Operational advantages of mobile refrigeration

using a closed loop heat rejection configuration

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ABSTRACT

The operational advantages of localised cooling, in particular moving the cooling source as close as possible to the area where cooling is required, has been investigated by different authors over a number of years. A notable advantage is the energy efficiency potential associated with cooling locally, mainly due to the savings obtained from a reduction in cooling water and the reduced dewatering pumping power of water back to surface. The challenges with supplying water from the cooling source to the remote areas where the cooling is required led to the development of mobile refrigeration units capable of providing localised cooling. The developed mobile refrigeration air cooling unit (ACU) alleviates some of these problems by increasing the amount of cooling that can be done per litre of water available. These result in more effective and energy efficient cooling, but these units do however still require cooling water to operate. This paper looks into the possible operational advantages, including energy efficiency and reliability, when the condenser circuit of the ACU is not connected to the main cooling water supply, but rather connected in a closed loop heat rejection configuration with the return airway (RAW).

1. INTRODUCTION

Engineers working in the mining industry in South Africa are continuously looking for ways to improve the mining operations with regards to energy usage, reliability, safety and cost. In labour intensive mining operations it is impossible to improve the overall mine performance without looking at the performance of the ventilation and cooling systems. Special emphasis is placed on the energy efficiency of the ventilation and cooling systems as the margins of profitability of mines are under pressure as the mining distance increases both vertically and horizontally.

Ramsden et al. (2001) states that several South African gold mines are examining the feasibility of extending workings to below 4000m. "Since 2010, the AngloGold Ashanti Technology & Innovation Consortium (ATIC), established by AngloGold Ashanti, has been looking for ways to leverage established technology in new ways, in an effort to not only extract additional gold from current depths of around 4000m, but also to realise its long-term vision to reach depths of 5000m and beyond." (AngloGold Ashanti, 2013). The increased travel distance for air to get from the shaft inlet to the working areas means larger heat gains and therefore more cooling required. This in turn means that the cost to mine in remote areas increases due to the increase in cooling demand and the increase in energy usage to supply cooling water to the areas and return it back to surface. The costs associated with the installation of infrastructure to enable mining in remote areas also make it less attractive to mine in these areas.

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2. COOLING METHODS

Infrastructure for the cooling of remote underground working areas usually consists of a cooling source (usually a fridge plant or ice plant), a chilled water reticulation system (consisting of storage dams, pipes, pumps, etc.), bulk air coolers (BACs) and localised cooling units.

2.1. Localised cooling units

Localised cooling units, as the name indicates, are used to cool air near the working areas. These units usually have a lower cooling capacity than larger BACs and can be moved when cooling is required elsewhere as the mining progresses.

2.1.1. Conventional cooling cars

Cooling cars (CC) are air-to-water heat exchangers mounted in a chassis on rolling stock, which enables them to be moved and installed in different areas of the mine. These units are installed near the working areas and are small in size to ensure that the units can be moved with relative ease. CCs have an inlet and outlet water connection to which the chilled water supply and return piping can be connected. A fan is mounted onto the CC to force air over the finned tube cooling coil (see Figure 2-1).

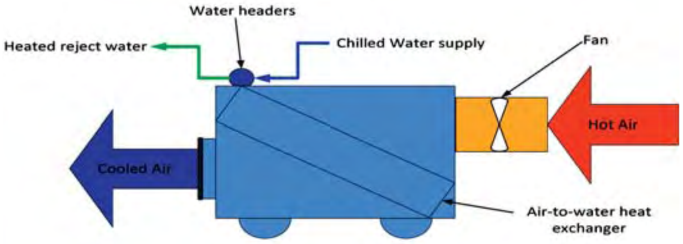

Figure 2-1. Illustration of a cooling car layout indicating water and air flow paths

The cooling capacity of these units are directly dependent on four inputs namely the air mass flow rate, the water mass flow rate, air temperature (dry-bulb and wet-bulb) and the water temperature.

