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Refrigeration and cooling system design – a case study

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Abstract

Rio Tinto's Palabora Mining Company (PMC) mines copper from its underground block cave operation in Limpopo, South Africa. The block-cave is situated below the discontinued open pit operation at an ultimate depth of 1,200 m below surface. Ore is currently extracted at over 30,000 t per day (11 Mtpa) and will be extended by 10 to 20% in loading crosscuts which will require additional air and cooling for undercut and crosscut development and ultimately mining.

In addition to the increase in airflow requirements, underground crusher airflow has to be increased to adequately cater for dust dilution. The increase in airflow is achieved by re-using ventilation air from the crushers and Belt Level, which are ventilated directly to the return airway system.

The air being re-used needs to be cleared of dust and cooled to an acceptable temperature. The air cooling required was calculated as 3,000 kW$_R$. Trade-off studies were conducted to determine the optimum refrigeration and cooling design. Options included refrigeration plant positioned on surface or underground, with several variations in the cooling associated system. Underground refrigeration and underground bulk air cooling proved to be the best option using a phase-in approach to match mine development scheduling.

Once the refrigeration and cooling requirements were confirmed, an underground air refrigeration plant and cooling spray chamber engineering design was initiated. The spray chamber will remove nuisance dust and heat from the conveyors and crushers before air is re-introduced to the intake system. An underground refrigeration plant will be installed to satisfy the current additional refrigeration demand of 3,500 kW$_R$.

1 Introduction and background

Rio Tinto's Palabora Mining Company (PMC) mines copper from its underground block-cave operation in Limpopo, South Africa. The block-cave is situated below the discontinued open pit operation at an ultimate depth of 1,200 m below surface. Ore is currently extracted at over 30,000 tons per day and will be extended by 10 to 20% in loading crosscuts which will require additional air and cooling for undercut and crosscut development and ultimately mining.

Primary airflow reticulation for PMC's underground workings services mainly four areas; Production Level, Belt Level, underground crushers and the workshop area. Additional air requirements for undercut and extraction crosscut development would necessitate either increasing the primary air quantity circulated through the mine, or altering the current air distribution.

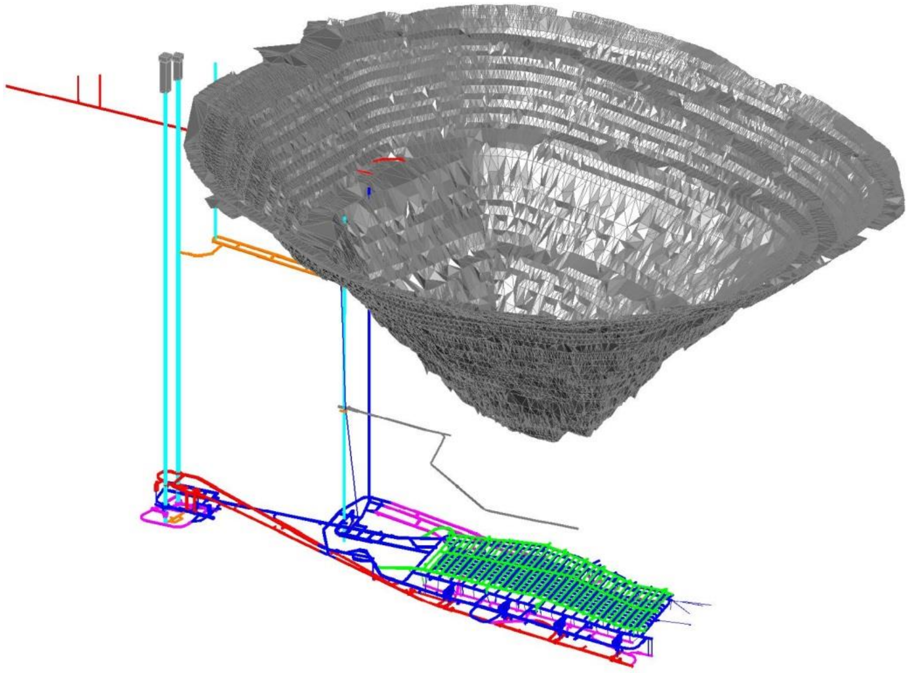

Figure 1 PMC underground layout

Development ventilation districts will each require nominally 58 kg/s flow; i.e. two undercut and two production level districts. The primary ventilation infrastructure is already utilised to maximum capacity and the increase in airflow will have to be achieved by re-using air from the crushers and Belt Level.

