TECHNO-ECONOMIC APPLICATION OF MODULAR AIR COOLING UNITS FOR DEEP LEVEL MINING AT MPONENG

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M.ENG.

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ABSTRACT

As mining explores greater depths beyond 4000m at Mponeng Mine the challenges of obtaining suitable working environments and complying with regulations becomes significant. These depths mean a considerable increase in the virgin rock temperature and the surrounding working environment. By law the mine is obligated to provide working temperatures not exceeding 32°C wet bulb. This then necessitates the need for an effective cooling medium that not only has a great efficiency but should also be sustainable in the current economical environment faced with power supply shortages.

Currently the advantages of ice are explored on Mponeng Below 120 level (120L) project with great effect. Due to the energy in the latent heat of fusion process, savings arise from lower pumping costs and conventional refrigeration plants are already being phased out. When applied in closed loop (U – tube) water cooling systems, colder water temperatures can be obtained at the working face.

Currently Mponeng Mine is using Conventional Cooling Cars (CWC) that are similar in design to radiators for extracting heat from the working areas. The system absorbs the heat at the cooling car and rejects it in the fridge plants. If water temperatures raise this system is ineffective and costly from the loss of production. A solution for this problem comes in the form of a modular Air Cooling Unit (ACU) based on heat pump technology that was designed for use as a localised cooling unit. It allows for high supply water temperatures and provides cooling in the region of 100 kW.

The study focuses on simulating the ACU in the proposed closed loop system for the Carbon Leader (CL) project and evaluating it with conventional cooling methods. Five different configurations between the 500 kW conventional cooler and 300 kW ACU are looked at and economically evaluated for the total life cycle costing (LCC).

The study indicates that in a closed loop system that uses ice as the cooling medium CWCs is the best economical option. However ACUs proved to be economically the best method for cooling in two cases. Firstly in development ends and secondly using the warm return water to do additional underground cooling between the settlers and hot return water pumps. Based on the results from the study Mponeng should look into installing ACUs between the settlers and hot water dams as this scenario had the best net present value cost of all the simulations done.

UITTREKSEL

Soos mynbou dieper gaan as 4000m by Mponeng Myn raak die uitdagings groter om 'n werkbare klimaat te skep wat by die regulasies hou. Hierdie dieptes beteken groot toenames in hitte weens die omringende klip en omgewing temperature. Volgens die wet word die myne vereis om nie temperature van meer as 32°C nat bulb te oorskry nie. Dit bring 'n behoefte vir 'n effektiewe verkoelings medium wat sal funksioneer in die huidige ekonomiese klimaat met die elektrisiteit kortkominge.

Een van die mediums wat huidiglik na gekyk word is die IDE ys masjiene wat op Mponeng Myn se Below 120L projek gebruik word. Danksy die energie wat opgeneem word tydens die latente smelting van die ys is daar aansienlike besparings rondom pomp koste en sommige verkoeling stelsels word uitgefaseer. Indien hierdie sisteem in 'n geslote lus (U –pyp) gebruik word is die water temperature wat by die werk areas aankom aansienlik kouer.

Huidiglik word konvensionele verkoelings hitteruilers met fin na pyp hitteoordrag gebruik om hitte uit die omgewing te onttrek. Die sisteem absorbeer die hitte by die verkoeling kar en ontslaan *dit na die omgewing by die verkoeling stelsel. Indien die temperature verhoog,* verlaag die effektiwiteit van die karre aansienlik en verminder produksie. 'n Oplossing vir die probleem is die modulêre verkoelings eenheid wat van hittepomp tegnologie gebruik maak om verkoeling te verskaf. Huidige eenhede kan tot 100kW se verkoeling verskaf en kan by aansienlike hoër water temperature funksioneer as die konvensionele verkoelings karre.

Die simulasie fokus op spesifieke gevalle waar die modulêre verkoeler vergelyk was met die konvensionele een vir die voorgestelde Carbon Leader (CL) projek by Mponeng Myn. Daar word gefokus of vyf spesifieke gevalle waar tydens die 500kW konvensionele verkoeler geevalueer word met die 300kW modulêre eenheid om te sien wat die mees effektiewe kostebesparing konfigurasie sal wees.

Die studie het aangedui dat in 'n geslote sisteem wat gebruik maak van konvensionele verkoelings karre die mees ekonomiese opsie van verkoeling sal wees. Alhoewel daar twee gevalle was wat getoon het dat die modulêre eenheid beter presteer. Eerstens by ontsluitings ente en dan tussen settlers' en warm water pompe. Van al die simulasies wat geobserveer was is die modulêre verkoelings eenheiddie beste finansiële opsie en moet Mponeng Myn dit ondersoek vir die CL projek.

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Nomenclature

A	Area	m^2
c_p	Specific heat at constant pressure	$J/(kg*K)$
h	Enthalpy	J/kg
h	Water heat transfer coefficient	$W/(m^2*k)$
i	Interest rate	%
k	Thermal conductivity	$W/(m*k)$
m,M	Mass flow rate	kg/s
p	Pressure	Pa
P	Power Input	W
q,Q	Heat Transfer	W
r	Raduis	m
T	Temperature	˚C

Greek Symbols

α	Coefficient	-
Δ	Delta or difference	-
η	Efficiency	-
ρ	Density	kg/m^3
Σ	Sum of	-

Abbreviations

ACU	Air Cooling Unit
AGA	AngloGold Ashanti
BEP	Best Efficiency Point
CL	Carbon Leader
CLR	Carbon Leader Reef
COP	Coefficient of Performance
CWC	Chilled Water Cooler
DB	Dry Bulb
ESKOM	South African Electrical Supply Utility
IMF	Ice Mass Fraction
LCC	Life Cycle Costing
MPVC	Modified Polyvinal Chloride
NERSA	National Energy Regulator of South Africa
NPV	Net Present Value
OEM	Original Equipment Manufacturer
P&ID	Pipe and Instrumentation Drawing
PRV	Pressure Relieve Valve
RAW	Return Airway
SCFD	System Computational Fluid Dynamic
SIS	Solids in Suspension
TV#	Tertiary Ventilation Shaft
UPVC	Unplastirsized Polyvinal Chloride
VCR	Ventersdorp Contact Reef
VRT	Virgin Rock Temperature
VSD	Variable Speed Drive
WB	Wet Bulb

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KEYWORDS

Chilled Water Cooler (CWC)
Air Cooling Unit (ACU)
Mponeng Mine
Carbon Leader Project
Closed Loop Reticulation
Refrigeration Plants
Ice Plants
Flownex

1. Introduction

1.1. Background

Mponeng Mine currently has a life expectancy towards the year 2020 and as the industry leader for AngloGold Ashanti in production the need arose to increase the life of the mine. Backing this is the high price of mineral resources on the market and the lack of trust in crude oil during the latter half of 2008. In the past four years the price of gold has increased from \$300.00/oz to a record high of \$988.00/oz and is currently stable at an average of \$750.00/oz providing some stability in the volatile markets.

The western level mines within the AngloGold Ashanti group are some of the deepest mines in the world with Mponeng Mine shaft bottom currently at 3450m. The gold reserves for Mponeng Mine include the Ventersdorp Contact Reef (VCR) and Carbon Leader Reef (CLR). The two reef bands are separated by approximately 350m and dip in a north south direction by about 22 degrees. Major mining is currently taking place on 120L with stoping and development expected to be completed by 2020. In order to increase the life of the mine there is a need to deepen and go to depths that have not yet been explored. This deepening will be known as the Below 120L VCR project and the Carbon Leader (CL) projects. The mine would go down to depths over 4000m and deepening will start early 2009 (Kruger, 2008). At these depths the Virgin Rock Temperature (VRT) will range between 50°C and 70°C depending on the region and could increase dramatically thereafter by more than 10°C/km. The Mine Health and Safety act requires that the employer shall provide an occupational environment not exceeding 32°C wet bulb and 37°C dry bulb (APCOR, 2008). If not well ventilated and cooled this working environment will never be obtainable and production could not be started.

Mponeng Mine makes use of underground Chilled Water Coolers (CWC) that are connected to chilled water via high pressure piping to cool the environment and achieve this legal requirement. Currently about 6500 tons of broken reef is produced per day and with a gold content of about 9.5g/ton. This amounts to 55kg of gold/day. Although this might seem like a large amount of money the production costs involved are significant, with electricity alone amounting to about R8 million per month.

One of the main challenges facing AngloGold Ashanti is the electricity shortage currently experienced by Eskom. This is mainly due to natural resources becoming depleted and Eskom not expanding with the economical growth experienced in South Africa. The problem is that all the mines have to decrease their peak electrical demand by 10% or pay considerable penalties. For AngloGold Ashanti this means that for 2008 the company as a whole will lose 200 000 ounces of gold production resulting in a company loss of about $79 million (Anon, 2008). In order to reduce this AngloGold Ashanti have to increase the efficiency of the way they use electricity and come up with innovative ways of mining.

Knowing all this and wanting to establish growth to extend the life of mine expectancy, engineers working on the CL Project have to incorporate innovative ideas and past experience to make it a success.

One of the concepts is the IDE ice plants that are currently used on Mponeng Mine. These plants reduce the monthly pumping cost to about a fifth due to the latent heat of fusion having a higher heat capacity than that of water (Livingstone, 1999). The ice is mixed underground with warm water returning from the working places and is then sends back via a closed loop system. This allows cooling to be closer to the working places and reduced losses from heat transfer. The closed loop system uses the head pressure of the water in a U-tube to press the water back to the ice dam, thus minimizing the need to pump water. This has a high efficiency if the water inlet temperature and mass flow rate is near design conditions, but as soon as one of these deviate the efficiency falls dramatically.

This results in the need to find possible alternatives to the current cooling philosophy. TauTona Mine is currently testing an alternative in the form of an ACU in an open loop system to reduce pumping cost and facilitate areas with cooling. The ACU is a modular and mobile heat pump unit that employs a vapour compression cooling cycle similar to that of a surface cooling plant. The major advantage of the ACU is the reduction in the amount of water in the system and reducing the infrastructure size and cost.

1.2. Purpose of Research

The final feasibility proposal of the CL project is due in February 2009. As part of this proposal a complete break down structure of the expected capital cost and operation costs need to be provided.

Usually engineering covers a major part of the cost and except for the installation of the shaft infrastructure, excavation and winders the pumping and refrigeration will make up a considerable amount. It is therefore very important to bring all the proposals with potential to the table and to provide accurate information on the expected results of the proposals.

The purpose of the study is the simulation of the CL refrigeration to determine the amount of water that will be needed for the cooling of mining areas. The capacity of cooling and the complete economical evaluation for expected implementation and running cost will be compared between that of the CWC and ACU. It will investigate the possible advantages and disadvantages of using the system in conjunction with the ice technology to obtain a higher system efficiency and lower operational cost.

At the end if this study the result provide valuable information on ACU units and the possible implementation benefits of the units on other AngloGold Ashanti operations.

1.3. Scope of Study

In the analysis the following issues will be addressed to reach the goals of paragraph 1.2:

- An in depth understanding of the cooling in a mining environment.
- A detailed simulation of the Mponeng Mine CL cooling system comparing both CWC and ACU cooling configurations. It is important to note that assumptions will be made for ground conditions including temperatures and cooling load as no results exist for mining at these depths.
- A techno-economic analysis will be done to determine the feasibility of the proposed system.
- Formulate design specifications for the proposed system and make recommendations to the layout if necessary.

1.4. Contribution of this study

The project will provide AngloGold Ashanti with relevant information as to what the expected cooling requirements and system layout should be to optimize different conventional cooling methods at great depths. It will also contribute to the significance of System Computational Fluid Dynamics (SCFD) for underground system design and optimization.

2. Literature Study

The literature study will be divided into two sections. Firstly, the application of different cooling systems in the mining environment will be studied and how their integration would affect the efficiency of operation. Secondly, the equipment used for cooling and ventilation and how they interact with the system will be discussed.

2.1. Cooling and Ventilation systems

The CL project is mainly focussing on the following system configurations for cooling:

- Surface and Underground Cooling Plants.
- Hybrid Systems (incorporate both surface and underground cooling).
- Energy Recovery Systems.

2.1.1. Surface and Underground Cooling Plants

Up to the 1970s' the tendency at deep mines was to locate the cooling plants underground in order to cool downcast air and minimize losses from heat transfer (Ramsden *et al*; 2004). This changed in the same decade as maintenance cost increased and the feasibility studies indicated that surface cooling would be cheaper.

The problem with underground plants comes from using return air as a discharge medium for the condensing circuit. The return air has a high concentration of foreign particles that causes fouling of the heat transfer surfaces in the cooling towers. The return air is at high temperatures and humidity staying almost constant throughout the year. This prevents the underground units to run at partial load during the winter months as is common with surface plants (Robbins, 2007) and reduces the energy savings potential.

The concept behind a surface and underground cooling plant is similar in the fact that they have to cool a certain load located at specific depths. The underground plant is situated closer to the load and has minimal heat losses as pipe distribution networks are shorter. It was found that shorter distribution networks increase the efficiency of the overall system and minimizes losses like auto-compression (Funnel *et al;* 2000). The surface cooling plants at Mponeng sends water down to depths exceeding 3000m and this increases the water temperature by more than 6°C. To achieve water temperatures of 10°C at the cooling cars underground water is reticulated between the surface cooling plants and the cooling towers to lower the evaporator water inlet temperature (Rawlins, 2000). This is discussed later in the chapter under the topic water cycles.

From the above it shows that there are both positive and negative points to surface and underground cooling plant installations. The surface cooling plants are more attractive to the mining industry for the following reasons compared to underground cooling plants (De Wet, 2008):

- Less maintenance from a reduced fouling rate.
- Excavation costs are reduced on surface.
- Underground plants are subject to possible falls of ground (Possible cave-in of the excavation or rock falling from the hanging wall).
- Original Equipment Manufacturer (OEM) warranty is longer for surface installations.
- Technical Services audits are more accurate on pipe leakages and corrosion.
- Refrigerant leakages are less severe on surface installations.
- Transportation of equipment underground takes up valuable production time.

Both these systems are subject to the same pumping costs. The production drills use a certain amount of water for drilling along with the coolers thus this will not change with the plant on surface or underground. For these reasons surface installations are the preferred option for plants at Mponeng and future AGA projects.

2.1.2. Hybrid Systems

As the depth of mining operations increases so do the costs involved with refrigeration. It has been shown that the use of hybrid systems that are a combination of underground and surface cooling plants is the most effective method of cooling (Hatting *et al*; 2000). Typical hybrid installations nowadays do away with the underground plants and use surface ice plants to remove the heat load. The ice is not a liquid so it is not subject to the auto-compression effect and simple melting from surface takes place (Kruger, 2008). Mponeng uses IDE ice plants to produce slurry with a 70% ice mass fraction for underground use. The measured temperature on 84L is about 1˚C for the incoming ice. This is significant as no current underground fridge plant within AGA has ever been able to produce the same temperatures at these depths (ANON, 2006).

Mponeng is currently the only mine using ice technology for more than five years. The system is used in conjunction with an underground closed loop circulation to cool water returning from the working areas in a chilled water dam. The essence of this is to have a cooling medium as close to the working areas as possible and so to minimize the cost and efficiency losses (Van der Westhuizen, 2000).

This system is currently reducing the pumping cost thanks to the latent heat of fusion (ice melting) as discussed in chapter 1. The following are some of the advantages of having such a system in place and further discussions will follow under ice plant technology:

- Reduces pumping load (Van der Westhuizen, 2000).
- Provides lower temperatures at workings (ANON, 2006).

- Ice production is cheaper than conventional plants given the same load (Sheer *et al;* 2002).
- Ice favours mines where the heat load is close to the maximum depth (Hatting *et al;* 2000).

2.1.3. Energy Recovery Systems

The focus of energy recovery systems is to look into the energy recovery component of the above mentioned systems. The emphasis of the study was to look at the different layouts that are used for cooling in the mining environment. The study also shows the limitation in the mining environment with regards to cooling.

The amount of service water used for underground cooling is normally in the region of one ton of water per ton of broken rock produced (Whillier and Ramsden, 1975). This water is returned to the level annex holes by using vertical spindle pumps. With the VRT approaching 70°C ventilation personnel have to look at a ratio of 3:1 for service water compared to the above mentioned ratio of 1:1 (Kruger, 2008). This amount of water in the system calls for effective usage thereof otherwise refrigeration and pumping costs would increase (Robbins, 2007).

There are currently a couple of options with regards to return water. Only the option of return water temperature optimization will be focussed on for this study. The options include the following:

- Hydro lift systems could amount to considerable savings if used correctly (Ramsden *et al;* 2000).
- To maximize the return water temperature as a heat rejection medium (Hatting *et al;* 2000).
- Ice requires less water in the system and should be looked at for infrastructure cost reductions.

This concludes the investigation of the systems used on mines for underground cooling. Several tasks have been done by Bluhm Burton Engineering (Ramsden *et al;* 2000) regarding the simulation of underground systems and the deepening to ultra-deep mines. From these it can be gathered that the value of the heat load in the simulation is always equal to the underground heat load taking into consideration the efficiency of the complete system as this will increase the plant work.

Important considerations to be made for a simulation process are:

- With increased depth there is an increase in cost for surface refrigeration plants.
- Less efficient systems require substantial amounts of water circulation to make up for the loss in efficiency.
- The best possible return water temperature from the cooler is equal to or above the haulage temperature.
- There is considerable cost saving effects if the refrigeration system is close to the point of usage.
- Water return to surface when used as a heat rejection medium will increase the overall system efficiency.

Simulation done on Mponeng for going past the year 2010

Mponeng uses a system that produces all the refrigeration on surface. It forms part of a hybrid system design with the closed loop water reticulation to save on pumping cost. If the ice production of the mine stays the same and underground plants is used there is substantial savings to be made. Maximum use should therefore be made of underground cooling plants when considering ultra-deep depths beyond 4000m (Ramsden *et al;* 2003).

2.2. Cooling and Ventilation Equipment

Regarding the refrigeration focus will be mainly on:

- Vapour compression cycle.
- Heat pump cycle.
- Absorption refrigeration cycle.
- Ice plant technology.

2.2.1. Vapour Compression Cycle

Most refrigeration plants currently used in the mining industry work on the basic vapour compression cycle where a refrigerant changes phases in a controlled environment by adding energy to the system through the compressor and gaining heat from the evaporation effect. Evaporation conditions depend on the refrigerant in use and normally the outlet approach temperature of the cooling effect minus 2°C is taken as the norm for the temperature at which evaporation should take place (Roux, 2007). Different types of refrigerants can be used in this system but only R407C, R134a and Ammonia will be focused on in this project. Figure 2.1 is an illustration of a Temperature (T) - Entropy (S) diagram to explain the refrigeration cycle.

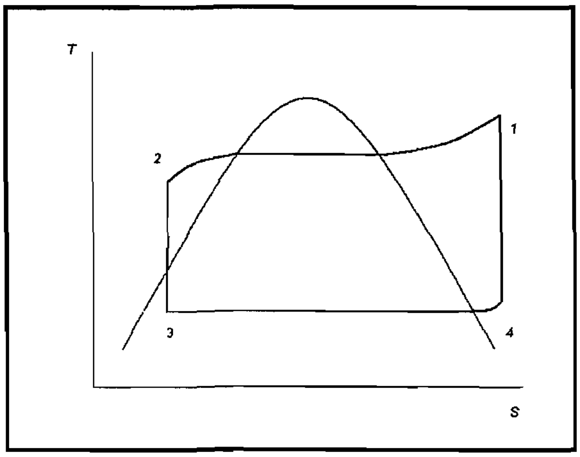

Figure 2.1. T-S Diagram of refrigeration cycle.

Condenser

Starting at point 1, high pressure and temperature refrigerant gas is ready to be condensed in the condensing circuit of the refrigeration plant. The condensing circuit is connected to cooling towers that reject the heat to atmosphere and the temperature and pressure of the system should be designed so that this condition is achievable with the gas. The average wet bulb (WB) temperature in South Africa is in the region of 18°C with a 2°C approach temperature (Kruger, 2008). For complete condensing to take place the gas must condense at 23°C allowing for warmer temperatures in the summer months. Mponeng uses 11 MW Hitachi refrigeration plants for cooling purposes. One plant circulates about 9000 kg of refrigerant R134a and the maximum pressure entering the condenser is in the region of 8 to 12 bar depending on the ambient temperatures. To effectively handle all the gas entering the condenser baffle plates are used to distribute the flow. At the bottom of the condenser there is a sub-cooler to allow for further cooling as the water entering the circuit from the cooling towers is introduced here and increases the capacity of the evaporator by reducing the inlet quality. This allows for increased heat transfer and improved efficiency.

Figure 2.2 shows layout of the Hitachi machine and components that will be discussed further.

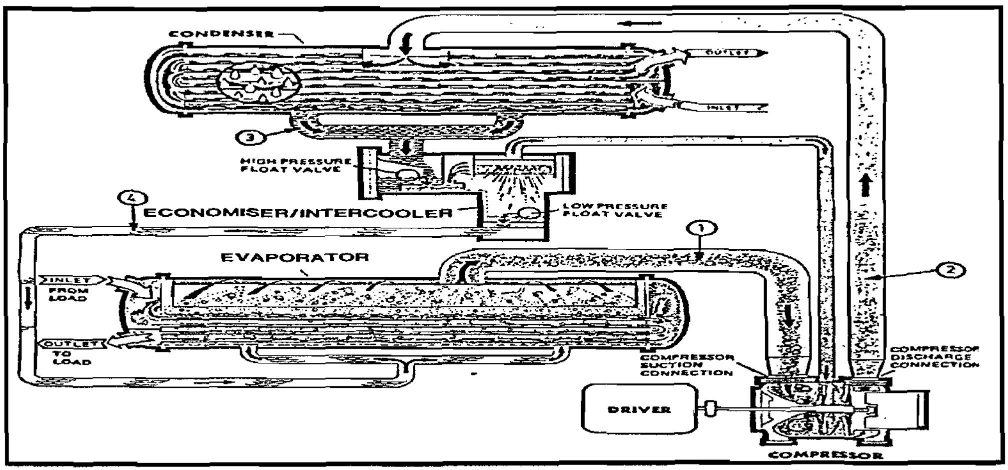

Figure 2.2. 11 MW Hitachi operation layout (Austin, 2008).

Economizer/Intercooler

Between points 2 and 3 of Figure 2.1, high pressure condensed liquid is put through the economizer or intercooler to lower the pressure and to prepare the gas for evaporation. Expansion valves are used here to allow for the pressure drop. There is a high pressure and low pressure expansion valve thus resulting in a two stages expansion. Rapid expansion of the liquid causes evaporation and so the need to limit the effect is done by using the stages. A float valve is used to limit the flow of refrigerant to the second stage whilst an accumulator absorbs the flash gasses at the top of the economizer to the second stage of compression in Figure 2.2.

Evaporator

Between points 3 and 4, the low pressure and low temperature liquid is gravity fed into the bottom of the evaporator. Here it is brought into contact with the liquid that needs to be cooled. Returned underground water from the surface cooling towers is used and sent to the evaporator at about 10°C and 230kg/s. The heat is then transferred to the liquid refrigerant and causes it to evaporate. The upper portion of the evaporator is filled with gas due to the lighter density than that of the liquid and is sucked to the first stage of the compressor at 2 bar. Figure 2.3 displays a side view of the Hitachi refrigeration plant with the water pipe entering the evaporator at the bottom and the gas discharge on the side of the economizer.

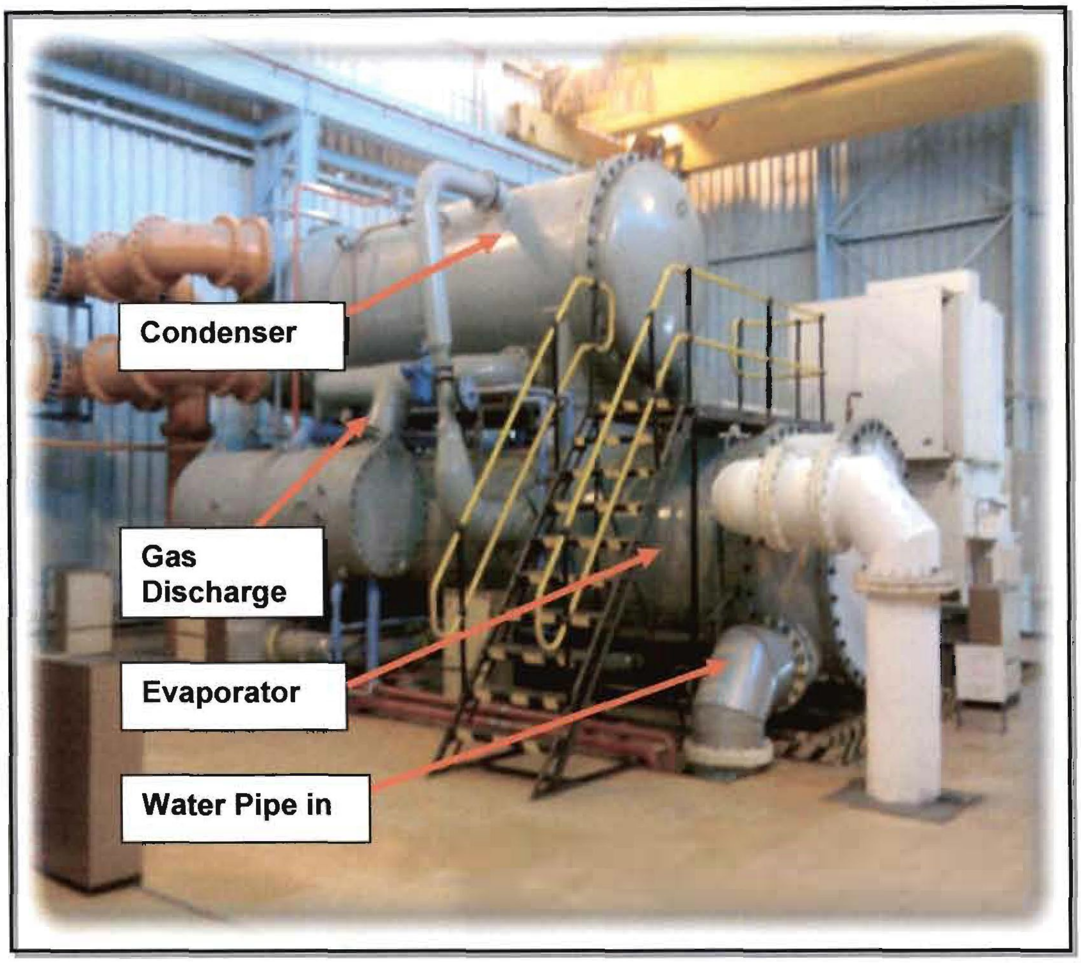

Figure 2.3. Evaporator unit at bottom of plant.

Compressor

At point 4, the low pressure gas has limited capacity left to exchange heat with the supply water from the cooling towers. The gas has to be compressed to reach a point where it could reject the energy to atmosphere via condenser cooling towers. For this a compressor is needed and at Mponeng a 2MW induction motor drives the compressor via a speed increasing gearbox. The compressor has inlet guide vanes that allow gas flow to be controlled and the outlet of the plant to be limited when needed. Synthetic oil is used to minimize cross contamination between the refrigerant and oil as this would lead to a loss in viscosity. There is high range and low range on the compressor gearbox to allow limiting of the compressor between summer and winter months. Figure 2.4 indicates the suction and discharge of the compressor with guide vane control on the suction side.

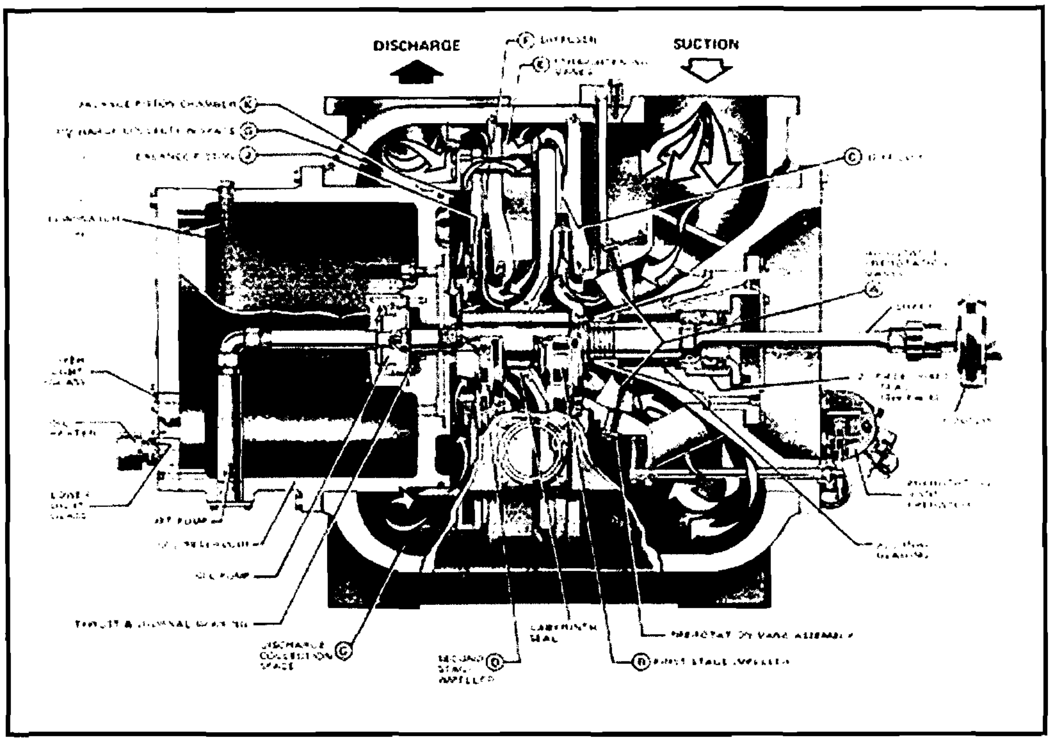

Figure 2.4. Section view of Hitachi compressor (Austin, 2008).

2.2.2. Heat Pump Cycle

The use of return water as a heat source medium is one of the most important factors to look at for rejecting heat and improving system efficiency (Hatting, 2004). The closer the return water temperature to the surrounding atmosphere the smaller the losses from heat transfer (Kruger, 2008).

Mponeng only uses surface refrigeration plants due to the problems experienced by some of the older mines like TauTona and Savuka in the West Wits region. Underground plants generally have higher maintenance costs from the condenser cooling towers being located in the Return Airway (RAW) so many dust particles will contaminate the heat transfer surface. Ramsden (Ramsden, 1990) stated that the underground plants have poor efficiencies that lead to higher operation cost. The motives for underground chillers are the same thinking that leads to heat pumps and spot cooling as mentioned in paragraph 2. The cooling must be done as close as possible to the place that it is needed for improved efficiency and to limit heat losses in long underground distribution networks. According to Cromberge (Cromberge, 2004) spot cooling would be the most effective method of ensuring high efficiency output and lowering increasing mine temperatures.

