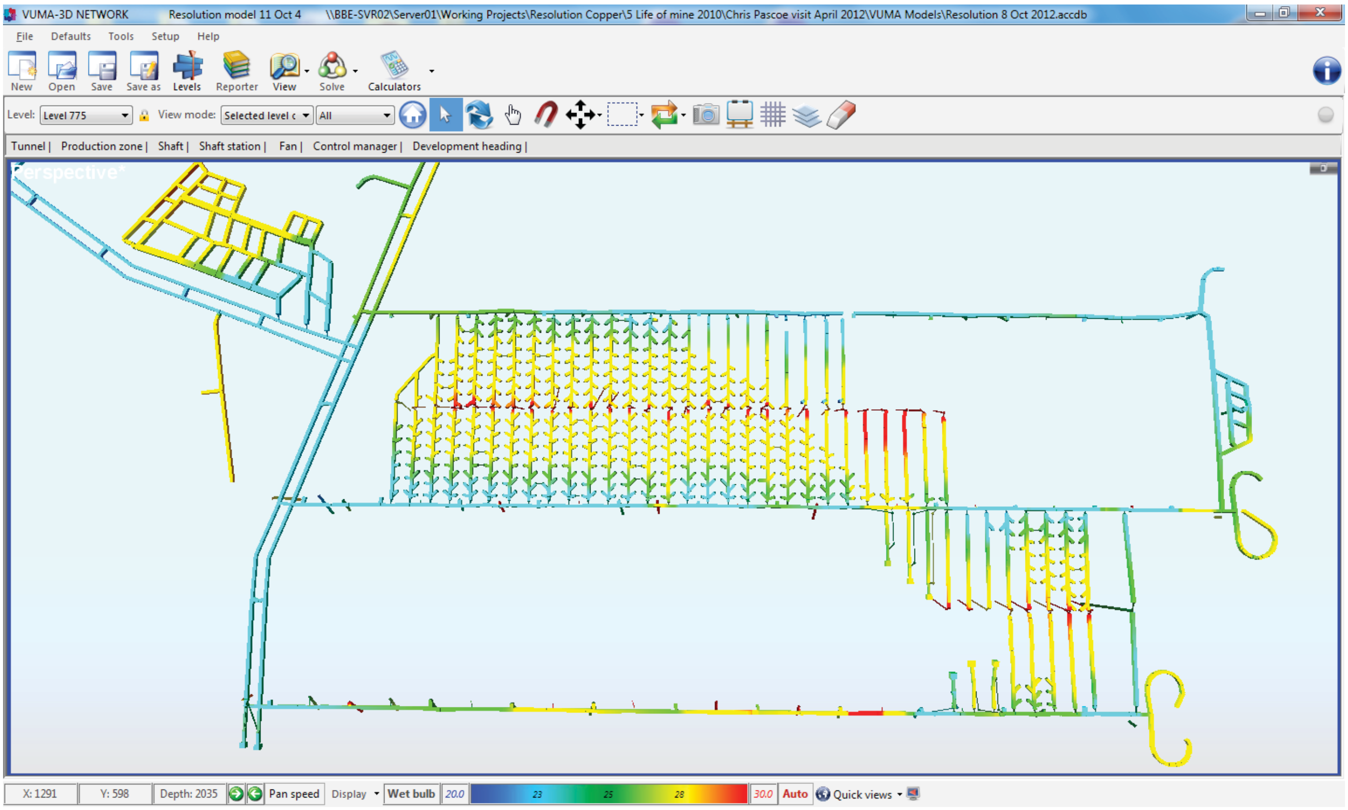

FIG 6 - Production level temperatures (blue = 20°C wb; red = 30°C wb).

- rail tip to belt feeders (rail tipping level, crusher level, transfer conveyor feeders)
- skip loading
- skip discharge
- shafts to surface conveyor drift.

For example, the concept for the rail tip, crusher and belt feeders is shown in Figure 7. In total there will be 755 kg/s allocated to dust control direct to return, this is some 25 per cent of the entire primary ventilation allocation.

As a further example, a number of scenarios of the skip discharge concept were examined including variations in the cross-sectional area of the skip dump bypass excavations to reduce shaft velocities in the skip discharge section of No 11 and No 12 Shafts, see VUMA screen dumps, Figure 8.