2.1.2. Mobile refrigeration units

The Air Cooling Unit (ACU) is a mobile refrigeration unit, which consists of a vapour compression system in a chassis mounted on rolling stock, which means that the cooling source can be moved closer to the working areas. The feasibility and energy efficiency of these cooling units was first investigated by van Eldik (2007).

The ACU MKI was developed capable of producing approximately 100 kW of cooling.

The unit was deemed a more energy efficient alternative to using CCs because the unit could utilise less water, which greatly reduces the total electrical power consumption to cool deep level mines.

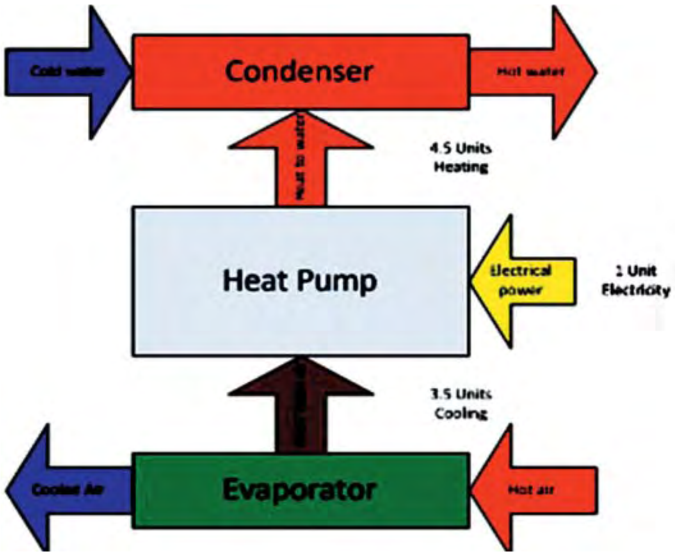

Figure 2-2. Typical vapour compression cycle energy balance

This saving is obtained because the ACU can utilise water as heat sink with a supply temperature of up to 40°C and still deliver effective cooling. Because of the vapour compression cycle used the ACU can heat water to much higher temperatures than with a conventional cooling car.

The larger temperature difference (ΔT) obtained by the unit reduces the amount of water required and therefore reduces the pumping costs. The ACU MKI was followed by the development of the ACU MKII capable of producing 250 kW of cooling.

Greyling (2008) investigated the energy efficiency potential of the ACU MKII for the use in the planned deepening of AngloGold Ashanti's Mponeng gold mine in the Carbon Leader and Below 120L VCR projects.

3. CLOSED LOOP ACU CONCEPT

The energy efficiency potential of the ACU has been investigated on a number of occasions and it has been found that the ACU can reduce the energy consumption of localised cooling applications when compared to conventional cooling cars. The unit does however still require the same infrastructure as the cooling cars to deliver water to it and then the infrastructure to pump water back to surface. The potential therefore exists to reduce the energy consumption by eliminating the need for a constant supply of cooling water for air cooling purposes altogether.

The closed loop ACU concept consists of the following:

- One ACU MKII cooling unit.
- Three 500 kW nominal cooling cars.
- Three 22 kW axial flow auxiliary mine fans mounted on the cooling cars.
- A circulation water pump.
- Piping for closed loop circulation of the water.

The philosophy is to transfer the heat in the water from the ACU condenser to the reject air in the mine 37 return airway (RAW). For this, the condenser circuit of the ACU is connected in a closed loop configuration with three conventional 500 kW cooling cars which is used to reject the heat to the air in the RAW. The water is then circulated back to the ACU condenser circuit using the water pump to complete the cycle (Figure 3-1). The system is dependent on an accessible return airway to be feasible, where the rejected