Return air from the crushers and Belt Level is dusty and hot and will therefore have to be re-conditioned before being re-introduced in the intake side of mining crosscuts. In addition to the increased airflow requirement for development, crusher airflow has to be increased to ensure adequate dust control. The planned re-use scheme will reintroduce 300 kg/s of air (previously ventilated directly to return) back into the mining footprint, allowing the planned development and mining as well as increased quantities to the four crushers.

Reconditioning of the re-used air requires capture of nuisance dust and air cooling to ensure acceptable working conditions. Based on calculations, ventilation network simulations and knowledge of the current mine, it was estimated that this system will require additional refrigeration of about 3,500 kW_R (Von Glehn et al., 2007). A Bulk Air Cooler (BAC) with 3,000 kW_R air cooling duty was designed with a new 3,500 kW_R underground refrigeration plant. The second stage of one leg of the BAC was commissioned in January 2012, and the Condenser Spray Chamber (CSC) has been constructed. The refrigeration machine is on-site and will be installed in mid 2012.

Trade-off studies were conducted to determine the optimum refrigeration and cooling design. Options included refrigeration plant positioned on surface or underground, with several variations in cooling associated system. Underground refrigeration and underground bulk air cooling proved to be the best option using a phase-in approach to match mine development scheduling.

This paper summarises the current status of the refrigeration and cooling trade-off studies and the first-order engineering design of the re-use bulk air cooler system.

2 Practical future cooling and refrigeration options

The objective of this part of the study was to determine the optimal cooling and refrigeration strategy for future mining. In this context, future mining included the possibility of a Lift 2 sometime into the future, to allow the best option over the long-term to be applied to the Lift 1 extension project. Based on the outcome of the optimal cooling strategy investigation, the optimal refrigeration strategy was determined (Marx et al., 2010; Marx et al., 2009).

2.1 Cooling options

Current cooling consists of a 15,000 kW_R surface bulk air cooler (BAC). Due to the nature of the block caving mining method, the heat load (broken rock and diesel vehicles) is concentrated in the loading crosscuts of the footprint. To allow adequate cooling from surface bulk air cooling in these areas implies that other areas of the mine, such as workshops, conveyor belts, crushers, and intake airways, are generally 'over-cooled'. The positional efficiency of surface bulk air cooling is therefore average for this mining layout.

The study indicated an optimal strategy with the surface BAC at its current duty and all future cooling applied underground. The cooling option for the peak demand system consists of underground cooling via BACs and development cooling coils, with the surface BAC delivering its current duty.

The following cooling is required at peak demand:

- Total air cooling required:
  - Surface BAC 15,000 kW
  - Underground BACs 7,500 kW
  - Underground re-use BAC 3,000 kW
  - Cooling coils 2,000 kW

2.2 Refrigeration options

The following options were developed at concept level to allow first-order engineering design of process and equipment. The first-order engineering designs were then used to conduct a cost comparison between the scenarios to ±30% confidence. Refrigeration Options 1a, 1b, 2a, 2b and 3 were designed to supply cooling to the above cooling strategy.

It may be noted that specified refrigeration plant duties include line losses and will therefore not correspond fully to the cooling requirements quoted above.