All AGA mines use CWCs for spot cooling of the working areas. Manos Engineering and Viper are the main suppliers of CWC and both work with the principle of a fan that blows over the water coil (Appendix B). Briefly the system at Mponeng uses chilled water that is supplied by an underground dam to the coolers. The coolers are very susceptible to change in water inlet temperature and flow rate. Figure 2.5 shows a Manos CWC with the inlet manifold to the cooling coils.

Figure 2.5.Manos Engineering CWC.

The heat pump cycle on which the Air Cooling Unit (ACU) is based works on the same operation principle as the vapour compression cycle. For the ACU refrigerant (R407C) absorbs energy in the evaporator coil. The gas is then compressed to a higher state of energy by the compressor and the total amount of heat is rejected in the condenser circuit. The difference between the CWC and ACU is that the CWC only has an evaporator coil that is supplied by chilled water at the working place and the ACU is a localized plant. With a heat pump the water is used as a heat sink to transfer the energy absorbed from the air. For the mining environment this means that for each 300kW of cooling done, 375kW of heat is rejected into the water circuit assuming a Coefficient of Performance (COP) of 4.

Currently there are nominal 100 $kW_{cooling}$ units in operation at TauTona mine but these machines are connected to a low pressure water system. Open loop or low pressure systems have Pressure Relieve Valves (PRV) at the station of the working level to reduce the pressure of the incoming chilled water to 12 bar. Depending on the depth of the mining levels the PRVs' would increase to sustain a 12 bar working pressure on the water. The open system is of an old design and most of the AGA mines try to adopt a high pressure closed loop system to considerably reduce the pumping cost of deep level mining. For this reason M-Tech Industrial (Rousseau & van Eldik, 2008) is in the concept design phase for developing a 300kW high pressure 200 bar ACU to operate in any current or future system.

2.2.3. Absorption Refrigeration Cycle

The absorption refrigeration cycle is similar to vapour compression in that it uses a refrigerant gas in a controlled environment for cooling of a substance. The system operates by using the waste heat from other systems to drive a blower that in turn circulates the refrigerant gas (Zaytsev, 2003). At AGA the after coolers on the compressors are ideal for such a system if the logistics are correct. For example, air leaving the 5MW compressors (used for supplying pneumatic drills) at Mponeng is at 136°C with the flow rate of the system equal to 8kg/s. Currently refrigerated water in co-junction with cooling towers are used to cool the after coolers. If an absorption system could be connected here the need for refrigerated water could be eliminated and the overall system efficiency could be improved. Heat caused by the VRT underground is still investigated but the heat exchangers of the absorption plant is insufficient to provide enough energy for driving the blowers. Figure 2.6 provides the working layout of a typical absorption refrigeration system.

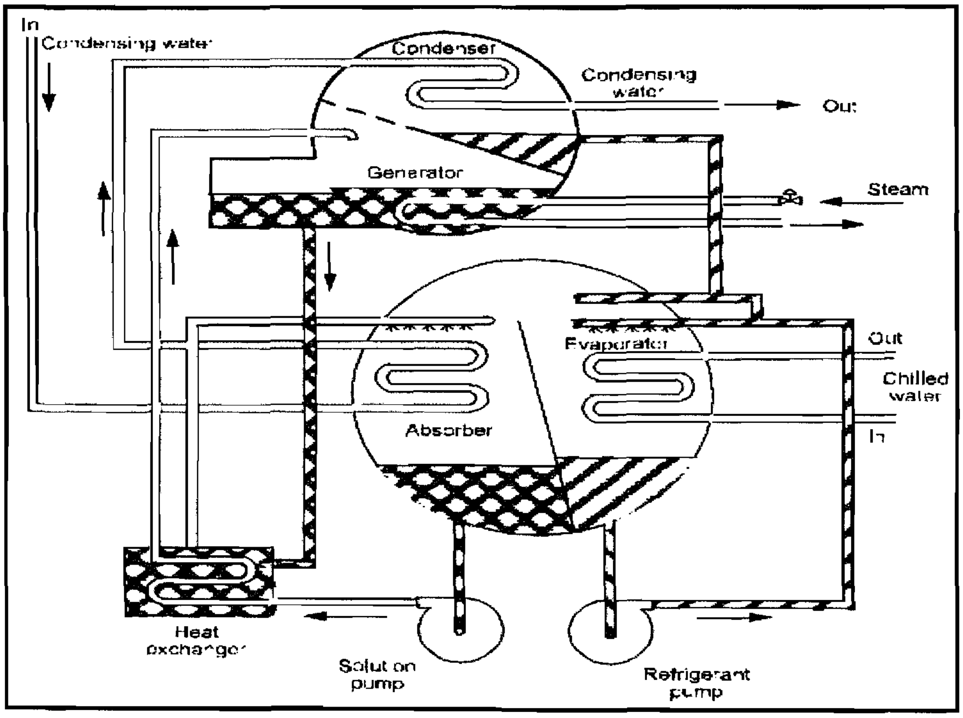

Figure 2.6. Absorption refrigeration cycle (Zaytsev, 2003).

2.2.4. Ice Plant technology

The 3MW ice plants currently used at Mponeng are manufactured by IDE in Israel (Livingstone, 1999). In Israel they are used to produce drinking water using a reverse osmoses process. The plant was designed to create the necessary temperatures for evaporation of the fluid by regulating the pressure vacuum inside the chambers and then compresses the vapour that formed for condensation. From the chamber the vapour is exposed to cold temperatures using water from the inter-stage cooling towers and condenses resulting in drinking water production. However, if the inlet water temperature is reduced enough the triple point of water comes into effect and the flashing gas will produce ice. The advantage of ice is its high latent heat of fusion (333kJ/kg) compared to water's sensible heating value of only 4.187kJ/kg. The process is illustrated in Figure 2.7 and all further related discussions will be based on.

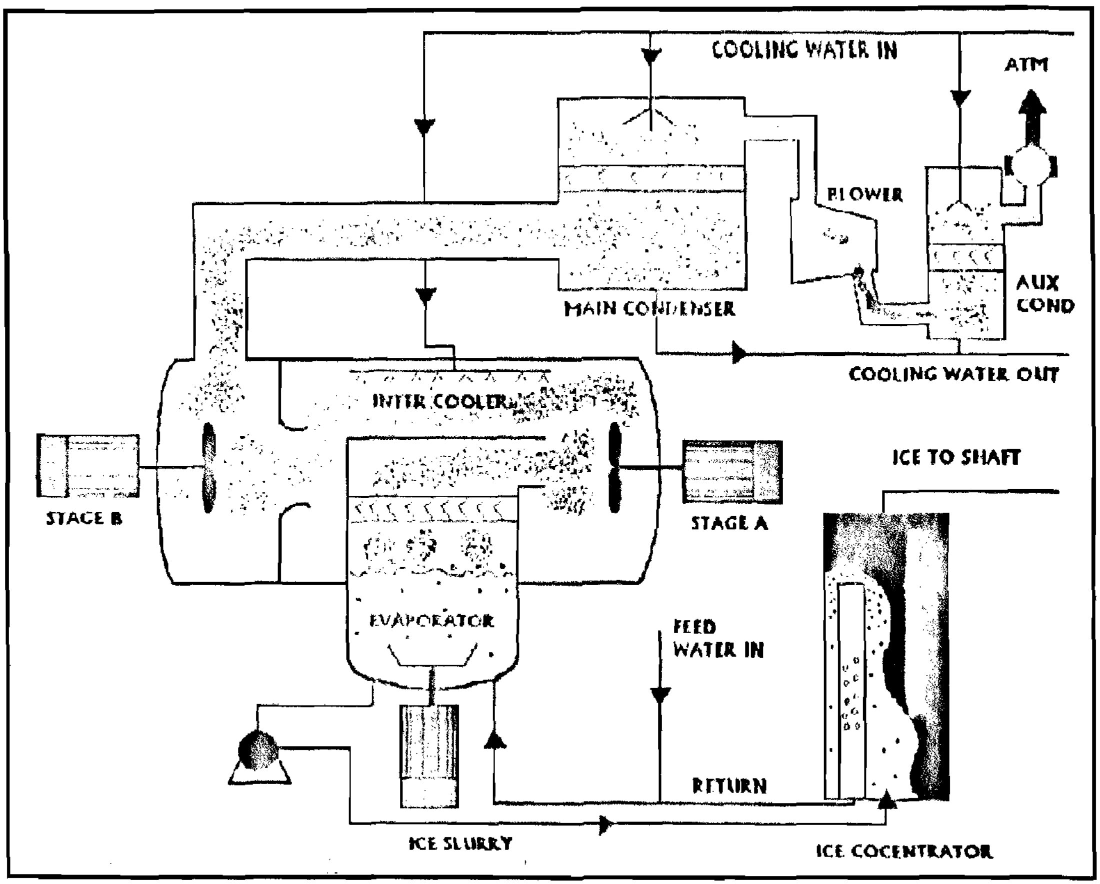

Figure 2.7.Ice Plant process layout (Livingstone, 1999).

Chilled surface water from the fridge plants, at 5°C is pumped into the freezer vessel, which is subjected to vacuum conditions. When water is subjected to a pressure (vacuum) below the triple point conditions, a portion of water will flash-off and evaporate. The latent heat required for this evaporation is extracted from the remaining water mass, which will consequently become partly frozen in the form of ice slurry (Livingstone, 1999).

The ratio of latent heat of evaporation to crystallisation is about 7.5:1, that is for every kilogram of vapour flashed off about 7.5 kilograms of ice crystals is produced. Under controlled conditions, pumpable ice slurry with an ice concentration of between 16 – 20% is formed within the freezer vessel. The ice is kept in dynamic suspension by an agitator, which is constantly renewing the water surface, whilst the minimum salinity in the vessel prevents the ice crystals from coalescing to form large ice chunks in the vessel.

Vapour is sucked from the vacuum chamber at a flow rate of $10m^3/s$ and directed towards the compressors. The diameter of the compressor is 3.1m and the blades are manufactured from carbon fibre. Due to the drive speed on the compressor that is directly coupled to the motor at $3600rmin^{-1}$ the tip speed of the impeller is close to the speed of sound. To prevent any disintegration of the carbon at the tips a titanium liner is used to absorb the high centrifugal forces. The radial carbon compressor is very flexible and allows for any flow irregularities from the drift eliminator. The ice plant uses two 500kW induction motors with a Variable Speed Drive (VSD) to increase the frequency to 60Hz for the drive speed.

The inter-stage cooling is done with the use of 4MW cooling towers that reject heat from compression to the atmosphere. The problem with the ice technology is surging of the compressors. In the original IDE design the effect that global warming might have on the machine was never considered. Currently during summer months the WB temperature is rising to above the 18°C design conditions of the inter-stage cooling, which result in the second stage compressor starting to surge. This limits the suction flow to the first stage compressor and the complete system stops from high temperature in the vacuum chamber. The supply water cannot be frozen due to a loss of the triple point conditions.

To increase the efficiency of the system the vapour that is formed must be condensed to reduce water wastage. Here additional water from the cooling towers is used to lower the temperature and allow for condensation of the vapour. The ice slurry that is produced is pumped from the vacuum chamber using positive displacement A-frame pumps to the ice concentrators. In the ice concentrator there are vertical candles with holes at the top. A 300µm filter is used to separate the water molecules from the ice before being sent to the tube conveyor. Tube conveyors are used in installations where the angle of drive is different to the angle of approach. The conveyor is a three ply belt that allows for bending. The ice is transported to the shaft and simply put down a shoot to the underground ice dams. The advantage of using ice is that solid particles are not subject to the effect of auto compression as is water.

Mponeng has six working ice plants that each produces 80 tons/hour. For the CL project there is a planned expansion to ten plants. Figure 2.8 shows the MK1 ice plant layout and Figure 2.9 shows the tube conveyer system for visualization.

Figure 2.8.MK 1 Ice Plant.

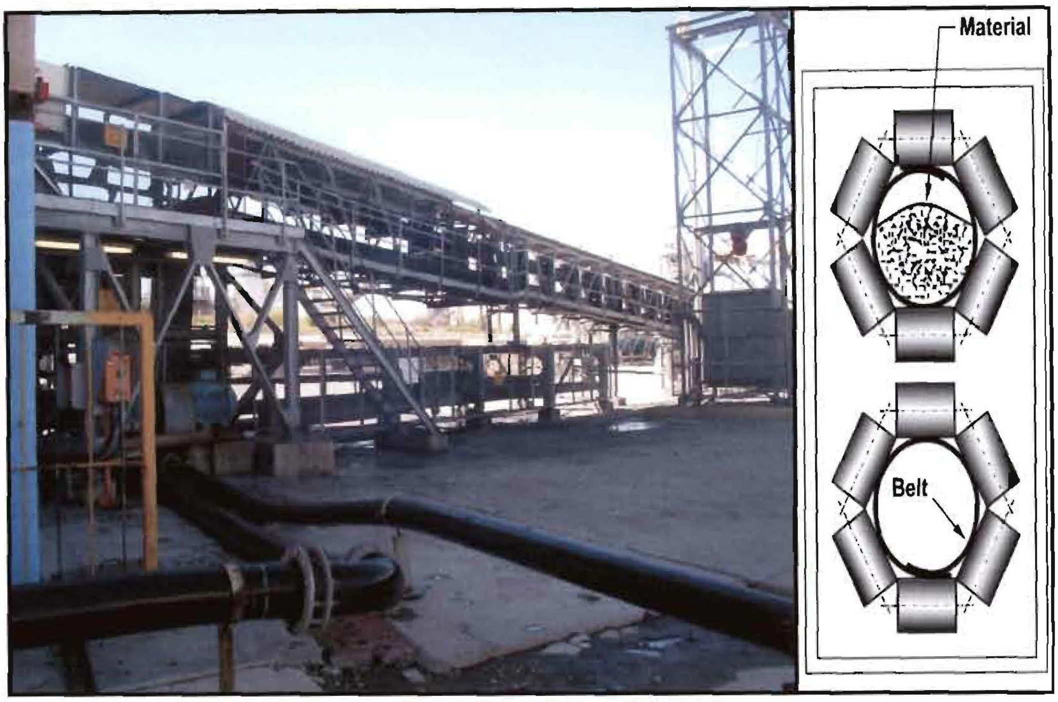

Figure 2.9.Tube Conveyor System.

2.2.5. Mponeng Chilled Refrigeration and Pumping system.

Water is passed from surface down the shaft using 400 NB pipes to the 45 level turbine. The turbine is designed to operate with 500l/s of water and also reduces the pressure of the water. Should the turbine be non operational there are dissipaters on the level to lower the pressure of the water. This process is repeated till water reaches 84L. From here Mponeng have an open water system taking water to the separate levels up to 109L. Between 109 and 110 level there is a dam that feeds the low levels up to 120L. These levels work on a closed loop system with booster pumps on 110L to overcome the friction head of the system. This complete system will now be discussed separately for clarification and design details.

Open Loop System

This water reticulation system is also known as the cascade system and is situated between surface and 109L. A level situated 10900 feet below surface.

Chilled water is supplied from surface down the mine through high pressure pipes (class 100) into different levels. A Pressure Relieve Valve (PRV) station reduces the pressure to a required pressure of 12 bar. The PRVs on the stations range between two and three depending on the amount of reduction in pressure needed. To increase the value of the PRV station (increase the pressure drop) the PRVs are put in series to get a total resistance similar to the calculation in a series electrical circuit with resistance. The pipes in this section are rated up to 16 bar although the working pressure is only 12 bar. The pipes currently used are galvanized steel but Mponeng is currently phasing these out and replacing them with Modified PolyVinyl Chloride (MPVC) pipes. The following table illustrates the advantages of doing this:

Table 2.1: Steel and MPVC comparison.

	Steel	MPVC
Cost	High	Low
Density	7000 kg/m^3	1200 – 2000 kg/m^3
Surface Roughness	0.015 mm	0 mm
Insulation	40 – 50 W/m.K	0.1 – 0.2 W/m.K

Closed Loop System

This is a high pressure system (109L to 120L) and the fundamental concept is shown in Figure 2.10. On 110L ice is introduced from surface into the closed loop chilled water dam with return water from the CWC. The dam is 30m high and allows for a suction pressure of 3 bar on the friction pumps. The pumps run at 18 bar to overcome the friction head of the closed loop system to return the water. Peak operation hours in the day are between 6 am – 10 am when the workers are drilling for the morning shift. During this period about 350kg/s of water is circulated in the closed loop system for cooling and drilling purposes.

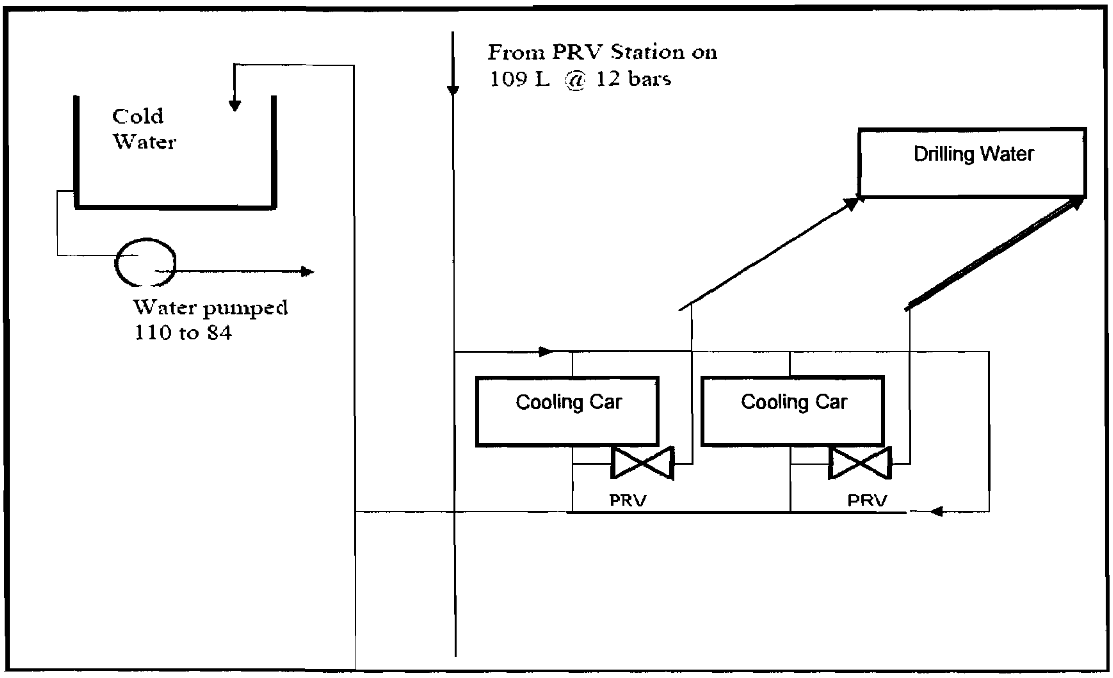

Figure 2.10.Closed loop system layout.

The high pressure water that leaves the cooler goes through a T-junction on the piping system to allow for drilling water to be tapped off and the rest of the water to be returned. The drills use on average about 200kg/hour at a pressure of 9 bar depending on the amount of drilling that takes place.

Mponeng currently uses 64 bar galvanized steel pipes in these sections to prevent pipes bursting under the high pressure. Calculations indicate that the maximum pressure that can be reached in these sections to be at 54 bar and the additional 10 bar is for safety purpose on 120L where the pressure is the highest. By using this design they reduce the pumping cost of water from these sections. The system uses ice technology to cool the water on 109L before it is reticulated to the cooling cars on the separate levels. So to have a complete overview of what is happening on the mine with regards to pumping Figure 2.11 is used.

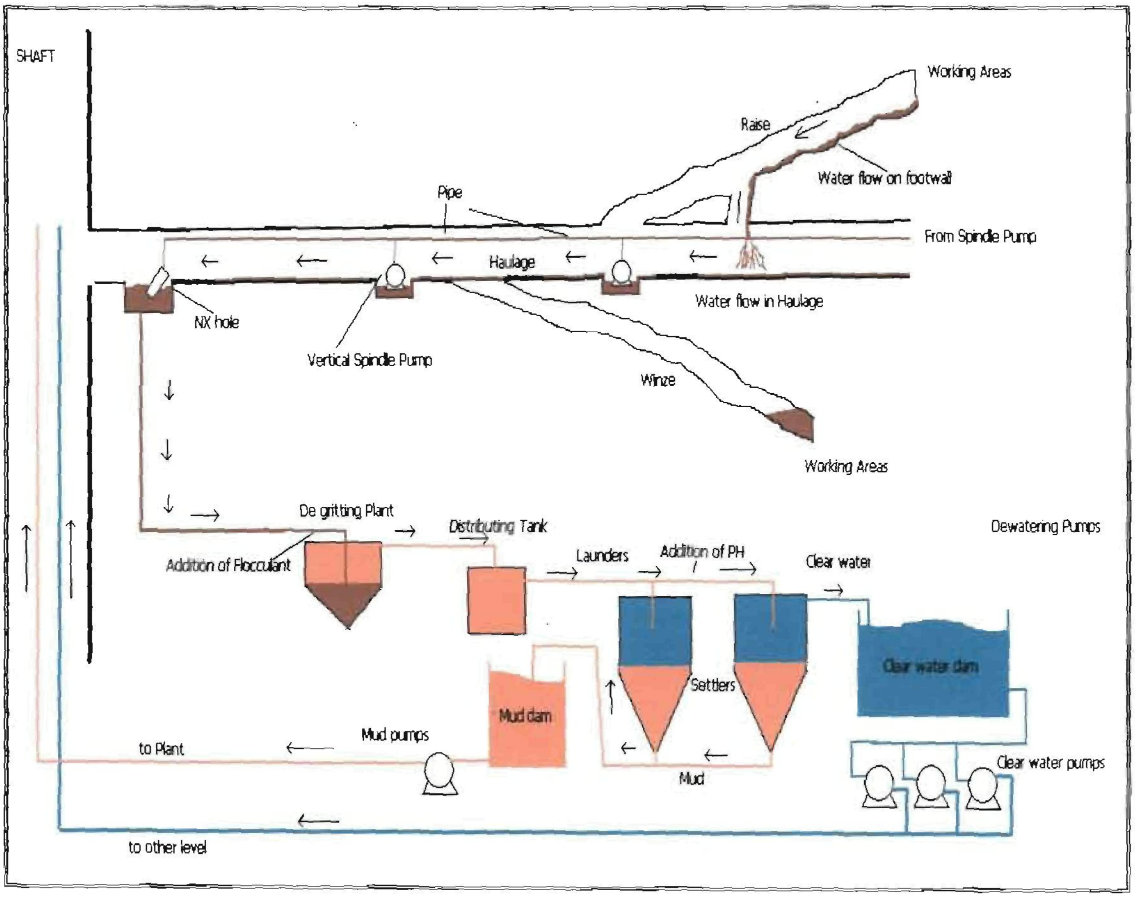

Figure 2.11.Drilling water flow and pumping on the shaft.

Water is supplied to the cooling cars on separate levels and then drained off to be supplied to the raise lines. It is used for drilling and cleaning of the face as well as cooling the surrounding areas. It picks up all the gasses from the explosives becomes acidic, and flows down the ore pass and into the water cubby at the bottom. Vertical spindle pumps are used to pump the water into a 6" column that eventually feeds to the level's annex holes. The water then runs down the annex hole to the pumping level where it first passed through de-gritting machines to remove excess rock from the water. From here it flows through launders where lime is added to raise the PH for the settlers and then to the hot water dams that feed the pumping stations. From the pumping stations the water is pumped back to surface and into the separate water cycles.

2.2.6. Water Cycles

There are two water reticulation systems on the mine, namely; potable water and chilled water. Potable water is supplied by Rand Water Board and used for washing, drinking and make-up to supply the cooling towers. The chilled water system water gets re-circulated daily and the shortfall gets topped up from the nursery dam and all cooling tower bleed offs.

Potable Water

Potable water must conform to the bacteriological standards in the specification and not contain any substance in concentration greater than the maximum allowable limits. The water must be continually monitored and treated to conform to the standards (De Wet, 2008).

Mponeng potable water is used for the following:

- Make-up in the Refrigeration plant condenser cooling towers.
- Make-up in the Ice plant condenser cooling towers.
- Make-up in the Winder cooling towers.
- Make-up in the Compressors cooling towers.
- Drinking and Washing.

Service Water

Hot return water from underground has an average temperature of 27°C and needs to be cooled before it can be reused underground. Pre-cooling towers are used to cool the water before it is pumped to the cold water storage dam (8Ml dam). From here it is pumped through the refrigeration plant where it is chilled down to +/- 3°C and then pumped back to the cold water storage dam. From the cold water storage dam water gets drawn off to three systems – some to the surface bulk air coolers, where it is used to cool the intake air going underground, some to the Ice plants and the rest is used as chilled service water underground.

The water leaving the surface bulk air coolers is returned to the pre-cooling tower sump. The service water is gravity fed to 45L through the energy recovery turbine generating 3.4MW into the chilled water dam. The service water supply line then feeds from 45.5L to 70L, going through an energy recovery turbine generating 2.4MW, and then feeds into a chilled water dam.

From 71L to 84L, again through an energy recovery turbine generating 0.9MW and into the ice dam. The ice from the ice plant is fed to the ice dam on 84L.The ice dam then feeds from 85L to the 84L bulk air coolers as well as supplying all the chilled service water to the Sub Shaft system. The water leaving the bulk air coolers on 84L is pumped to the cold water dam on 84L. From 85L, 12Ml of water at 16°C is pumped to TauTona daily.

To reduce and give a constant pressure at each level, pressure reducing valves (PRVs) are installed to supply the water at a working pressure of 12 to 14 bar. From the PRVs the water is supplied through 350mm pipes to the east/west split. From the split the water is supplied east and west through 250mm pipes and is reduced to 150mm pipes into the crosscuts. From the 150mm pipes the cooling cars are fed, whilst the majority of the water goes with 100mm/150mm pipes into the stopes to a manifold. The manifold supplies water to the rock drills and water-jets.

From the stopes the water runs down to the crosscuts into drains where it is gathered in pumping sumps and then pumped with vertical spindle pumps towards the shaft annex holes through 200mm Unplastisized PolyVinyl

Chloride (UPVC) pipes. Annex holes are pilot-drilled holes, inter-connecting each level to the one below. Through the annex hole system water flows from the highest level to the lowest level, through the screens into the settlers where solids are separated from the water.

The clear water (over-flow) from the settlers goes to the clear water dams and is pumped using multi-stage pumps to designated area. At the hot water dam on 120L, water is pumped from 121L to hot water dam on 109L. At the hot water dam on 109L, water is pumped from 110L to hot water dam on 84L. At the hot water dam on 84L, water is pumped from 85L to hot water dam on 45L. At the hot water dam on 45L, water is pumped from 45L to square reservoir dams on surface.

The chilled service water cycles starts again as the hot return water from the underground workings goes to the square reservoir dams on surface. This cycle is constantly repeated daily resulting in 64 Ml being circulated. Figure 2.12 gives an illustration of the surface water reticulation.

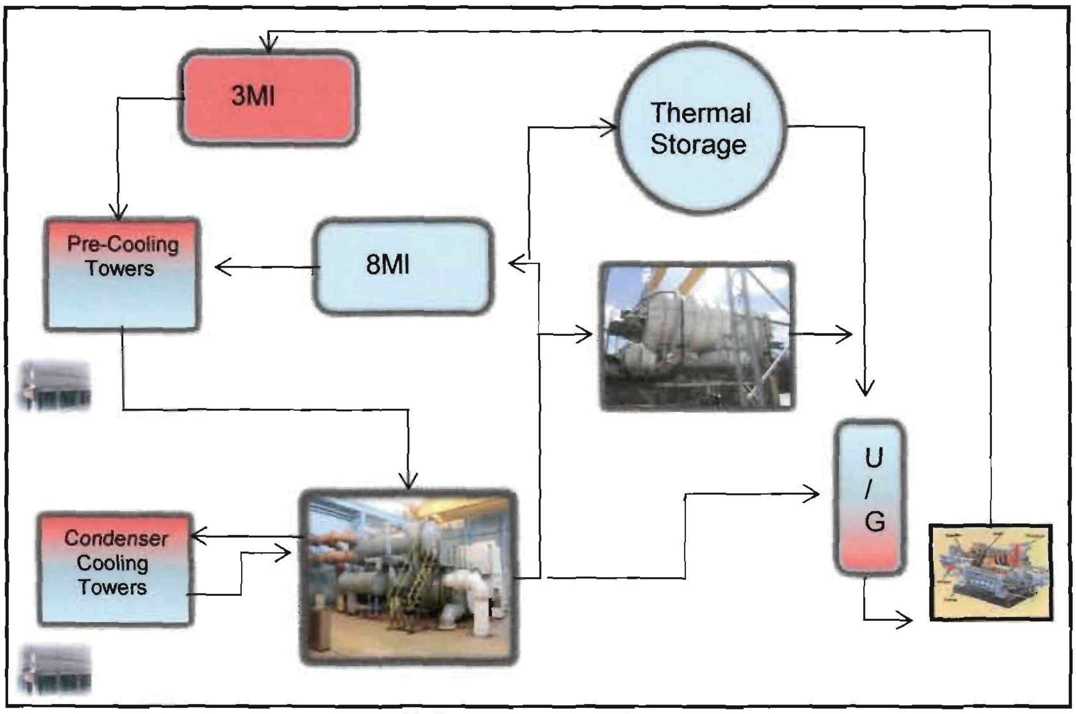

Figure 2.12.Surface water reticulation at Mponeng.

2.2.7. De-gritting

When water enters the pumping station it contains a number of impurities, such as small pieces of gravel, mud acids and more as will be discussed later in this report. The first stage in cleaning the water before it can be pumped is to remove these small pieces of gravel.

The water from the sections enters the de-gritting plant into the top of the tank. The pipe is extended to halfway into the tank. The water discharges into the bottom half of the tank. The water will now flow past the grid. The water and the grit separate. The grit falls into the bottom of the tank and the water fills the tank and overflows into the launders that are around the tank at the top. The grit that accumulates at the bottom of the tank is pumped by means of a B frame pump into hoppers. The ore in the hoppers is discharged into the tips.

A chemical called PH is added to the water in the PH tank. This chemical is added to the water to ensure that the pH level of the water stays between 8.5 and 9. Acids are formed in the water because of the operations in the stope sections. By ensuring that the pH level in the water stays as close as possible to neutral, it will help to prevent the formation of corrosion in the system.

Figure 2.13 shows the de-gritting assembly used at Mponeng and Figure 2.15 illustrates the water pH as it flows through the system.