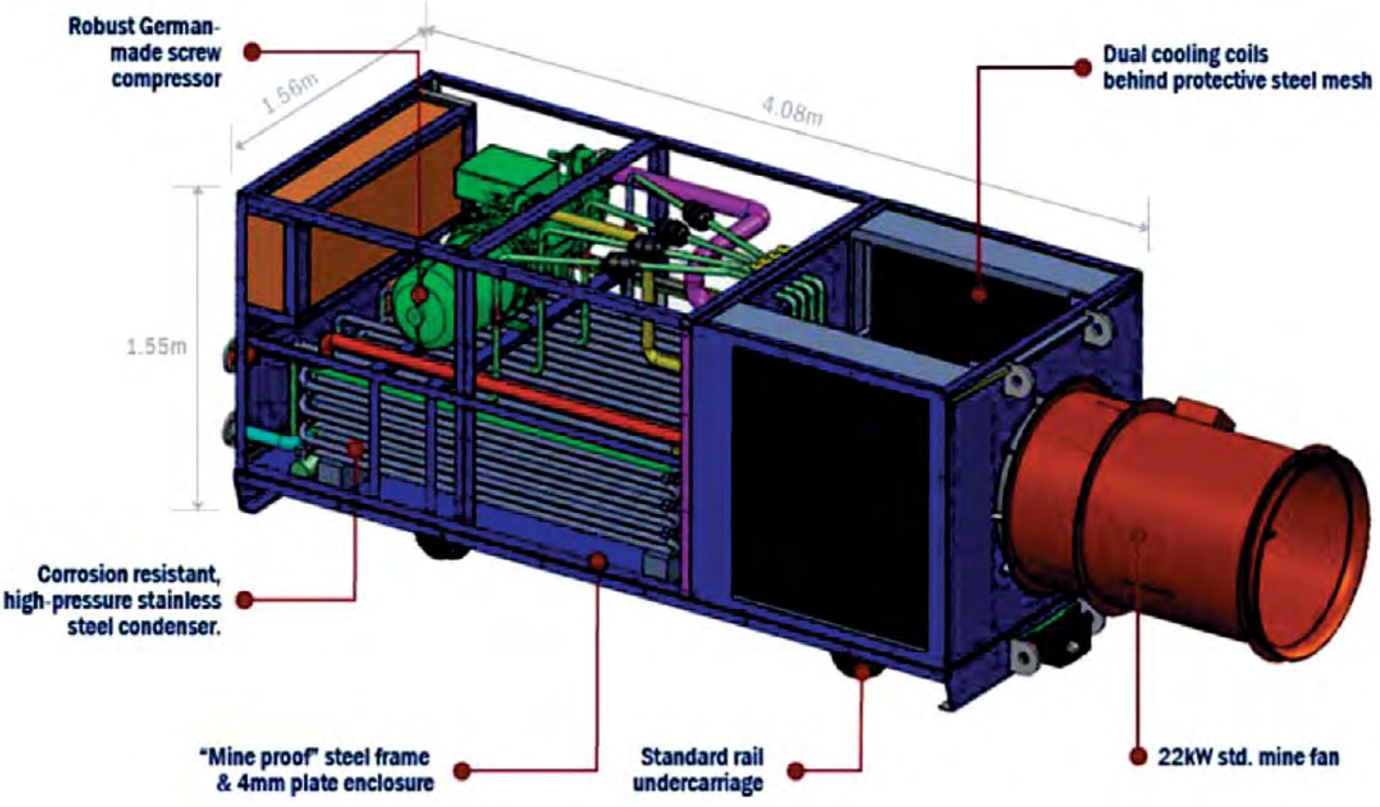

Figure 2-3. Illustration of the ACU MKII component layout

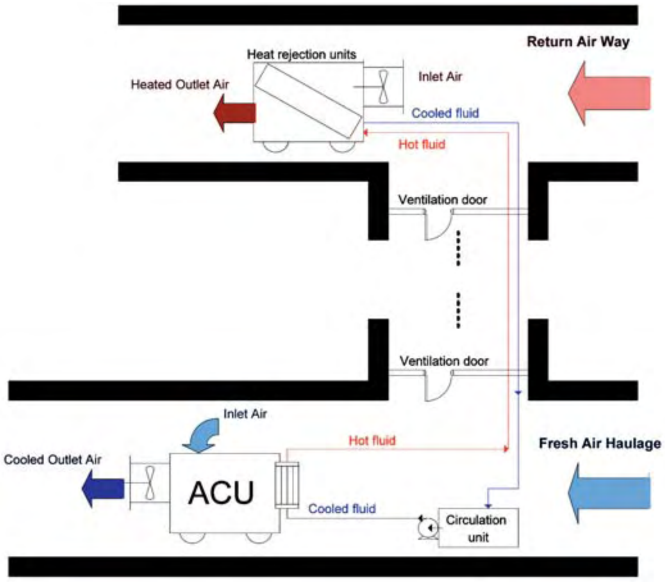

Figure 3-1. Closed loop ACU configuration

heat will not negatively affect any workings, or increase temperatures above legal limits for persons in the areas.

4. ENERGY EFFICIENCY INVESTIGATION

To investigate the energy efficiency potential of the closed loop ACU configuration, a simulation model was created to simulate the following:

- Cooling at different vertical depths using a conventional 500 kW cooling car.
- Cooling at different vertical depths using a conventional ACU MKII cooling configuration.
- Cooling at different vertical depths using an ACU MKII connected in a closed loop heat rejection configuration as described above.

Flownex SE® was used to create the models for the individual components (cooling equipment, water reticulation, airflow paths, etc.) as well as the total integrate mine model.

The energy efficiency of the three cooling strategies was evaluated based on the total cooling per kW electrical power required to do the cooling.

4.1. Simulation model

A model mine was simulated using real mine data, but a hypothetical level was added to simulate at a depth of 4000m. The three different cooling applications were then plugged into the mine model at different depths to evaluate the different cooling performances.

The first cooling application simulation was the localised cooling at different depths using CCs connected to the chilled water reticulation network as illustrated in Figure 4-1. The conventional ACU configuration is modeled similar to the CC with the ACU being connected to the chilled water network.

The water is heated in the ACU condenser circuit and rejected through the mine water reticulation system back to surface where it is recooled first by a precooling tower and then the surface fridge plants.