- **Option 1a:** Surface refrigeration supplying low pressure underground cooling system

  Refrigeration duty: 22.5 MW_R (excluding existing refrigeration for 15,000 kW BAC)

  Water flow: 325 l/s

  System absorbed power: 10.9 MW_E

- **Option 1b:** Surface refrigeration supplying high pressure underground cooling system

  Refrigeration duty: 21.5 MW_R (excluding existing refrigeration for 15,000 kW BAC)

  Water flow: 325 l/s

  System absorbed power: 5.5 MW_E

- **Option 2a:** Surface refrigeration supplying a low pressure underground cooling system via Pelton turbine

  Refrigeration duty: 19.8 MWR (excluding existing refrigeration for 15,000 kW BAC)

  Water flow: 325 l/s

  System absorbed power: 6.5 MWE (including 3.8 MWE recovered)

- **Option 2b:** Surface refrigeration supplying a low pressure underground cooling system via three-chamber-pipe-feeder

Refrigeration duty: 19.1 MWR (excluding existing refrigeration for 15,000 kW BAC)

Water flow: 325 l/s

System absorbed power: 6.1 MWE (including 4.2 MWE recovered)

- **Option 3:** Underground refrigeration supplying a low pressure underground cooling system

  Refrigeration duty: 15.0 MWR (excluding existing refrigeration for 15,000 kW BAC)

  Water flow: 250 l/s

  System absorbed power: 5.1 MWE

CAPEX (capital expense) costing included excavations (chambers and dams), civil, mechanical, electrical and controls, shaft electrical cables, refrigeration machines, coils, pumps, pipes, valves, turbines, thermal insulation and labour.

Table 1 provides a summary of the CAPEX and power cost comparison of the previous scenarios (NPV for 15 year life-of-mine at 10% interest) giving a total owning cost.

From Table 1 it is evident that Option 3 proves to be the best refrigeration option (Figure 2).