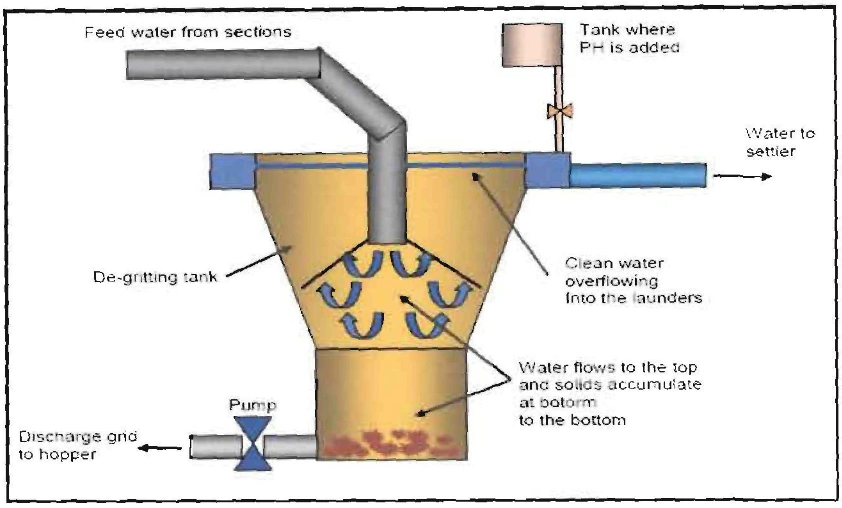

Figure 2.13.De-gritting plant.

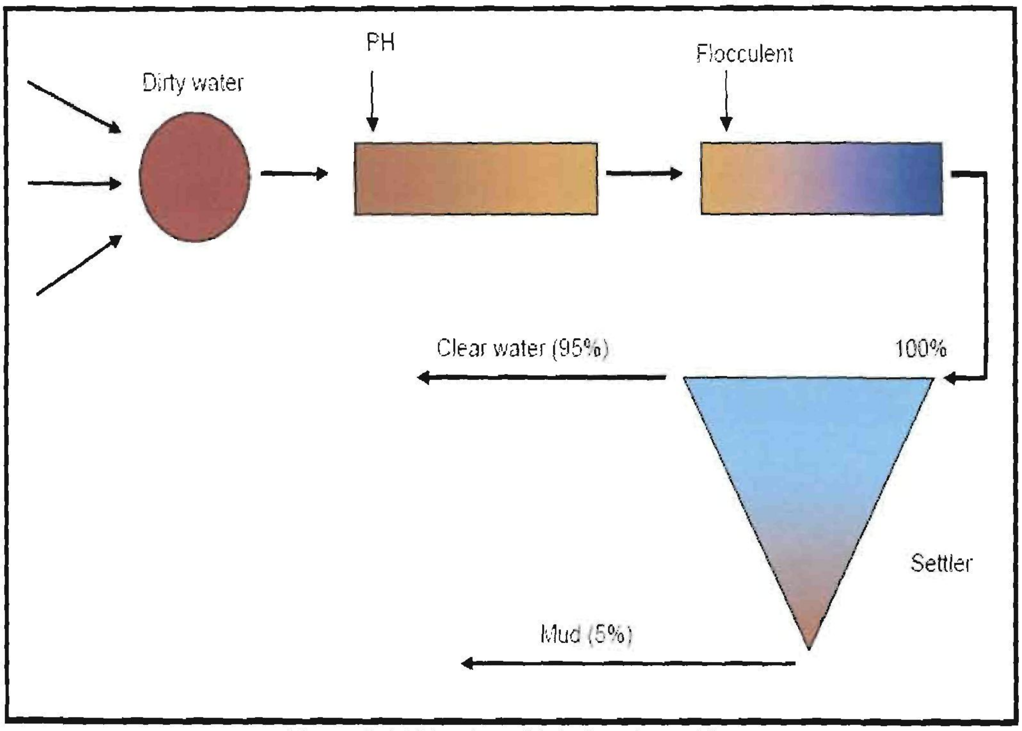

Figure 2.14.Varying pH during the settler process.

2.2.8. Settlers.

Two types of settlers are in common use; relatively shallow settlers with horizontal flow and deep settlers with vertical flow. Three different types of settlers are discussed in this text, namely: horizontal flow settling sump, CSIR design for settling sump and conventional settling sump.

Horizontal Flow Settlers

These operate on the principle that with a sufficiently low and uniform velocity through the sump, the particles will settle, the cross-sectional area and the length being arranged to provide sufficient time for settlement of solids as water passes from the inlet end to the outlet end of the sump.

To obtain undisturbed flow, it is important that the sides are concreted to a smooth finish, since eddy currents will be detrimental to the settling process. The cost of concreting could possibly be compensated for by the increased efficiency of the settler. To obtain the same efficiency if walls were left rough would require a larger excavation.

The settler may be considered in two parts; the upper or water space through which the dirty water flows and the lower part in which the mud collects. It is essential that the settler should have sufficient depth in order that the moving water and the settling mud should not interfere with one another.
The required volume of the settler depends on a number of factors; the dirtiness of the water, the size of the smallest particle desired to settle and the efficiency of flocculation, if employed.

The rate of fall of a particle in a liquid varies as the square of its diameter. Since outgoing water is drawn from the surface it is not necessary for all particles to reach the mud level, provided that the water is clean at outlet for a reasonable depth and the water leaves the settler without turbulence.

At the inlet, water is evenly distributed across the sump by means of a weir and a shallow baffle is placed in front of the weir to prevent surface eddying. A slotted deep baffle to provide vertical distribution of the water is sometimes preferred. At the outlet end lip launders are normally provided.

The method of disposing of mud varies to a marked degree. In some installations, after the inflow is stopped, no decantation is employed and the mud is passed through a strainer to a centrifugal pump and pumped to the surface. The concentration of solids is low for this method. The efficiency of the pump decrease over a period of time due to wear in normal operation, with consequent increased clearances.

Frequently, after the inflow is stopped, clear water is decanted and the mud pumped to the surface by three reciprocating pumps. Sometimes further settlement is carried out in special sumps prior to the mud being hoisted in skips. Some mines use a press. The mud is pumped or gravitated to a close vertical winze in which it settles, clear water being decanted. When a reasonable quantity of mud has accumulated, compressed air is applied. This consolidates the mud and after further decantation of water it is trammed to either the reef or waste box, according to the gold content.

Vertical Flow Settlers

With this type of settler the upward velocity of the water must be lower than the downward velocity of the material to be settled. Without flocculation the settling velocity of a particle of 0.005mm is approximately 0.1m/hour. Thus for reasonable settlement without flocculation the upward velocity would be restricted to about 0.1m/h or 16.7mm/min. This would mean that for every m^2 of cross-sectional area, only $0.1m^3$ or 100ℓ could be treated per hour. To attempt to operate vertical settlers without the use of flocculants would be futile (Pretorius, 2000).

With efficient flocculation upward velocities of the order of 75mm/min and more are possible. It is claimed that the amount of excavation required is only 40% of that for a horizontal flow settler of equal duty. The flocculating reagent should be introduced at a distance from the settler that 30 to 60 seconds is allowed for mixing before entry to the settler. A high degree of turbulence is necessary for satisfactory mixing. If a launder is used instead of a pipe, the installation of baffles to create a zigzag flow is advisable.

When dirty water is pumped, pump parts most prone to wear are the slip rings, together with the mating exterior of the impeller suction eye and of the impeller boss, the balancing disc and seat wearing rings and the metering sleeve between the last impeller and the balancing disc. In order to reduce wear the metering disc has been sprayed in some cases with ceramic material and the balancing disc and seat wearing rings made of abrasion resisting material.

To increase the life of impellers, suction eyes and bosses may be turned down and rings shrunk on. This necessitates the provision of ample metal thickness in order to ensure that the suction eye and boss and the shrink-rings have sufficient strength to resist the load imposed by shrinking. Figure 2.15 illustrates the workings of a vertical flow settler.

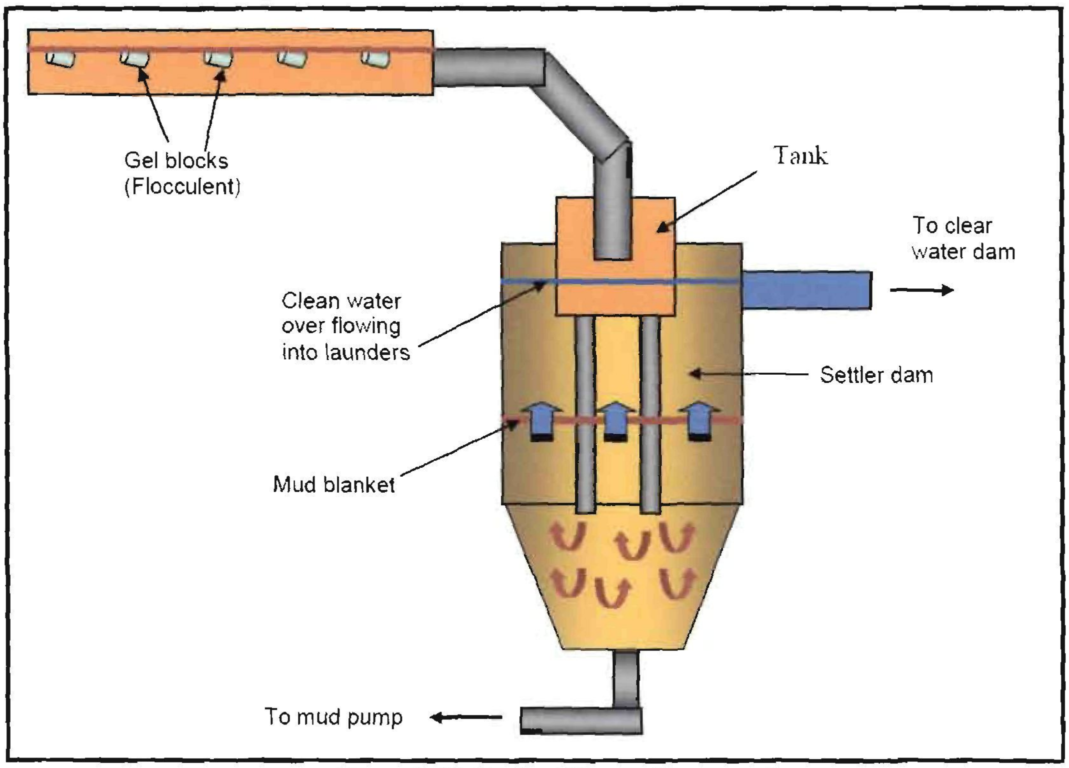

Figure 2.15. Vertical Flow settler operation.

Different types of additives are available in the market. The main function of additives is to increase the adhesion properties of the dust particles, and as a result the density. Gel flocculent is used as an additive added ahead of the settler. Lime (pH powder) is added before adding the flocculent to control the pH level of the water. The gel flocculent is effective at pH levels between 7.5 and 9.5. The quantity of the flocculent added must be controlled to achieve effective and efficient operation of the settler. Samples are taken to measure the SIS (Solids in Suspension) levels which helps in controlling the quantity added to reasonable limits.

Dosages which are too high will drop the floc-blancket and if it falls below the level of the bottom of the skirt, filtering action will be lost with a consequent drop in efficiency. Too low dosages cause the floc-blancket to rise and possibly to overflow, resulting in a considerable increase in turbidity of the overflowing water. An increase in turbidity of the incoming water calls for an increase in dosage and vice versa.

2.3. Conclusion

There are a limited amount of cooling methods to use in the mining environment. The best option comes from the use of hybrid systems (both surface and underground cooling plants) as they have the best efficiency at the lowest cost. There is however different equipment that can be used in the system. It is important to note that the water reticulation system is made up of many components and all must be taken into consideration for design calculations and different scenarios. This chapter provided a broad overview of systems in general and focussed intensively on the Mponeng system. This is done to provide a clear understanding of the components and how changes would affect the system.

3. Carbon Leader Project

In this chapter information regarding the refrigeration requirements for the CL project is presented and discussed with performance results for the CWC and ACU. This chapter will also show component specifications regarding pumping, piping and insulation with the haulage development plans.

3.1. CL Design Specifications

The CL project will involve the sinking of three vertical tertiary shaft systems starting from 116L to 143L shaft bottom. The bank (Upper most loading point of the shaft) for this system will be located on 120L with the one shaft catering for men and material and the second shaft for all service systems. Ventilation will be directed down the Tertiary Ventilation (TV#) downcast shaft. Development is underway on 116L to establish the winding compartments and head gear assembly. The project will enable Mponeng to access both the VCR and CL simultaneously for production. The planned production is 4000 tons/month for VCR and 130000 tons/month for CL.

In the next section the refrigeration and ventilation requirements of the CL project will be discussed. The entire system had to be reassessed with mine personnel to calculate the refrigeration capacity required and determine the ventilation distribution and strategy to be used.

3.1.1. Refrigeration

The current installed refrigeration capacity at Mponeng is 73MW. This comprises of five 11MW refrigeration plants and six 3MW ice plants. The total system capacity was upgraded during 2008 to 83MW by adding three more ice plants to cater for the VCR Below 120L project. The system will be operated with one ice plant on standby to cater for maintenance purposes. There is an expected total heat load addition of 40MW due to production on the CL project. To cater for this Mponeng will increase the number of 3MW ice plants by ten and adding an additional 10MW fridge plant on surface. Figure 3.1 provides the expected refrigeration requirements for the CL project. Reductions in 2017, 2019 and 2020 are due to the overcompensation of the heat load and the planned development for shaft deepening. It must be noted that the VRT on 140L will be 60°C. To overcome this load three Bulk Air Coolers (BAC) will be installed on 120L, 121L and 123L to cool the ventilation air down from 25.4°C to about 21°C (Kruger, 2008). A closed loop water circulation circuit will be incorporated with CWCs situated close to the workings.

Figure 3.2 indicates the positioning of the CWC at the raise line with a cooler cubby for ventilation.

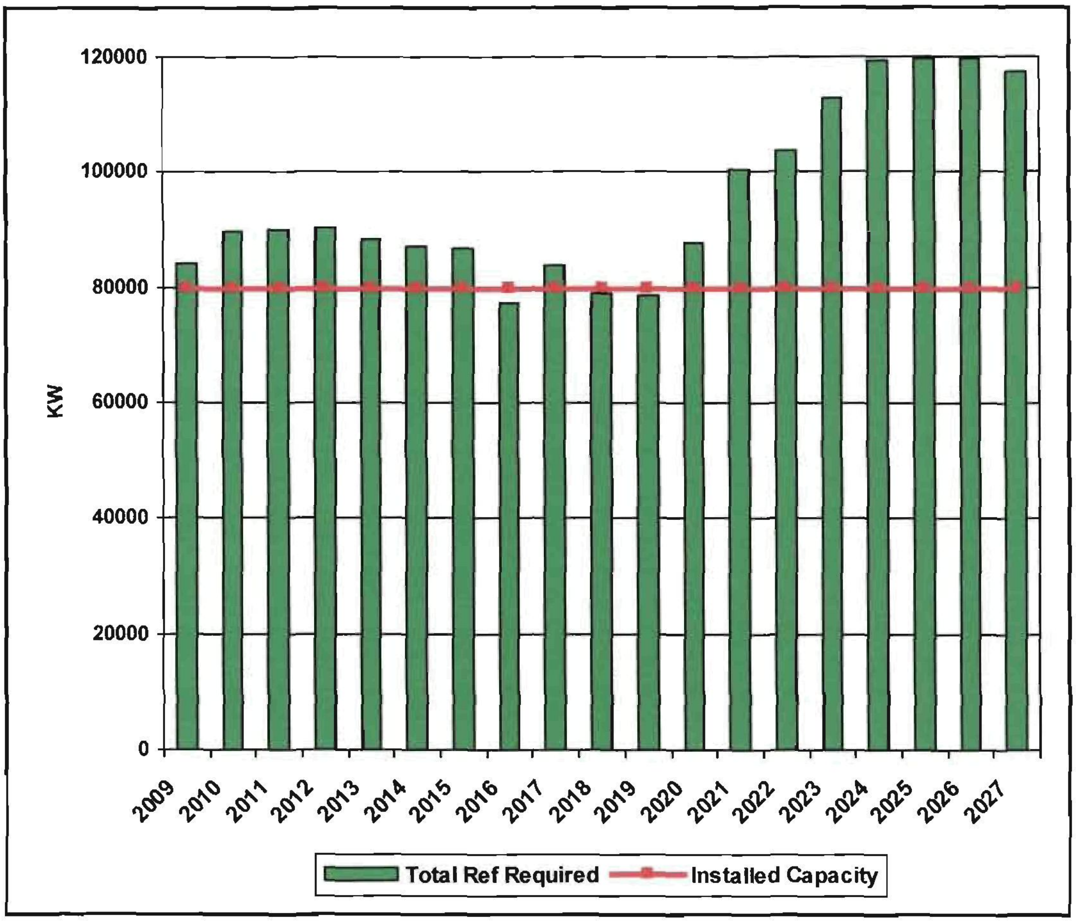

Figure 3.1 Expected thermal load increase due to CL project (Kruger, 2008).

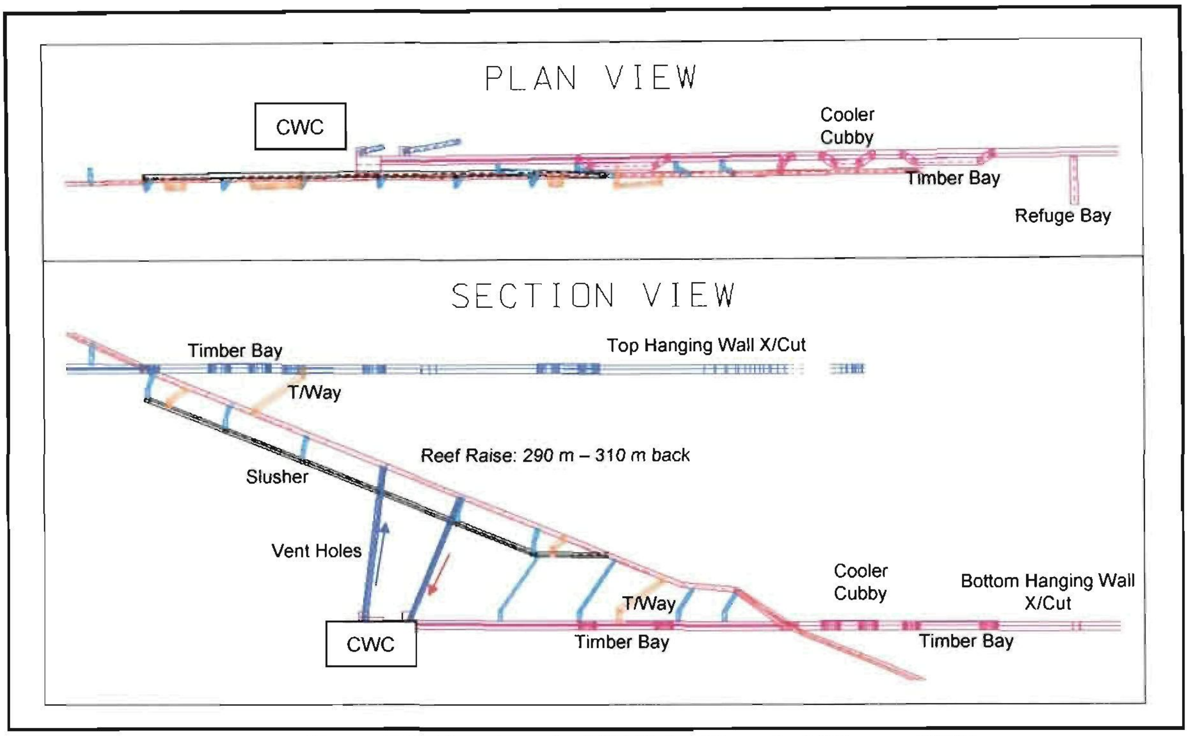

Figure 3.2. View layout of CWC for CL project (Kruger, 2008).

To maintain acceptable environmental conditions on the reef, intake and return ventilation holes with cooler installations on the footwall were allowed for during the mining design. The proposed ice system will use the existing ice columns to 85L and an additional column will be introduced between 85L and 120L. On 120L two ice dams with a combined capacity of 3Ml will be constructed to allow for water flow in the closed loop system.

The boundary conditions used for the refrigeration calculated purposes are as follows:

a) Surface ambient air temperature for refrigeration equipment calculations:
   - Surface bulk air coolers – 18.0/28.0°C.
   - Surface pre-cooling tower – 18.0°C WB
   - Conventional refrigeration plant condenser – 23.0°C WB.
   - Ice plants 1 & 2 condenser – 19.5°C WB.
   - Ice plants 2 & 3condenser – 20.5°C WB.

- Ice plants 3 & 4 condenser – 20.5°C WB.
- Closed circuit chilled water system using cooling coils with service water tapped off the return side used below 109L.
- Open circuit chilled water system used in working areas above 109L - Split water system.
- Average service water flow rate – 2.2 tons/ton.
- Peak service water flow rate – 4.0 tons/ton.

b) Losses:

- Surface chilled water dam loss 0.3°C.
- Chilled water piping from ice dams to workings based on Δt of 2.0°C.
- Dam losses in shaft 1.94°C.
- Pipe insulation and friction in shafts 1.3°C.
- Turbines 1.43°C, based on 80% efficiency.
- Joules Thompson (auto – compression) included.
- Return dams: pump heat included at 1.32°C per 1000m vertical height.
- Ice loss – 75% ice mass fraction on surface – 20% kW losses during transportation underground.

c) Heat removal capacity of service water based on:

- Above 109 Level Δt of 14.0°C.
- Below 109 Level Δt of 8.0°C.

d) Heat removal capacity and flow rates of secondary air coolers:

- Above 109 Level Δt of 12.0°C.
- Below 109 Level Δt of 10.0°C.

This complete system Pipe and Instrumentation Drawing (P&ID) is illustrated in Figure 3.3 for overview purposes.

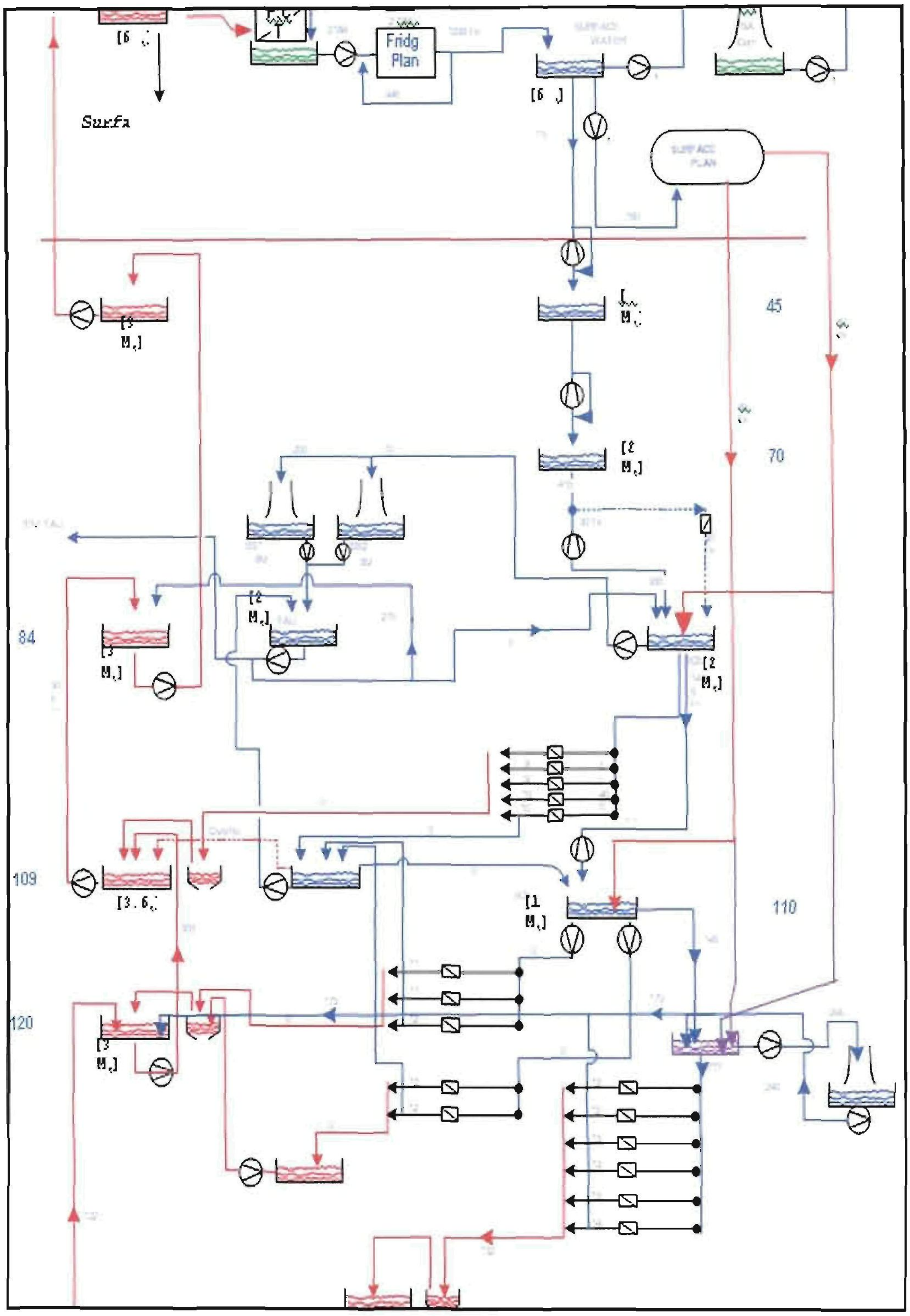

Figure 3.3.Complete refrigeration layout.

3.1.2. Ventilation

The overall air mass flow rate that is available at Mponeng Mine is 1230kg/s. This air mass flow rate is dictated by the up and down cast velocities and the main surface fans that are currently running at maximum capacity. The current air mass flow rate is insufficient to ventilate the planned workings in the VCR area and re-use of air is planned to overcome this constraint. In order to ventilate the CL, a strategy was adopted to make use of the Savuka Mine system to increase the air volume at Mponeng Mine (Refer to ventilation diagram Figure 3.4 and Figure 3.5). Air will be transferred on 81L and on 75L. Booster fans are planned to increase the air mass flow rate by 260 kg/s. A simulation on the VUMA (VUMA, 2008) network (Mponeng SHE Department) was done to determine the effect of increased velocities in the current downcast and up cast compartments below 75L using the Savuka Mine system to increase the overall air volume. The results indicated that the pressure drop will only marginally increase without affecting the performance of the surface fans at Mponeng. Additional VUMA (VUMA, 2008) network simulations will have to be done to determine the exact pressure requirements of the planned booster fans between Mponeng and Savuka Mines. The air mass flow rate can be further increased by utilizing the connection on 120L to TauTona once mining is completed at TauTona. The opportunity exists to increase the air volume by establishing an intake and return airway on 120L between Savuka and Mponeng Mine.

a) Boundary conditions used for the ventilation calculations:
   - Mean face wet-bulb air temperature of 27.5°C.
   - Maximum face wet-bulb air temperature of 27.5 + 2.0 = 29.5°C.
   - Stopes face velocity – above 1m/s.
   - Specific cooling power – 300W/m^2.
   - Horizontal distances of workings from shaft calculated per year.
   - Air utilization in stopes - 80%.

- Increased station air wet-bulb temperature – 4.5°C per 1 000 meters vertical.
- Total mass flow rate – 1 230kg/s.
- Mass flow rate available in workings: 1 230kg/s, minus 10% air leakage, minus 84 kg/s for auxiliary ventilation.
- Heat production based on heat model built by AGA.
- Factor of $0.06m^3/s$ per rated kW diesel equipment at point of operation.

b) Additional heat from human presence and diesel engines:
  - 89 to 109L - 35kW/kT.
  - 109L and below – 42.5kW/kT.

c) Mean rock breaking depth and virgin rock temperature:
  - 109 level VRT: 50.1°C.
  - 120 level VRT: 53.4°C.
  - 126 level VRT: 55.4°C.
  - 137 level VRT: 59.0°C.

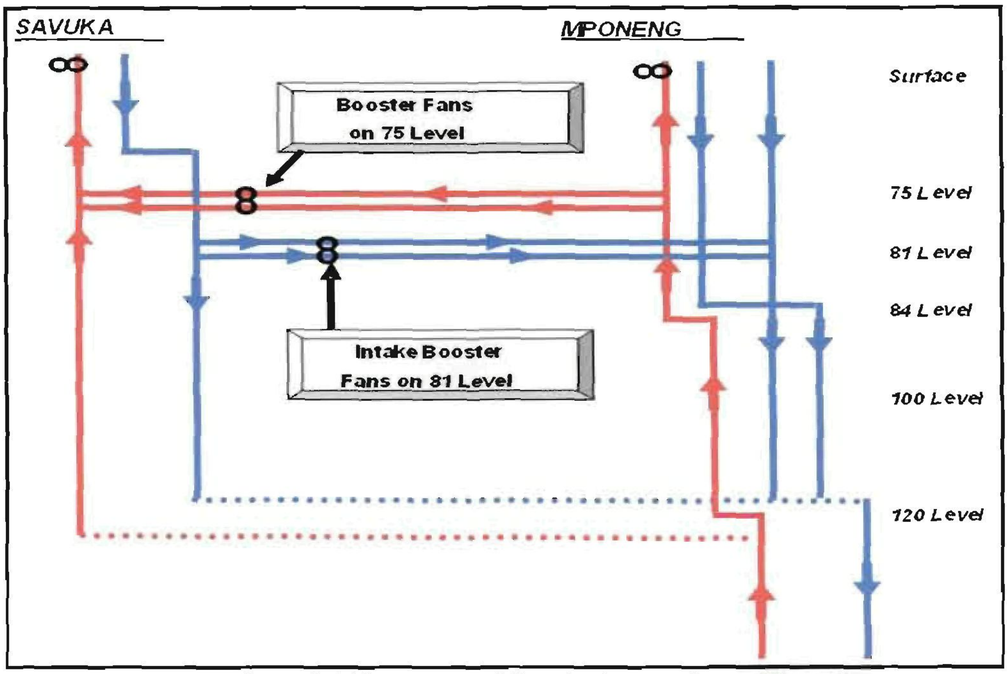

Figure 3.4.Mponeng and Savuka booster fan configuration.

