DEMAND-SIDE ENERGY MANAGEMENT OF A CASCADE MINE SURFACE REFRIGERATION SYSTEM

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Dissertation submitted in partial fulfilment of the requirements for the
Degree Magister in Mechanical Engineering at the
North-West University

Promoter: **Dr. M. Kleingeld**

November 2007
Pretoria

ABSTRACT

Title:	Demand-side energy management of a cascade mine surface refrigeration system
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Faculty:	Engineering
Degree:	Master of Engineering (Mechanical)

The world is energy-dependant and depending on electricity more than anything else. With unsustainable resources such as coal and fossil fuels diminishing, the generation of sufficient electricity is becoming more strenuous.

Eskom is currently struggling to supply the South African consumer demand-side evening peak. The problem with energy supply and demand is set to last until 2012. Load shedding occurred more than once across South Africa in 2007. Eskom has started Demand-Side Management (DSM) projects to reduce the evening peak time demand.

The mining industry is one of the largest energy consumers in South Africa. The deeper that mining companies mine gold, the more energy intensive and costly the mining becomes. Mining gold deeper causes an uninhabitable hot and humid environment due to the virgin rock temperature at depth.

It is a legal requirement that mines cool down the working environment. This is done with chilled water from the mine's refrigeration systems. Using water as a cooling medium adds to the water pumping load of the mine.

The large electricity consuming systems on the mine are the rock hoisting, compressed air, water pumping and refrigeration systems. With the refrigeration system as one of the largest electricity consuming systems on the mine it warrants investigations for Demand-Side Management projects.

The investigations focus on load shifting, load clipping and energy efficiency through control strategies. Load shifting is achieved by increasing the amount of work done in the Eskom non-peak period. This then results in a decrease in the Eskom peak time work load.

The mine refrigeration system is modelled and verified with the data. A simulation is made from the model and the simulation is used to develop the new control strategy and new operational parameters. Predicted results are verified to be within production operational constraints.

A case study was carried out to prove the effectiveness of the newly developed control strategy and operational parameters. Firstly the cascade mine surface refrigeration system is automated to allow remote viewing and control of the system from a central point. The control strategy is tested through implementation on automated mine refrigeration systems.

The real-time energy management system (REMS) is set up and the communication with the SCADA is tested through observing dam level temperatures and stopping and starting refrigeration machines. The decisions the controllers make are monitored until the system is fully automated.

The results of the new control system on the flows, temperatures, dam levels, thermal energy and electrical energy are validated and verified. An assessment of the case study proved that DSM can be done on cascade mine refrigeration systems. A 4.2 MW load shift was predicted and research found an over performance of 0.3 MW. It is clear from the results that utilising the thermal storage in cascade mine surface refrigeration systems, will allow DSM load shifting.

In general, this dissertation proved DSM can be done on refrigeration systems and it is recommended that further studies be done on underground mine refrigeration systems.

SAMEVATTING

Titel:	Aanvraag-kant energie bestuur van 'n kaskade myn oppervlak verkoelingsaanleg
Outeur:	Abraham Jacobus Schutte
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Die wêreld is energie-afhanklik en is meer afhanklik van elektriese energie as van enige iets anders. Met nie-volhoubare bronne van energie soos steenkool en met fosiel brandstowwe wat minder word, word die opwek van elektriese energie moeiliker.

Eskom sukkel huidiglik om die verbruiker se aanvraag-kant aandpiek te genereer. Die probleme rakende die opwekking van elektrisiteit word verwag om tot 2012 voort te duur. Eskom se las verminderings inisiatief is meer as een keer regoor Suid-Afrika in 2007 toegepas. Tans is Eksom besig met aanvraag-kant bestuur projekte om die las van die aandpiek te verminder.

Die mynbou bedryf is een van die grootste energie verbruikers in Suid-Afrika. Hierdie bedryf word egter meer energie intensief en duurder hoe dieper die goud of stof gemyn word. Die ontblote rots temperature op die dieptes van die goud-myn veroorsaak 'n onbewoonbare warm en bedompige werksomgewing.