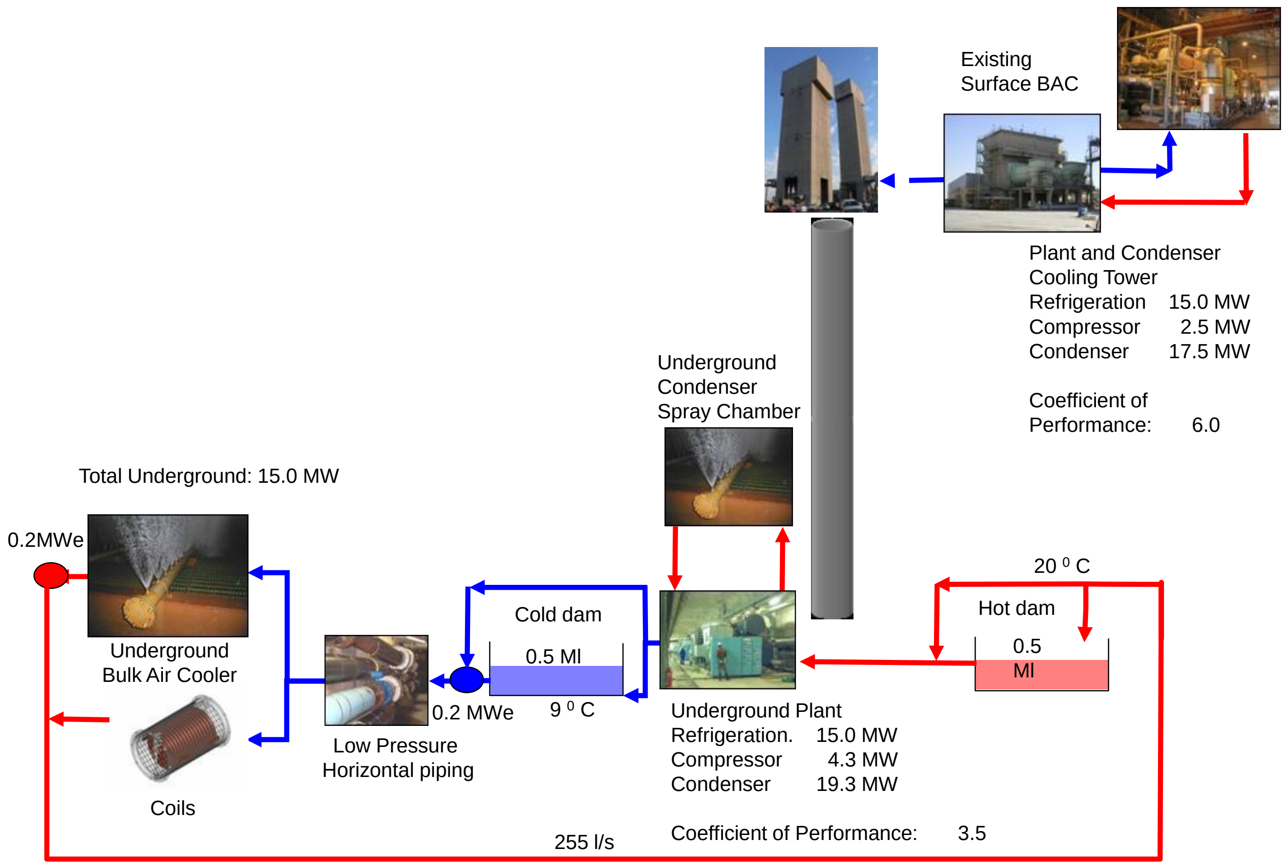

Figure 2 Cooling and refrigeration strategy - Option 3

Table 1 Cost comparison of refrigeration scenarios

CAPEX												
	Option 1a		**Option 1b**		**Option 2a**		**Option 2b**		**Option 3**		**Option 4**	
	Size	**Cost**	**Size**	**Cost**	**Size**	**Cost**	**Size**	**Cost**	**Size**	**Cost**	**Size**	**Cost**
Package 01 - Condenser Cooling Tower	26.3 MWR	US$ 1.75 m	25.30 MW	US$ 1.75 m	23.0 MWR	US$ 1.75 m	22.2 MWR	US$ 1.75 m	19.3 MWR	US$ 0.81 m	47.0 MWR	US$ 3.32 m
Package 02 - Refrigeration plant*	22.5 MWR	US$ 4.59 m	21.50 MW	US$ 4.59 m	19.8 MWR	US$ 4.59 m	19.1 MWR	US$ 4.59 m	15.0 MWR	US$ 7.57 m	39.0 MWR	US$ 12.61 m
Package 03 - BAC (Under ground)	10.0 MWR	US$ 2.94 m	-	-	10.0 MWR	US$ 2.94 m	10.0 MWR	US$ 2.94 m	10.0 MWR	US$ 2.94 m	3.0 MWR	US$ 0.88 m
- BAC (Surface)	-	-	-	-	-	-	-	-	-	-	30.0 MWR	US$ 1.79 m
Package 04 - Cooling coils	2.5 MWR	US$ 0.21 m	12.5 MWR	US$ 3.16 m	2.5 MWR	US$ 0.21 m	2.5 MWR	US$ 0.21 m	2.5 MWR	US$ 0.21 m	2.5 MWR	US$ 0.21 m
- Replacement coils	-	-	10.00 MWe	US$ 3.70 m	-	-	-	-	-	-	-	-
Package 05 - Piping	325 l/s	US$ 7.23 m	325 l/s	US$ 10.86 m	325 l/s	US$ 7.23 m	325 l/s	US$ 7.23 m	250 l/s	US$ 3.97 m	150 l/s	US$ 3.11 m
Package 06 - Primary Pumps	5.47 MWa	US$ 3.33 m	1.47 MWa	US$ 1.93 m	5.47 MWa	US$ 3.33 m	1.47 MWa	US$ 1.93 m	-	-	-	-
Package 07 - Turbine	-	-	-	-	5.47 MWe	US$ 3.33 m	-	-		US$ 0.00 m	-	-
Package 08 - 3 CPF	-	-	-	-	-	-	1.47 MW	US$ 2.50 m	-	-	-	-
Package 09 - Dams (Under ground)	2.00 Ml	US$ 1.16 m	-	-	2.00 Ml	US$ 1.16 m	2.00 Ml	US$ 1.16 m	1.00 Ml	US$ 0.98 m	1.00 Ml	US$ 0.98 m
- Dams (Surface)	2.00 Ml	US$ 0.50 m	2.00 Ml	US$ 0.50 m	2.00 Ml	US$ 0.50 m	2.00 Ml	US$ 0.50 m	-	-	-	-
Package 10 - In-shaft electrical cable	7500 m	US$ 0.56 m	-	-	5000 m	US$ 0.38 m	5000 m	US$ 0.38 m	5000 m	US$ 0.38 m	2500 m	US$ 0.19 m
TOTAL		**US$ 22.26 m**		**US$ 26.48 m**		**US$ 25.40 m**		**US$ 23.17 m**		**US$ 16.86 m**		**US$ 23.09 m**