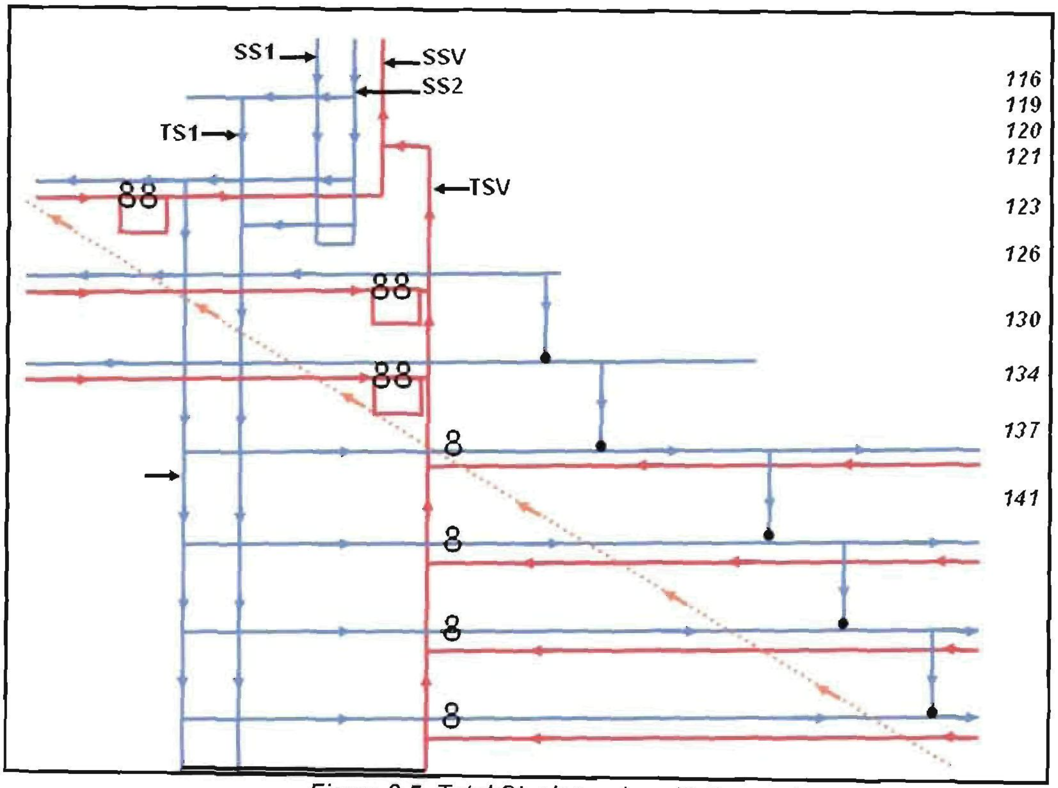

Figure 3.5. Total CL planned ventilation system.

3.2. Chilled Water Cooler

Currently there are two brands of CWCs used by AGA, the Manos 350kW, 500kW and the Viper 500kW cooling car (Appendix A – Cooling coils). These coolers consist of heat exchange coils that are connected to the chilled water column and air flow port. Depending on the size of the cooler a 45kW forced draft fan is connected to the suction side of the cooler to blow $8m^3/s$ of air over the heat transfer surface. The coolers are rated to about 100 bar of pressure and use flow orifices to acquire the water mass it needs. Typically for a 500kW cooler the water mass flow rate must be in the region of 10kg/s at a supply temperature of 10°C.

For project data the Manos CWC was used as the Viper unit only recently got introduced to AGA and no design characteristics were known. Design data is included in Appendix A where all the coolers used on Mponeng since 2002 are listed with their respective efficiencies. These values together with the coil coefficient values of the Manos cooler for variable water mass flow and temperature provides a good performance indication as to what the expected performance of the CWC would be. Figure 3.6 and 3.7 shows the Manos and Viper cars respectively with their design similarities.

Figure 3.6. Manos Engineering CWC.

Figure 3.7. Viper CWC.

The next section verifies the results of the simulation and gives realistic cooling coil efficiencies for production consumption. For the simulation in Chapter 4 assumed efficiencies were based on results from this section and Appendix A. The complete system is simulated and in the economical analysis the coefficients determine the amount of coolers needed. The performance of the Manos CWC is calculated from the following boundary conditions:

Table 3.1: Boundary Conditions for Manos cooler Simulation.

Air inlet Temperature Wet / Dry bulb	30/32°C
Water inlet Temperatures.	10/12.5/15°C
Barometric Pressure	120kPa

A statistical equation that fits a curve through actual values and compares them to calculated values was used in Excel Solver (Appendix B – Excel Curve Fitting). The design duty of the coolers as provided from the manufacturer is determined by the difference in water temperature (ΔT_{water}), the water mass flow rate (Δm_{water}) and the air temperature (ΔT_{air}) at the boundary conditions. The following equation is the fitting value curvature for this process:

$$\begin{aligned}
Q_1 &= a_0 + a_1 M_{air} + a_2 M_{water} + a_3 T_{ai} + a_4 M_{air}^2 + a_5 M_{water}^2 + a_6 T_{ai}^2 + a_7 M_{water} M_{air} + a_8 M_{water} T_{ai} + a_9 M_{air} T_{ai} \\
Q_2 &= a_{10} M_{air}^2 M_{water} + a_{11} M_{water}^2 M_{air} + a_{12} M_{air}^2 T_{ai} + a_{13} T_{ai}^2 M_{water} + a_{14} T_{ai}^2 M_{water} + a_{15} T_{ai}^2 M_{air} + a_{16} T_{ai}^3 \\
Q_3 &= a_{17} M_{air}^3 + a_{18} M_{water}^3 \\
Q_{total} &= Q_1 + Q_2 + Q_3
\end{aligned} \quad 3.1$$

The calculation of the error between the actual curve and the resulting curve is as follows from equation (3.1):

$$Error = \left(Q_{actual}^2 - Q_{input}^2\right) \quad 3.2$$

From here the Solver is used to minimize the error between the curves and so provide the best possible fitting and equation (3) is used to analyze the percentage error of the process.

$$Total_{error} = \sum_{i=1}^{n} error(n) \tag{3.3}$$

The coefficients for values α0 to α18 are:

Table 3.2: Actual Curve Coefficient Values.

Coefficient	350 kW	500 kW
α0	-0.97858	1.451352
α1	42.50682	42.63896
α2	41.03773	41.64724
α3	-20.258	-10.7734
α4	-1.9773	-2.09379
α5	-2.54187	-3.07965
α6	2.367589	1.446519
α7	2.633166	3.49714
α8	-1.56927	-1.55563
α9	-1.78369	-1.87586
α10	-0.01359	-0.01721
α11	-0.05209	-0.0774
α12	0.036496	0.040933
α13	0.043115	0.053315
α14	-0.00357	-0.01018
α15	0.000117	-0.00384
α16	-0.06336	-0.03611
α17	0.029032	0.028792
α18	0.050944	0.072777

From the fault analysis of the coefficients the average sum of the error is:

Table 3.3: Average and Sum Error Values.

	350 kW	500 kW
Average Error	1.82 %	0.16 %
Sum Error	40 %	4.4719 %

$$Error = \left(\frac{Q_{actual}}{Q_{total}} \right) * 100 \tag{3.4}$$

$$Average\ Error = \left(\frac{\sum error}{\eta} \right) \tag{3.5}$$

$$Sum\ Error = \sum Average\ Error \tag{3.6}$$

The total sum of the error made on the 500kW Manos is 4.4710% and considering the underground environment, that is an acceptable margin for the amount of variables that contribute to the cooling effect. Most of the boundary conditions are estimated from the expected VRT and as more experimental data is gathered during the deepening process the values will be updated.

3.3. Air Cooling Unit

There is currently no 300kW ACU unit in operation. The discussions in this section will focus on the proposed unit (Rousseau and van Eldik, 2008) that

M-tech Industrial is busy developing. The main attributes of the unit's design are that it would have a rated water pressure of 200 bar for the closed loop pressure. For cooling, the design is to provide 300kW capacity at 3.6kg/s condenser water mass flow rate if the water supply temperature is 15°C. The calculations showed that for a nominal cooling capacity of 300kW the expected evaporation temperature will be in the region of 12°C and the condensing temperature about 50°C. The COP of the unit is in the region of 4. The preliminary layout of the components in the unit is similar to the 100kW unit used at TauTona and would fit inside the Mponeng cage. Figure 3.8 shows the 100kW unit that is used at TauTona and Table 3.4 provides expected technical calculations on the 300kW unit.

Figure 3.8. 10 kW ACU Unit (Rousseau and van Eldik, 2008).

The principle operation of the ACU is similar in design to a refrigeration plant. It has the same four main components with the difference that the ACU has a higher condensing temperature to minimize the amount of water required. The evaporator is made up of an air-to-refrigerant finned tube heat exchanger and the condenser of a tube-in-tube heat exchanger. Figure 3.9 shows how heat is absorbed in the evaporator coil and then pumped to the condenser via the compressor. The high state of energy allows heat to flow from the refrigerant to the water according to the first law of thermodynamics.

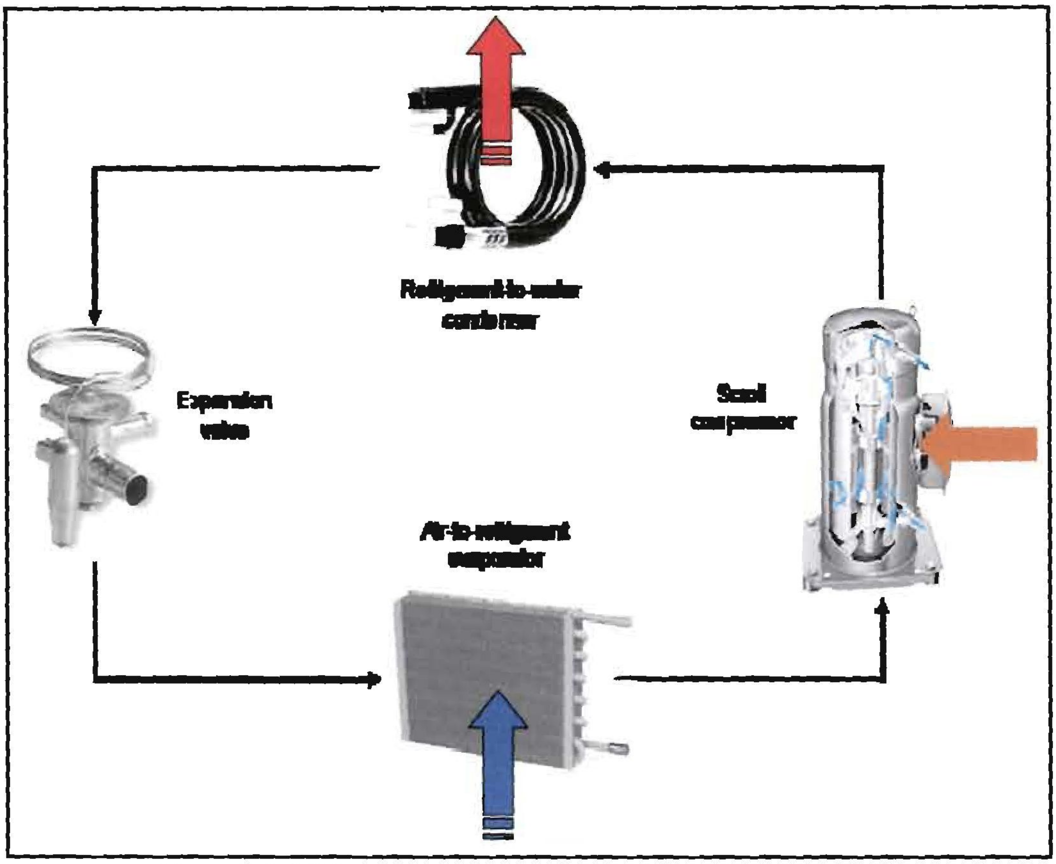

Figure 3.9. ACU component layout and heat flow (Van Eldik, 2007).

The main advantage of the ACU over the CWC is its ability to use warmer incoming water to disperse the heat in the condenser. The higher outlet water temperature, in the region of 40°C to 45°C, results in the effective use of the surface cooling towers. This is considered as free cooling in the mining environment as there is a limited amount of energy input to the induced draft fans. Figure 3.10 shows the typical conditions for CWCs in an open loop system. Due to a typical water temperature rise of 8°C through the CWC the amount of water pumped to surface is much more than for the same scenario with ACUs shown in Figure 3.11.

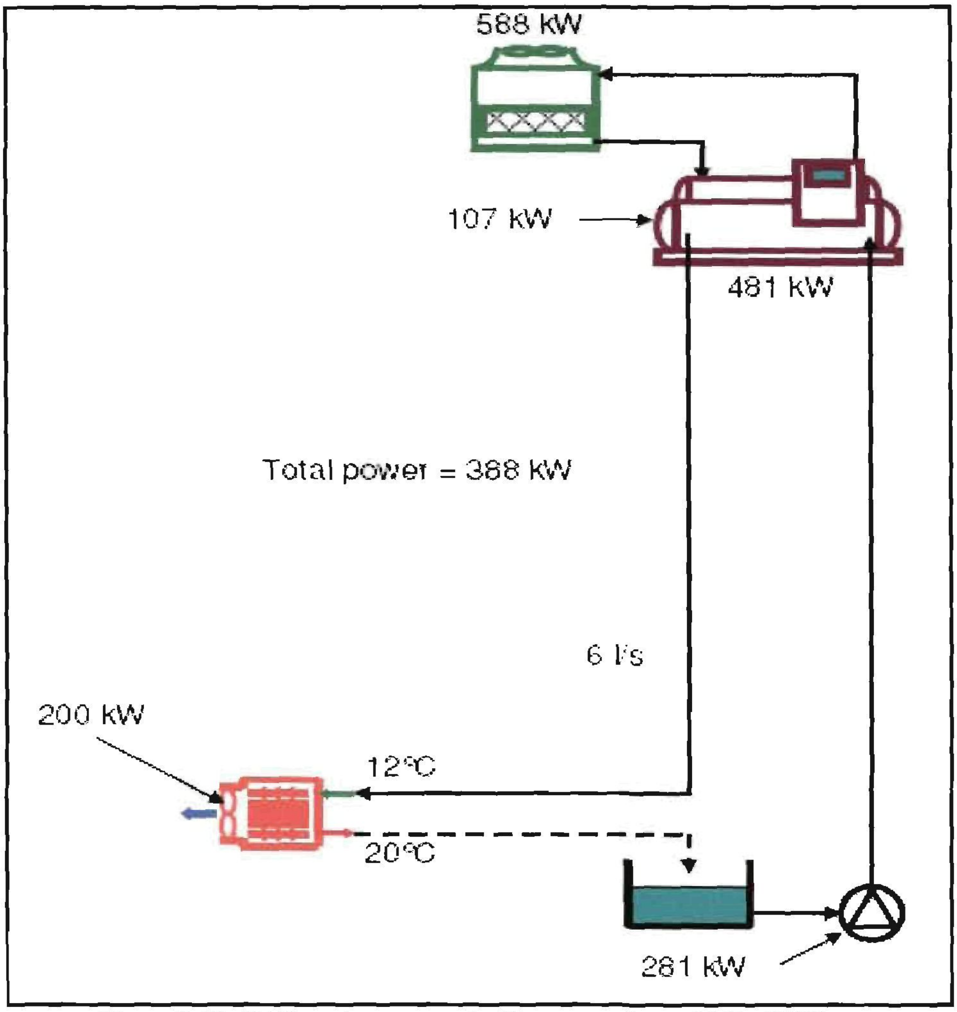

Figure 3.10. CWC system scenario (Rousseau & van Eldik, 2008).

In this scenario water is produced by the fridge plant at 8°C and if we include the Joule Thompson (auto – compression) effect the approach water temperature to the CWC is 12°C. To produce 200kW of cooling the water mass flow rate needed is 6kg/s. Pumping the water 3000m to surface, 281kW of work is needed at a pump efficiency of 70%. So the surface refrigeration plant has to extract 481kW of energy from the system. If the COP of the surface plant is approximately 4 that means the compressor work needed is 107kW. The total power used by the system is equal to the compressor work and the pumping power which is 388kW.

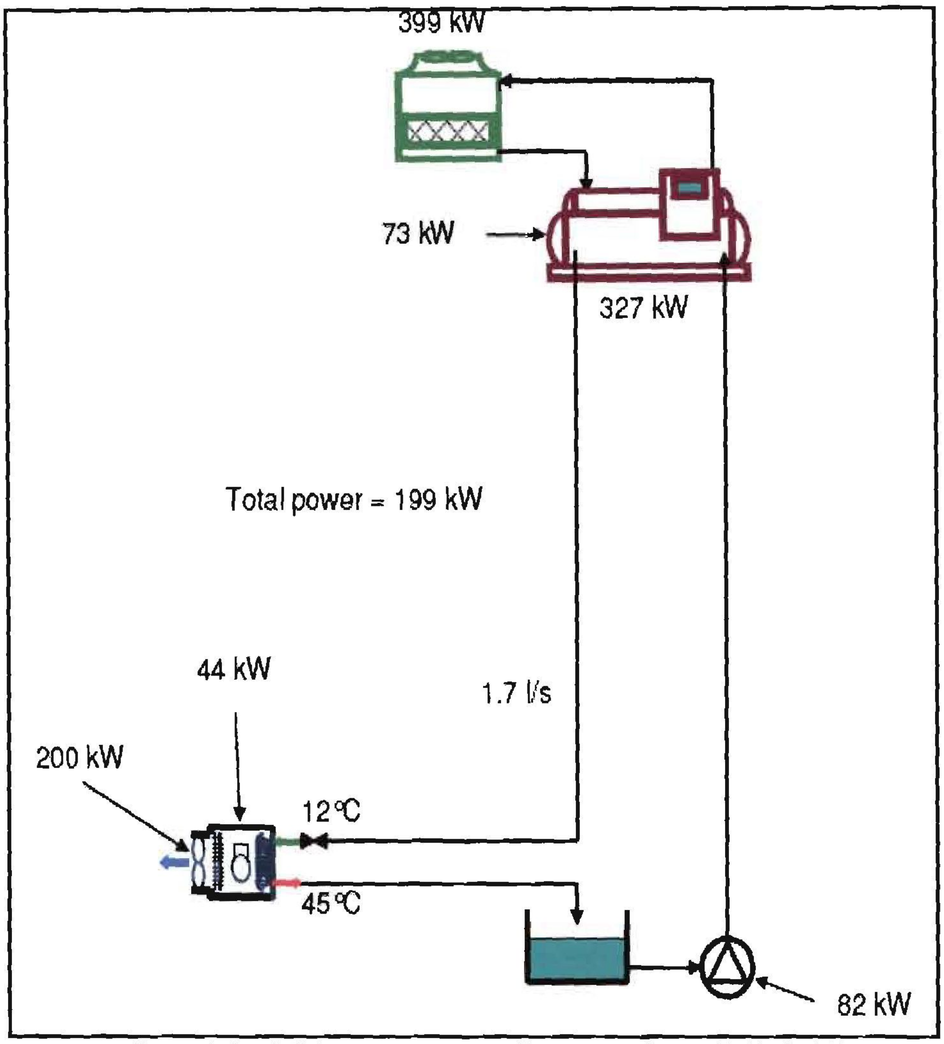

Figure 3.11. ACU system scenario (Rousseau & van Eldik, 2008).

For this scenario shown in Figure 3.11 water is again sent to the condensing circuit of the ACU at 12°C approach temperature. To produce 200kW of cooling the ACU needs 44kW of compressor work at a water mass flow rate of 1.7 kg/s. The pumping power required to pump the water 3000m to surface is 82kW at a pumping efficiency of 70%. The surface plant has to extract all this energy from the water so 327kW is needed on the evaporation coil. If the plant has a COP of approximately 4 the compressor work needed for this is 73kW. If calculated the total work for the system adds up to 199kW, which is about 100kW less than the CWC scenario. This supplements the development of the ACU for open loop systems. It is important to note that the calculations are for open loop systems without energy recovering turbines that use the head pressure and flow of the system to recover energy.

Table 3.4: 300 kW Air Cooling Unit design conditions.

Evaporator		
	Cooling Capacity:	*300 kW @ 12.5°C E°C Evap. and 50°C Cond.*
	COP:	*± 4.*
	Fins:	*AL with epoxy coating, 6 fins/inch.*
Compressor		
	Semi – Hermetic Screw:	*± 75 kW Input power.*
Condenser		
	Water Temp Out:	*40°C.*
	Water Mass Flow:	*6.0 kg/s @ 25°C inlet.*
		3.6 kg/s @ 15°C inlet.
Electrical		
	Supply:	*525V*
	Control:	*110V*

3.4. Pumping, Piping and Insulation.

The CL project design is such that theoretically within the closed loop system the water that is put down the U-tube will return to the same level if there is no friction. The problem is that there are components in the system with restrictions like valves, pipes, bends and orifices. To surpass this problem friction pumps need be installed that have a delivery pressure that equals the system pressure at its Best Efficiency Point (BEP). This will allow for running conditions with high efficiency. Currently Mponeng uses the Sulzer pump (HPH 33 – 17.5 3 Stage) that allows for 15 bar delivery pressure at 160kg/s. Figure 3.12 shows the pumping curve with the BEP.

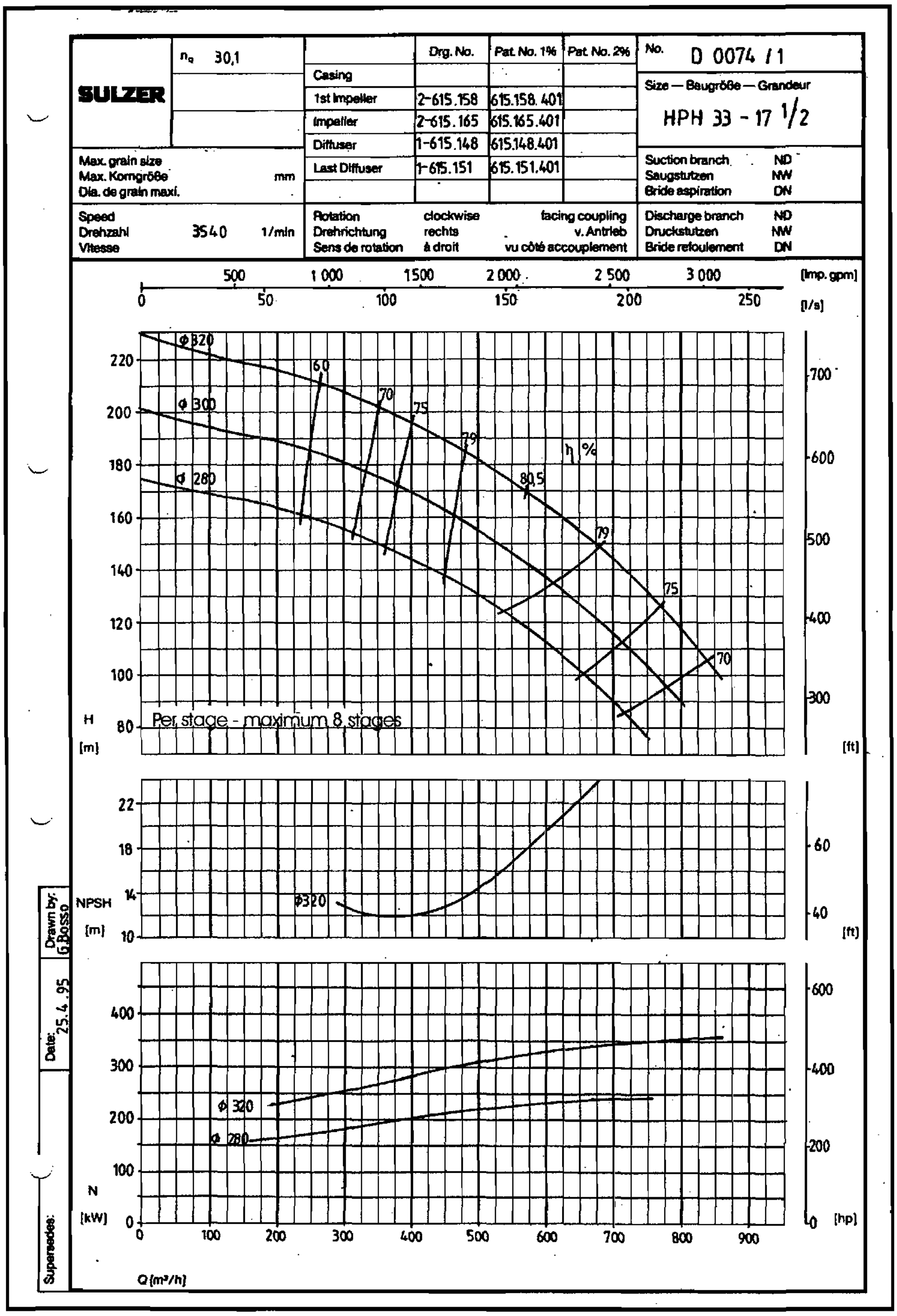

Figure 3.12. Sulzer HPH (33 – 17.5 3 stage) Pumping Curve.

A wide variety of chilled water pipes are used on the mine. These pipes are able to withstand operation pressures of up to 64 bar with a safety margin of 10 bar in the closed loop system. On the open loop 25 bar and 40 bar pipes make up most of the infrastructure. The harsh underground environment combined with high haulage temperatures affect the heat transfer from the pipe to surrounding atmosphere.

At Mponeng chilled water pipes have an inside wall that is made of YSKOR steel (SAB 719 gr.B) (Van der Westhuizen, 2000). The ability for high heat flow resistance to the surroundings is thanks to Phenolix Foam (Robbins, 2007). The foam wraps around the steel pipe covering the outside area and flange fittings. The thickness of the layer is about 25mm and has a heat transfer coefficient of 0.037W/m°C. The foam is protected with a thin sleeve that is made of galvanised steel (Z275) with a thickness of 6 mm. These pipes are called the 4000/3 chilled water pipe and cost ±R6000.00 per/meter. Table 3.5 provides information regarding the wall thicknesses of the pipes mentioned at variable diameters.

Table 3.5: Chilled water piping wall thickness.

Pipe Diameter (mm)	25 bar wall thickness (mm)	40 bar wall thickness (mm)	64 bar wall thickness (mm)
100	6	6	6
150	7.1	7.1	7.1
200	6	6	10
250	6	8	10
300	6	8	12

For the heat transfer calculations the total resistance of the pipe is important to determine the losses. Figure 3.13 provides a section view of the pipe and how the three layers contribute to the overall resistance is found in equation (3.7).

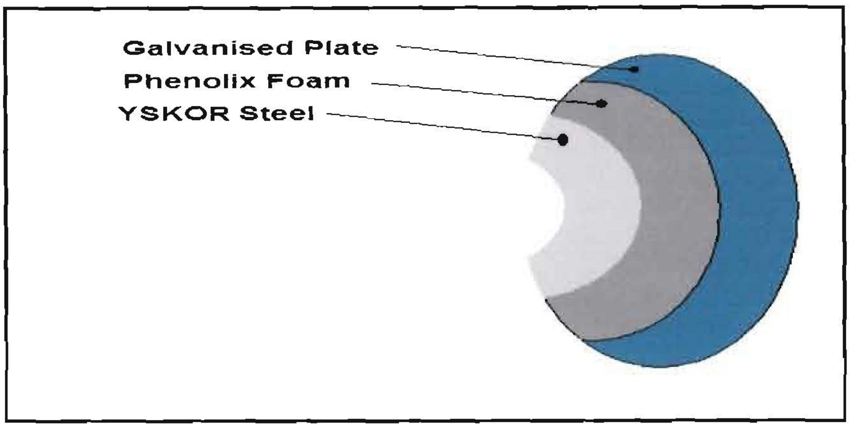

Figure 3.13. Section View of chilled water pipes.

The value of UA (Heat transfer area and resistance) is determined as a function of all the surfaces by equation (3.7).

$$\frac{1}{UA}=\frac{1}{h_{water}A_{water}}+\frac{\ln(\frac{r_2}{r_1})}{2\pi K_1 L}+\frac{\ln(\frac{r_3}{r_2})}{2\pi K_2 L}+\frac{\ln(\frac{r_4}{r_3})}{2\pi K_3 L}+\frac{1}{h_{air}A_{air}} \tag{3.7}$$

Table 3.6: Variable data for equation 3.7.

h_{water}	Heat transfer coefficient of water. (W/m^2°C)
A_{water}	Surface area of water. (m^2)
r_1	Inside radius of Steel.(m)
r_2	Inside radius of Phenolix Foam. (m)
r_3	Inside radius of Galvanised Steel. (m)
r_4	Outside radius of Galvanised Steel. (m)
K_1	Heat transfer coefficient of Steel. (W/m^2°C)
K_2	Heat transfer coefficient of Phenolix Foam. (W/m^2°C)
K_3	Heat transfer coefficient of Galvanised Steel. (W/m^2°C)

h_{air}	Heat transfer coefficient of air. ($W/m^2{}^\circ C$)
A_{air}	Surface area of air. (m^2)

This then concludes all the technical data for the simulation of the CL project. Most of the values used in this section are bound to change as the simulation provides information on the pressure ratings on the levels and the expected water temperatures.

The next chapter focuses on the actual simulation of the CL project and the different scenarios that were investigated. It will provide the platform for discussion under the economical analysis.

4. Simulation

The chapter focuses on the simulation of different scenarios that were evaluated for the CL project. The proposed systems were firstly created in Flownex (Flownex, 2008) to confirm expected flow rates with mining personnel after modifications were made as required. From the design of the CL as discussed in Chapter 3, there is no final heat load that could be used as the values of VRT were only estimated. For this reason the difference in refrigeration installation between 96MW and 120MW will be used as the assumed increase in heat load for the simulation.

4.1. Simulation Design

The basic pipe network layout for the CL is currently unknown and only flow diagrams based on the VCR Below 120L project exists. AGA Pipe Network Design Engineers confirmed that the VCR flow diagram is adequate for supply and return pipe modelling and all associated sizing. The first model in scenario 1 then uses the VCR pipe layout for the simulation of the expected flow and pumping load. This also confirmed the assumption of the refrigeration requirements on the CL project equalling the surface installation capacity increase of 24MW. Supply piping on 120L and all supply and return piping don't have any insulation as is standard within AGA. There are four Sulzer pumps installed on 120L for the booster configuration with two running and two on standby. The estimated actual level temperatures were gathered from VUMA (VUMA, 2008) simulations for the calculation of the convection heat transfer between the air and chilled water. Figure 4.1 provides an illustration of one working level of the layout used in Flownex with the appropriate pipe sizes, reservoir, pump and insulation provided in Table 4.1.

A brief description of the process is that hot return water is mixed at 1 with ice to provide an outlet temperature of 8.5°C. The water is then put down the shaft to 123L. Here it is put through the CWC and returned to 1 whilst heat is transferred from the surroundings to the water.