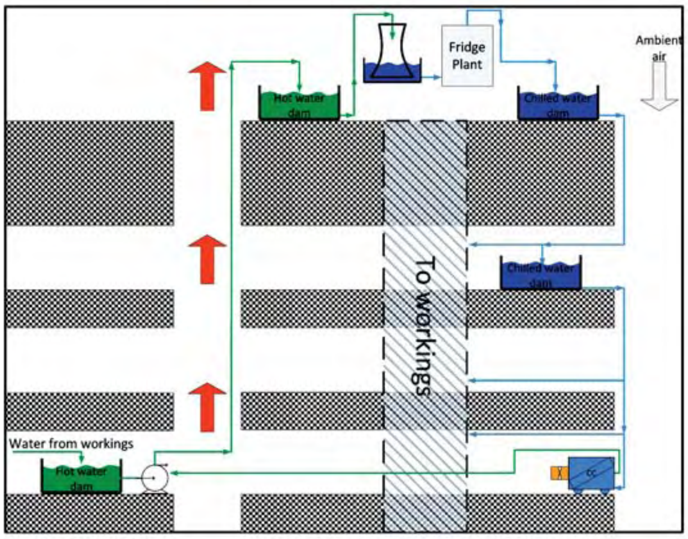

Figure 4-1. Cooling car connected to chilled water diagram

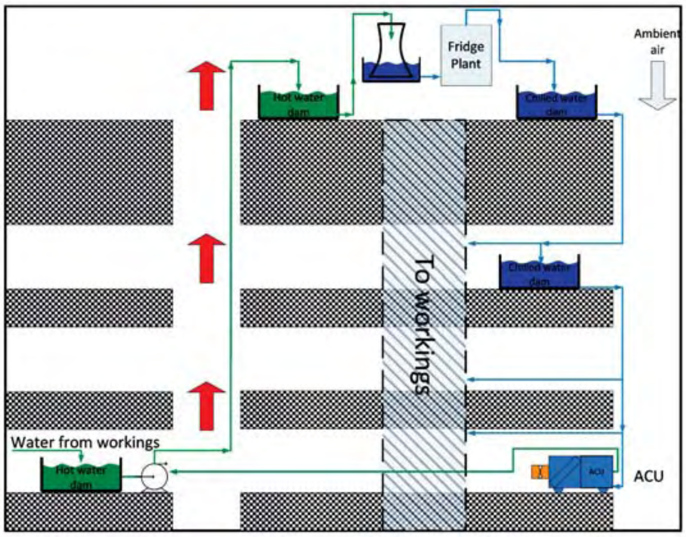

Figure 4-2. ACU connected to chilled water diagram

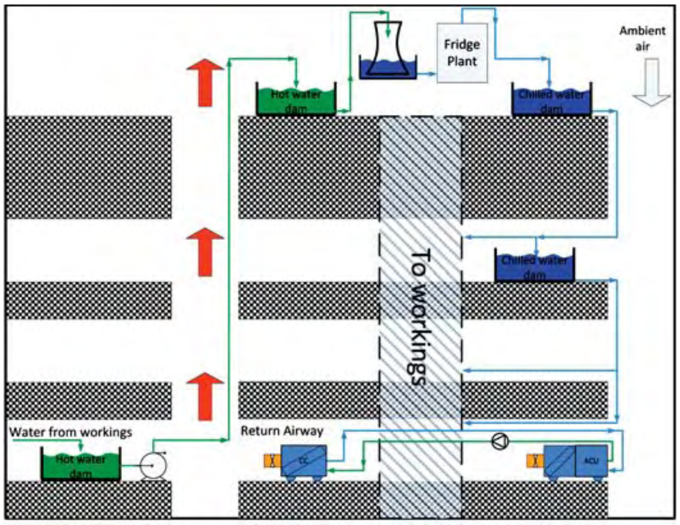

Figure 4-3. ACU with closed loop condenser heat rejection diagram

Table 4-1. Simulation results summary

	Units	CCs	ACU	ACU CL	CCs	ACU	ACU CL	CCs	ACU	ACU CL	CCs	ACU	ACU CL
Depth (model)	m	2472.00			3018.00			3312.00			4000.00		
Air inlet DB	°C	29.32			31.29			32.35			35.13		
Air inlet WB	°C	23.74			25.90			27.04			29.64		
RAW inlet DB	°C	36.00			36.00			36.00			36.00		
RAW inlet WB	°C	32.70			32.77			32.76			32.85		
ACU/CC air flow rate	m³/s	14.11	9.52	9.52	14.12	9.52	9.52	14.13	9.52	9.52	14.14	9.52	9.52
Heat rejection CC air flow rate (per coil)	m³/s	-	-	9.87	-	-	9.88	-	-	9.88	-	-	9.89
Cooling	kW	233.81	306.54	44.65	254.46	306.54	43.92	265.56	306.54	43.56	294.33	306.54	42.83
Pump electrical power	kW	388.38	99.46	2.34	474.22	127.39	1.92	520.38	143.70	1.75	628.51	185.90	1.45
Fridge plant electrical power	kW	120.58	30.88	0.00	120.59	32.40	0.00	120.59	33.30	0.00	120.59	35.67	0.00
Total fan electrical power	kW	37.27	20.75	80.01	39.30	21.89	84.90	40.43	22.53	87.65	43.15	24.07	94.35
Compressor power	kW	0.00	66.75	79.72	0.00	66.75	79.72	0.00	66.75	79.72	0.00	66.75	79.72
Total electrical power	kW	546.23	217.84	162.08	634.11	248.43	166.54	681.40	266.27	169.12	792.25	312.38	175.53
Electrical power per cooling	kWe/kWc	2.47	0.74	0.68	2.61	0.84	0.69	2.68	0.90	0.71	2.79	1.05	0.73
Energy saving per kW cooling	%	0.00%	70.15%	72.58%	0.00%	67.94%	73.39%	0.00%	66.57%	73.67%	0.00%	62.49%	73.80%

The closed loop ACU configuration is modeled with the ACU in the supply air stream and the three CCs in the RAW to reject the heat from the ACU condenser coil with a water pump for circulation.