OPEX-Power cost over 15yr L-O-M												
	Option 1a		**Option 1b**		**Option 2a**		**Option 2b**		**Option 3**		**Option 4**	
	Size	**Cost**	**Size**	**Cost**	**Size**	**Cost**	**Size**	**Cost**	**Size**	**Cost**	**Size**	**Cost**
Package 01 - Refrigeration machines	3.80MWe	US$ 5.56 m	3.60MWe	US$ 5.27 m	3.20MWe	US$ 4.68 m	3.20MWe	US$ 4.68 m	4.30MWe	US$ 6.29 m	7.10MWe	US$ 10.38 m
Package 02 - Primary Pumps	5.50MWe	US$ 8.04 m	1.50MWe	US$ 2.19 m	5.50MWe	US$ 8.04 m	1.30MWe	US$ 1.90 m	0.00MWe	US$ 0.00 m	0.00MWe	US$ 0.00 m
- Evaporator Pumps	0.20MWe	US$ 0.29 m	0.00MWe	US$ 0.00 m	0.20MWe	US$ 0.29 m	0.20MWe	US$ 0.29 m	0.20MWe	US$ 0.29 m	0.20MWe	US$ 0.29 m
- BAC Pumps	1.00MWe	US$ 1.46 m	0.00MWe	US$ 0.00 m	1.00MWe	US$ 1.46 m	1.00MWe	US$ 1.46 m	0.20MWe	US$ 0.29 m	0.20MWe	US$ 0.29 m
- BAC Fans	0.40MWe	US$ 0.59 m	0.40MWe	US$ 0.59 m	0.40MWe	US$ 0.59 m	0.40MWe	US$ 0.59 m	0.40MWe	US$ 0.59 m	0.40MWe	US$ 0.59 m
Package 03 - Turbine	0.00MWe	US$ 0.00 m	0.00MWe	US$ 0.00 m	-3.80 MWe	-US$ 5.56 m	0.00MWe	US$ 0.00 m	0.00MWe	US$ 0.00 m	0.00MWe	US$ 0.00 m
TOTAL	**10.90MWe**	**US$ 15.94 m**	**5.50MWe**	**US$ 8.04 m**	**6.50MWe**	**US$ 9.51 m**	**6.10MWe**	**US$ 8.92 m**	**5.10MWe**	**US$ 7.46 m**	**7.90MWe**	**US$ 11.55 m**
TOTAL OWNING COST		**US$ 38.20 m**		**US$ 34.52 m**		**US$ 34.90 m**		**US$ 32.09 m**		**US$ 24.31 m**		**US$ 34.64 m**

3 First-order engineering design of refrigeration cooling system

The proposed mine cooling and refrigeration equipment includes bulk air coolers, cooling coils and refrigeration and heat rejection systems. The design of the re-use BAC and associated refrigeration system had to consider future mining requirements, for instance, the plant room will eventually host another three refrigeration machines similar to the one required for the re-use system.

The scope of work included the 'for-construction' design of mechanical, electrical, civil and structural components. PMC scope of work included mine-wide supervisory control and data acquisition (SCADA), all haulage piping, and instrumentation and control.

Dust at PMC contains no silica and the purpose of scrubbing is merely to remove nuisance dust and to ensure visibility in the down-stream loading drives. Dust loads in air returning from the conveyor belt and crusher areas were measured by the mine. These dust loads were then used to calculate the amount of dust that will be captured in the BAC and a filter blow-down system was included in the design to allow reasonable control of mud settling in the BAC sump.

The cooling facility will operate automatically and will be monitored remotely without the need for permanent on-site operators and provision has been made for appropriate monitoring and control systems. The engineering design was mainly directed to the re-use BAC as part of the longer term viable Option 3 as indicated in Section 2.2.