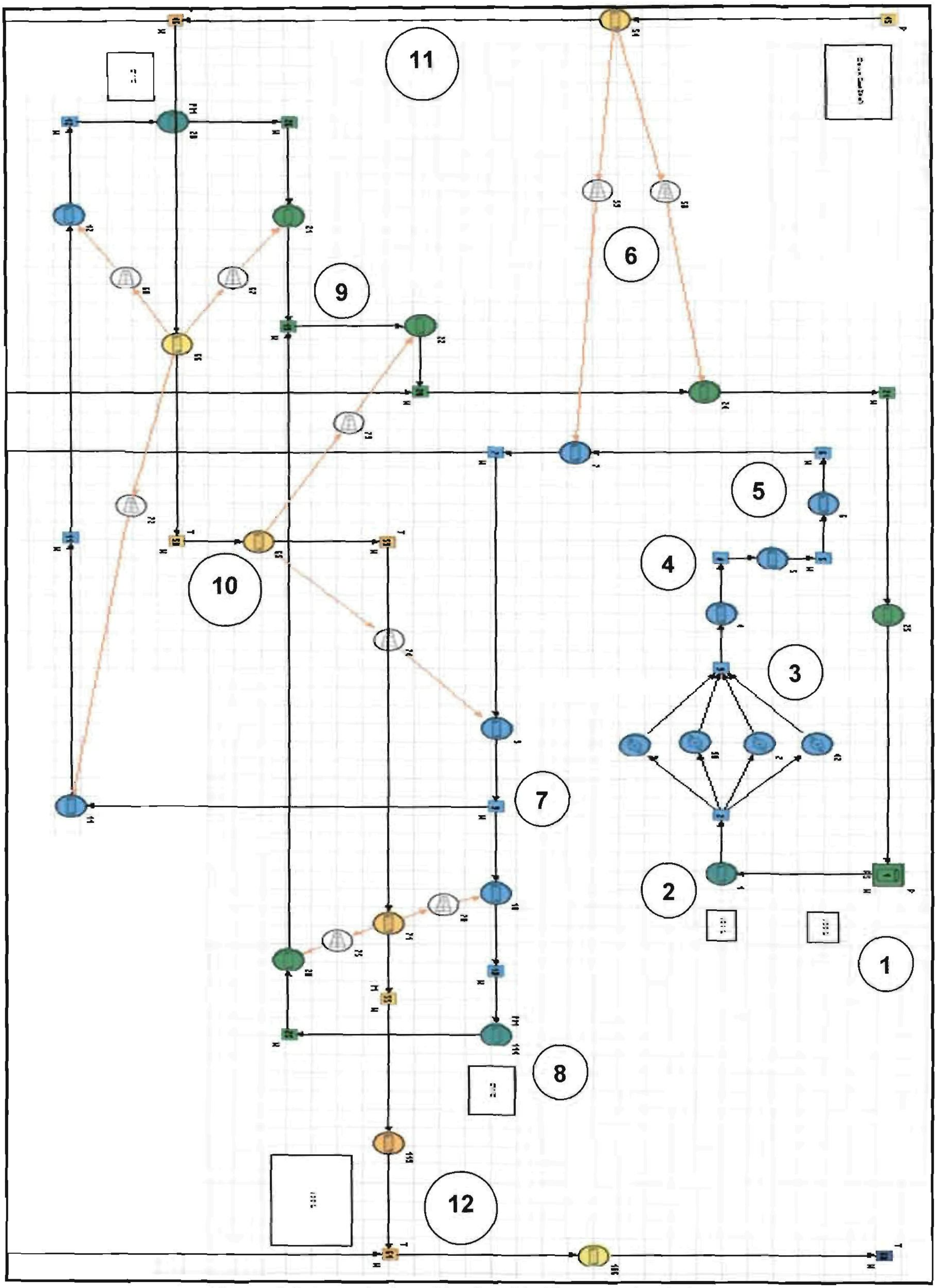

Figure 4.1. Layout of working level in Flownex simulation.

Table 4.1: Component classification in Flownex.

Component	Classification
1	3 Ml Reservoir located between 120L and 121L. Also known as the chilled water dam, ice from surface is mixed with the return water from the closed loop to provide cold water back into the system. It is important to keep the outlet temperature at ± 9°C.
2	Feed pipe that supplies the booster pumps. This is the biggest pipe in the network with a 600 NB. It would generally also be known as the feed manifold pipe.
3	The four planned booster pumps for CL reticulation. The operating philosophy will be two pumps running and the other two on standby for maintenance purposes.
4	Supply piping after the pumps. The pipes are still located on 121L and have no insulation.
5	The configuration of the excavation calls for pipes to return to 120L where the bank for the conveyances of the CL would be situated. This is the point of entry for the pipes into the lower working levels. An isolation valve is also situated here.
6	The feed pipes will be located in the downcast ventilation shaft or TV#. Here there is heat transfer from the hot air to the cold water as it flows down the system. For each section of piping heat transfer is calculated along with the effect of auto compression to provide the inlet water temperatures to a level.
7	This is the East West breakaway on 123L. 2700m of piping is used to obtain the furthest position of CWC operation.
8	The chilled water cooler in the system. The temperature and pressure of the water are calculated as it reaches the CWC. The CWC is simulated as a pipe with a 3MW heat load. From this the outlet water temperature is determined. This is based on the Mponeng model of three active raise lines in operation and 1MW of cooling on each of the raises.
9	This is the point of return for the water in the closed loop system. This point is next to the East - West breakaway as

	discussed in 7. The water will travel back to the shaft from this point to return to the ice dam.
10	The heat transfer that happens between the hot air in the haulage and the chilled water is calculated. The pipes have cladding in this section and the thermal resistance thereof was build into the Flownex simulation.
11	This is the downcast air for ventilation of the workings. The shaft is 9m in diameter and will cater for all the services piping like chilled water, compressed air, backfill and potable water.
12	The return air from the workings that is drawn out to surface. For the CL this is known as the TV shaft.

This provides an overall picture of how the water and air in the CL are envisaged during production. The model runs on a 1:1 ratio between water and production tonnages in scenario 1. This serves as a base model with which to compare the other scenarios.

The validation of this model was very important to justify the capital expenditure for the CL project and the associated production values. During the design phase Mponeng SHE personnel were consulted to verify the flow of air to and from the working places. As mentioned in chapter 3 haulage velocities must be in the region of 3m/s and temperature must not exceed 32°C (WB). The cooling in the system is based on a heat load of 24MW, which means with four working levels it amounts to 6MW per level. Sequential grid (Method of having a long face split into smaller faces) is the current mining method at Mponeng and will be used for the CL production. Taking the current production on the closed loop levels there will be three raise lines working on the East and West breakaway. With the estimated VRT of 70°C, 1MW of cooling is needed per raise line with an air flow rate of $8m^3/s$.

Flownex determines the water mass flow rate to each CWC considering the water inlet temperature and a specified outlet temperature. The water flow rate then determines the amount of ice needed for a dam outlet water temperature of 8.5°C. The system has a built-in function for pumps and fans and by inserting the pipe diameters and surface roughness along with the pump curves it calculates the pressure delivered and return pressure of the system. The design of the VCR below 120L and CL project is similar to that of the current closed loop system. This facilitated in the design of the simulation to verify system pressures and pressure losses. For the CWC system simulation the pressure delivered by the pumps in Flownex and the actual values on Mponeng differ by 1 bar and given the size of the installation it is acceptable.

4.2. Simulation Scenarios

Five different scenarios were analyzed and simulated in Flownex. The idea is to determine for each of them the amount of water that circulates in the system, the return water temperature and calculate the amount of ice needed to cool the system. This would then provide the values for calculation of the total power consumed by the system. Knowing that a certain amount of cooling is needed the number of CWCs are calculated using their capacities and efficiencies. For the ACU the water is used as a heat sink and the total number of units is calculated from the COP and rated compressor size. This leads us to the following scenarios:

- Scenario 1 – Simulation of the CWC in a closed loop network.
- Scenario 2 – Simulation of the ACU in a closed loop network.
- Scenario 3 – Simulation of the CWC along with an ACU in the closed loop network.
- Scenario 4 – Simulation of an ACU at a development end.
- Scenario 5 – Simulation of the ACU between the settler and hot water dam.

This chapter only focuses on the technical aspects and results with Chapter 5 focussing on the economical implications of the different systems. The haulage dry bulb (DB) temperature is on average 42.5°C for the simulation as provided by the VUMA (VUMA, 2008) simulation of the CL project (Kruger, 2008).

4.2.1. Simulation of the CWC in a closed loop network

The closed loop as explained in Chapter 2 with its design parameters was used to set up the model for the CWC simulation. Figure 4.2 provides the layout of the system and the values for water mass flow and temperatures as determined in Flownex. Please note that there are four working levels each with 6MW of cooling resulting in the 24MW of cooling needed.

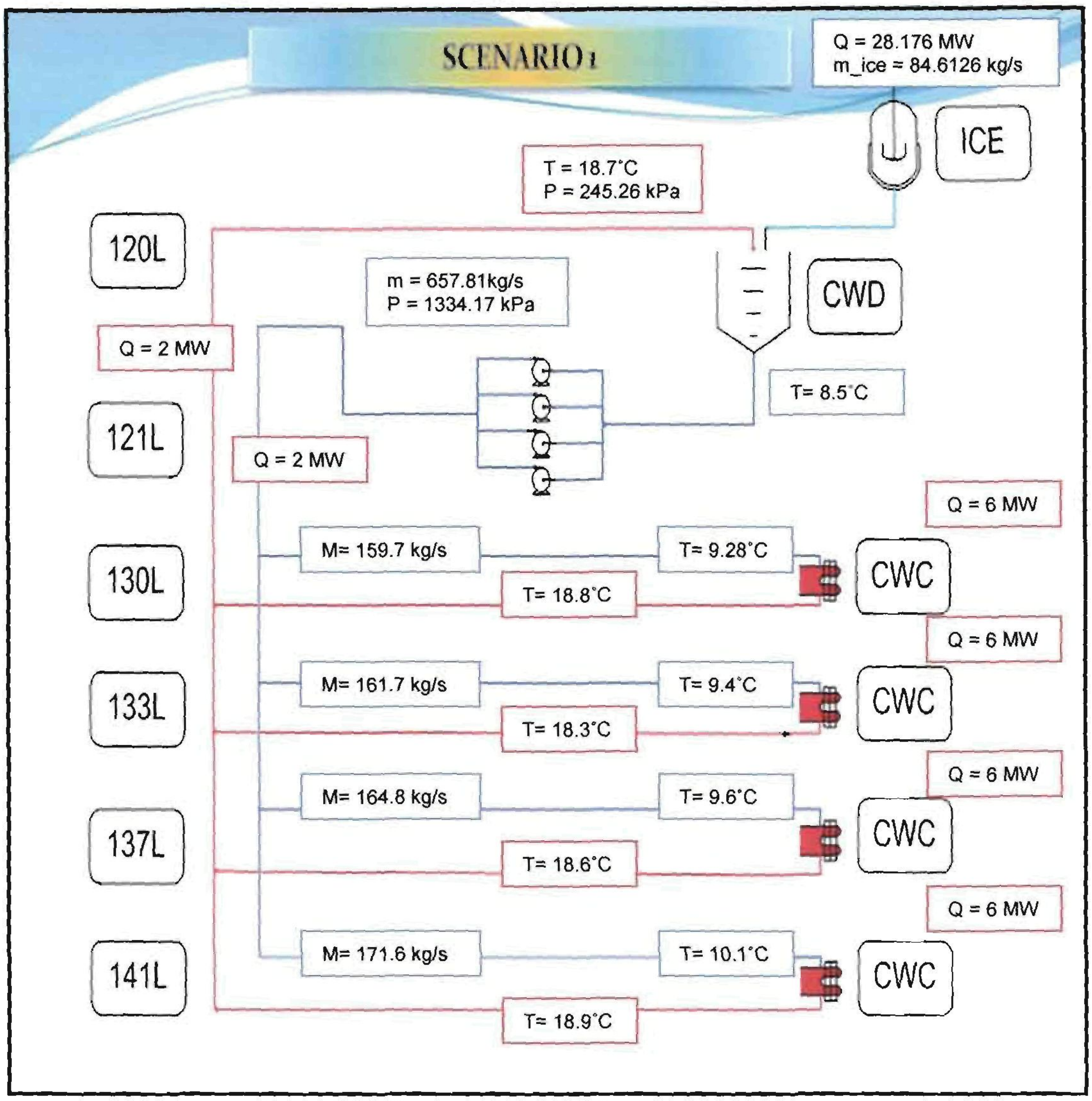

Figure 4.2. Scenario 1 – CWC in closed loop.

In scenario 1 to obtain 24MW of underground cooling the supply has to cater for 28.176MW of cooling and a total load of 44.986MW. The latter comes from the 4.176MW of heat gained underground due to the warm air surrounding the pipes. The amount of water that needs to be circulated is 658kg/s if the outlet temperature of the Chilled Water Dam (CWD) is 8.5°C and the return temperature 18.7°C. The Sulzer pumps will supply this flow at 18.03 bar and this would ensure a safe return pressure of 2.45 bar at 1.502MW electrical power. With an overall efficiency of 57%, 85 CWCs are needed for the required cooling and ads up to 3.825MW electrical power. Figure 4.2 indicates this system and compressor work on surface combines to 11.483MW of electrical power from the ice and fridge plant.

4.2.2. Simulation of the ACU in a closed loop network

For scenario 2 the same piping configuration of scenario 1 was used. The CWCs were removed from the system and replaced by ACUs. The programming in Flownex specified that the water outlet temperature from the units should be 40°C regardless of the water inlet temperature. The total evaporator output of the ACUs in a section is 3MW that results in 3.75MW of heat in addition to the chilled water for a cooling COP of approximately 4. The system then also calculates the heat gain from the surrounding air.

Figure 4.3 indicates the results of the ACU simulation. A total of 32.385MW of cooling from the ice is needed to provide a cooling of 24MW at a total load of 52.116MW. The total comes from the 6.924MW of compressor work, and the fan electrical power on the unit. From the simulation there is a heat gain from the surrounding air that amounts to 7.5MW. The simulation indicated how the losses in the pipe network are minimized if the return water temperature is close to the haulage temperatures. About 246.31kg/s of water must be circulated in the system if the supply temperature is 8.5°C with a return temperature of 39.5°C. From this flow the pumps will produce a delivery pressure of 21.7 bar and return pressure of 1.31 bar with a 676.61kW electrical load. The return pressure provides about 13m head and is sufficient for the CL project. The system requires a total of 79 ACUs for the cooling of 24MW. Figure 4.3 indicates this system and compressor work on surface combines to 12.548MW of electrical power from the ice and fridge plant.

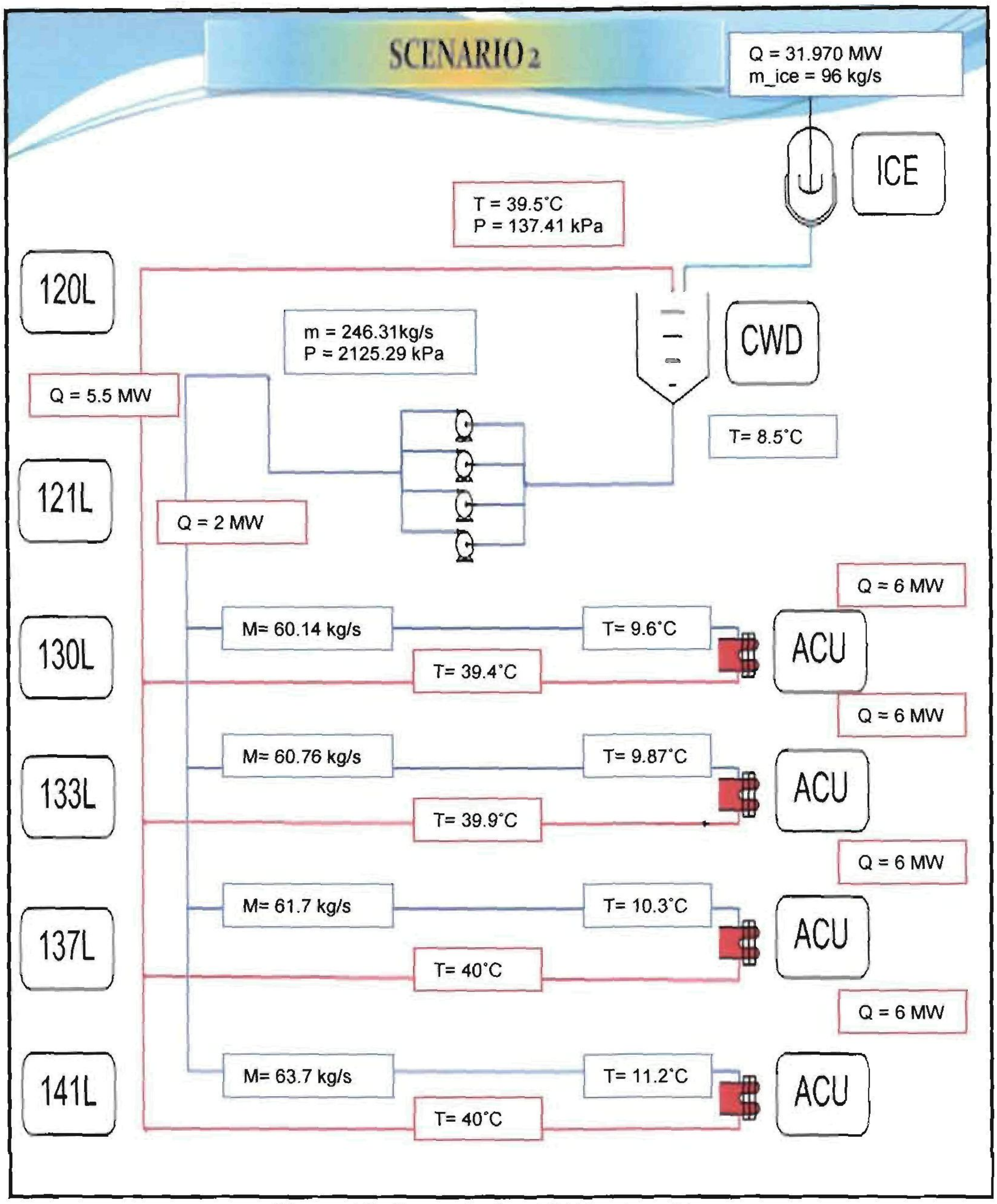

Figure 4.3. Scenario 2 – ACU in closed loop.

4.2.3. Simulation of the CWC along with an ACU in the closed network

The idea behind this simulation comes from the fact that water leaving the CWC is at 18°C. There is still enough potential for the ACU to use the water for cooling by increasing the temperature to 40°C. Although this is simulated in a closed loop system the flow rate that the CWC requires for cooling is different from what the ACU needs. A bypass pipe between the CWC and ACU was used to overcome the problem of return water that was not used by the ACU. The fundamentals of the simulation stayed the same in that each raise line had to produce 1MW of cooling but for this scenario it would be split equally between the CWCs and ACUs. Figure 4.4 provides a visual illustration of the network configuration and Figure 4.5 the bypass pipe used in Flownex.

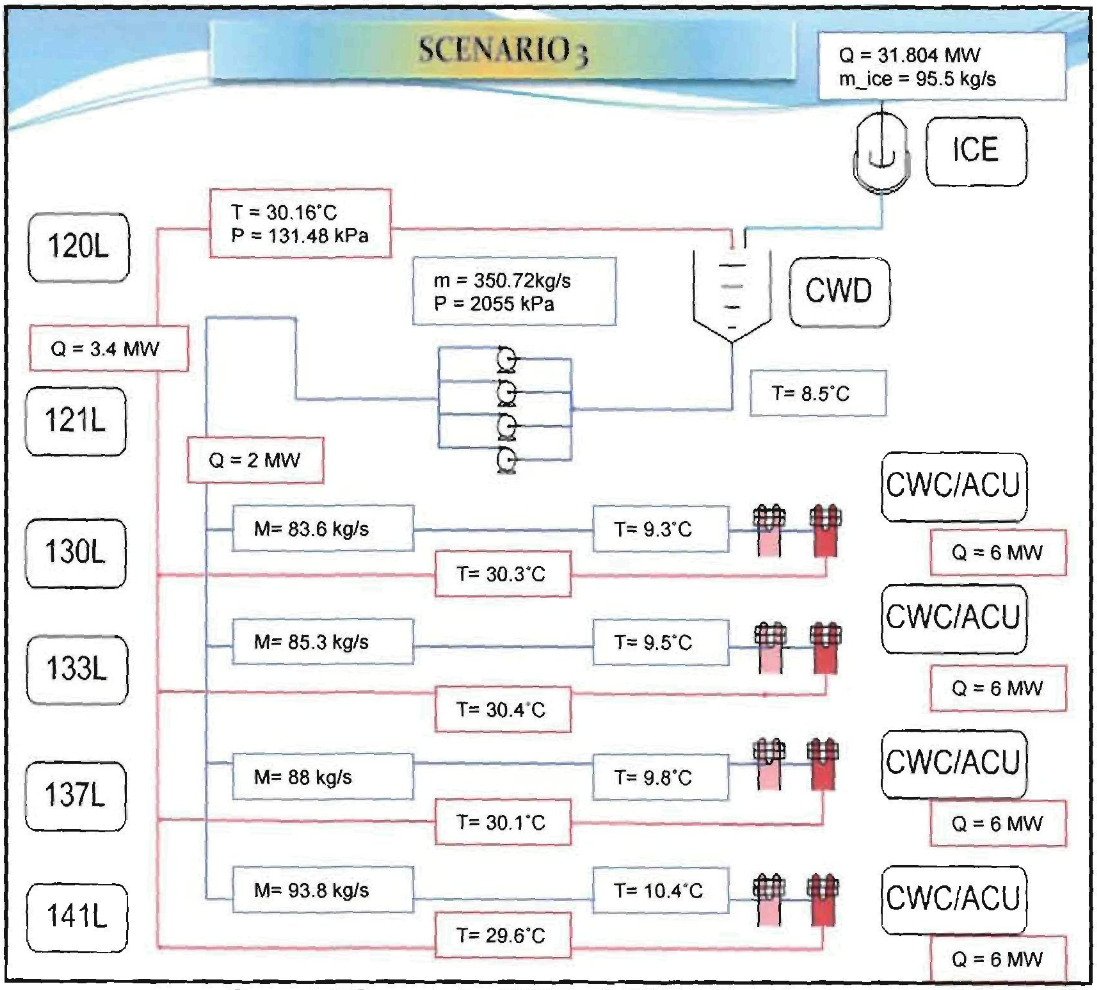

Figure 4.4. Scenario 3 – CWC and ACU in closed loop.

For a cooling load of 24MW underground, 31.804MW of cooling is needed from the ice at a total load of 50.634MW. This result comes from 5.371MW compressor work, and electrical fan power. Water circulated in the system is in the region of 350.72kg/s and this will produce a return temperature of 30.16°C if the supply is at 8.5°C. The reason for the low return temperature is a mixture of water from the CWC that uses approximately 10kg/s of water and the ACUs at about 4.2kg/s. For simulation purposes the CWC outlet temperature was set at 18°C and the ACU at 40°C resulting in the flow rates being solved by Flownex. The higher mass flow rates of the CWCs reduce the water temperature that returns to the CWD from the bypass pipes. For a flow rate of 350.72kg/s the pumps produce a delivery pressure of 20.55 bar and this would result in a return pressure of 1.3 bar at 911kW.

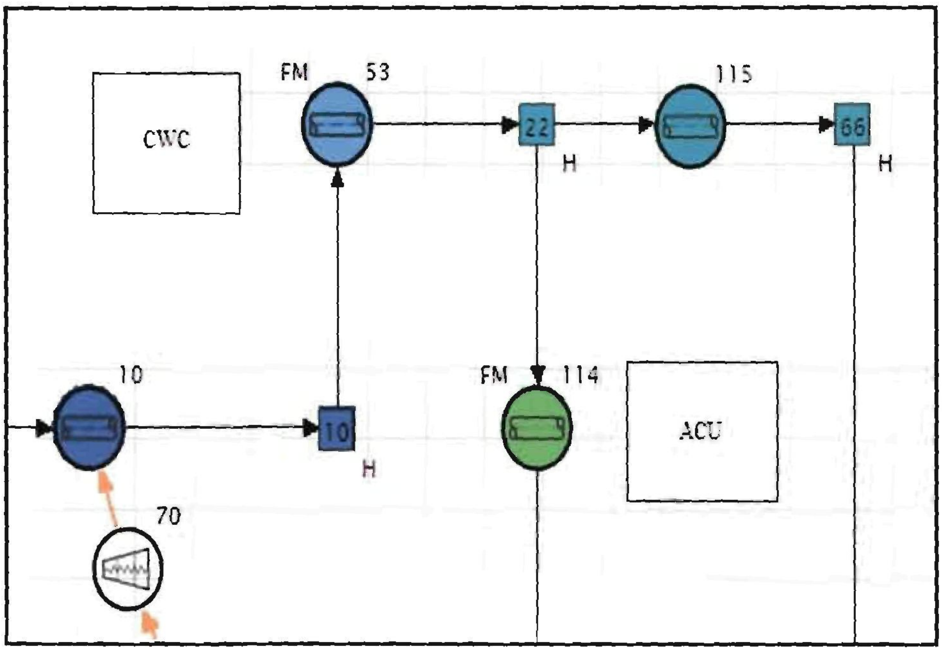

Figure 4.5. Scenario 3 – Bypass pipe system.

Figure 4.5 illustrates the bypass pipe concept used for the simulation of scenario 3. The chilled water feed pipe (Pipe 10) is directly coupled to the CWC (FM 53). The water then flows via node 22 to either the ACU (FM 114) or the bypass pipe (Pipe 115). Flownex determines the amount of water needed by the ACU to produce the necessary cooling with the rest flowing through the bypass system. The bypass system again connects again at the East - West breakaway for return to surface.

4.2.4. Simulation of an ACU at a development end

Development is the mining process where tunnels are made to access the ore body. A development end would advance anything from 2m to 3m daily and the problem with this is that the permanent piping infrastructure quickly falls behind. Typically coolers are placed at the X/Cut breakaway or several meters back in the haulage. The problem with this is that as the permanent piping in the system falls behind, inadequate water flow to the coolers are experienced. As mentioned the CWC is very susceptible to water flow changes and temperature changes that are experienced from the pipe installation problem. The mining personnel connect the cooler via a 50mm flexible hose that is not insulated with cladding. This results in severe heat loss through the pipe to the surroundings and a high temperature at the inlet of the cooler. With this in mind the scenario of rather using ACUs on development ends was done. The simulation used was based on the work done by M-Tech Industrial for Mponeng Mine shown in paragraph 3.3, Figure 3.10 and 3.11. It indicates clearly the advantage of the ACU at an isolated location with limited water supply and elevated temperatures compared to the CWC. Scenario 4 is split between simulating the ACU and CWC at the location without turbines in an open system. The business case is attached in Appendix C (Mponeng ACU business case).

4.2.5. Simulation of the ACU between the settler and hot water dam

Mponeng Mine settlers are designed for a flow of 240kg/s. The water temperature from the settler is at 28°C towards the hot water dam. If the ACU outlet water temperature is set to 40°C the amount of cooling that is available for extraction is about 9.6MW. The current planning on the CL project is to install BACs on 120L and 121L (Kruger, 2008). This installation could be replaced by ACUs that use the feed water from the launders. Important to note is that BACs are typically located at the shaft area as are the settlers and hot water dam. Reason being it reduces friction and bend losses in the pipes to a minimum and thus no need to simulate in Flownex. The hot water dam temperature is increased to 40°C and more free cooling becomes available at the surface cooling towers due to larger temperature differences. Figure 4.6 illustrates the layout of the system with the ACU situated between the settler and hot water dam.

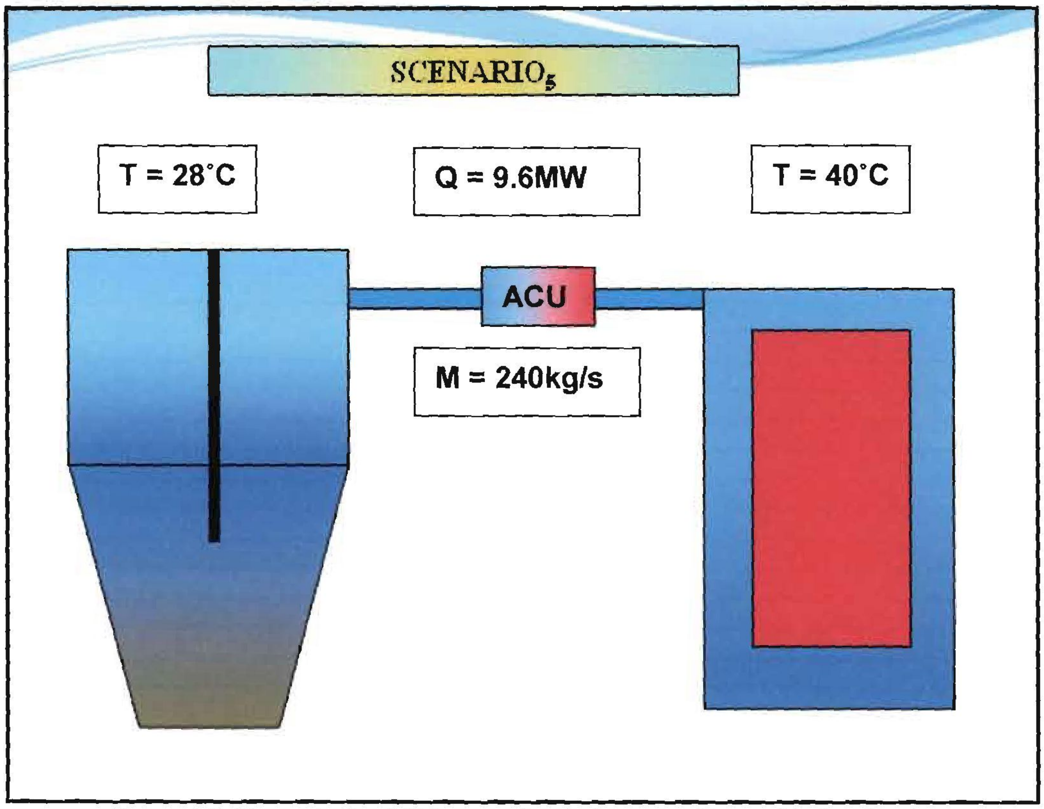

Figure 4.6. Scenario 5 – ACUs operating between settler and hot water dam.

To compare this scenario with the previous ones the concept of a load factor was used. The total cooling extracted underground by this system as it runs currently with scenario 1 is 33.783MW (Refer to Table D.3, appendix D – Total Load CWC). To evaluate this against the base cooling load of 24MW the cooling extracted in this scenario was reduced by a factor of 0.71. The initial total load due to compressor work and heat losses added up to 35MW but by reducing it with the load factor it reduces to 24.85MW. This is due to the fact that the system requires no additional cooling from ice as it runs with scenario 1 and its cooling load. The additional heat added to the water is extracted on surface in the cooling towers and in the mining industry that is considered as free cooling (Robbins, 2007).

4.3. Simulation Summary

Table 4.2: Summary of simulation scenarios.