Die Suid-Afrikanse wetgewing verplig myne om die werksomgewing af te koel. Die myne koel en ontwasem die werksplekke deur gebruik te maak van verkoelde water vanaf die myn se water verkoelingsaanleg. Deur water te gebruik as verkoelings medium dra by tot die myn water pomp stelsel se las.

Die groot elektriese energie verbruik stelsels op die myn is die rots heisers, druk lug, water pomp en water verkoelings stelsels. Met die verkoelings aanlegte as een van die grootste elektriese energie verbruikers op die myn en word dus ondersoek vir Aanvraag-kant bestuurs projekte.

Die ondersoeke fokus daarop om die elektriese aanvraag las te skuif, die aanvraag las te sny en die stelsel meer energie effektief te maak met behulp van beheerstelsels. Las skuif word gedoen deur meer werk buite die Eskom aand piek tyd te doen en sodoende die werkslas in die aand piektyd te verminder.

'n Model van die myn se verkoellingstelsel is gebou en geverivieer met data. Vanaf die model is die sisteem gesimuleer. Die simulasie is gebruik om 'n nuwe beheer strategie te ontwikkel asook nuwe operasionele parameters te verkry.

'n Gevalle studie is gedoen om te bewys hoe effektief die nuwe beheer strategie en nuwe operasionele parameters werk. Die kaskade myn oppervlak verkoelingsaanleg is heel eerste geoutomatiseer om afstand beheer en monintering vanaf 'n sentrale punt te bewerkstellig. Die beheer strategie is getoets deur dit op die geoutomatiseerde stelstel te implementeer.

Die intydse energie beheer systeem is opgestel en kommunikasie met die SCADA stelsel is getoets deur damvlak-temperature waar teneem sien en deur masjiene te stop en begin. Besluite wat deur die beheerder gemaak word is fyn dopgehou, totdat die stelsel ten volle outomaties gewerk het.

Die resultate van die nuwe beheerder op die stelsel se vloei, temperature, dam vlakke, elektriese energie en termiese energie is geldig verklaar en geverifieer. Uit die gevalle studie is bewys aanvraag-kant energie bestuur op kaskade myn oppervlak verkoelingsaanlegte, gedoen kan word.

Daar is voorspel dat 4.2 MW las geskuif kon word, maar navorsing het gevind dat die sisteem oorpresteer met 0.3 MW. Dit is dus duidelik dat aanvraag-kant energiebestuur las geskuif kan word op kaskade myn oppervlak verkoelingsaanlegte, deur van termiese energie storing gebruik te maak.

In die algemeen het hierdie verhandeling bewys dat aanvraag-kant energie bestuur op verkoelingsaanlegte, gedoen kan word en daar word voorgestel dat verdere navorsing gedoen word op ondergrondse myn verkoelingsaanlegte.

ACKNOWLEDGEMENTS

This dissertation represents my own research. Other contributions were also received through discussions, co-operation, etc. As far as possible, recognition has been given to all sources of information.

I apologise if the necessary recognition has not been given. If anyone is of the opinion that I did not give recognition to their idea or opinion, please contact me to make the necessary corrections.

I would like to use this opportunity to express my gratitude to Prof. E.H. Mathews and Prof. M. Kleingeld for giving me the opportunity to complete this study under their guidance and support.

I would also like to express my gratitude to Quinten Crew, Coen Benadie and their colleagues from South Deep Gold Mine for granting me the privilege to do my case study on their mine.

I would like to thank F. Geyser, J. van Rensburg and J. van der Bijl for their contributions throughout the course of this study.

I thank my family and friends for all their ongoing love and support throughout my life.

Finally I thank God for my talents and for giving me the opportunity to glorify His name.