3.1 Bulk air coolers

For the ultimate process design condition (peak demand), two underground BACs and cooling coils will be used to provide 12,500 kW cooling. The cool air will be introduced to production crosscuts and development headings. The BACs are two-stage horizontal cross flow units with high quality mist eliminators to prevent water carry-over. To enhance heat transfer, chilled water circulation through the sprays is optimised to achieve a high water-to-air ratio. The re-use BAC (Figure 3), has the following process specifications:

- Duty 3,000 kW
- Airflow (cooled air) 320 kg/s
- Air wet-bulb temperature on 24°C
- Air wet-bulb temperature off 21°C

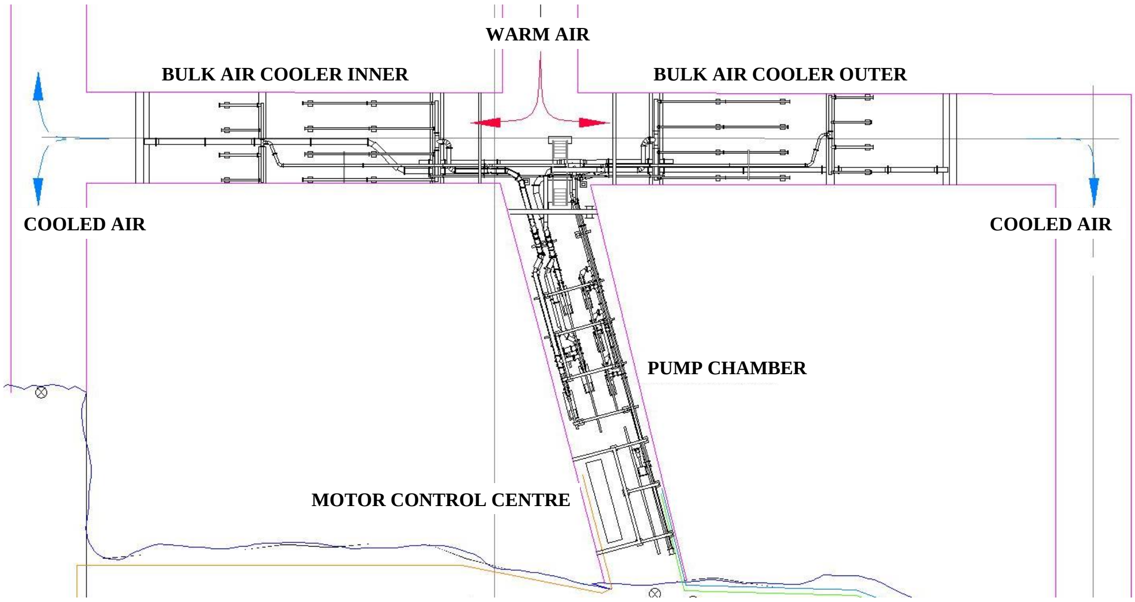

Figure 3 General arrangement of BAC

3.2 Refrigeration machines

The ultimate refrigeration plant (Figure 4) consists of four packaged York CYK machines configured in two lead-lag pairs to deliver 15,000 kW_R. Each refrigeration package will include: centrifugal compressors, shell-and-tube heat exchangers, lubrication system and connecting piping and cabling. Capacity control will modulate down to 30% by using pre-rotational guide vanes to automatically maintain constant cold water leaving temperature. The refrigeration plant will be supplied with control units to enable easy interface with system control PLC and remote monitoring facilities. Each lead-lag pair has the following general process specification:

- Duty 7,500 kW
- Chilled water flow rate 125 l/s
- Water temperature on 20°C
- Water temperature off 5°C

3.3 Condenser spray chamber

The ultimate condenser spray chamber design was two-stage horizontal cross flow units, similar to BAC design. Make-up water supply, piping and control system were included to provide for evaporation losses. Each of the two condenser spray chambers (one per lead-lag pair) was sized for the following process specification:

- Duty 8,400 kW
- Water flow 300 l/s
- Water temperature on 38°C
- Water temperature off 33°C