Scenario	Total Cooling Load (MW)	Temp Water in (°C)	Temp Water out (°C)	Water mass flow (kg/s)	Delivery Pressure (kPa)	Return Pressure (kPa)
1	28.176	18.70	8.5	657.81	1334	245
2	31.967	39.50	8.5	246.31	2125	137
3	31.804	30.20	8.5	350.72	2055	131
4	Business case in Appendix C.					
5	24.85	18.70	8.5	657.81	1334	245

The simulations indicate sufficient return water pressure and that the pumps will not cavitate. This illuminates the need to address the pipe layout and configuration as mentioned in the project outcomes in Chapter 1. From the above table it is clear that for a cooling load of 24MW scenario 5 has the smallest total load. The section showed the difference between the ACU and CWC in a closed loop system with their advantages as well as using the ACU as a bulk air cooling alternative for the technology analysis. A complete economical analysis will follow in the next chapter for the different scenarios to evaluate the best possible alternative for usage.

5. Economical Analysis

The economical analysis covers the cost associated with each scenario technically discussed in Chapter 4. A complete analysis of the total energy input for each of the systems is looked at and the capital and running cost involved with it. At the end of this chapter the economical analysis will indicate the most viable option for AGA to investigate for the CL project.

The economical analysis will follow a Life Cycle Costing (LCC) approach that looks at installation and running costs of the scenarios. Maintenance costs are looked at but due to a lack of information will not form part of the LCC evaluation.

5.1. Cost Calculations

5.1.1. Capital Cost Calculations

From Chapter 4 it is known that the CWCs need to cool 24MW on the CL project. This value and the fact that we can estimate the efficiency of the CWCs we are able to calculate the amount of units needed. The total capital cost is calculated as follows:

$$No\ of\ CWCs = \left(\frac{24MW}{Capacity * \eta} \right) \tag{5.1}$$

$$Capital_{cost} = \left(No\ of\ CWCs * Cooler\ Cost \right) \tag{5.2}$$

5.1.2. Operational Cost Calculations of CWC

The operational cost of the CWC is made up from the following:

- Fan power
- Water pumping electrical power in the closed loop
- Compressor electrical power of the ice plants
- Compressor electrical power of the fridge plants

The following equation indicates how the power is calculated from the fan with the fan power equal to 17kW and a fan efficiency of 70%:

$$kW_{Fan} = (\text{No of CWCs*Fan Power}) \tag{5.3}$$

$$kW_{electrical} = \left(\frac{kW_{fan}}{\eta}\right) \tag{5.4}$$

The water pumping electrical power is calculated from:

$$kW_{pump} = (\Delta P * VolumeFlow) \tag{5.5}$$

$$kW_{electrical} = \left(\frac{kW_{pump}}{\eta}\right) \tag{5.6}$$

The efficiency of the Sulzer HPH (33 – 17.5 3 stage) is taken as 80% according to in AGA (Robbins, 2007).

The cooling load underground that the ice must cool is equal to the total cooling load in Table 4.2 or $Q_{cooling}$ in equation (5.7). The amount of ice and electrical power needed is calculated as follows:

$$Mass_{ice} = \left(\frac{Q_{cooling}}{Cp_{ice}} \right) \tag{5.7}$$

A 3MW ice plant is designed to produce 80 tons/hour of ice. To determine the amount of running plants needed we calculated the following:

$$Plants = \left(\frac{80000}{3600} \right) \tag{5.8}$$

Each plant has a COP of 3 i.e. 1MW of input power for the compressors and using an input efficiency of 83% the electrical power input is calculated as follows:

$$kW_{electrical} = \left(\frac{Plants * 1MW}{\eta} \right) \tag{5.9}$$

The amount of water needed to produce the ice considering an IMF of 70% is in the order of 1.375:1 (Livingstone, 1999). This means that for every 1.375 kg of water used only 1 kg of ice is produced. The amount of water that the fridge plant supply is:

$$Mass_{water} = \left(Mass_{ice} * 1.375\right)$$

5.10

The design of the 11MW Hitachi machines allows for a flow through the evaporator of 350kg/s. This is directly coupled to the compressor input power needed:

$$COP = \left(\frac{Q_{cooling\_evap}}{Q_{work\_comp}}\right)$$

5.11

The Hitachi machines have a COP of 5 (Robbins, 2007) and from this the electrical input power of the compressor is calculated with:

$$P_{ref} = \left(\frac{Q_{work\_comp}}{\eta}\right)$$

5.12

The total electrical power required for the system is then calculated from the sum of all the electrical inputs:

$$kW_{Total\_electrical} = \sum kW_{electrical}$$

5.13

Assuming the system being operational 95% of the year for maintenance purposes, the total kWh consumption over an annual basis is calculated from:

$$kWh = \left(Hours * Days_{year} * kW_{electrical}\right) * 95\%$$

5.14

The total operational cost is shown in equation (5.15).

$$Operation_{\cos t} = \left(kWh * Cost_{kWh}\right)$$

5.15

South African major operations are billed according to the MEGAFLEX tariff (Eskom, 2008). If the consumer has more than 1MVA installed capacity they are subject to the following charges:

- Service and admin charge (R/day)
- Network charge (R/kVA)
- Active energy charge (c/kWh)
- Reactive energy charge (c/karh)
- Rate rebalancing levy (c/kWh)

This study only focuses on a kWh rate of R 0.28 that is currently used for billing AGA. Eskom rates will change in March 2009 and increase by 22.5% (NERSA, 2008) but will not form part of this study.

5.1.3. Operational Cost Calculations of ACU

The difference in operation between the ACU and CWC in the closed loop system is the compressor that adds additional load to the system. The total heat that is rejected in the water by the condenser is equal to:

$$Q_{condenser} = \left(Q_{compressor} + Q_{evaporator}\right)$$

5.16

$Q_{evaporator}$ is equal to 300kW and $Q_{compressor}$ is 75kW based on the fact that the unit has a COP of 4 (Rousseau and van Eldik, 2008) as calculated from equation (5.11). The compressor work of the units is added to the total electrical power needed for the calculation of the operation cost, with the remainder of the calculations staying the same.

5.1.4. Operational Cost Calculations of ACU in open loop system

The business case used in Appendix C looks at similar calculations for the total work done by the system. The scenario focuses on an open loop reticulation with no energy recovery on it. This is why the system is similar to production for the development ends. The water is sent to the cooler and after the cooling process on both the CWC and ACU it is dumped on the foot wall and pumped back to surface. The scenario has been presented to Mponeng Mine and the study indicated that the total running cost is significantly lower than for normal operating conditions with the CWC. This shows that the ACU has great potential and is the most feasible option to run at development end production sites.

5.1.5. Operational Cost Calculations of ACU between the settler and hot water dam

As with the calculation of the ACU in the closed and open loop system the operational cost calculation between the settler and hot water dam focused on:

- Capacity for cooling extraction as in scenario 5
- Compressor electrical power input for ACU
- Fan electrical power input to the ACU
- Ice and refrigeration plant electrical power needed on surface

The following section provides the results of the total power consumption with the resulting costs for scenario 1 to 5, with 4 excluded. The complete table is attached in Appendix D (Economical Analysis) for referencing.

5.2. Electrical and Economical Evaluation

The life expectancy of the CL is 25 years for which a Net Present Value (NPV) was calculated. The interest over the period is kept at 12% but will change with inflation. The capital cost is used as the initial investment that must be made to obtaining the equipment. From there the operational cost is used to calculate the yearly expenses for each scenario. Maintenance is left out in the economical evaluation due to a lack of data available for the different systems evaluated. The life expectancy of both the ACU and CWC is in the region of six years. There is however no ACU that's been operational for that period and Mponeng Mine has only started complete monitoring of their CWCs from November 2007. Future studies must look into this as data becomes more available on both units. The calculations are for a fin efficiency of 50% on the CWC and COP of 4 on the ACU.

Table 5.1: Scenario 1 – Electrical and Economical.

Electrical	
Fan	4 320 kW
Compressor	0 kW
Ice Plant	11 000 kW
Refrigeration Plant	483.50 kW
Pumping	1 502.08 kW
Total Electrical	**17 306 kW**
Economical	
Amount of Units	96
Capital Installation Cost	R15.168m

Operational Cost	R36m
NPV of 25 years	**R297m**

Table 5.2: Scenario 2 – Electrical and Economical.

Electrical	
Fan	1 252 kW
Compressor	6 108 kW
Ice Plant	12 000 kW
Refrigeration Plant	548 kW
Pumping	676.61 kW
Total Electrical	**20 584.61 kW**
Economical	
Amount of Units	79
Capital Installation Cost	R60m
Operation Cost	R42.83m
NPV of 25 years	**R395m**

Table 5.3: Scenario 3 – Electrical and Economical.

Electrical	
Fan	1 976 kW
Compressor	3 847 kW
Ice Plant	12 000 kW
Refrigeration Plant	545.97 kW
Pumping	911.93 kW
Total Electrical	**19 280.9 kW**
Economical	
Amount of Units	(CWC 48) & (ACU 39)

Capital Installation Cost	R36.834m
Operation Cost	R40.11m
NPV of 25 years	**R351.5m**

Table 5.4: Scenario 5 – Electrical and Economical.

Electrical	
Fan	546 kW
Compressor	2 411 kW
Ice Plant	11 000 kW
Fridge Plant	483.50 kW
Pumping	1 502 kW
Total Electrical	**15 942 kW**
Economical	
Amount of Units	(CWC 48) & (ACU 39)
Capital Installation Cost	R37.6m
Operation Cost	R29m
NPV of 25 years	**R272m**

To summarize the above tables Figure 5.1 is used. Firstly the lines of the graph don't go through zero as it indicates the initial capital investment that must be made to obtain the units. From there the scenarios operational cost is added yearly with an interest rate of 12% over a 25 year period and indicated on the graph. A higher operational cost is indicated by a steeper gradient on the lines as visible for scenario 2. Generally the graph that has the lowest cost after the 25 year period is the most feasible option for the CL project as it would result in the lowest overall cost to AGA during this period. Scenario 5 in simulation – (Operation of the ACU between the settler and hot water dam) was the least expensive option for the CL project. On development ends the ACU is the best economical choice as it has the lowest operational cost.

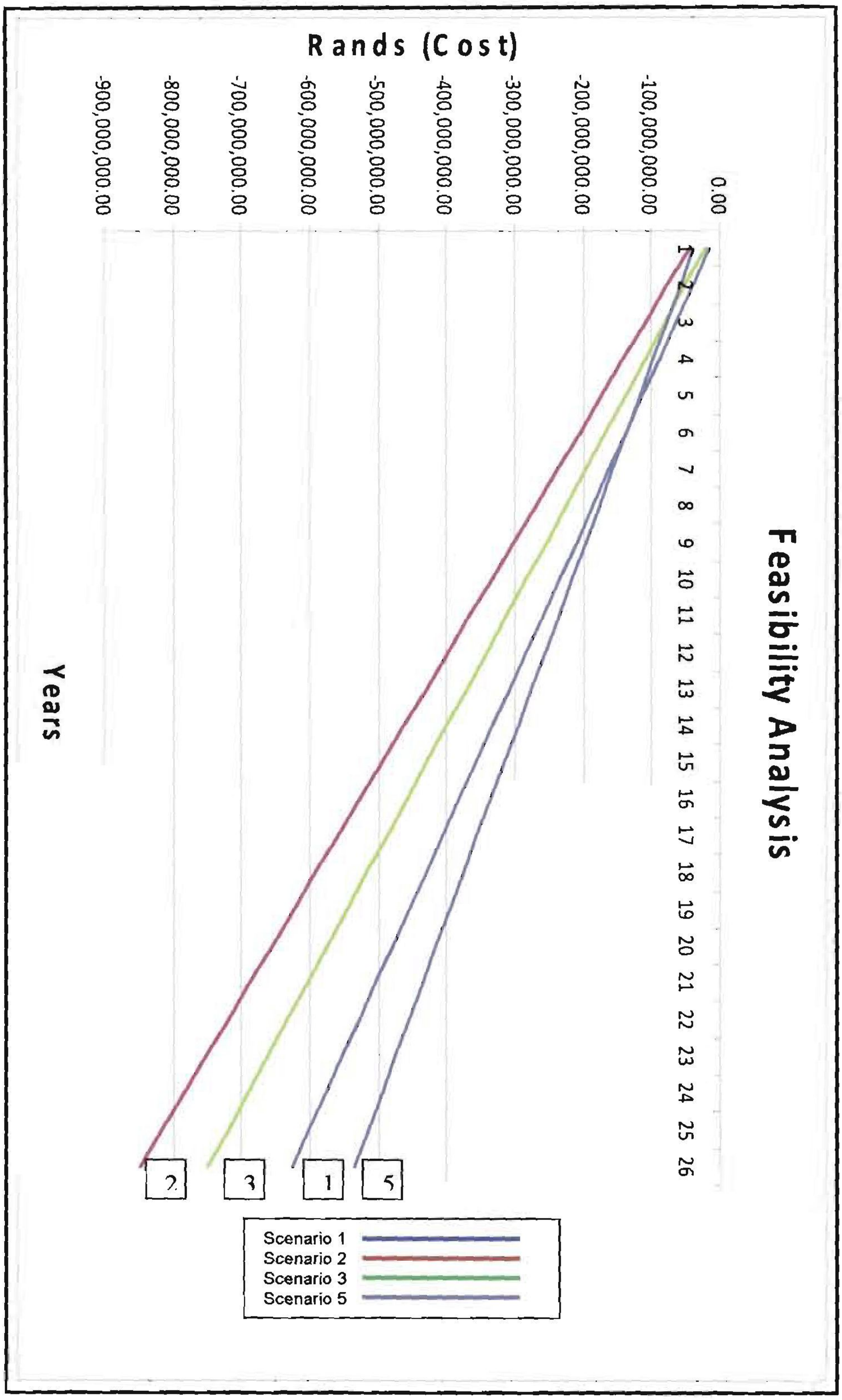

Figure 5.1.Resulting LCC of the different scenarios.

5.3. Summary.

From the LCC it is clear that employing CWCs in the closed loop is the best option from a cost perspective. Although the efficiency of the CWC is only at 50% the capital cost involved with the ACU is too expensive with the total load it puts on the closed loop system. Using ice reduces the total cost of the system and a separate study must be done for the same system using only refrigeration plants. As was mentioned in Chapter 2 the utilization of the return water is the most viable option to gain both efficiency and cost reduction which also becomes evident in scenario 5. The business case for using ACUs for development in isolated location saves operational cost and has a good payback.

There are definitely two undeniable scenarios for the ACU in deep level mining applications such as at Mponeng Mine. Firstly, return water must be utilized and by increasing the temperature of the water as close as possible to the haulage temperatures minimize losses. Secondly, the heat pump technology that the ACU is based on has great potential for cooling development ends.

6. Summary

6.1. Conclusion

The CL project at Mponeng has great energy savings potential considering the technology available on the market for refrigeration and ventilation. The outcomes of this study indicated that each mine has a unique layout with its installed refrigeration systems. The essence is to understand the system and the dynamics that contributes to the operation.

Exploring depths of beyond 4000m is certainly one of the biggest challenges facing the mining industry for exploring their ore reserves. If virgin rock temperatures of up to 70°C are expected, ice has proven to be the most efficient and cost saving solution for the primary cooling systems at Mponeng. The emphasis is on increasing the return water temperature to as close as possible to the haulage temperatures. This reduces the losses in the system and increases the efficiency of the refrigeration. The concept of spot cooling for usage on development ends is motivated by this fact as the losses in the system are minimized.

The results of five scenarios indicated that in the closed loop reticulation the CWC is the most viable option due to a low NPV of R206m. The efficiency compared from total work input to output indicated the ACU is the preferred option in the closed loop as it is not reliable on fin efficiency. If the capital cost of the units could be reduced it would be the best option to run in a closed loop system. When considering cooling on development ends the ACU is far superior to the CWC by saving about 49% on BAC for the total system (Appendix C). This comes from the proven results that the CWC is much more sensitive to a change in water inlet temperature and flow rate compared to the ACU.

6.2. Recommendations for further work

All the calculations and research have focused on results from estimates as to what the VRT and heat load are beyond 4000m. As exploration into these depths starts happening the temperatures and flow rates must be updated for a more complete simulation of the actual system.

Future work must look at the following:

- The 300kW ACU is still in a design phase and needs to be manufactured and tested in a mining environment.
- The output of the 300kW ACU needs to be evaluated in a mining area and the maintenance costs that are involved with it.
- Simulation with SCFD codes in the mining industry as it has proven to be a valuable resource for the study. Flownex was able to simulate the complete chilled water reticulation system and showed great comparisons to the actual values recorded on the mine. AGA must look towards these software packages to prevent water hammer and pipe flow losses.
- Methods for cleaning and improving the efficiency of the CWCs. Although much work has been done on this, companies overlook the different mines and their systems and what the operating conditions of CWC are underground that contribute to efficiency losses.

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Appendix A – Cooling Coil Efficiency

The appendix shows the table provided by Mponeng SHE personnel for the coolers used on the mine. Table A-1 shows all the recorded data for coolers used on Mponeng since 2003 and their respective operation efficiencies.

Table A.1: Cooling coils data - 2008.

Cooler Position:	Make of Cooler	Cooler T/Circuit/ Open	BP	Duty	Design Duty	Efficiency
94/67 x/cut	HI Energy	Open	111.4	225	500	44.94825
113-46x/cut	Manos	Open	113	227	500	45.30829
B120 PROJECT	VIPER	Tight circuit	121.9	416	500	83.12306
B120 PROJECT	VIPER	Tight circuit	121.9	500	500	100
B120 PROJECT	VIPER	Tight circuit	121.9	112	500	22.47332
B120 PROJECT	Manos	Tight circuit	118	146	300	48.61488
109-66 X/cut Cooler	Manos	Open	116.9	164	500	32.81025
104/66 X-CUT	HI Energy	Open	115.7	107	500	21.45946
99/68 X/C	U Airbrand	Open	113.8	245	500	49.04756
113/39 haulage	HI Energy	Tight circuit	119	260	500	52.08674
120/51 Hlge	Manos	Open	121	405	500	80.93762
120/51 Hlge	Manos	Open	121	400	500	79.96929
120/51 Hlge	Manos	Open	121	409	500	81.74639
109/40 X/C	Manos	Tight circuit	113	36	500	7.289264
109/40 X/C	Manos	Tight circuit	113	80	500	15.98935
113/40 X/C	Manos	Tight circuit	113.9	39	500	7.895062
109/66 x/c	Manos	Open	117.6	302	500	60.39632
104/66X-CUT	HI Energy	Open	115.7	59	500	11.80199
116/48 X/C	Manos	Tight circuit	117.9	75	500	14.93926
116/48 X/C	Manos	Tight circuit	117.9	119	500	23.83605
120/51 Hlge	Manos	Open	121	405	500	80.93762
113/39	Manos	Tight circuit	115.3	233	500	46.5848
113/40	Manos	Tight circuit	115.3	500	500	100
104/68 (67-68)	Joules	Tight circuit	115.7	326	500	65.29108
116-39	HI Energy	Open	116	269	500	53.89403
113/39 X/cut	HI Energy	Open	113	190	500	37.94022
116/42 X/C	Manos	Tight circuit	115	106	500	21.25652
116/42 X/C	Manos	Tight circuit	115	169	500	33.82181
104/65x-cut	HI Energy	Open	115.7	334	500	66.81772
113/52 x-cut	VIPER	Open	119	157	500	31.4856
116/48 X/C	Manos	Tight circuit	117.9	50	500	10.01142
116/48 X/C	Manos	Tight circuit	117.9	72	500	14.35415
120/48 X/C	Manos	Tight circuit	118.9	164	500	32.72686
120/48 X/C	Manos	Tight circuit	118.9	109	500	21.81221
120/49 x/c	Manos	Tight circuit	125	356	500	71.1186
120/49 X/C	VIPER	Tight circuit	125	188	500	37.59319
120/39	VIPER	Open	121	387	500	77.34887
120/40	VIPER	Open	121	418	500	83.55219

116/39 x/cut	HI Energy	Open	113	160	500	32.08384
113/39 X/cut	HI Energy	Open	113	72	500	14.46507
113/46	HI Energy	Open	113	117	500	23.33665
116/48 X/C	Manos	Tight circuit	117.9	84	500	16.7153
116/48 X/C	Manos	Tight circuit	117.9	228	500	45.6324
120/40	VIPER	Open	121	439	500	87.7298
120/51 x/c	Manos	Tight circuit	117	306	500	61.23285
120/51 x/c	Manos	Tight circuit	116.7	216	500	43.10925
120/42 X/C	Manos	Tight circuit	117	63	500	12.50497
120/42 X/C	Manos	Tight circuit	117	63	500	5
113/39	Manos	Tight circuit	115.3	181	500	36.26923
113/40	Manos	Tight circuit	115.3	500	500	100
116/49 x/c	Manos	Tight circuit	119	73	500	14.52388
104/68 (67 - 68)	jOULES	Tight circuit	115.7	378	500	75.50944
120/48 X/C	Manos	Tight circuit	118.9	183	500	36.53834
120/48 X/C	Manos	Tight circuit	118.9	93	500	18.58072
120/44 x/cut No:2	HI Energy	Open	116.2	321	500	64.1145
120/44 x/cut No:1	HI Energy	Open	116.4	190	500	38.06207
116/44 x/cut	HI Energy	Open	115.4	286	500	57.18276
120/51 Hlge	Manos	Open	121	435	500	87.07767
113-42 x/cut	Manos	Open	114.8	507	500	101.3218
116/56	Manos	Open	121	388	500	77.67621
109/65 x-cut	HI Energy	Open	117.6	130	500	26.00649
116/40	Manos	Open	121	444	500	88.73148
116/42X/C	Manos	Tight circuit	115	173	500	34.522
116/42 X/C	Manos	Tight circuit	115	62	500	12.3466
116/51	Viper	Open	121	423	500	84.6494
120/44 No:2	HI Energy	Open	117.1	373	500	74.5084
120/44 No:1	HI Energy	Open	117.1	288	500	57.6223
116/44 x/cut	HI Energy	Open	116.5	333	500	66.68161
120/51X/CUT	Manos	Open	117	454	500	90.86537
116/51 x/cut	Manos	Open	116.7	296	500	59.1237
120/42 X/C	Manos	Tight circuit	117	66	500	13.21872
120/42 X/C	Manos	Tight circuit	117	66	500	13.21872
94/67 x/cut	HI Energy	Open	111.4	157	500	31.47685
113/39 X/cut	HI Energy	Open	116	262	500	52.32349
11/39 x/cut	HI Energy	Open	115	103	500	20.54417
116-39	HI Energy	Open	115	431	500	86.11727
116/48 X/C	Manos	Tight circuit	117.9	79	500	15.87668
116/48 X/C	Manos	Tight circuit	117.9	243	500	48.59905
113/46 X/cut	HI Energy	Open	113	87	500	17.38056
116/45 X/cut	Manos	Open	114.5	329	500	65.80887
109-66 X/cut Cooler	Manos	Open	116.9	129	500	25.8819
104/67	Manos	Open	115.7	191	500	38.16694
120/40	vIPER	Open	121	106	500	21.19427
113/52 x-cut	Viper	Open	119	172	500	34.36906
109/40 X/CUT	Manos	Open	113	393	350	112.4028
113/40 X/CUT	Manos	Open	113.9	115	500	23.0768
113/40 HLGE	HI Energy	Open	113.6	405	500	80.99012
104/42 raise	Manos	Open	113	249	350	71.06965
104-42X/cut Cooler	HI Energy	Open	113	359	500	71.81487
116/40 IN HLGE	HI Energy	Open	114.7	266	500	53.25147

116/40 x/cut	HI Energy	Open	114.7	469	500	93.87061
104/65 x-cut	HI Energy	Open	115.7	324	500	64.78367
99/68 X/CUT	U Airbrand	Open	113.8	220	500	44.08053
109/42 x/cut	HI Energy	Open	113	300	500	60.09556
116/56	Manos	Open	121	433	500	86.51207
120/45 No:2	HI Energy	Open	116.4	287	500	57.38969
120/45 No:1	HI Energy	Open	116.4	316	500	63.17707
116/39X-cut	Manos	Open	121	413	500	82.66205

Table A.2: Cooling coils data - 2007.

Cooler Position:	Make of Cooler	Cooler T/Circuit/ Open	BP	Duty	Design Duty	Efficiency
116/49 x/c	Manos	Tight circuit	119	377	500	75.49817
116/51	Viper	Open	121	423	500	84.6494
116/51 Hlge	Viper	Open	121	441	500	88.24731
120/49 x/c	Manos	Tight circuit	125	416	500	83.14411
120/49 x/c	Manos	Tight circuit	125	431	500	86.22118
109/65x-cut	HI Energy	Open	117.6	169	500	33.82033
120/40	Viper	Open	121	456	500	91.1338
120/48 X/C	Manos	Tight circuit	118.9	207	500	41.35136
120/48 X/C	Manos	Tight circuit	118.9	207	500	41.35136
120/48 X/C	Manos	Tight circuit	118.9	65	500	13.09922
113/49 x/c	Manos	Tight circuit	113	383	500	76.54071
120/51 Hlge	Manos	Open	121	422	500	84.41203
120/51	Manos	Open	121	457	500	91.39052
120/51 Hlge	Manos	Open	121	422	500	84.41203
120/51	Manos	Open	121	457	500	91.39052
116/56	Manos	Open	121	432	500	86.43307
116/48 X/C	Manos	Tight circuit	117.9	171	500	34.14033
113/52 x/c	viper	Open	119	401	500	80.12034
116/42 X/C	Manos	Tight circuit	115	152	500	30.47815
116/42X/C	Manos	Tight circuit	115	141	500	28.26324
120/44 No:2	HI Energy	Open	114.8	415	500	82.95391
120/44 No:1 cooler	HI Energy	Open	114.8	369	500	73.85302
116-45 x/cut	HI Energy	Open	114.3	225	500	45.06957
113/42 x/cut	Manos	Open	114.2	442	500	88.43842
120/49 x/c	Manos	Tight circuit	125	89	500	17.82987
120/49 x/c	Manos	Tight circuit	125	58	500	11.60038
116/51 Hlge	Viper	Open	121	414	500	82.79899
116/49 x/c	Manos	Tight circuit	119	233	500	46.62552
116/40 x/cut	HI Energy	Open	119.6	447	500	89.36559
120/48 X/C	Manos	Tight circuit	118.9	55	500	11.05432
120/48 X/C	Manos	Tight circuit	118.9	290	500	57.9237
104/65 x-cut	HI Energy	Open	115.7	275	500	55.01461
120/42 X/C	Manos	Tight circuit	117	224	500	44.8489
109/66 -67	Manos	Open	117.6	376	500	75.25766
104/66X-CUT	HI Energy	Open	115.7	209	500	41.7659
116/48 X/C	Manos	Tight circuit	117.9	177	500	35.32966
109/42X/C	Manos	Tight circuit	117.9	289	500	57.71249

120/40	Viper	Open	121	427	500	85.49085
94/67 x/cut	HI Energy	Open	111.4	175	500	34.96236
113/51 x/c	Manos	Tight circuit	113	96	500	19.15098
120/51 Hlge	Manos	Open	121	400	500	79.96929
120/51	Manos	Open	121	488	500	97.55498
94 East Haulage	Manos	Tight circuit	11.04	323	500	64.58041
104/67	Manos	Open	115.7	184	500	36.86775
113/52 X/C	VIPER	Open	119	231	500	46.13367
109-66 X/cut	HI Energy	Open	116.9	148	500	29.53852
116/56	Manos	Open	121	432	500	86.38049
113/40 x/cut	Manos	Open	114.1	233	500	46.55863
109/40 x/cut	Manos	Open	113.8	353	300	117.7394
116/51 Hlge	Viper	Open	122	383	500	76.53163
116/51	Viper	Open	121	70	500	14.0418
113/49 x/c	Manos	Tight circuit	113	450	500	89.97943
109-66 -67	Manos	Open	117.6	193	500	38.67649
116/40 x/cut	HI Energy	Open	119	326	500	65.10003
116/40 x/cut	HI Energy	Open	119	166	500	33.26394
113/40 x/cut	HI Energy	Open	118.9	487	500	97.39245
116/42 X/C	Manos	Tight circuit	115	253	500	50.53184
116/42 X/C	Manos	Tight circuit	115	215	500	43.03982
116/42 X/C	Manos	Tight circuit	115	215	500	43.03982
116/42 X/C	Manos	Tight circuit	115	215	500	43.03982
116/42 X/C	Manos	Tight circuit	115	215	500	43.03982
116/42 X/C	Manos	Tight circuit	115	215	500	43.03982
116/42 X/C	Manos	Tight circuit	115	215	500	43.03982
104/66X-CUT	HI Energy	Open	115.7	134	500	26.7391
116/38	Manos	Open	122	191	500	38.29877
109/49 X/C	Manos	Tight circuit	117.9	26	500	5.175251
94/67 x/cut	HI Energy	Open	111.4	385	500	77.07013
113/39 x/cut	HI Energy	Open	115	54	500	10.7655
113/39 x/cut	Manos	Open	115	144	500	28.84791
120/42 X/C	Manos	Tight circuit	117	69	500	13.87444
120/42X/C	Manos	Tight circuit	117	69	500	13.87444
104/68 X/cut	Manos	Tight circuit	15.7	90	500	17.91496
104/69 (68-69)	Manos	Tight circuit	115.7	194	500	38.75368
104/68 (67 -68)	Joules	Tight circuit	115.7	96	500	19.13605
99/68 X/C	U Airbrand	Open	113.8	273	500	54.62917
120/51 Hlge	Manos	Open	121	422	500	84.41203
120/51	Manos	Open	121	480	500	95.92906
104/65 x-cut	HI Energy	Open	115.7	189	500	37.71149
116/56	Manos	Open	121	413	500	82.6576
116/51	Viper	Open	121	410	500	81.94731
120/45 No:2	HI Energy	Open	115.4	277	500	55.32488
120/45 No:1	HI Energy	Open	115.8	108	500	21.60208
116/45 x/cut	Manos	Open	114.9	271	500	54.27132
116/45 x/cut	Manos	Open	114.9	271	500	54.27132
109-40 x/cut	Manos	Open	115.2	196	300	65.40035
113/51 x/c	Manos	Tight circuit	113	172	500	34.44553
109/42 X/C	Manos	Tight circuit	117.6	167	500	33.4143
109/64	Manos	Tight circuit	117	407	500	81.33277

104/64	HI Energy	Tight circuit	115	303	500	60.69754
104/64	HI Energy	Open	115	0	500	5
104/65 x-cut	HI Energy	Open	115.7	236	500	47.1765
120 NO:1	HI Energy	Open	116	138	500	27.59387
120/44 NO:1	HI Energy	Open	116	282	500	56.49402
116/44 X/CUT	HI Energy	Open	116	140	500	27.96244
113/44 IN HAULAGE	Manos	Open	115.4	238	500	47.66957
113/42	Manos	Open	115.4	216	500	43.29898
120/40	Viper	Open	121	425	500	84.97242
99/68 X/Cut	U Airbrand	Open	113.8	135	500	27.01369

Table A.3: Cooling coils data - 2006.