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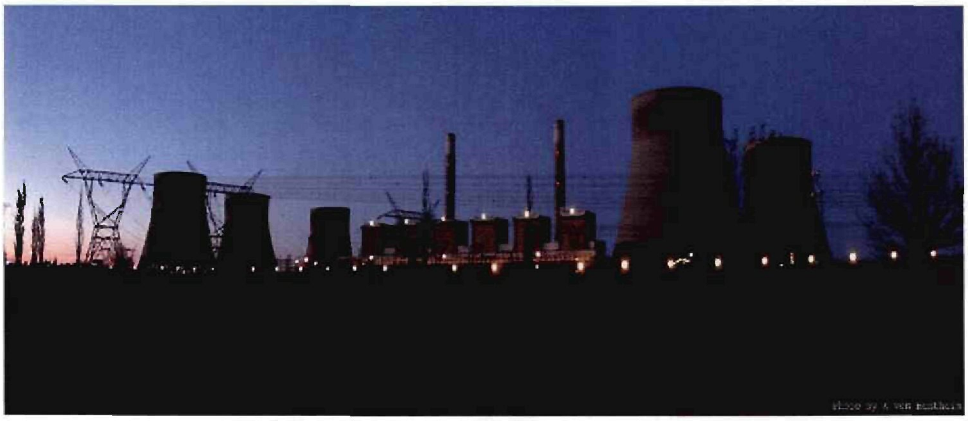
NOMENCLATURE

A	Amps
BAC	Bulk Air Cooler
CFC	Chlorofluorocarbon
CO_2	Carbon dioxide
Cond.	Condenser
COP	Coefficient of performance
C_p	Specific heat
Diff., diff.	Differential
DSM	Demand-Side Management
DB	Dry bulb
DE	Discharge end
E	Electrical energy
ESCO	Energy Service Company
Evap.	Evaporator
GW	Gigawatt
h	Hour
HCFC	Hydro chlorofluorocarbon
kPa	Kilo Pascal
LiBr	Lithium bromide
LMTD	Log Mean Temperature Difference
$\dot{m}$	Mass flow
m	Metre
m^2	Square metres
m^3	Cubic metres
MW	Megawatt
M&V	Measurement and verification
NAESCO	National Association of Energy Service Companies
NER	National Energy Regulator
NO_2	Nitrogen dioxide
NDE	Non Discharge End
Pa	Pascal

PLC	Programmable logic controller
PID	Process instrumentation diagram
Q	Thermal Energy
R12	Dichlorodifluoromethane
R134A	1,1,1,2-Tetrafluoroethane
R717	Ammonia
RPM	Revolutions per minute
s	Second
SA	South Africa
SCADA	Supervisory Control And Data Acquisition
SO_2	Sulphur dioxide
T, Temp, temp.	Temperature
T_i	Inlet temperature
T_o	Outlet temperature
TOU	Time of use
USA	United States of America
V	Volts
VC	Ventilation and Cooling
VRT	Virgin rock temperature
V&V	Validation and Verification
W	Watt
WB	Wet bulb
x	Number of refrigeration machines
°C	Degrees Celsius
°	Degree
Δ	Delta
#	Number or amount
%	Percentage

1

INTRODUCTION



In South Africa the energy demand is out-growing the supply.

1. INTRODUCTION

1.1. Background on the South African energy demand

Energy is a critical resource and the future of mankind depends on affordable and clean energy resources. The supply of electrical energy on earth is expensive and must be carefully managed [1]. This specifically applies if environmental impacts, such as carbon footprinting, are quantified.

There is a steady increase in the energy consumption of the world. In the past few decades, the energy consumption grew 11% in third world countries [2]. South Africa uses some 40% of the total electricity consumed on the African continent [3]. In South Africa, it was predicted that the energy consumption would increase by 59% from 1990 over a period of 30 years [4].

It is stated that there has been a constant year-on-year average growth of 3% for the economic activities in South Africa since 1970 [5]. In South Africa the growth of industry, residential areas and mining, increased rapidly over the past few years [6]. This increase in population and economic activities caused South Africa to become more energy intensive, as well as more energy sensitive [7].