The closed loop ACU system component configuration is designed taking into account possible fouling on the air side when sizing the capacity of the heat rejection coils.

Flownex® heat exchanger components were used to model the performance of a Manos Zeus cooling coil based on the manufacturer's performance charts.

The total electrical power consumption of each cooling strategy was calculated based on the following:

- Fridge plant power input required to chill water for use in the cooling equipment.
- Fans mounted on the cooling cars and ACUs.
- Pumps used to return water to surface or to circulate the closed loop water.
- Compressor power of the ACU.

4.2. Energy efficiency investigation results

Results were generated from the simulations at different depths including the expected temperatures of the air, water temperatures, cooling duties, etc.

To ensure that the different cooling strategies can be compared with one another special focus is placed on the electrical power consumption of the strategies per unit cooling delivered.

This was done for different depths below surface and a summary of the results can be seen in Table 4-1.

From the simulation results, it can be seen that there are large energy savings potential when using either the ACU or the ACU closed loop (ACU CL) configuration compared to the conventional CC application.

The results show a savings potential of 68.5% for the conventional ACU configuration and 71% for the ACU CL configuration at a depth of 2472m below surface.

The energy saving potential of the ACU CL configuration increases to 73.8% at a depth of 4000m, while the conventional ACU decreases to 62.5%. From the results it can also be seen that the closed loop ACU configuration has the potential to save an additional 2.5% at 2472m and 11.3% at a depth of 4000m more than the stand alone ACU.

5. ECONOMIC EVALUATION

Based on the simulation results obtained above, an economic analysis was done to investigate the economic feasibility of the closed loop ACU configuration.

The capital costs of one installation of each of these cooling strategies were calculated as well as the operational cost based on the active energy charge (based on 2016 Megaflex tariffs) to deliver cooling with the different strategies. A five year cost forecast was done to compare the cost of the cooling over a five year period taking into account an 8% yearly electricity increase. The time value of money is not taken into account in this evaluation.

Sibisi (2014) estimated the cost of installing one kilowatt of cooling infrastructure (fridge plants and all required infrastructure) to be between R8,000 and R10,000 in 2014. Du Plessis et al. (2014) proposed the installation of underground fridge plants at Sibanye's Beatrix 4#. The capital costs calculated in their study showed a cost of R10,222 per kilowatt cooling for underground fridge plants. The largest influencing factor on the cost of surface fridge plants and infrastructure in the past 2 years was the decreased value of the South African rand compared to the United States (US) dollar. The exchange rate was R10.49 to $1.00 on 1 January 2014 compared to the rate in October 2016 of R13.86 to $1.00, which means a total increase of 32.16% from 1 January 2014 to 27 October 2016. Using R8000/kWc from Sibisi (2014) as the base rate in 2014 and incorporating the 32.16% increase, the cost of cooling infrastructure per installed kilowatt was then calculated as R10,572.

The capital cost of the cooling cars and the conventional ACU strategies increased with an increase of depth due to the need for more chilled water and therefore larger surface fridge plant capacity. This was taken into account in the capital expenditure calculations.

From Figures 5-1 and 5-2, it can be seen that the ACU CL becomes an especially attractive option if central cooling infrastructure still needs to be installed, even more so with an increase in vertical depth of mining. This also makes the closed loop ACU configuration more attractive for new mines that do not yet have the cooling infrastructure installed and would like to postpone large capital expenditure.

It can also be a solution for marginal profit mines that need the cooling to open up working areas, but do not have the capital available to install large cooling plants.

6. OPERATIONAL ADVANTAGES

There are a number of operational advantages of having small localised cooling units with a closed loop configuration which can be moved with relative ease without requiring additional cooling from surface.