Cooler Position:	Make of Cooler	Cooler T/Circuit/ Open	BP	Duty	Design Duty	Efficiency
109/65x-cut	HI Energy	Open	117.6	253	500	50.63415
109/67 - 68	Manos	Tight circuit	117.6	181	500	36.2004
113 - 56 x/cut	HI Energy	Open	119	172	500	34.36327
120/51 Hlge	Manos	Open	119	268	500	53.5672
120/51	Manos	Open	121	480	500	95.92906
120/49 x/c	Manos	Tight circuit	125	81	500	16.22718
120/49 x/c	Manos	Tight circuit	125	128	500	25.64032
120/48 X/C	Manos	Tight circuit	118.9	231	500	46.27719
120/48 X/C	Manos	Tight circuit	118.9	125	500	24.95587
116/49 x/c	Manos	Tight circuit	119	221	500	44.27917
113/52x-cut	viper	Tight circuit	119	307	500	61.39552
120/52	Manos	Open	121	472	500	94.42302
116/48 X/C	Manos	Tight circuit	117.9	216	500	43.24407
116/48 X/C	Manos	Tight circuit	117.9	98	500	19.53675
116/48 X/C	Manos	Tight circuit	117.9	98	500	19.53675
116/56	Manos	Open	121	465	500	93.0107
116/51	Viper	Open	121	410	500	81.94731
120/42 X/C	Manos	Tight circuit	121	32	500	6.338863
116 West	Viper	Open	121	425	500	84.99353
116/48 X/C	Manos	Tight circuit	117.9	238	500	47.63927
116/48 X/C	Manos	Tight circuit	117.9	117	500	23.37246
120/40	Viper	Open	121	427	500	85.4387
120/48 X/C	Manos	Tight circuit	118.9	280	500	55.94753
120/48 X/C	Manos	Tight circuit	118.9	51	500	10.20169
120/45 x/cut	HI Energy	Open	117.9	19	500	3.851889
120/45 x/cut	HI Energy	Open	117.9	92	500	18.31861
116/42 X/C	Manos	Tight circuit	115	67	500	13.35108
116/42 X/C	Manos	Tight circuit	115	45	500	8.984153
116/42 X/C	Manos	Tight circuit	115	83	500	16.51826
99/68 X/C	U Airbrand	Open	113.8	168	500	33.63375
109-66 X/cut Cooler	Manos	Open	116.9	73	500	14.67132
116/40	Manos	Open	117	280	500	55.91188
104/65	HI Energy	Open	115.7	159	500	31.73135
113/40 in hlge	Manos	Open	116	226	500	45.28146
120/52 X-cut	Manos	Open	121	438	500	87.59614

113 Haulage East	Manos	Tight circuit	119	67	500	13.45107
104/69 (68 - 69)	Manos	Tight circuit	115.7	384	500	76.75156
104/68 (67 - 68)	Joules	Tight circuit	115.7	505	500	101.0393
116/45 x/cut	Manos	Open	116	298	500	59.58863
116/51	Viper	Open	121	410	500	81.94731
104-66 X/cut Cooler	HI Energy	Open	114.8	144	500	28.79168
113/52X-CUT	viper	Tight circuit	119	217	500	43.47962
120/51	Manos	Open	121	480	500	96.07543
120 Haulage East	Manos	Open	121	412	500	82.33735
120/44 No.1	Manos	Open	118.5	100	500	19.98662
120/44 No.2	Manos	Open	118.3	124	500	24.7541
116/44 X/C	Manos	Tight circuit	117.4	274	500	54.88856
116/56	Manos	Open	121	405	500	80.9249
109/42 X/C	Manos	Tight circuit	117.6	79	500	15.78462
109/42 X/C	Manos	Tight circuit	117.6	8	500	1.578462
116/51	Viper	Open	121	253	500	50.67617
120/49 x/c	Manos	Tight circuit	125	153	500	30.57836
120/49 x/c	Manos	Tight circuit	125	267	500	53.31886
116 West	Viper	Open	121	425	500	84.99353
104/68 (67 - 68)	Joules	Tight circuit	115.7	433	500	86.60502
104/69 (68 -69)	Manos	Tight circuit	115.7	386	500	77.28365
104/67	Manos	Tight circuit	115.7	465	500	93.06659
104/65	HI Energy	Open	115.7	177	500	35.49624
94 East Hlghe	Manos	Tight circuit	111.04	252	500	50.47835
109/65x-cut	U Airbrand	Open	117.6	197	500	39.44024
113/52x-cut	viper	Tight circuit	119.4	217	500	43.47006
113/39	vIPER	Open	119	410	500	82.07414
113 West Hlge before 39	Manos	Tight circuit	119	248	500	49.60284
113 West Hlge 38	Viper	Open	119	129	500	25.77829
113 Haulage East	Manos	Tight circuit	119	55	500	10.99461
113/56	Viper	Open	119	239	500	47.88766
109/67 - 68	Manos	Tight circuit	117.6	329	500	65.89958
120/52	Manos	Open	121	425	500	84.99353
99/68	U Airbrand	Open	113.8	164	500	32.74004
99/68	U Airbrand	Open	113.8	0	500	5
99/69	Manos	Tight circuit	113.8	449	500	89.81573
120/51	Manos	Open	121	480	500	96.07543
113/42	Manos	Open	114.6	372	500	74.32376
113/42 x/cut	Manos	Open	114.5	372	500	74.30882
89/67 X/C	U Airbrand	Open	110.4	326	500	65.20207
116/42 X/C	Manos	Tight circuit	115	139	500	27.72329
116/42 X/C	Manos	Tight circuit	115	62	500	12.43256
116/52	Viper	Open	121	418	500	83.57064
116/52	Manos	Open	121	356	500	71.15853
116/51	Viper	Open	121	342	500	68.40576
109-66 X/cut Cooler	Manos	Open	116.9	131	500	26.29813
116/48 X/C	Manos	Tight circuit	117.9	186	500	37.25875
113/49 x/cut	Manos	Tight circuit	117	162	500	32.46551
113/49 x/cut	Manos	Tight circuit	113	692	500	138.4028
109/66	Manos	Tight circuit	116.8	86	500	17.19873
116 West	Viper	Open	122	345	500	69.09146

94 East	Manos	Tight circuit	111.04	236	500	47.22851
113/51 x/cut	Manos	Tight circuit	113	157	500	31.39737
113/51 x/cut	Manos	Tight circuit	113	0	500	5
104-66 X/cut Cooler	HI Energy	Open	114.8	140	500	27.94658
120/48 X/C	Manos	Tight circuit	118.9	46	500	9.131503
120/48 X/C	Manos	Tight circuit	118.9	46	500	9.131503
120/48 X/C	Manos	Tight circuit	118.9	124	500	24.81333
113/40 haulage	Manos	Open	116.4	174	500	34.71488
116/49 x/c	Manos	Tight circuit	119	502	500	100.3755
116/49 x/c	Manos	Tight circuit	119	451	500	90.16464
120/42	Viper	Open	121	457	500	91.33477
113 East Haulage	Manos	Tight circuit	119	107	500	21.43642
113/56	Viper	Open	119	387	500	77.31711

Table A.4: Cooling coils data - 2005.

Cooler Position:	Make of Cooler	Cooler T/Circuit/ Open	BP	Duty	Design Duty	Efficiency
120/45 X/C	U Airbrand	Tight circuit	119.8	125	500	25.08237
120/45 X/C	U Airbrand	Tight circuit	119.8	125	500	25.08237
113/40 Haulage	Manos	Tight circuit	115.3	652	500	130.4813
113/39 Haulage	Manos	Tight circuit	115.3	436	500	87.12744
99/69	Manos	Tight circuit	113.8	495	500	98.95093
99/69	Manos	Tight circuit	113.8	340	500	68.03583
113/52x-cut	viper	Tight circuit	119.4	263	500	52.69026
120/51	Manos	Open	121	480	500	96.07543
104/65	HI Energy	Open	115.7	187	500	37.34161
109/67 -68	Manos	Tight circuit	117.6	293	500	58.61191
104/68 (67 - 68)	Joules	Tight circuit	115.7	533	500	106.6337
104/69 (68-69)	Manos	Tight circuit	115.7	413	500	82.5528
104/68	Manos	Tight circuit	115.7	416	500	83.21766
99/68 X/CUT	U Airbrand	Open	113.8	213	500	42.57057
116/52	Viper	Open	121	418	500	83.57064
116/45 X/CUT	Manos	Open	117	254	500	50.7946
116/44 X/CUT	Manos	Open	117.4	273	500	54.67454
120/44 No.2	Manos	Open	118.3	220	500	43.98827
120-44 x/cut No1	Manos	Open	118.5	146	500	29.28645
116/40 x/cut	HI Energy	Open	117.4	282	500	56.44554
113/56	Viper	Open	119	476	500	95.10843
113 East Haulage	Manos	Tight circuit	119	183	500	36.64455
116/51	Viper	Open	121	338	500	67.56102
109/64	Manos	Open	117.7	137	500	27.43819
94 East Haulage	Manos	Tight circuit	111.04	205	500	41.08952
116 West(40/42)	Viper	Open	122	372	500	74.34479
113/39 Haulage	Manos	Tight circuit	115.3	238	500	47.52471
113/40 Haulage	Manos	Tight circuit	115.3	431	500	86.2702
109 East (66-67)	Manos	Open	117.6	451	500	90.17738
109/66	Manos	Tight circuit	117.6	292	500	58.48631
120/42	Viper	Open	121	457	500	91.39052
120/45 X/C	U Airbrand	Tight circuit	119.8	224	500	44.70014

120/45 X/C	U Airbrand	Tight circuit	119.8	110	500	22.0426
120/45 X/C	U Airbrand	Tight circuit	119.8	0	500	5
104/69 (68 - 69)	Manos	Tight circuit	115.7	416	500	83.15319
104/68 (67 -68)	Joules	Tight circuit	115.7	452	500	90.39066
104/66 X/cut Cooler	HI Energy	Open	114.8	137	500	27.3426
104/68	Manos	Tight circuit	115.7	407	500	81.32382
120/51	Manos	Open	121	468	500	93.63284
120/51	Manos	Open	122	666	500	133.2909
120/52	Manos	Open	122	462	500	92.45775
116/48 X/C	Manos	Tight circuit	117.9	301	500	60.11725
116/48	Manos	Tight circuit	117.9	155	500	31.01127
120/48 X/C	Manos	Tight circuit	118.9	100	500	20.07406
120/48 X/C	Manos	Tight circuit	118.9	100	500	20.07406
120/48 X/C	Manos	Tight circuit	118.8	218	500	43.59267
120/48 X/C	Manos	Tight circuit	118.9	100	500	20.07406
99/67	HI Energy	Open	113.8	69	500	13.82417
120/52	Manos	Open	122	462	500	92.45775
94/67 X/C	U Airbrand	Open	111.4	246	500	49.12038
89/67 X/Cut	U Airbrand	Open	110.4	373	500	74.58125
99/69	Manos	Open	113.8	160	500	32.02788
116/52	Viper	Open	121	418	500	83.57064
113 East Haulage	Manos	Tight circuit	119	104	500	20.77712
113/56	Viper	Open	119	453	500	90.60859
116/51	Viper	Open	121.1	221	500	44.22525
109/65 x-cut	viper	Open	117.6	280	500	56.04906
116/42 X/C	Manos	Tight circuit	115	179	500	35.70425
113/42 travelling way	Manos	Open	114.7	450	500	89.97703
109/42 x/cut	U Airbrand	Open	113.8	482	500	96.36803
116 West(40/42)	Viper	Open	121.2	330	500	66.0636
104/64	U Airbrand	Open	115.7	178	300	59.27332
104/65	HI Energy	Open	115.7	224	500	44.7275
104/65 x-cut	viper	Open	115.7	217	500	43.37212
99/67	HI Energy	Open	113.8	72	500	14.3637
99/69	Manos	Open	113.8	477	500	95.33394
104/68	Manos	Tight circuit	115.7	406	500	81.19947
104/63	U Airbrand	Open	115.7	155	300	51.51726
120/44/42	Viper	Open	121.2	388	500	77.65913
109-66	Manos	Tight circuit	116.9	118	500	23.58848
104-66 X/cut Cooler	HI Energy	Open	114.8	77	500	15.33683
120/42	Viper	Open	121	457	500	91.44635
113/52 x-cut	Viper	Tight circuit	119.4	216	500	43.19355
120/52	Manos	Open	121.1	384	500	76.75114
120/51	Manos	Open	121	511	500	102.237
109 East (66-67)	Manos	Tight circuit	117.6	368	500	73.61589
120/52	Manos	Open	122	354	500	70.85778
89/67 X/C	U Airbrand	Open	110.4	246	500	49.13797
89/67 x/c	U Airbrand	Open	110.4	246	500	49.13797
120/45 X/C	U Airbrand	Tight circuit	119.8	105	500	20.9687
120/45 X/C	U Airbrand	Tight circuit	119.8	209	500	41.83794
120/45 X/C	U Airbrand	Tight circuit	119.8	105	500	20.9687
116/52	Viper	Open	121	418	500	83.57064

113/56	Viper	Tight circuit	119	522	500	104.4025
116/40 (in haulage)	HI Energy	Open	119.6	74	500	14.70141
116/52	Manos	Open	121.5	333	500	66.62691
113 East Hlge	Manos	Tight circuit	119	389	500	77.7343
104-64	U Airbrand	Open	115.7	166	300	55.18635
116/51	Viper	Open	121.1	155	500	31.01687
109/65 x-cut	viper	Open	117.6	75	500	15.03404
120/48 X/C	Manos	Tight circuit	118.8	215	500	42.93597
120/48 X/C	Manos	Tight circuit	118.9	103	500	20.54529
89/67 X/C	U Airbrand	Open	110.4	268	500	53.53037
116/48 X/C	Manos	Tight circuit	117.9	177	500	35.48201
116/48 X/C	Manos	Tight circuit	117.9	106	500	21.15271
116 West(40/42)	Viper	Open	121.1	321	500	64.21278
116/44 X/CUT	Manos	Open	114	284	500	56.77577
104/65	open spray	Open	115.7	274	200	136.7551
120/52	Manos	Open	121.2	376	500	75.24907

Table A.5: Cooling coils data - 2004.

Cooler Position:	Make of Cooler	Cooler T/Circuit/ Open	BP	Duty	Design Duty	Efficiency
104/67	Manos	Tight circuit	115.7	425	500	85.0812
120/52	Manos	Open	121.2	376	500	75.24907
120/45 X/C	U Airbrand	Tight circuit	119.8	212	500	42.45418
120/45 X/C	U Airbrand	Tight circuit	119.8	23	500	4.612304
120/45 X/C	U Airbrand	Tight circuit	119.8	239	500	47.79443
120/51	Manos	Open	121	489	500	97.70383
113/52 x-cut	viper	Tight circuit	119	248	500	49.64407
104-66 X/cut Cooler	HI Energy	Open	115.4	0	500	5
120/44/42	Viper	Open	121	385	500	76.90991
120/42	Viper	Open	121	457	500	91.44635
109/42 x/cut cooler	U Airbrand	Tight circuit	117.6	378	500	75.62982
113/44 IN HLGE	Manos	Open	114.7	315	500	63.07961
113/44 X/CUT	Manos	Open	114.7	203	500	40.63138
116/42 X/C	Manos	Tight circuit	115	45	500	8.975846
116/42 X/C	Manos	Tight circuit	115	130	500	25.96365
109East (66-67)	Manos	Tight circuit	117.6	375	500	74.99927
120/44 x/cut	Manos	Open	118.2	257	500	51.34
120/ 51	Manos	Open	118	249	500	49.81137
120/52	Manos	Open	122	426	500	85.11134
116/52	Viper	Open	121	402	500	80.41143
113/56	Viper	Open	119	426	500	85.25841
113 East Haulage	Manos	Tight circuit	119	26	500	5.197679
116/52	Manos	Open	121.2	230	500	46.08537
120/45 X/C	U Airbrand	Tight circuit	119.8	205	500	40.98897
120/45 X/C	U Airbrand	Tight circuit	119.8	111	500	22.10979
120/45 X/C	U Airbrand	Tight circuit	119.8	205	500	40.98897
120/45 X/C	U Airbrand	Tight circuit	119.8	111	500	22.10979
104/64	U Airbrand	Open	115.7	115	300	38.27122
99/69 x/cut	Manos	Open	113.8	206	500	41.22129

120/52	Manos	Open	121.2	354	500	70.72573
116 West(40/42)	Viper	Open	119.2	329	500	65.74068
116 West(40/42)	Viper	Open	119.5	500	500	100
116 West(40/42)	Viper	Open	119.5	500	500	100
94 Haulage	Viper	Open	111.04	243	350	69.40695
109/64x-cut	Manos	Open	117.6	175	500	34.92036
109 East (66 - 67)	*Manos*	*Tight circuit*	*117.6*	*306*	500	61.25255
109 East (66 - 67)	Manos	Tight circuit	117.6	309	500	61.80939
120/42	Viper	Open	121	411	500	82.12388
104/63	U Airbrand	Open	115.7	148	300	49.42164
99/67	HI Energy	Open	113.8	12	500	2.400128
120/42	Viper	Open	121	327	500	65.30596
104/67	Manos	Tight circuit	115.7	421	500	84.10736
104/68 (67 - 68)	Joules	Tight circuit	115.7	208	500	41.66023
120/48 X/C	Manos	Tight circuit	118.9	86	500	17.27872
120/48 X/C	Manos	Tight circuit	118.8	117	500	23.4011
120/48 X/C	Manos	Tight circuit	118.8	117	500	23.4011
113/42 x/cut	Manos	Open	114.3	277	500	55.48243
109-42 x/cut	HI Energy	Open	113.5	220	500	44.00121
116/48 X/C	Manos	Tight circuit	117.9	60	500	11.96348
116/48 X/C	Manos	Tight circuit	117.9	129	500	25.77239
99/68 X/C	U Airbrand	Open	111.38	123	500	24.64229
120/42	Viper	Open	121	500	500	100
116/48 X/C	Manos	Tight circuit	117.9	69	500	13.75351
116/48 X/C	Manos	Tight circuit	117.9	129	500	25.77239
120/52	Manos	Open	121	387	500	77.32589
116/56 X-cut	Viper	Open	119	453	500	90.54555
113 East Haulage	Manos	Tight circuit	119	209	500	41.768
113/52	viper	Tight circuit	115.3	192	500	38.40829
120/51 x-cut	Manos	Open	409	881	500	176.2411
109/ (42 - 40)	U Airbrand	Tight circuit	117.6	163	500	32.50873
116/52	Manos	Open	101	80	500	16.05592
116/51	Viper	Open	119.2	223	500	44.54461
104/64	U Airbrand	Open	115.7	110	300	36.64824
99/66	HI Energy	Tight circuit	112.4	93	500	18.5979
116 West(40/42)	Viper	Open	119.2	302	500	60.37837
104/65	open spray	Open	115.7	216	500	43.2385
116-44 x/cut	Manos	Open	114.8	172	500	34.47039
116/42 X/C	Manos	Tight circuit	115	175	500	34.95405
120/45 X/C	U Airbrand	Tight circuit	119.8	92	500	18.49718
99/67	HI Energy	Open	113.8	76	500	15.29856
120/45 X/c	U Airbrand	Tight circuit	119.8	190	500	37.99727
120/45 X/C	U Airbrand	Tight circuit	119.8	92	500	18.49718
120/45 X/C	U Airbrand	Tight circuit	119.8	190	500	37.99727
120/42	Viper	Open	121	400	500	79.99311
120/44/42	Viper	Open	121	318	500	63.64564
109/63	U Airbrand	Open	117.6	80	300	26.63384
109/63	U Airbrand	Open	117.6	0	300	5
109/65 x-cut	viper	Open	117.6	230	500	45.90101
109 East (66-67)	Manos	Tight circuit	117.6	419	500	83.77281
109/65 x-cut	viper	Open	117.6	328	500	65.57287

120/48 X/C No1	Manos	Tight circuit	118.9	111	500	22.13092
120/48X/C No 2	Manos	Tight circuit	118.8	179	500	35.74339
120/52	Manos	Open	121.2	286	500	57.21447
113-42 x/cut	Manos	Open	114.6	216	500	43.19388
109-42 x/cut	HI Energy	Open	113	367	500	73.30484
113/42 x/cut	Manos	Open	114.6	216	500	43.19388
109-42 x/cut	HI Energy	Open	113	346	500	69.17659
116/45 x/cut	Manos	Open	113.6	417	500	83.37622
104-66 X/cut Cooler	HI Energy	Open	114.8	28	500	5.666035
104/68 (67 -68)	Joules	Tight circuit	115.7	648	500	129.6821
104/66-67	Manos	Tight circuit	117.6	193	500	38.52374
99/69	Manos	Open	113.8	330	500	66.00857
113/42 T/way	Manos	Open	115	234	500	46.7365
109/63	U Airbrand	Open	117.6	40	300	13.33087
120/42	Viper	Open	121.2	431	500	86.14348
120/44/42	Viper	Open	121	409	500	81.89481
116/56	Viper	Open	119	311	500	62.23106
116/ 52	Viper	Open	119	374	500	74.7349
113 East Haulage	Manos	Tight circuit	119	446	500	89.19965

Table A.6: Cooling coils data - 2003.

Cooler Position:	Make of Cooler	Cooler T/Circuit/ Open	BP	Duty	Design Duty	Efficiency
120/44 No:2	Manos	Open	117	254	500	50.8754453
120/44 No:1	Manos	Open	117	261	500	52.2468219
109/64 x-cut	Manos	Open	117.6	176	500	35.2331193
116/48	Manos	Tight circuit	117.9	218	500	43.6073862
116/48 X/Cut	Manos	Tight circuit	117.9	218	500	43.6073862
116/48 X/Cut	Manos	Tight circuit	117.9	118	500	23.6439729
116/48 X/Cut	Manos	Tight circuit	117.9	118	500	23.6439729
116/48	Manos	Tight circuit	117.9	487	500	97.3074049
116/48 X/Cut	Manos	Tight circuit	117.9	118	500	23.6439729
116 West (42/44)	Viper	Open	119.2	319	500	63.7327246
116 West (40/42)	Viper	Open	119.2	302	500	60.3783707
120/49 X/Cut	Manos	Tight circuit	125	228	500	45.5304867
120/49 X/cut	Manos	Tight circuit	125	260	500	51.9306079
109 East (66 - 67)	Manos	Tight circuit	117.6	331	500	66.2770663
99/69	Manos	Open	113.8	428	500	85.5481495
120/48 No 2	Manos	Tight circuit	118.9	129	500	25.8445229
120/48 No 2	Manos	Tight circuit	118.8	227	500	45.4529031
94/67 X/C	U Airbrand	Open	111.4	300	500	60.05994
104/63	U Airbrand	Open	115.7	175	500	34.9386738
109-52	HI Energy	Tight circuit	115.3	198	500	39.6781324
116/49 Stope	Manos	Tight circuit	119	278	500	55.5107934
116/49 X/Cut	Manos	Tight circuit	119	235	500	46.9348802
104/65 X/C	U Airbrand	Open	114.4	264	500	52.7551043
120/45 X/C	U Airbrand	Tight circuit	119.8	70	500	13.9822616
120/45 X/C	U Airbrand	Tight circuit	119.8	199	500	39.7759726
99/66	HI Energy	Tight circuit	112.4	66	500	13.1099191

120/52	Manos	Open	121.2	303	500	60.513268
113/51 x/cut	Manos	Tight circuit	113	111	500	22.2306011
104/68 (67 -66)	Joules	Tight circuit	115.7	530	500	106.049552
104 /66 - 67	Manos	Tight circuit	117.6	437	500	87.4977919
104/68 (67 - 66)	jOULES	Tight circuit	115.7	71	500	14.1956093
104/40 X/Cut	U Airbrand	Open	115	224	500	44.8000774
120/51	Manos	Open	121.2	342	500	68.3718542
94 Haualage	Viper	Open	111.04	59	350	16.8180997
116/52/51	Viper	Open	119.2	424	500	84.8176211
116/44	Viper	Open	119.2	302	500	60.3783707
116/42	Viper	Open	119.2	319	500	63.7327246
116/52/51	Viper	Open	119.2	742	500	148.430837
116/56/57	Viper	Open	119.2	341	500	68.1062824
116/51	Viper	Open	119.2	218	500	43.5831502
120/44/42	Viper	Open	121.2	365	500	72.9688572
120/44/42	Viper	Open	121.2	365	500	72.9688572
120/42 X-cut	Viper	Open	121.2	431	500	86.143481
113 East Haulage	Manos	Tight circuit	119	341	500	68.10656
89/67 X/C	U Airbrand	Open	110.4	515	500	103.04269
99/68	HI Energy	Open	112.4	173	500	34.6669472
104/42 Center raise	Manos	Tight circuit	115	246	500	49.1472383
104/42 X/C	Manos	Tight circuit	115	151	500	30.294452
113/40 Haulage	Manos	Tight circuit	115.3	443	500	88.5590022
120/44 x/cut (No.2)	Manos	Open	117.5	164	500	32.7281463
120/44 (No.1)	Manos	Open	117.5	259	500	51.7074669
116/44 x/cut	Manos	Open	115.9	442	500	88.4938851
116/44 (in hlge)	HI Energy	Open	115.9	412	500	82.4873758
109/63	U Airbrand	Open	117.6	40	500	7.99851983
99/67	HI Energy	Open	113.8	62	500	12.4370128
109 East (66-67)	Manos	Open	117.6	544	500	108.760721
109/66	Manos	Tight circuit	117.6	506	500	101.262192
113 East Haulage	Manos	Tight circuit	119	410	500	82.0725171
113/44 HLGE	HI Energy	Open	115.4	360	500	72.0625383
113/44 x/cut	HI Energy	Open	115.8	139	500	27.8189172
109/44 x/cut	Manos	Open	113.9	432	500	86.3655416
104/66 - 67	Manos	Tight circuit	117.6	334	500	66.7161462
104/68 (67 - 66)	Joules	Tight circuit	115.7	500	500	100
104/64	U Airbrand	Open	115.7	141	500	28.2736179
104/64	U Airbrand	Open	115.7	0	500	3.3621E-14
104/65 x-cut	U Airbrand	Open	115.7	187	500	37.4518033
120/48 No 1	Manos	Tight circuit	118.8	361	500	72.2743327
120/48 No2	Manos	Tight circuit	118.9	223	500	44.630014
109/62	Viper	Open	117.6	230	500	46.030834
94 Haulage	Viper	Open	111.04	243	350	69.3433412
99/69	Manos	Open	113.8	126	500	25.2866725
109/65 x-cut	viper	Open	117.6	175	500	35.0594546
120/48 N0 2	Manos	Tight circuit	118.8	340	500	68.0710293
120/48 no 1	Manos	Open	118.9	223	500	44.6994719
120/48	Manos	Tight circuit	118.8	0	500	5
120/48 No1	Manos	Tight circuit	118.9	223	500	44.6994719
120/48 No 1	Manos	Tight circuit	118.8	340	500	68.0710293

104/66 x-cut	HI Energy	Open	115.7	245	500	48.9182154
104/63	U Airbrand	Open	115.7	187	500	37.4949386
104.63	U Airbrand	Open	115.7	187	500	37.4367808
120/45 X/C	U Airbrand	Tight circuit	119.8	302	500	60.416245
120/45	U Airbrand	Tight circuit	119.8	111	500	22.2596744
113/49 X/Cut	Manos	Tight circuit	117	305	500	61.010275
120/52	Joules	Open	121.2	435	500	86.9799904
120/51	Manos	Open	121.2	475	500	95.0756112
113/51 Stope	Manos	Tight circuit	113	233	500	46.5939896
116/40	Viper	Open	119.2	55	500	10.9713455
116/44	Viper	Open	119.2	150	500	29.9754725
116/42	Viper	Open	119.2	103	500	20.5632758
120/48 X/cut	Manos	Tight circuit	115	254	500	50.7078784
120/48 X/Cut	Manos	Tight circuit	115	169	500	33.8944571
104/42 X/Cut	Manos	Tight circuit	115	126	300	42.1241289
116/48 X/Cut	Manos	Tight circuit	117.9	125	500	24.9986667
116/48 X/cut	Manos	Tight circuit	117.9	369	500	73.828822
116 Haulage	Manos	Tight circuit	115	0	500	0
120/42&40	Viper	Open	121.2	450	500	90.047197
120/44 &42	Viper	Open	121.2	365	500	72.9688572
116/44	HI Energy	Open	119.2	379	500	75.7064407
113/49 X/Cut	Manos	Tight circuit	117	247	500	49.3141663
99/67	HI Energy	Open	113.8	46	500	9.12912989

The averages for each year are shown in Figure A1. The average is steadily declining from the fact that more measurements are now taken to look at the overall system efficiency.

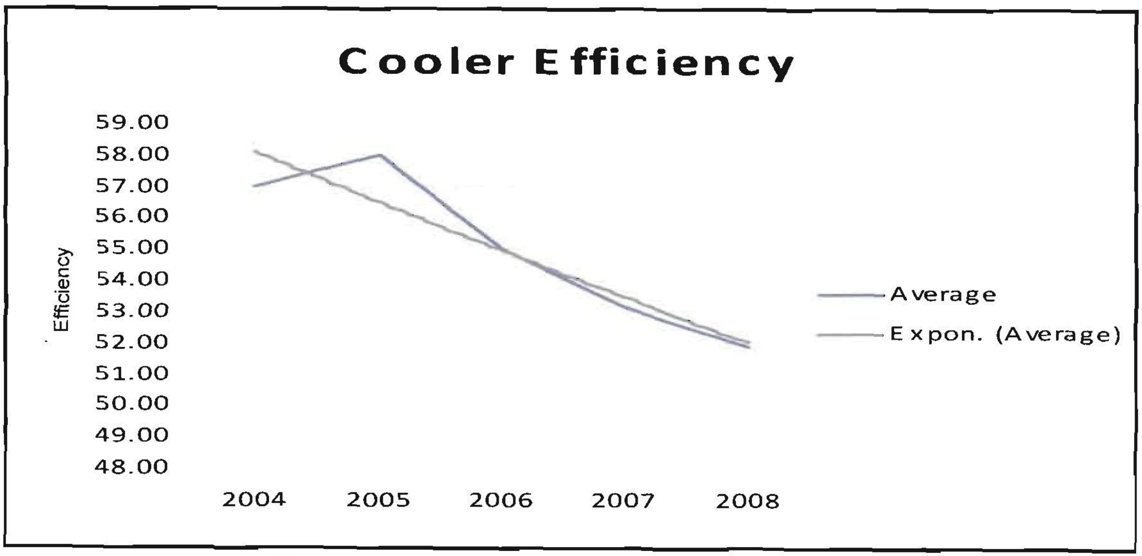


Figure A.1. Yearly averages for the CWCs at Mponeng.

Appendix B – Curve Fitting Data

This section covers the curve fitting (Q_{fit}) to determine the coefficients for the actual curve (Q) and the fitted curve. The procedure followed was to take the expected output at certain conditions (water flow, air flow, water temperature and air temperature) from the tables provided by Manos Engineering and edit it into EXCEL. With the use of the solver function the coefficients changed by minimizing the error for the curve. The following was the result of this process.