Due to the relation between the economic and energy growth in South Africa, as mentioned above, it is obvious that there will be an increase in the energy demand as the economy grows. This increase in growth of energy demand is illustrated in Figure 1. Therefore, it can be expected to have the same average energy demand growth in the future [8].

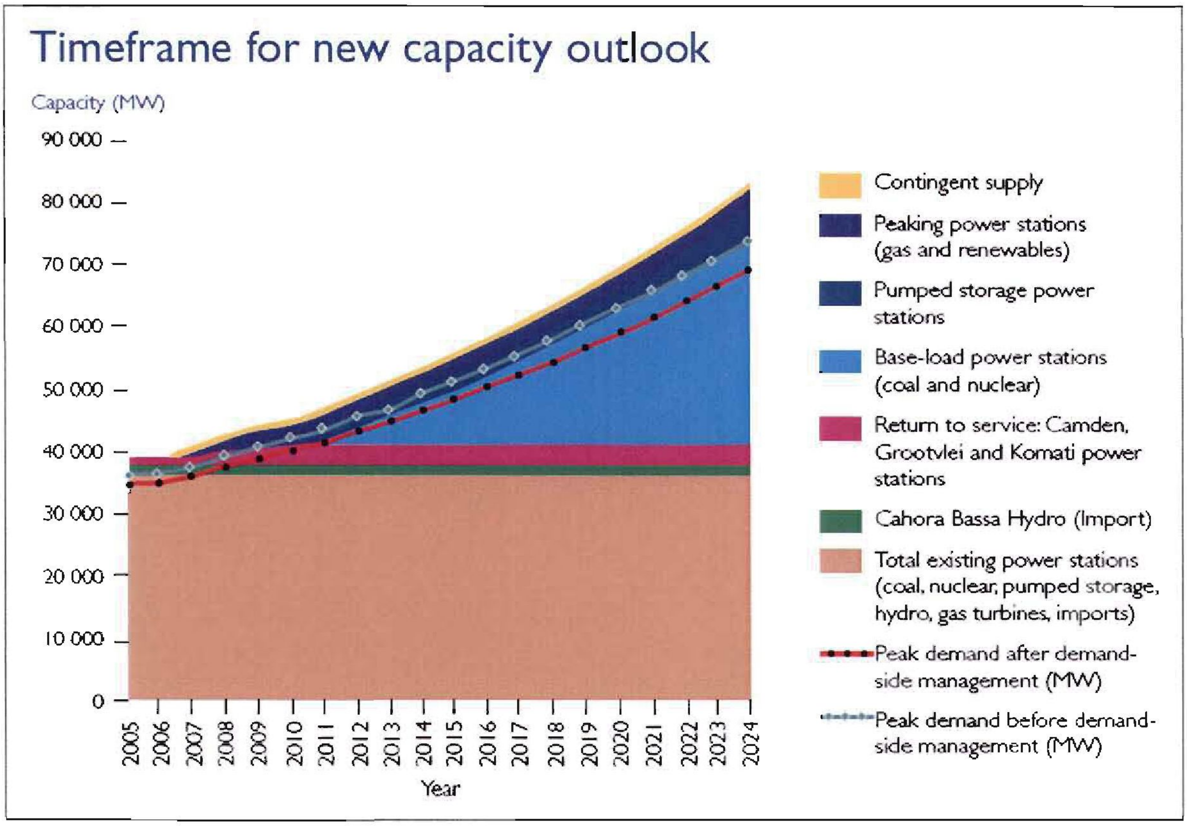


Figure 1 - Timeframe for new capacity outlook [9]