VUMA HEAT LOAD AND ENERGY BALANCE MODELLING

The design snapshot scenario in the life-of-mine (Figure 2) was selected as the critical design year for sizing the ultimate ventilation and refrigeration needs. The specialised VUMA network software was used to model the full mine layout and to simulate the different ventilation and refrigeration strategies. This includes the full interactive computer simulation of the heat flow, ventilation and cooling systems to determine the air temperatures, flow rates, heat loads and cooling requirements, Figure 9. The simulation uses an iterative process to determine heat loads and cooling needs and the sizing and positioning of the air coolers and the refrigeration components. The simulations take full account of the block cave mining details. This software is unique in that it deals with the fundamentally important effects of broken rock and advancing rock faces.

This design snapshot relates to the period when the first panel is approaching completion and the second panel is starting production. This was relevant because of the relatively high mix of development tonnage, the duplicity of a number of excavations and the fact that the workings are furthest from the main infrastructure. The production during this period will include about seven per cent from 'quartzite rich' zones. Other scenarios towards the end of life-of-mine as well as the development phases were modelled separately (but are not discussed here).

As noted, the heat load due to all the mobile equipment and static equipment facilities will be about 32 MW and this was input at the relevant nodes and branches. Also as noted, the heat flow from the broken rock in the underground mine will be about 30 MW and this was input at the relevant nodes and branches as linear or spot sources with relevant VUMA moisture ratings. This heat load was distributed on the loading level, rail level and shaft, production level up to crusher, transfer to crusher and belt, conveyor belt systems, loading stations and shaft barrels.

With these and other VUMA inputs for excavation branch sizes, connections, age, wetness, geothermal data, etc, the models indicated that the mine heat loads will be satisfied with the following resources:

- chilled ventilation downcast ex from surface 3120 kg/s at 10.5°C wb
- surface bulk air cooler duty 105.2 MW
- chilled service water 150 L/s at 4°C
- underground secondary air coolers 38.5 MW.

The surface bulk air coolers will be served by a central surface refrigeration plant and the underground secondary air coolers will be served by a central underground refrigeration plant. In addition, the service water to be supplied from surface will be chilled and will create an important cooling (and dust management) effect underground.

The global energy balance can be satisfied by different combinations of higher airflow rates with cool air or lower airflows with colder air. The optimum selection is dictated