Table B.1: Water temperature of 10˚C and the varying flow of air and water.

Twi	10				
Water	Air	Q	Q_fit	Err^2	Percentage fault
7	8	333.36	330.65	7.370717	0.8144%
8	8	349.06	347.41	2.729773	0.4733%
9	8	361.83	361.33	0.247568	0.1375%
10	8	372.45	372.86	0.16457	0.1089%
11	8	381.39	382.41	1.048908	0.2685%
12	8	389	390.44	2.086771	0.3714%
13	8	395.58	397.38	3.252769	0.4559%
14	8	401.28	403.67	5.701369	0.5950%
				22.60244	0.4031%
7	9	352.44	350.39	4.190805	0.5808%
8	9	370.7	369.20	2.252438	0.4049%
9	9	385.75	385.01	0.543665	0.1911%
10	9	398.33	398.27	0.003607	0.0151%
11	9	408.95	409.41	0.209475	0.1119%
12	9	418.08	418.86	0.612382	0.1872%
13	9	425.94	427.07	1.279598	0.2656%
14	9	432.84	434.47	2.65781	0.3766%
				11.74978	0.2667%
7	10	369.2	368.09	1.242114	0.3019%
8	10	389.98	388.90	1.164154	0.2767%
9	10	407.19	406.57	0.385724	0.1525%
10	10	421.69	421.53	0.02695	0.0389%
11	10	434.07	434.21	0.019157	0.0319%
12	10	444.68	445.05	0.139363	0.0840%
13	10	453.94	454.50	0.310479	0.1227%
14	10	462	462.98	0.954036	0.2114%
				4.241977	0.1525%
7	11	384	383.90	0.010863	0.0271%
8	11	407.14	406.69	0.206019	0.1115%
9	11	426.55	426.17	0.141379	0.0881%

10	11	442.93	442.80	0.017928	0.0302%
11	11	456.99	456.99	8.28E-07	0.0002%
12	11	469.12	469.19	0.004846	0.0148%
13	11	479.7	479.83	0.018045	0.0280%
14	11	489	489.36	0.129535	0.0736%
				0.528616	0.0467%
7	12	397.12	398.00	0.768143	0.2207%
8	12	422.58	422.73	0.021649	0.0348%
9	12	444.03	444.00	0.000864	0.0066%
10	12	462.29	462.25	0.001333	0.0079%
11	12	478.03	477.92	0.011562	0.0225%
12	12	491.64	491.44	0.038339	0.0398%
13	12	503.54	503.26	0.08104	0.0565%
14	12	514.08	513.79	0.082647	0.0559%
				1.005576	0.0556%
7	13	408.88	410.56	2.823191	0.4109%
8	13	436.5	437.20	0.485647	0.1597%
9	13	459.95	460.22	0.073716	0.0590%
10	13	480.01	480.07	0.003692	0.0127%
11	13	497.35	497.18	0.028455	0.0339%
12	13	512.44	511.99	0.202665	0.0879%
13	13	525.74	524.93	0.651358	0.1535%
14	13	537.44	536.45	0.985414	0.1847%
				5.254138	0.1378%
7	14	419.4	421.76	5.569218	0.5627%
8	14	449.14	450.27	1.272602	0.2512%
9	14	474.47	475.01	0.291013	0.1137%
10	14	496.25	496.42	0.029124	0.0344%
11	14	515.19	514.94	0.063323	0.0488%
12	14	531.72	531.00	0.519519	0.1356%
13	14	546.34	545.04	1.690243	0.2380%
14	14	559.28	557.50	3.178842	0.3188%
				12.61388	0.2129%
7	15	428.92	431.77	8.112471	0.6640%
8	15	460.58	462.11	2.351704	0.3330%
9	15	487.75	488.54	0.619689	0.1614%
10	15	511.25	511.48	0.051044	0.0442%
11	15	531.71	531.37	0.118086	0.0646%
12	15	549.68	548.65	1.070879	0.1883%
13	15	565.58	563.75	3.352568	0.3237%
14	15	579.68	577.11	6.581707	0.4426%
				22.25815	0.2777%

Table B.2: Water temperature of 12.5˚C and the varying flow of air and water.

Twi	12.5				
Water	Air	Q	Q_fit	Err^2	Percentage fault
7	8	293.54	293.26	0.078903	0.0957%
8	8	307.6	307.56	0.001653	0.0132%
9	8	319.1	319.29	0.035376	0.0589%
10	8	328.64	328.88	0.058564	0.0736%
11	8	336.66	336.78	0.013864	0.0350%
12	8	343.52	343.41	0.011669	0.0314%
13	8	349.5	349.22	0.077641	0.0797%
14	8	354.64	354.64	6.49E-06	0.0007%
				0.277676	0.0485%
7	9	310.14	309.84	0.089504	0.0965%
8	9	326.44	326.18	0.065182	0.0782%
9	9	339.9	339.80	0.00955	0.0288%
10	9	351.16	351.13	0.000886	0.0085%
11	9	360.7	360.61	0.008981	0.0263%
12	9	368.88	368.66	0.046689	0.0586%
13	9	375.98	375.74	0.056182	0.0630%
14	9	382.2	382.28	0.006247	0.0207%
				0.283222	0.0476%
7	10	324.7	324.57	0.016359	0.0394%
8	10	343.16	342.93	0.055145	0.0684%
9	10	358.54	358.40	0.020401	0.0398%
10	10	371.52	371.42	0.009072	0.0256%
11	10	382.54	382.44	0.009105	0.0249%
12	10	392.08	391.89	0.034852	0.0476%
13	10	400.38	400.21	0.029718	0.0431%
14	10	407.64	407.82	0.033904	0.0452%
				0.208554	0.0418%
7	11	337.54	337.63	0.007338	0.0254%
8	11	358.12	357.95	0.027714	0.0465%
9	11	375.38	375.25	0.018084	0.0358%
10	11	390	389.94	0.003806	0.0158%
11	11	402.54	402.47	0.005105	0.0177%
12	11	413.4	413.27	0.016154	0.0307%
13	11	422.86	422.79	0.00518	0.0170%
14	11	431.2	431.45	0.062791	0.0581%
				0.146172	0.0309%
7	12	348.98	349.17	0.037744	0.0557%
8	12	371.56	371.44	0.013804	0.0316%
9	12	390.58	390.52	0.00359	0.0153%
10	12	406.84	406.84	1.34E-05	0.0009%
11	12	420.82	420.85	0.000893	0.0071%
12	12	433	432.98	0.000603	0.0057%
13	12	443.66	443.66	9.18E-06	0.0007%

14	12	453.04	453.33	0.084763	0.0643%
				0.14142	0.0227%
7	13	359.18	359.39	0.04439	0.0587%
8	13	383.64	383.56	0.005644	0.0196%
9	13	404.42	404.39	0.000697	0.0065%
10	13	422.24	422.31	0.005408	0.0174%
11	13	437.7	437.76	0.003763	0.0140%
12	13	451.12	451.17	0.002881	0.0119%
13	13	462.94	462.99	0.002227	0.0102%
14	13	473.44	473.64	0.039425	0.0419%
				0.104436	0.0225%
7	14	368.34	368.45	0.011589	0.0292%
8	14	394.6	394.49	0.011372	0.0270%
9	14	417.06	417.04	0.000448	0.0051%
10	14	436.4	436.52	0.014571	0.0277%
11	14	453.22	453.38	0.024232	0.0343%
12	14	467.96	468.04	0.006457	0.0172%
13	14	480.94	480.95	0.000131	0.0024%
14	14	492.44	492.55	0.011148	0.0214%
				0.079948	0.0205%
7	15	376.59	376.52	0.005196	0.0191%
8	15	404.6	404.40	0.039708	0.0493%
9	15	428.62	428.63	7.25E-05	0.0020%
10	15	449.44	449.64	0.039173	0.0440%
11	15	467.62	467.87	0.060324	0.0525%
12	15	483.56	483.75	0.035435	0.0389%
13	15	497.7	497.72	0.000505	0.0045%
14	15	510.28	510.22	0.003028	0.0108%
				0.183442	0.0276%

Table B.3: Water temperature of 15°C and the varying flow of air and water.

Twi	15				
Water	Air	Q	Q_fit	Err^2	Percentage fault
7	8	253.16	255.75	6.713011	1.0234%
8	8	265.46	267.46	4.005783	0.7540%
9	8	275.53	276.87	1.787641	0.4853%
10	8	283.95	284.40	0.206436	0.1600%
11	8	291.02	290.51	0.260017	0.1752%
12	8	297.11	295.62	2.217496	0.5012%
13	8	302.34	300.17	4.694202	0.7166%
14	8	306.92	304.60	5.362529	0.7545%
				25.24711	0.5713%
7	9	267.28	269.12	3.380567	0.6879%

8	9	281.5	282.87	1.884464	0.4877%
9	9	293.28	294.17	0.787081	0.3025%
10	9	303.15	303.44	0.083259	0.0952%
11	9	311.53	311.12	0.16522	0.1305%
12	9	318.75	317.66	1.190762	0.3423%
13	9	325.02	323.48	2.368638	0.4735%
14	9	330.48	329.03	2.111981	0.4397%
				11.97197	0.3699%
7	10	279.68	280.84	1.346818	0.4149%
8	10	295.78	296.60	0.678744	0.2785%
9	10	309.2	309.75	0.305471	0.1787%
10	10	320.51	320.72	0.045663	0.0667%
11	10	330.21	329.95	0.065791	0.0777%
12	10	338.55	337.88	0.450517	0.1983%
13	10	345.82	344.94	0.78106	0.2556%
14	10	352.2	351.56	0.406468	0.1810%
				4.080532	0.2064%
7	11	290.6	291.09	0.23949	0.1684%
8	11	308.5	308.83	0.107257	0.1062%
9	11	323.52	323.80	0.076359	0.0854%
10	11	336.31	336.43	0.015014	0.0364%
11	11	347.25	347.17	0.005967	0.0222%
12	11	356.71	356.45	0.065706	0.0719%
13	11	365.02	364.71	0.09491	0.0844%
14	11	372.32	372.38	0.00412	0.0172%
				0.608822	0.0740%
7	12	300.33	300.04	0.085299	0.0972%
8	12	319.94	319.72	0.049982	0.0699%
9	12	336.52	336.47	0.002417	0.0146%
10	12	350.67	350.74	0.0046	0.0193%
11	12	362.85	362.95	0.010825	0.0287%
12	12	373.47	373.56	0.007422	0.0231%
13	12	382.78	382.98	0.040328	0.0525%
14	12	391.04	391.66	0.390246	0.1598%
				0.59112	0.0581%
7	13	309.04	307.86	1.394845	0.3822%
8	13	330.26	329.44	0.666826	0.2473%
9	13	348.29	347.95	0.116301	0.0979%
10	13	363.79	363.81	0.000498	0.0061%
11	13	377.25	377.47	0.048448	0.0583%
12	13	388.95	389.36	0.167281	0.1052%
13	13	399.3	399.92	0.379029	0.1542%
14	13	408.44	409.58	1.292148	0.2783%
				4.065375	0.1662%
7	14	316.84	314.73	4.472375	0.6675%

8	14	339.58	338.18	1.956721	0.4119%
9	14	359.06	358.40	0.431027	0.1828%
10	14	375.87	375.83	0.0017	0.0110%
11	14	390.49	390.89	0.16298	0.1034%
12	14	403.31	404.03	0.525566	0.1798%
13	14	414.62	415.69	1.143146	0.2579%
14	14	424.68	426.29	2.601863	0.3798%
				11.29538	0.2743%
7	15	323.88	320.81	9.428579	0.9481%
8	15	348.1	346.10	3.990084	0.5738%
9	15	368.92	368.01	0.833388	0.2475%
10	15	386.99	386.96	0.000905	0.0078%
11	15	402.77	403.40	0.393869	0.1558%
12	15	416.63	417.76	1.269637	0.2705%
13	15	428.94	430.47	2.353617	0.3577%
14	15	439.88	441.99	4.436731	0.4788%
				22.70681	0.3800%

Figure B 1 shows the accuracy of the fitting to the actual curve. The average error made on the fitting was 0.16 %.

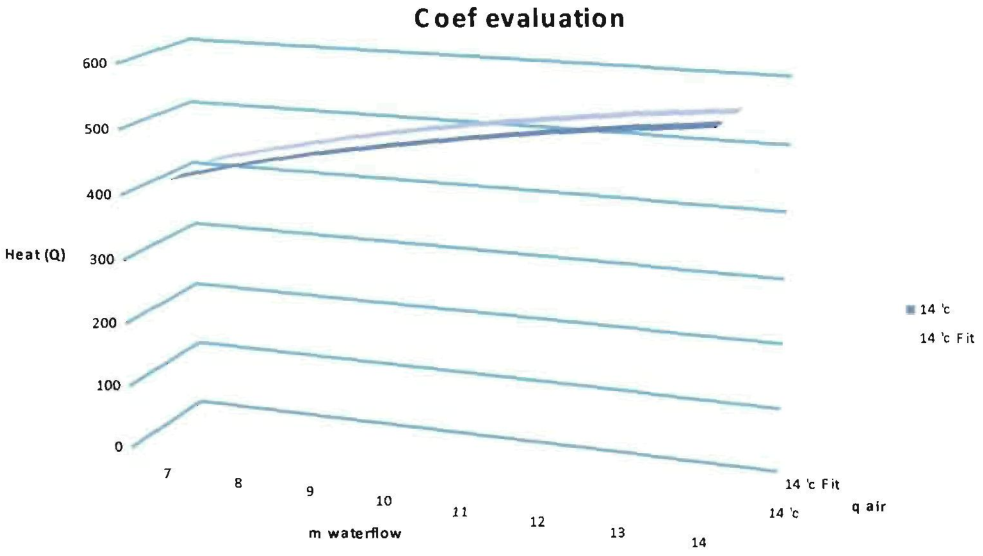
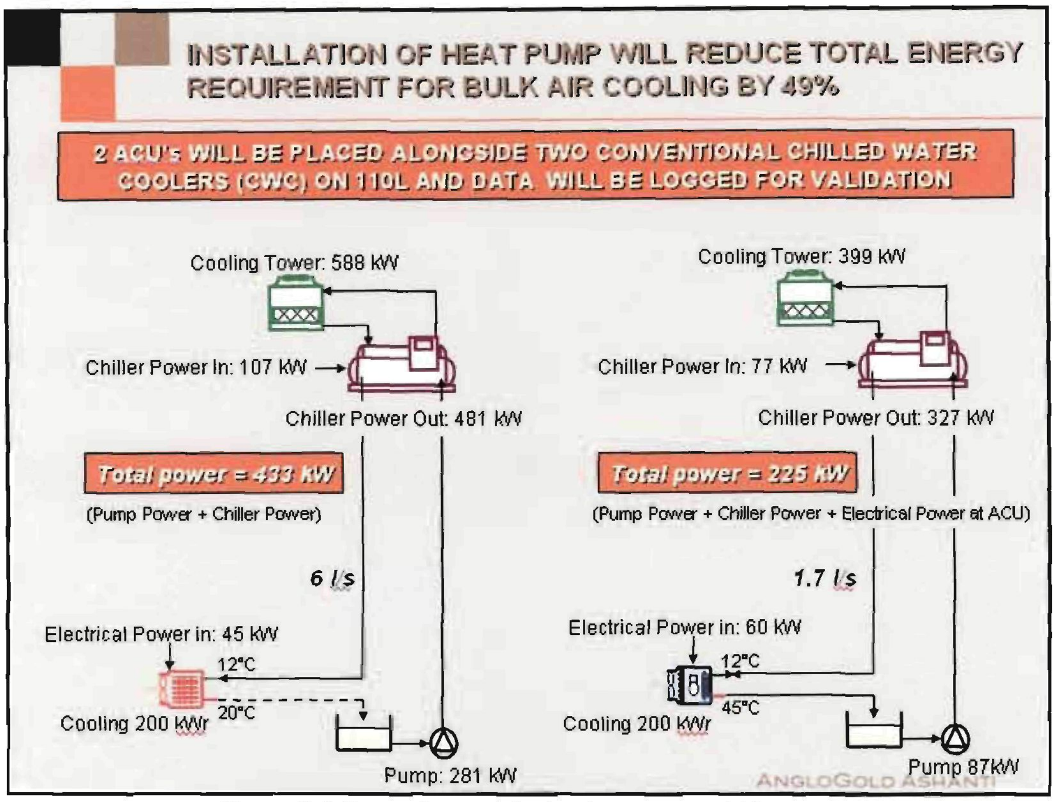


Figure B.1.Curve fitting result.

Appendix C – Mponeng Business Case

The business case focuses on the presentation that M -Tech Industrial did along with MSP (Mining Support Products) at Mponeng. Figure C.1 shows the comparison between the ACU and CWC if operated on 100L with no energy recovery turbines in the system.



INSTALLATION OF HEAT PUMP WILL REDUCE TOTAL ENERGY REQUIREMENT FOR BULK AIR COOLING BY 49%

2 ACU's WILL BE PLACED ALONGSIDE TWO CONVENTIONAL CHILLED WATER COOLERS (CWC) ON 110L AND DATA WILL BE LOGGED FOR VALIDATION

Figure C.1.Scenario used for business case at Mponeng.

Table C.1: Business case done for Mponeng Mine.

Technical requirements:		
Required cooling load	200	[kW]
Assume average chilled water inlet temperature to CWC or ACU	11.6	[C]
Assume pump efficiency	70.0%	
Water must be pumped back up to surface from level	110	
Elevation against which water must be pumped back to surface	3353	[m]
Required static pump head i.e. neglecting frictional losses	32856	[kPa]
Assume average annual utility running time of plant	95.0%	
For CWC/SC:		
Assume water temperature rise through CWC	8.0	[C]

Required chilled water mass flow rate through machine	6.0	[kg/s]
Required pumping power	281	[kW]
Required surface chiller cooling load	481	[kW]
Required surface cooling tower cooling load	588	[kW]
Assume surface chiller COP as	4.5	
Required chiller compressor power	107	[kW]
Total required pumping and compressor power	433	[kW]
Capital cost of CWC or SC per kW cooling capacity	R 640	[R/kW]
Capital cost of surface chiller per kW cooling capacity	R 3,600	[R/kW]
Capital cost of surface cooling tower per kW cooling capacity	R 150	[R/kW]
Capital cost of pumps per kW pumping power	R 0	[R/kW]
Required capital cost	R 1,946,803	
For ACU:		
Control outlet water temperature from machine at	45.0	[C]
Water temperature rise through machine	33.4	[C]
Required chilled water mass flow rate through machine	1.7	[kg/s]
Required pumping power	82	[kW]
Assume ACU COP conservatively as	4.5	
Required ACU compressor power	44	[kW]
Required surface chiller cooling load	327	[kW]
Required surface cooling tower cooling load	399	[kW]
Assume surface chiller COP as	4.5	
Required chiller compressor power	73	[kW]
Total required pumping and compressor power	199	[kW]
Capital cost of ACU per kW cooling capacity	R 2,800	[R/kW]
Required capital cost	R 1,795,753	

Comparison between ACU and CWC/SC:			
Delta in power requirement between ACU and CWC/SC	-233	[kW]	
Delta in energy requirement per year	-1,941,996	[kWh]	
Delta in capital cost requirement	-R 151,050		
ESKOM CDSM parameters:			
Activate ESKOM subsidy (Y/N)	y		
ESKOM subsidy based on total or additional cost (T/A)	t		
Delta in average power requirement between ACU and CWC/SC	222	[kW]	
Required total/additional capital cost for ACUs per kW saving	8,100	[R/kW]	
Potential ESKOM subsidy	R 775,912		
Assumed financial analysis variables:			
Current weighted average kWh cost	R 0.16		
Discount rate	6.5%		
Delta in energy cost for year 0	-R 310,719		
Cash flow and cost benefit analysis:			
Cash flow year 0	R 926,962		
1	R 357,327	15.0%	nu al ele ctri city

2	R 410,926	15.0%	
3	R 437,637	6.5%	
4	R 466,083	6.5%	
5	R 496,378	6.5%	
6	R 528,643	6.5%	
PP of total delta in capital and running cost	**0.0**	years	
NPV of total delta in capital and running cost	**R 2,886,353**		

Appendix D – Economical Analysis

This section covers the complete economical analysis for the closed loop and settler scenarios.

Table D.1 shows the evaluation of the total power requirements for the closed loop scenario with an underground cooling load of 24MW.

Table D.1: Calculation of the total load underground.

CL Project - ACU Feasibility Study							
Scenario 1	CWC		Scenario 2	ACU		Scenario 3	CWC - ACU
Reservoir							
Boundary Conditions							
Bp_120L (bar)	1.21		Bp_120L (bar)	1.21		Bp_120L (bar)	1.21
Average haulage DB ('C)	35		Average haulage DB ('C)	35		Average haulage DB ('C)	35
Flownex Simulation Values							
T_wo Ice Dam ('C)	8.5		T_wo Ice Dam ('C)	8.5		T_wo Ice Dam ('C)	8.5
T_wi Ice Dam ('C)	18.73		T_wi Ice Dam ('C)	39.497		T_wi Ice Dam ('C)	30.1581
M_w (kg/s)	657.81		M_w (kg/s)	246.31		M_w (kg/s)	350.725
M_ice (kg/s)	84.61256		M_ice (kg/s)	95.99761		M_ice (kg/s)	95.50933163
Cp_water (kJ/kg)	4.187		Cp_water (kJ/kg)	4.187		Cp_water (kJ/kg)	4.187
Cp_ice (kJ/kg)	333		Cp_ice (kJ/kg)	333		Cp_ice (kJ/kg)	333
P_wo (Bar)	18.0393		P_wo (Bar)	21.7011		P_wo (Bar)	20.55
P_wi (Bar)	1.18879		P_wi (Bar)	1.31486		P_wi (Bar)	1.31486
1.Power Requirements - Cooler							
Water - System							
Q_Out Underground (kW)	24000		Q_Out Underground (kW)	24000		Q_Out Underground (kW)	24000
Q_cooling System (kW)	28175.98		Q_cooling System (kW)	31967.21		Q_cooling System (kW)	31804.60743
Q_Coolers (kW)	48000		Q_Coolers (kW)	30000		Q_Cooler CWC	24000
Cooler_efficiency	50%		C.O.P	4		Q_Cooler ACU	14400
Slider - Coils Efficiency	50		Slider - COP	40		Q_Cooler Total (kW)	38400
						C.O.P	4
						Cooler_efficiency	50%
Electrical - Coolers							
Unit (kW)	500		Unit (kW)	300		Unit (kW)	500
Fan Power (kW)	45		Fan Power (kW)	17		Fan Power (kW)	45
Coolers	96		Coolers	80		Coolers	48
						Unit (kW)	300
						Fan Power (kW)	17
						Coolers	39

Q_Fan (kW)	3024		Q_Fan (kW)	952		Q_Fan (kW)	1976.1
Q_Compressor (kW)	0		Q_Compressor (kW)	4800		Q_Compressor (kW)	2400
Q_Motor (kW)	4320		Q_Motor (kW)	7360		Q_Motor (kW)	5823
Pumping - System							
Pressure (kPa)	1803.93		Pressure (kPa)	2170.11		Pressure (kPa)	2054.11
Flow (m^3/s)	0.65781		Flow (m^3/s)	0.24631		Flow (m^3/s)	0.350725
Q_Pump (kW)	1186.643		Q_Pump (kW)	534.5198		Q_Pump (kW)	720.4277298
Q_Motor (kW)	1502.08		Q_Motor (kW)	676.6073		Q_Motor (kW)	911.9338351
2.Power Requirements - Ice Plant							
Electrical - ICE PLANTS							
Plant - IDE 3 MW							
Input - Compressor (kW)	4000		Input - Compressor (kW)	5000		Input - Compressor (kW)	5000
Ice Plants Needed	4		Ice Plants Needed	5		Ice Plants Needed	5
COP	3		COP	3		COP	3
3.Power Requirements - Fridge Plant							
Electrical - FRIDGE PLANTS							
Plant - 11 MW Hitachi							
Input - Compressor (kW)	664.813		Input - Compressor (kW)	754.267		Input - Compressor (kW)	750.4304628
Fridge Plants Needed	0.332406		Fridge Plants Needed	0.377133		Fridge Plants Needed	0.375215231
Water (kg/s)	116.3423		Water (kg/s)	131.9967		Water (kg/s)	131.325331
COP	5		COP	5		COP	5
Total Power Consumption							
Total Load (kW)	38662.88		Total Load (kW)	45758.08		Total Load (kW)	44289.97173

Table D.2: Cost calculation of scenario 1-3.

	CWC	ACU	ACU & CWC		
Cooler Capacity	500.00	300.00	300.00	500.00	kW
Efficiency and COP	50%	4			
Effective Cooler Capacity	250.00	375.00	375.00	285.00	kW
Refrigeration Load	28,175.98	31,967.21	31,804.61		kW
Compressors - ICE	4,000.00	5,000.00	5,000.00		kW
Compressors - FRIDGE	664.81	754.27	750.43		kW
Fan Load - Electrical	4,320.00	7,360.00	5,823.00		kW
Pumping Load	1,502.08	676.61	911.93		kW
Total Load on System (TL)	38,662.88	45,758.08	44,289.97		kW
Cooling Extracted	24,000.00	24,000.00	24,000.00		kW
Compared Cooling on TL	24,000.00	24,000.00	24,000.00		kW
Delta on Load	0.00	7,095.20	5,627.10		kW
Capital Cost Per Unit	158,000.00	750,000.00	750,000.00	158,000.00	R

Number of units Required	96.00	80.00	39.00	48.00	
Capital Cost Per kW cooling Capacity	632.00	2,000.00	2,000.00	554.39	R/kW
Assumed Plant Availability	95.00	95.00	95.00	95.00	%
Delta on energy requirement per year	0.00	59,046,289.33	46,828,696.76		kWh
Total Capital Cost	15,168,000.00	60,000,000.00	36,834,000.00		R
Current Weighted average kWh cost	0.28	0.28	0.28		R/kWh
Cost of Consumed Energy per annum	24,436,138.50	32,134,943.65	29,092,896.47		R
Delta in Capital Cost	0.00	44,832,000.00	21,666,000.00		R
Year 0	-15,168,000.00	-44,832,000.00	-21,666,000.00		R
Year 1	-39,604,138.50	-76,966,943.65	-50,758,896.47		R
Year 2	-64,040,276.99	-109,101,887.29	-79,851,792.94		R
Year 3	-88,476,415.49	-141,236,830.94	-108,944,689.42		R
Year 4	-112,912,553.99	-173,371,774.58	-138,037,585.89		R
Year 5	-137,348,692.49	-205,506,718.23	-167,130,482.36		R
Year 6	-161,784,830.98	-237,641,661.88	-196,223,378.83		R
Year 7	-186,220,969.48	-269,776,605.52	-225,316,275.31		R
Year 8	-210,657,107.98	-301,911,549.17	-254,409,171.78		R
Year 9	-235,093,246.47	-334,046,492.82	-283,502,068.25		R
Year 10	-259,529,384.97	-366,181,436.46	-312,594,964.72		R
Year 11	-283,965,523.47	-398,316,380.11	-341,687,861.20		R
Year 12	-308,401,661.97	-430,451,323.75	-370,780,757.67		R
Year 13	-332,837,800.46	-462,586,267.40	-399,873,654.14		R
Year 14	-357,273,938.96	-494,721,211.05	-428,966,550.61		R
Year 15	-381,710,077.46	-526,856,154.69	-458,059,447.09		R
Year 16	-406,146,215.95	-558,991,098.34	-487,152,343.56		R
Year 17	-430,582,354.45	-591,126,041.99	-516,245,240.03		R
Year 18	-455,018,492.95	-623,260,985.63	-545,338,136.50		R
Year 19	-479,454,631.44	-655,395,929.28	-574,431,032.98		R
Year 20	-503,890,769.94	-687,530,872.92	-603,523,929.45		R
Year 21	-528,326,908.44	-719,665,816.57	-632,616,825.92		R
Year 22	-552,763,046.94	-751,800,760.22	-661,709,722.39		R
Year 23	-577,199,185.43	-783,935,703.86	-690,802,618.87		R
Year 24	-601,635,323.93	-816,070,647.51	-719,895,515.34		R
Year 25	-626,071,462.43	-848,205,591.16	-748,988,411.81		R

Table D.3: Cost calculation of scenario 5.

Scenario5		
Water - Settler		
Two - S (Settler)	28	°C
Twi - HD (Hot Dam)	40	°C
Flow	240	kg/s
Specific Heat Cap	4.187	kJ/kg.k
Heat Extracted S-HD	12058.56	kW
Total Load on System	42,458.45	kW
Cooling Extracted	33,783.00	kW
Load on System		
CWC		
Refrigeration Load	28,175.98	kW
Fan Power	4,320.00	kW
Compressors - ICE	4,000.00	kW
Compressors - FRIDGE	664.81	kW
Pumping Load	1,502.08	kW
Total Load CWC	38,662.88	kW
ACU		
Fan Power	546.65	kW
Compressors	2,411.71	kW
Total Load ACU	3,795.58	kW
Total Load	42,458.45	kW
Cost Analysis		
Unit		
CWC Cost	15,168,000.00	R
ACU Cost	22,509,312.00	R
Annual Operation Cost		
Fan Power CWC	8,987,760.00	R
Fan Power ACU	1,137,315.14	R
Compressor Power ACU	5,017,566.82	R
Total Installation Cost	37,677,312.00	R
Total Operation Cost	27,972,862.76	R
Energy		
Additional Energy Extracted	12,058.56	kW
Comperative Load Value	9,551.73	kW
Cost of Annual Load	19,872,382.75	R
Economic Analysis		
Year 0	-37,677,312.00	R
Year 1	-57,549,694.75	R
Year 2	-77,422,077.49	R
Year 3	-97,294,460.24	R
Year 4	-117,166,842.98	R
Year 5	-137,039,225.73	R
Year 6	-156,911,608.47	R

Year 7	-176,783,991.22	R
Year 8	-196,656,373.96	R
Year 9	-216,528,756.71	R
Year 10	-236,401,139.45	R
Year 11	-256,273,522.20	R
Year 12	-276,145,904.94	R
Year 13	-296,018,287.69	R
Year 14	-315,890,670.44	R
Year 15	-335,763,053.18	R
Year 16	-355,635,435.93	R
Year 17	-375,507,818.67	R
Year 18	-395,380,201.42	R
Year 19	-415,252,584.16	R
Year 20	-435,124,966.91	R
Year 21	-454,997,349.65	R
Year 22	-474,869,732.40	R
Year 23	-494,742,115.14	R
Year 24	-514,614,497.89	R
Year 25	-534,486,880.63	R
NPV over 25 years @ 12%	-193,538,397.11	R
Energy Ratio	0.80	
Factor to Base Case	0.710416482	