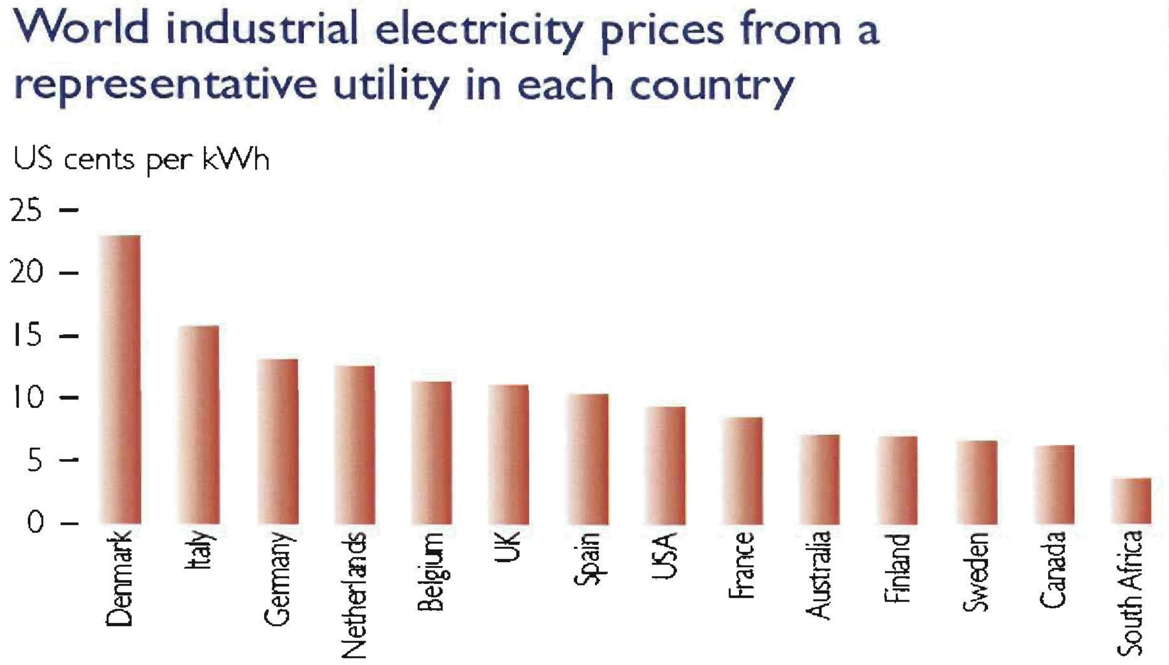
Eskom is the fifth largest and second cheapest international supplier of electricity in the world [10]. In South Africa energy is taken for granted. One consequence is that South Africa's energy consumption in term of gross domestic product (GDP), is higher than that of other developing nations [3].

The main energy resource used in South Africa is electricity [11]. Eskom is South Africa's main electricity supply utility and supplies 95% of the electricity [12]. Eskom focuses on enhancing productivity, increasing efficiency and profitability of its customers, rather than exhausting new energy resources [3].

Eskom already accelerated spending plans last year (2006) to take account of higher economic growth estimates – it is now working on a 4% average annual increase in electricity demand over the next two years, up from 2,3% [13].

All of this has motivated Eskom to race back to the National Energy Regulator of South Africa (NERSA) to ask that the 5,9% tariff increase, which it agreed on for next year (2008), be tripled to 18%, followed by a further 17% increase in 2009 [13].

Eskom benchmarks its tariffs using the NUS Consulting Group survey, which shows that South Africa is now 74% cheaper than the next cheapest electricity supplier (Canada) – up from 30% last year [13].



The survey is based on prices at 1 April 2007 for the supply of 1 000kW for an organisation with a monthly usage of 450 000kWh. All prices are in US cents per kilowatt hour and exclude VAT. Where there is more than a single supplier, an unweighted average of available prices was used. Where available in each country, deregulated or liberalised contract pricing was used. The percentage change is calculated using the local currency to eliminate currency movement distortion.

Source: Extract from © 2006 – 2007 NUS Consulting Group International Electricity Survey and Cost Comparison, April 2007

Figure 2 - World industry electricity price index [9]

South Africa's economy is based largely on mineral extraction and processing, which by its nature is very energy intensive. While South Africa's historically low electricity price has contributed towards a competitive position, it has also meant that there has been little incentive to save electricity [3].

It was projected that the electrical energy demand will exceed the peak generation capacity by the winter of 2007 [14]. As predicted, this did happen and Eskom now finds itself in a position where the demand for electricity may exceed the available supply from time to time [15].