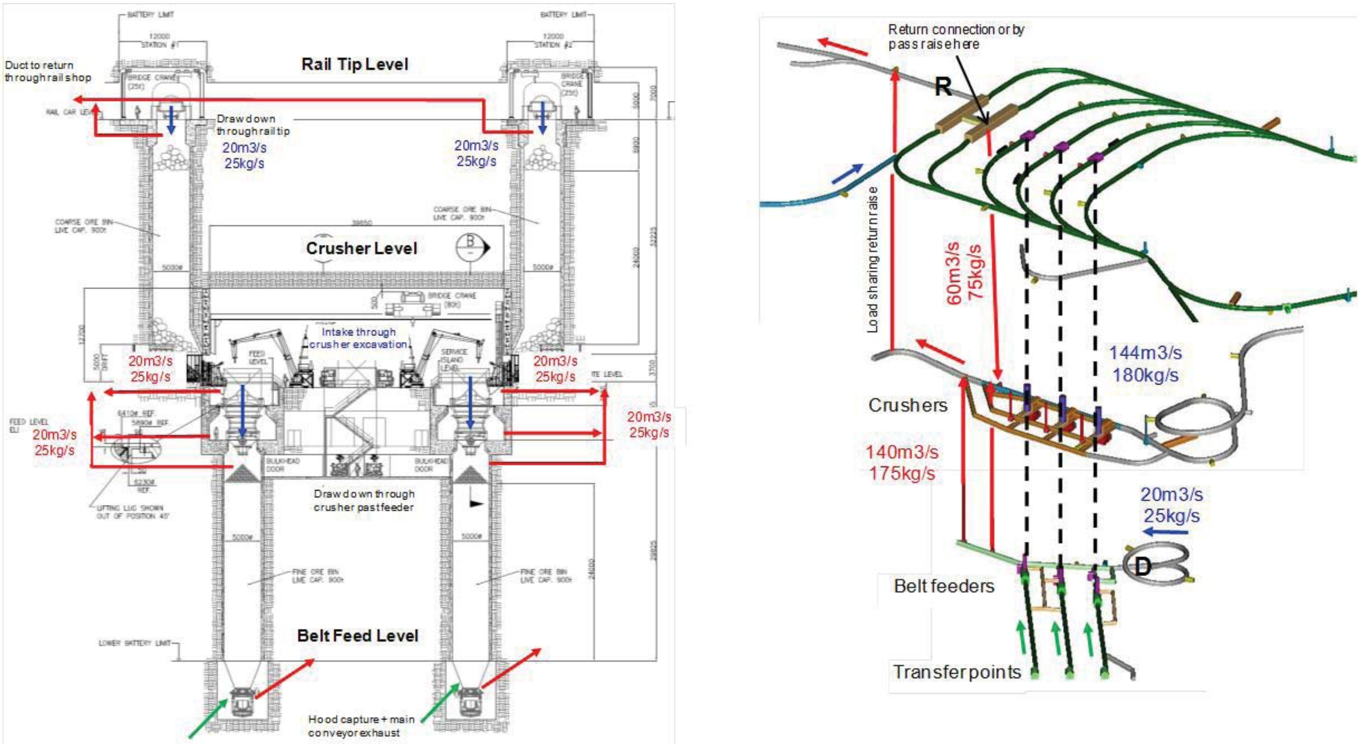

FIG 7 - Rail tip crusher and belt feeders.

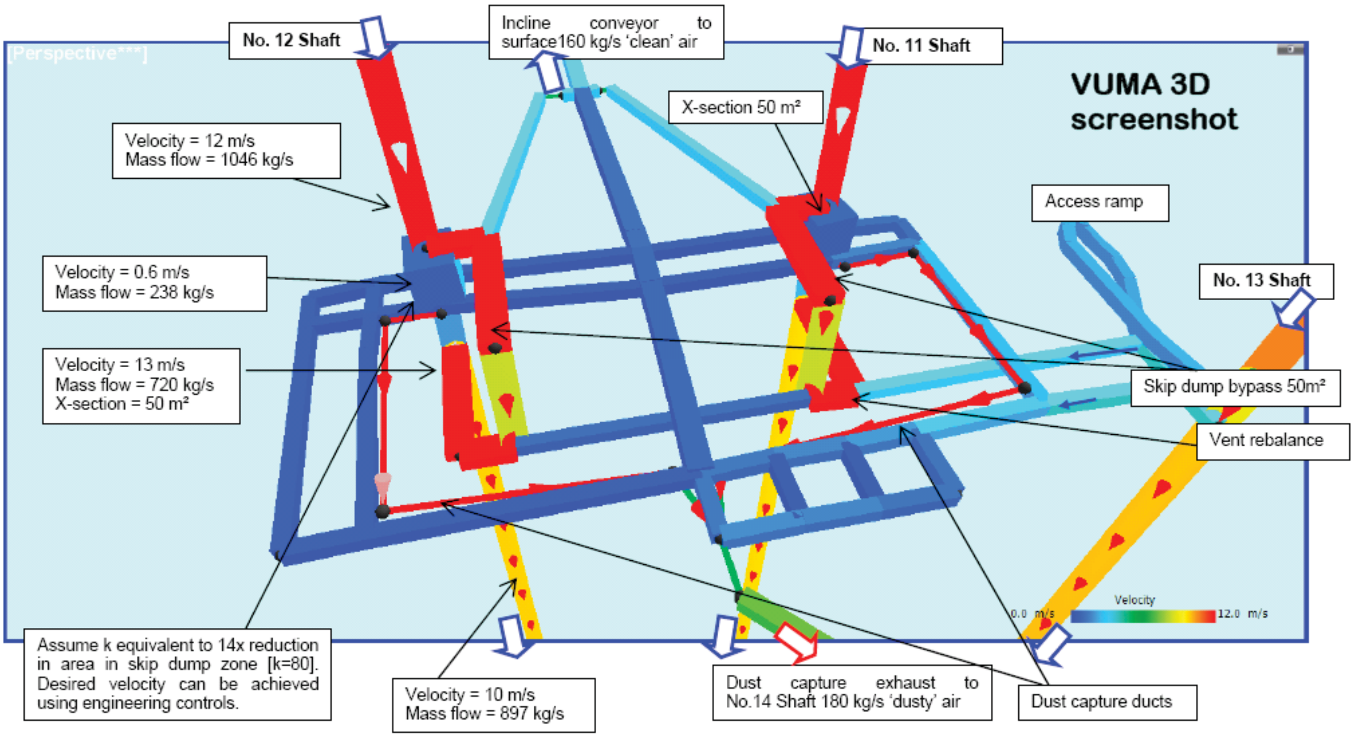

FIG 8 - VUMA snapshot with skip bypassed arrangement.

by issues such as available downcast capacities, capital and running costs of the ventilation and cooling systems, standard equipment capacities and phase in needs. Following a number of iterations which included the sizing of the shafts, sensitivity studies (of more or less underground refrigeration, use of ice, etc), the above mix of flow rate and refrigeration capacity is considered to be fairly close to optimum. Trade off studies were conducted with different splits between surface and underground refrigeration as well as the manner in which the cooling is distributed.