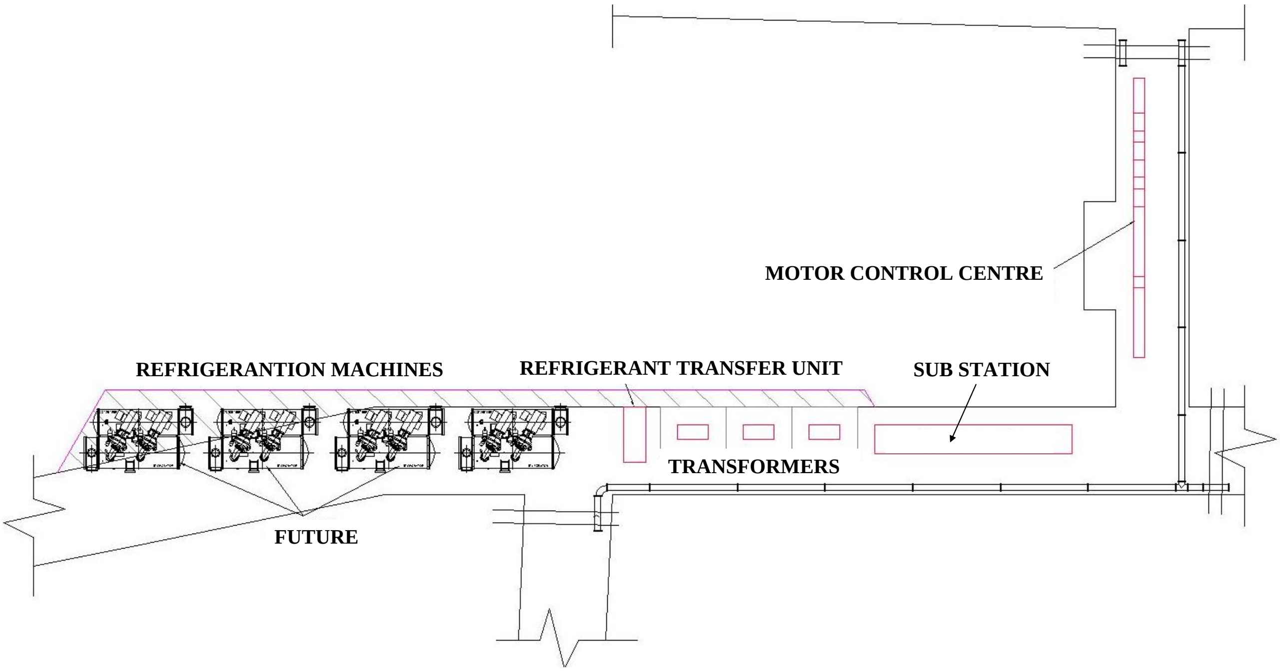

Figure 4 General arrangement of refrigeration plant

3.4 Water and pump systems

The condenser water system will circulate water from the spray chamber sumps to the refrigeration machine condensers and back. Provision was made for six off (four operational, two standby) pump-motor sets for this purpose. The cooling coil system will circulate water from the cold water dam to the cooling coils in closed circuit and back to warm water dam. Provision was made for four off (three operational, one standby) pump-motor sets for this purpose.

The re-use system evaporator water is supplied to the spray chambers from the cold water dam. Spray chamber return pumps return water to the warm water dam. Provision was made for three off (two operational; one standby) pump-motor sets for this purpose.

4 Conclusions

The following brief discussion and notes apply to the whole study.

Rule-of-thumb would normally suggest bulk air cooling from surface for a generic mine at 1,200 m depth. However, due to PMC's mining layout, the study has shown that the best option is an underground cooling system.

Due to the optimum cooling system being underground, the study further indicated the best refrigeration option will be an underground installation as the total owning cost is significantly less than alternative surface systems.

The first major challenge of the engineering design was to cater for different phases in the future of the mine by ensuring that pipes, pumps, refrigeration machines, and electrical systems could cater for many different duty conditions.

The second major challenge was to ensure that all equipment fitted into minimal excavation sizes underground while still allowing access for maintenance and repairs.

Finally, the project success largely depends on commitment from the mine personnel, which in this case was outstanding.

Acknowledgements

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