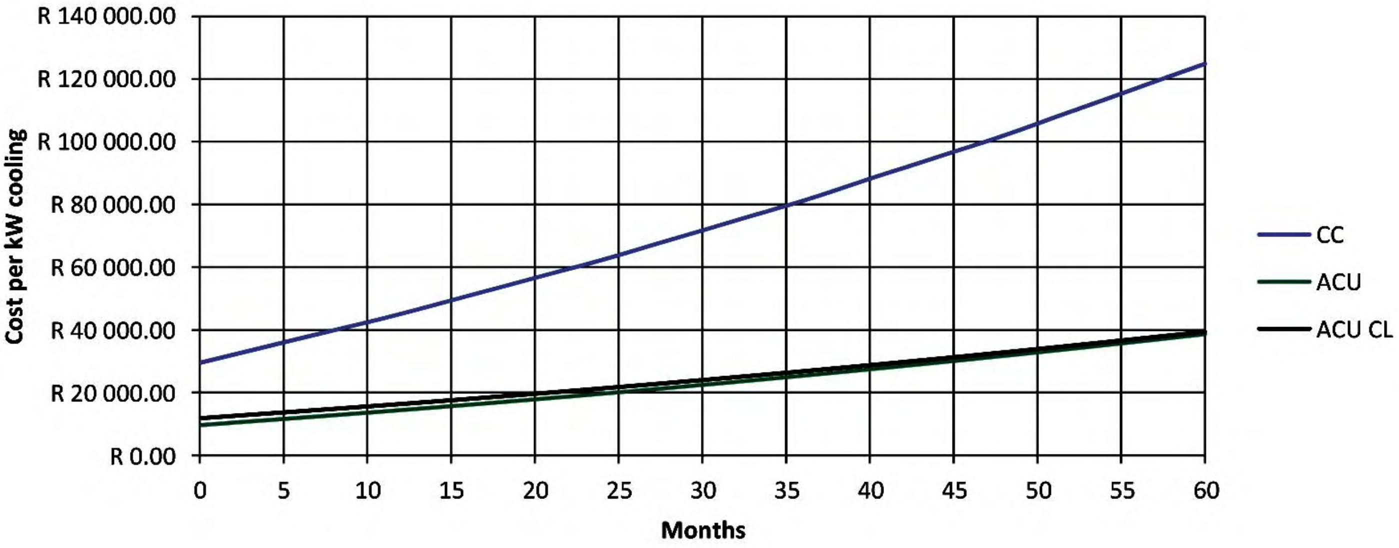

Figure 5-1. 5 Year total cost to mine prediction per kW cooling at 2472m depth below surface