In summary, a significant refrigeration capacity will be on surface however, the underground refrigeration capacity will be extremely important during the development phases and will provide the essential high positional efficiency air coolers directly in the workings during production phases.

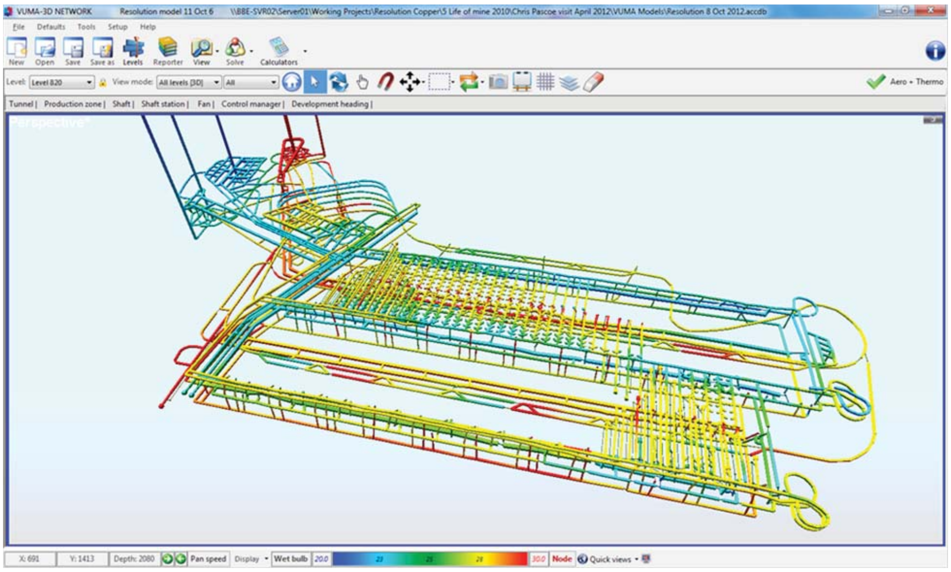

FIG 9 - Ultimate VUMA model (blue = 20°C wb; red = 30°C wb).

DESCRIPTION OF SURFACE REFRIGERATION SYSTEM

The surface refrigeration system will comprise:

- central surface refrigeration plant room and refrigeration machines (and thermal store)
- surface bulk air coolers at each downcast shaft
- service water refrigeration system to provide chilled surface water to underground.

There will be a central surface refrigeration machine facility (and thermal store) from which chilled water will be served to surface bulk air coolers at each of No 11, No 12 and No 13 Shafts, Figure 10. In addition, there will be a supplementary surface refrigeration system that will provide general chilled service water to all workings.

The primary refrigeration machine system will comprise main base load machines prechilling water flow from the bulk air coolers. From these plants, chilled water will then flow to the thermal storage dam containing tube banks through which subzero glycol is circulated. Ice will be formed on the outside of the tubes during the colder part of the day and then melted by the circulating water during the warm part of the day. The chilled water will leave the thermal storage dam at temperatures close to 0°C. The thermal storage will allow peak load damping and energy management facilities. The combined plant and ice store system will provide the following capacity during the hot part of the day (14h00).

- total surface bulk air cooler duty (at air coolers) 105.2 MW
- thermal losses and pump effects 4.0 MW
- total refrigeration effect (including ice dam) 109.2 MW.

There will be a number of large refrigeration machine modules chilling water and glycol, Figure 11. All the refrigeration machines will be similar with interchangeable components (however glycol plant will have a different gear speed selection). The refrigeration machine modules will be factory assembled and packaged plants with R134a centrifugal compressors and shell-and-tube evaporators/condensers. Each plant will have differing process conditions that will depend on final equipment and manufacturer selection. However, for example, the lead water chilling plants may have specifications as follows:

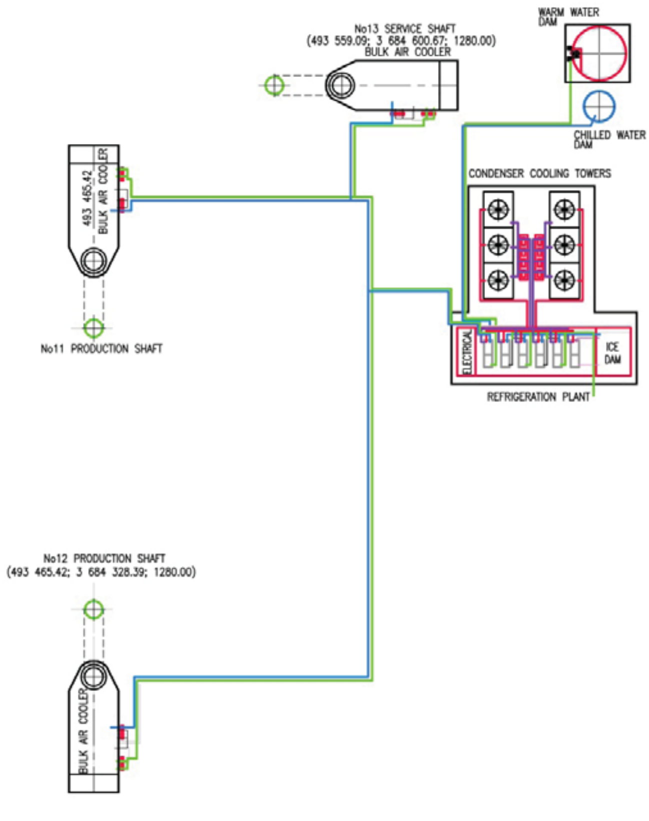

FIG 10 - Site layout.

- evaporator cooling duty 22.1 MW
- evaporator water flow 900 L/s
- evaporator inlet water temp 15.0°C
- evaporator outlet water temp 9.1°C
- condenser duty 25.6 MW
- condenser water flow 700 L/s
- condenser inlet water temp 24.0°C.

The water chilling effect (14h00) of overall refrigeration system, including ice melt effect, will be:

- water chilling ex refrigeration machines 80.8 MW
- water chilling ex ice store and glycol 28.4 MW
- total 109.2 MW.

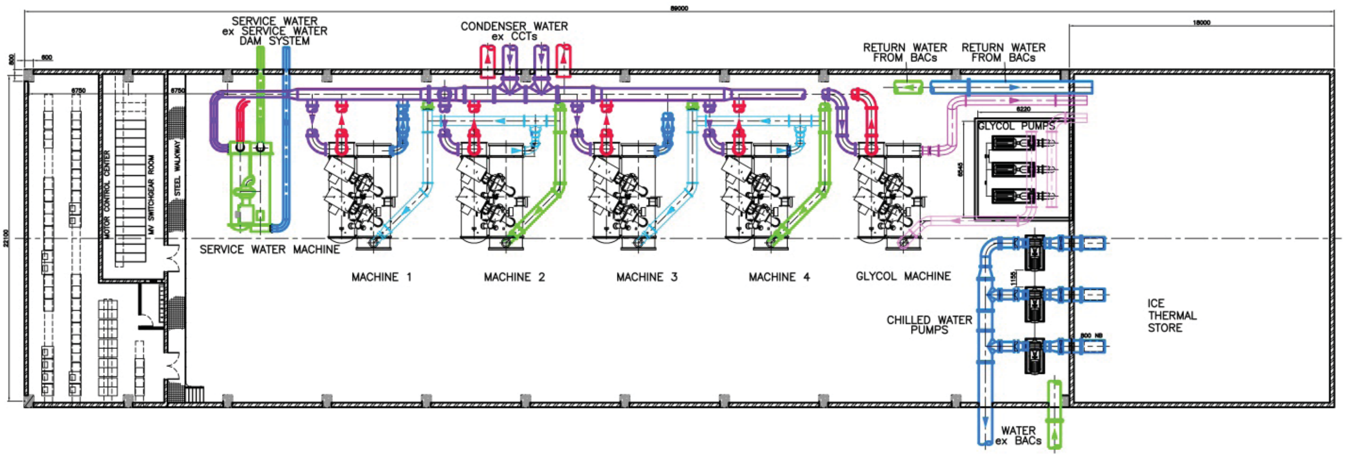

FIG 11 - Plant room.

The gross refrigeration machine duty (and absorbed compressor) power will be:

- water chilling refrigeration machines 80.8 MW (13.4 MW)
- glycol chilling refrigeration machines 14.2 MW (3.4 MW)
- total 95.0 MW (16.8 MW).

The chilled service water will be a very important part of the underground cooling. The chilled service water will be used for dust control, localised cooling sprays and mine service needs and will provide effective localised cooling wherever it is applied. Thus, on surface, in addition to main refrigeration system, there will be a separate independent surface refrigeration system that will provide general chilled service water to all the underground workings. The overall chilled water for underground cooling system will include a precooling tower and, following this, the water will be chilled in a conventional standard refrigeration module and delivered to an enclosed surface chilled service water dam. This system will remain separate and independent of the bulk air cooler(s) chilled water system.The surface heat rejection system will be in the form of wet direct contact packed cooling towers rejecting some 135 MW condenser heat. An assessment was done comparing dry and wet cooling towers because the alternative dry cooling tower approach will save water. However, this approach will introduce higher condensing temperatures and, as a result, greater capital cost for refrigeration machines and cooling towers as well as greater power cost for refrigerant compressors. These costs are orders of magnitude higher than that of water consumed in the wet systems and, even acknowledging the secondary environmental issues, there remains a compelling motivation to use the conventional wet system approach.