Eskom's current licensed capacity is around 39.8 GW, where the net maximum operational capacity is about 35 GW [16]. 2007 was a record-breaking winter, with demand exceeding 36 GW seven times [13] and peaking at 36 513 MW [17]. Eskom's 24 power stations can currently generate just over 38 GW [13]. Figure 3 shows Eskom's generation plant capacity and maximum demand.

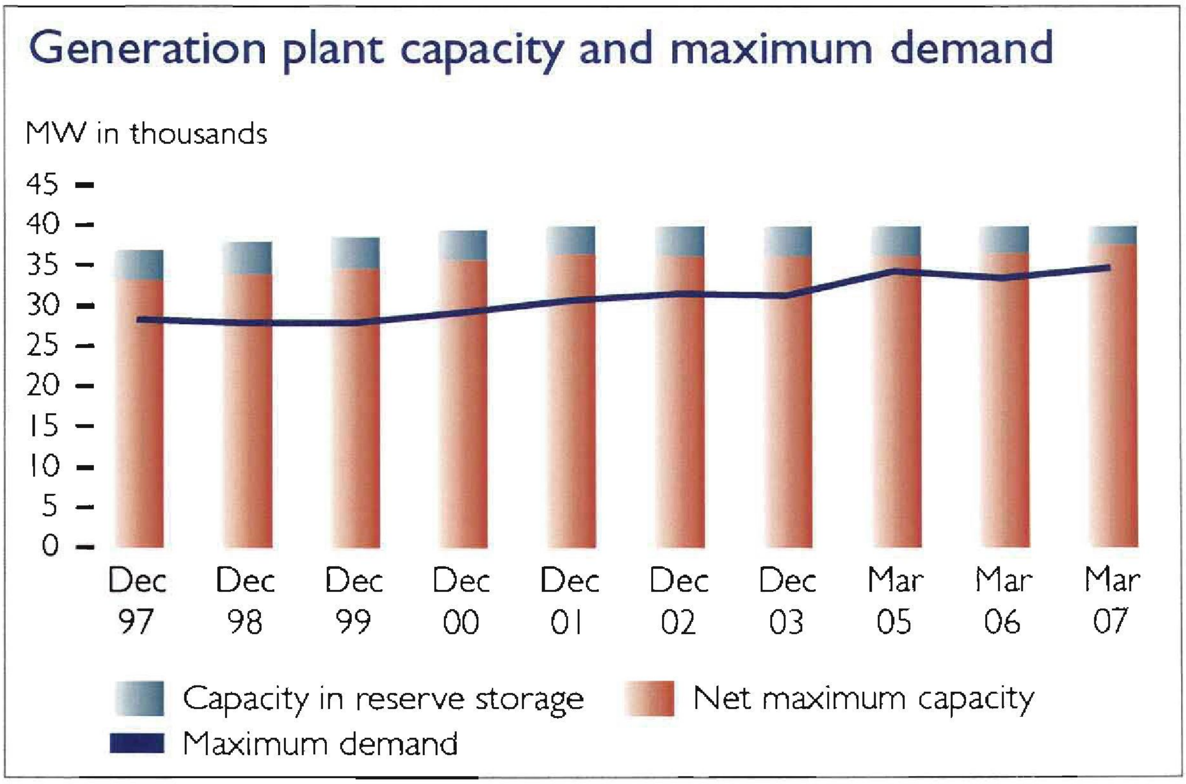


Figure 3 – Eskom's plant capacity and maximum demand [9]

Eskom is doubling its capacity to 80GW over the next 20 years [13]. Nuclear power plants will contribute 20GW to the national grid by 2025 [18]. Presently, when there is insufficient electricity available to meet the demand of all Eskom's customers, it could be necessary to interrupt supply to certain areas. This is called load shedding [19].

A further development is Eskom's Demand-Side Management (DSM) programme. This aims to reduce the national peak power demand, thereby deferring the immediate need for additional power generation capacity [3], during the winter evening peak time.