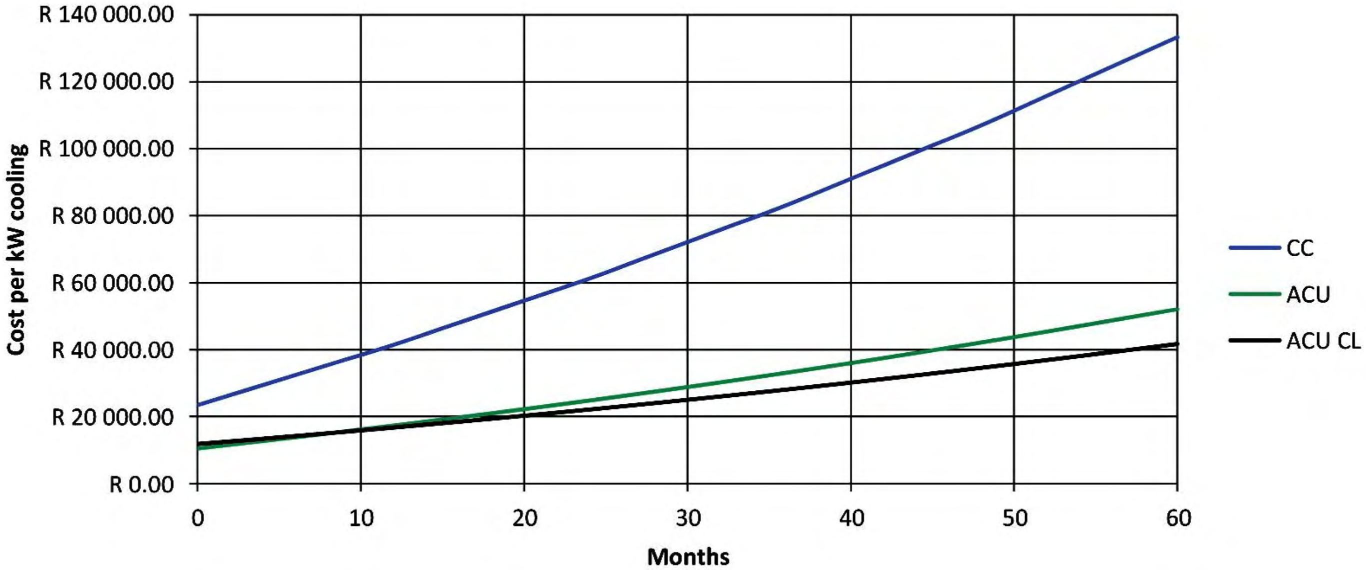

Figure 5-2. 5 Year total cost to mine prediction per kW cooling at 4000m depth below surface

6.1. Relatively small and easy to install

The closed loop ACU configuration installation consists of the following equipment:

- ACU MKII.
- 3 x CCs for heat rejection.
- Piping and fittings between the ACU and the RAW CCs.
- Circulation water pump.
- Fans mounted on heat rejection CCs and the ACU.

It can therefore be installed with relative ease and much quicker than the required infrastructure of larger cooling plants.

These units can be installed as a mine develops, postponing the installation of large cooling plants and infrastructure and the installation time and capital expenditure associated with it.

6.2. Cooling on demand

The closed loop ACU configuration allows for immediate cooling on demand of specific areas without the need for cooling from another source such as surface or underground fridge plants. This means that the areas served by closed loop ACUs are independent of the larger mine cooling infrastructure and therefore not affected by the maintenance schedules of the fridge plants and chilled water reticulation network.

6.3. Maintenance and reliability

The ACU CL configuration consists of off-the-shelf items and can be maintained by qualified personnel.

It is however necessary to monitor the condition of the ACU as a major repair requires the extraction of the unit from underground. The largest component of the ACU is the condenser coil. Replacing this coil requires that the ACU be extracted from the mine to be replaced on surface.

The effects of the return air in the RAW on the heat rejection installation, including the heat rejection coils and fans, must be considered. These components may be subject to increased corrosion and fouling due to the impurities in the return air and also the humidity of the air. These components must be inspected frequently and cleaned, as required, to increase the life expectancy of these components.

For mines with poor RAW air quality this may result in the heat rejection coils being replaced more frequently, thus negatively impacting the total operational cost of the ACU CL concept. There is however a benefit of the closed loop configuration with regards to corrosion. This due the fact that by keeping the water in the ACU condenser circuit in a closed loop, one enables better management of the water quality and therefore a reduction in the effects of corrosion and erosion on the water side of both the ACU and the RAW cooling coils.

Another advantage of using a closed loop water circuit rather than water from the chilled or service water network is that the water pressure in the closed loop can be controlled for optimum operation.

7. CONCLUSION

There are a number of operational advantages of installing mobile refrigeration units for localised cooling using a closed loop heat rejection configuration, as discussed in this paper.

These advantages are even greater for new mines, which do not yet have the larger cooling infrastructure or marginal profit mines with limited capital to install large fridge plants.

The energy efficiency potential of the closed loop ACU configuration could also greatly reduce the operational cost for localised cooling in especially outlying areas of deep mine expansion.

The closed loop ACU shows even greater energy savings potential than the stand alone ACUs and this energy benefit increases with an increase in mining depth.

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