Each of the downcast shafts will be served by bulk air coolers in the form of horizontal spray heat exchangers in which the air is forced through an intense spray of chilled water in a horizontal concrete tunnel, Figure 12 (Bluhm, Funnell and Smit, 2001). Within the sprays, heat exchange will occur directly across the large surface area of the spray drops. Two stages of spraying will be used to achieve high thermal efficiencies. The spray chambers will be constructed in concrete and the layout, spray system and mist eliminator format have all been selected for ensuring minimum maintenance. Water distribution will be achieved by manifold piping and multiple spray nozzles with relatively large orifice diameters to ensure that blocking is not a problem. Where the cool air emerges

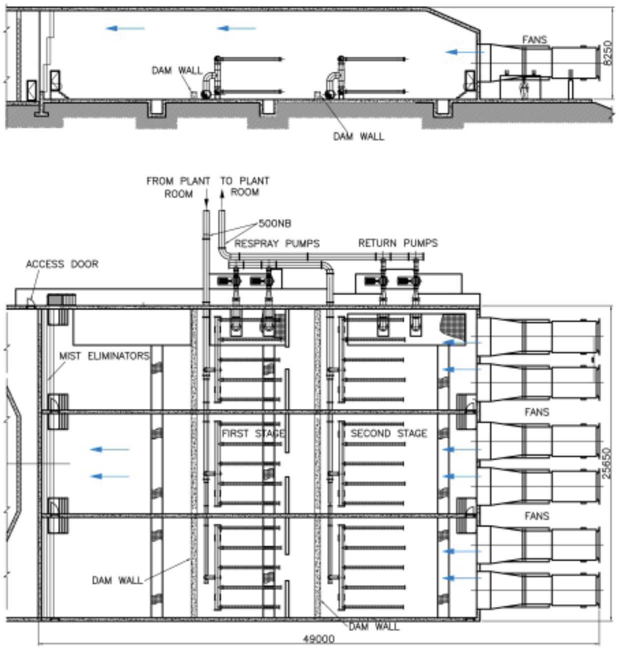

FIG 12 - Surface bulk air cooler layout.

from the chamber, mist eliminators will be installed to ensure that no water is carried out.

The bulk air cooler will all be similar (but No 13 Shaft slightly larger) and the same equipment and mechanical modules will be used. For example, the No 13 Shaft bulk air cooler will have the following process specification:

- air cooler air duty (from after fans) 39.6 MW
- air cooler airflow 1087 kg/s
- air temperature onto air cooler fans (ambient air) 21.0°C wb
- air temperature off air cooler 9.5°C wb
- ambient air from above brow 88 kg/s
- in shaft mixed air temperature at surface 10.5°C wb.

Bulk air cooler fans will force airflow through the air coolers and into the shaft and these fans will be relatively low pressure, axial flow units with direct coupled in line motors. Fan blade angles will be manually adjustable and fan motors will have variable speed drives.

The total installed electrical rating with all compressors, fans, pumps, etc, will be about 31 MW and the absorbed power at the summer design condition will be about 27 MW.

DESCRIPTION OF UNDERGROUND REFRIGERATION SYSTEM

There will be a single central underground refrigeration plant chamber located near the mining block off the exhaust vent level. The main return ventilation system will be used for heat rejection from the refrigeration plant. The refrigeration machines will provide cold water, in an insulated closed circuit network, to cooling coil air coolers situated strategically throughout the underground workings. Some of the air coolers will remain in one location but many of the units will be moved from time to time as the development and production progresses. Thus the underground refrigeration system will comprise two main components:

1. centralised underground refrigeration plant chamber and refrigeration machines
2. suite of underground air coolers and cold water distribution system.

The required secondary air cooler overall duty will be 34.5 MW and the underground refrigeration plant must be capable of providing the following cooling capacity.

- total refrigeration machine capacity 40.0 MW
- total secondary air cooler duty (at air coolers) 34.5 MW
- thermal losses and pump effects 5.5 MW.

The refrigeration installation will ultimately have six 8 MW refrigeration machines (five running, one stand by).