1.2. Demand-Side Management in South Africa

Eskom is now down to a "reserve margin" of only 8% between peak demand and supply, compared with the preferred benchmark of 15% [13].

Eskom is investing in new power generation, but it is mandatory that there is an intervention to reduce peak electricity demand at current energy usage levels and national economic development projections [3].

By considering electricity as a main energy resource, the constant growth in energy consumption will result in the electricity demand reaching the energy supply capacity of Eskom in years to come [6]. Eskom has launched a Demand-Side Management (DSM) programme to postpone the predicted date when the electricity demand will reach the generated capacity [20].

Eskom's demand-side management programme aims to provide lower-cost alternatives by focusing on the judicious use of electricity rather than expanding the generation system [21]. Eskom's main focus for the winter of 2008 is on demand-side management and energy-saving initiatives [17].

The first DSM programme was developed in the USA in 1980 and was later adopted in the United Kingdom, Europe and Australia [20].

South Africa's electrical demand patterns are illustrated in Figure 4. It shows that there are two consumer/demand-side peak periods – the morning peak time (08:00 – 12:00) and the evening peak time (18:00 – 20:00).

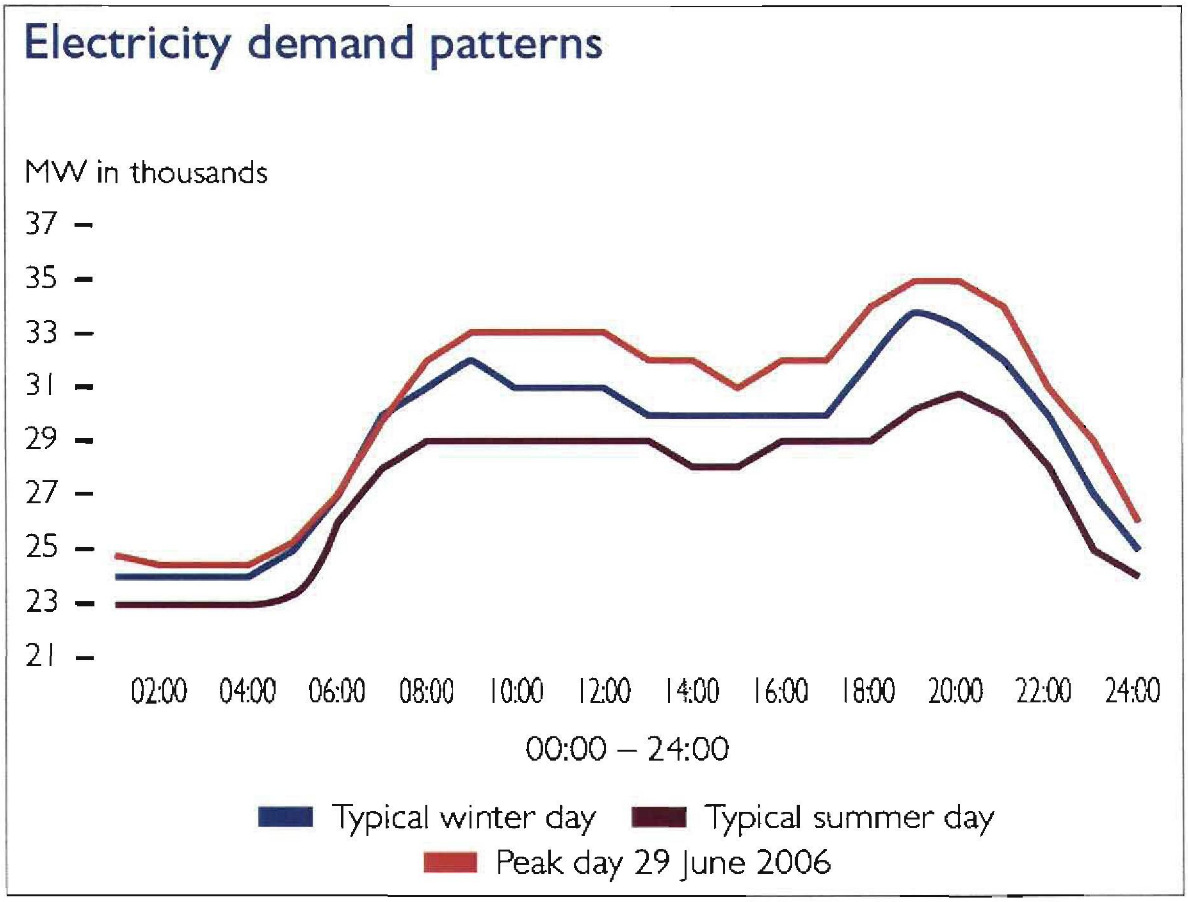


Figure 4 - Electrical demand patterns [9]

Due to the construction of additional generation capacity/plants being extremely costly and a lengthy process, Eskom has embarked upon a DSM programme in order to reduce the capacity and costs of such an investment. This is done by using a combination of energy efficiency measures, load management and negotiated interruptible supplies [3].

It is fortunate for SA that research has been done in this area for over thirty years, but a scheme for the SA environment had to be established differently [22]. This scheme for SA must be tailor-made for the economic, environmental, social and technical factors that differ from other countries like the USA. Eskom officially recognised the DSM scheme in 1992 and the first DSM programme was produced in 1994 [23].

Although the main objective of SA's DSM programme is to delay the imminent shortage of generation capacity until as far as 2025, there are other benefits as well [14]. These are [20]:

- Reduction of fuel consumption at power stations
- Reduction in distribution losses
- Reduction in transmission loss
- Reduction in water used through generation
- Reduction in the emissions of CO_2, SO_2 and NO_2 from power stations