There will be insignificant seasonal variation in load because of the deep location underground. Thus the need for operational flexibility is not dominant and a smaller number of larger machines was preferred. The maximum size of an individual machine is limited by transportability of the heat exchangers, both in terms of physical size and mass for slinging limitations. The machines will operate in parallel (on both evaporator and condenser sides) and this arrangement will allow the system to adjust to changes in chilled water demand.

There is little or no choice in the type of refrigeration machine for underground operation. The machine will use refrigerant R134a and will include high speed, multistage, centrifugal compressors. The refrigeration machines will be identical packaged units with compressor motor sets and shell and tube evaporators/condensers. The individual machines will have the following equipment selection specifications:

- evaporator cooling duty 8.0 MW
- evaporator water flow 130 L/s
- evaporator inlet water temp 18.7°C
- evaporator outlet water temp 4.0°C
- condenser duty 10.5 MW
- condenser water flow 250 L/s
- condenser inlet water temp 38.0°C.

The overall combined machine system duty (total five plants) will have a cooling duty of 40.0 MW and a chilled water flow of 650 L/s (total condenser heat rejection will be 52.5 MW).

In the plant room layout (Figure 13), various orientations of the plant were examined, particularly with respect to end clearances required for tube maintenance and rock mechanic considerations. The most compact layout proved to be two machine rooms each about 50 m long × 10 m wide × 9 m high with the machines arranged in line. The plant chambers can be mined and constructed in two distinct phases to suit the build-up in cooling needs. The machines will be connected to water manifolds running the length of each chamber. The chilled water pumps and condenser water pumps will be grouped in common pump chambers adjacent to their respective dams. Although the refrigeration plant will be

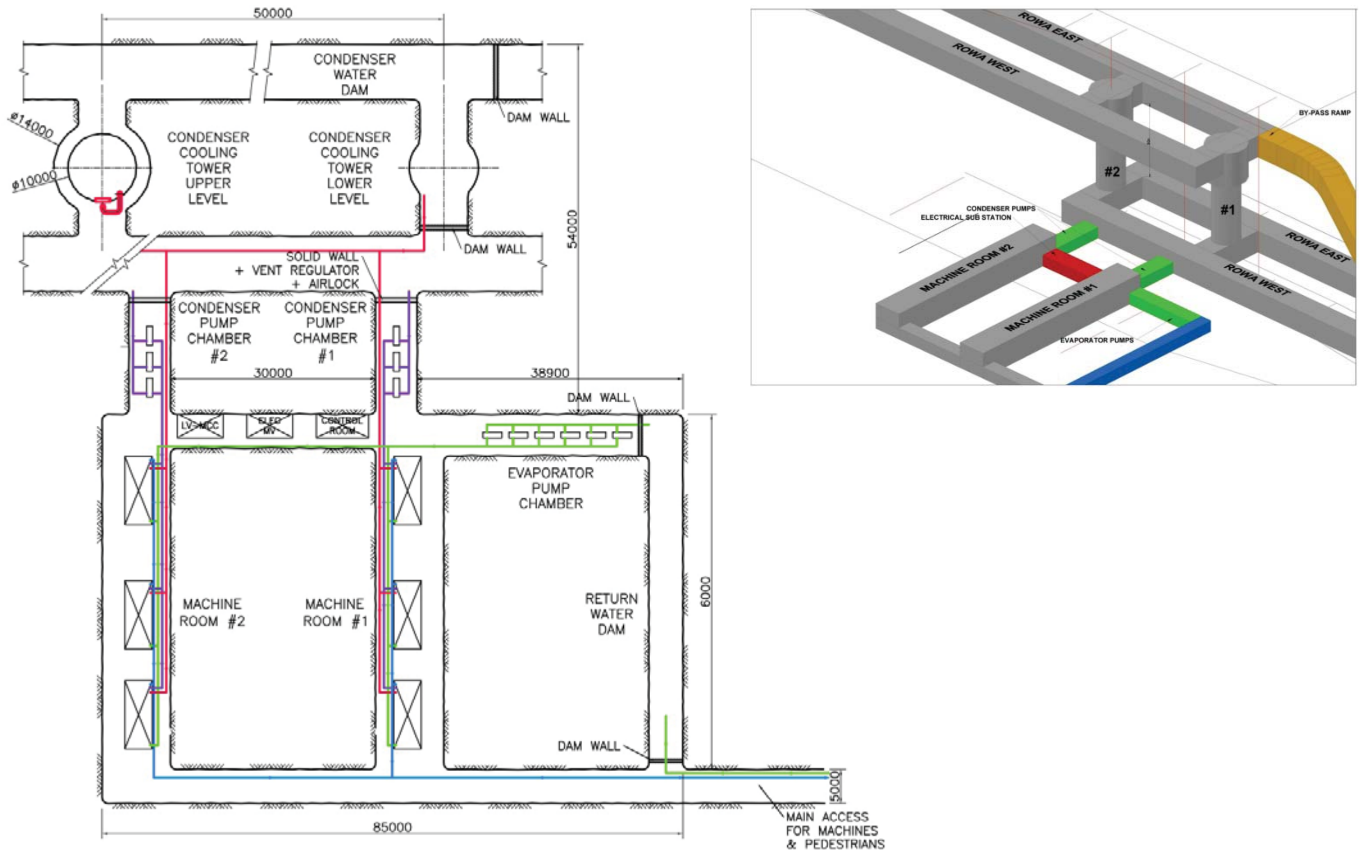

FIG 13 - Underground refrigeration plant excavation layout.

located adjacent to the return ventilation infrastructure, there will be a direct connection to an intake airway which will allow for the allocation of cool fresh air to serve the plant chambers. It is anticipated that the main compressor motors will be water cooled, which will minimise the heat load within the refrigeration chamber.

Heat rejection will be achieved in cooling towers in the form of spray filled vertical excavations rejecting heat into the return ventilation. The refrigeration plant will be adjacent to two main large return airways which will ultimately carry a flow rate of about 1700 kg/s. For heat rejection purposes, some 1200 kg/s of this air will be utilised in the two cooling towers. The towers will be located above a condenser water dam over which the inlet air will flow, turn vertically into the tower barrel and the air will discharge from the towers at a higher elevation. The selection of two towers was based on the available quantity of air and dimension limits imposed by rock engineering considerations. This also provides acceptable turn down ratios for the spray systems as well as operational flexibility for maintenance purposes.

For the ultimate life-of-mine scenarios, there will be numerous underground secondary air coolers with duties ranging from 0.5 - 3.0 MW, with a total air cooling effect of 34.5 MW. These secondary air coolers will be in the form of closed circuit cooling coils, Figure 14. For each air cooler, multiple coil modules will be installed with suitable manifold piping and steel cowlings. Within the cooling coils, heat exchange will occur across the large surface area of finned tubes. Typically coil tube diameters will be 16 mm with a fin pitch of 250 per m. Inlet air cooler fans, generally direct drive axial flow units, will force air through the cooling coil assemblies. External spray wash systems will be fitted to minimise external fouling.

The main chilled water piping will comprise a 500 mm insulated system near the plants reducing as the network splits up down to ultimately 150 mm insulated pipe sections. The thermal insulation will generally include a phenolic foam (40 mm), packed in a vapour barrier and a steel sleeve mechanical barrier.

The total installed electrical rating with all compressors, fans, pumps, etc, will be about 16 MW and the absorbed power will be about 14 MW.

CONCLUSION AND SUMMARY

The mine is planned as a large, deep and hot, block cave operation. The production rate will 120 kton/day and the mining method will be an advance undercut panel cave operation. The rock will have high silica content >30 per cent and the mine will be deep in hot virgin rock temperature (>80°C). Thus dust issues and thermal issues dominate the design evaluations.

The mine will employ three hoisting and service shafts and three upcast shafts and the total primary ventilation capacity will about 3000 m^3/s. The general approach to dust management will be to direct contaminated air to return and some 25 per cent of the total primary airflow will be allocated in this manner. The primary intake system will include two large airways (>60 m^2) which will be used as high speed dedicated intakes with booster fans. These airways will be no-go zones operating at >11 m/s air speed and will carry more than 60 per cent of all underground ventilation.

The specialised VUMA network software was used to model the full mine layout and to simulate different ventilation and refrigeration strategies. The simulation uses an iterative process to determine heat loads and cooling needs as well as the sizing and positioning of refrigeration system components. The large heat load components were the broken rock flow, surrounding rock conduction and mobile and static equipment facilities. It was determined that the mine heat loads will be satisfied with the following:

FIG 14 - Typical cooling coil units.

- chilled ventilation downcast ex surface 3120 kg/s at 10.5°C wb
- surface bulk air cooler duty 105.2 MW
- chilled service water 150 L/s at 4°C
- underground secondary air coolers 38.5 MW.

The surface bulk air coolers will be served by surface refrigeration plant and the underground secondary air coolers will be served by underground refrigeration plant. In addition, the service water to be supplied from surface will be chilled and will create an important cooling (and dust management) effect underground. In total, more than 140 MW refrigeration duty will be applied.

This will be a very challenging mine to ventilate and cool, but this work has demonstrated that it will be technically achievable with the application of existing technology.

ACKNOWLEDGEMENT

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