Eskom used the methodology of independent companies to execute a DSM programme at feasible sections on the sites of their consumers. This type of company is called an ESCO (Energy Service Company). Currently there are 150 ESCOs registered with Eskom in SA [24]. Eskom is spending R3-billion to support the initiatives of ESCOs [24].

With South Africa's electricity supply challenge set to persist until at least 2012, serious effort is now being given to energy efficiency and demand-side management [24]. With an "Accelerated DSM" programme, Eskom is aiming to save 3 000 MW by 2012 and 8 000 MW by 2025. The equivalent of two six-pack coal-fired power stations [24].

In layman's terms, the purpose of DSM is to create more efficient systems that will consequently build a "virtual power station" [25].

An important representative of the ESCO industry in the USA – NAESCO – defines an ESCO as "... a business that develops, installs and finances projects designed to improve the energy efficiency and reduce maintenance cost for facilities over a 7 to 10 year time period..." [26].

The technical and performance risks of running these projects are the responsibility of the ESCO [27].

An ESCO offers services that play a big role in the cost of the projects and are then compensated through the resultant savings [8]. The following services are included during the implementation of a typical project [8]:

- Developing, designing and financing the project
- Installation of infrastructure for project
- Monitoring the performance of the project
- Taking the responsibility to generate the proposed savings

ESCOs provide existing and potential customers with opportunities to optimise their energy usage, in order to lower the demand for power, especially during the morning and evening peak times. This they do by controlling the critical processes after upgrading the customer's infrastructure.

The ESCOs in SA are not only supporting Eskom in solving the energy problem, but also creating additional jobs in the ESCO industry. Contractors and facilities are also involved in their projects. One third of the capital invested in existing ESCO implementations has been awarded to labour [28].

An ESCO investigates and executes the DSM programme at a section of one of Eskom consumers' sites, if the DSM potential is practicable. This is done with consideration to their tariff structure. The tariff structure is initially designed to encourage the consumers to use less electricity during the peak periods and more in the off-peak periods [8].

1.3. Industrial and mining sectors

The industrial and mining sectors combined are the largest users of energy in South Africa as shown in Figure 5 [3]. It is estimated that mining accounts for 15% of the overall energy consumption in South Africa [9].

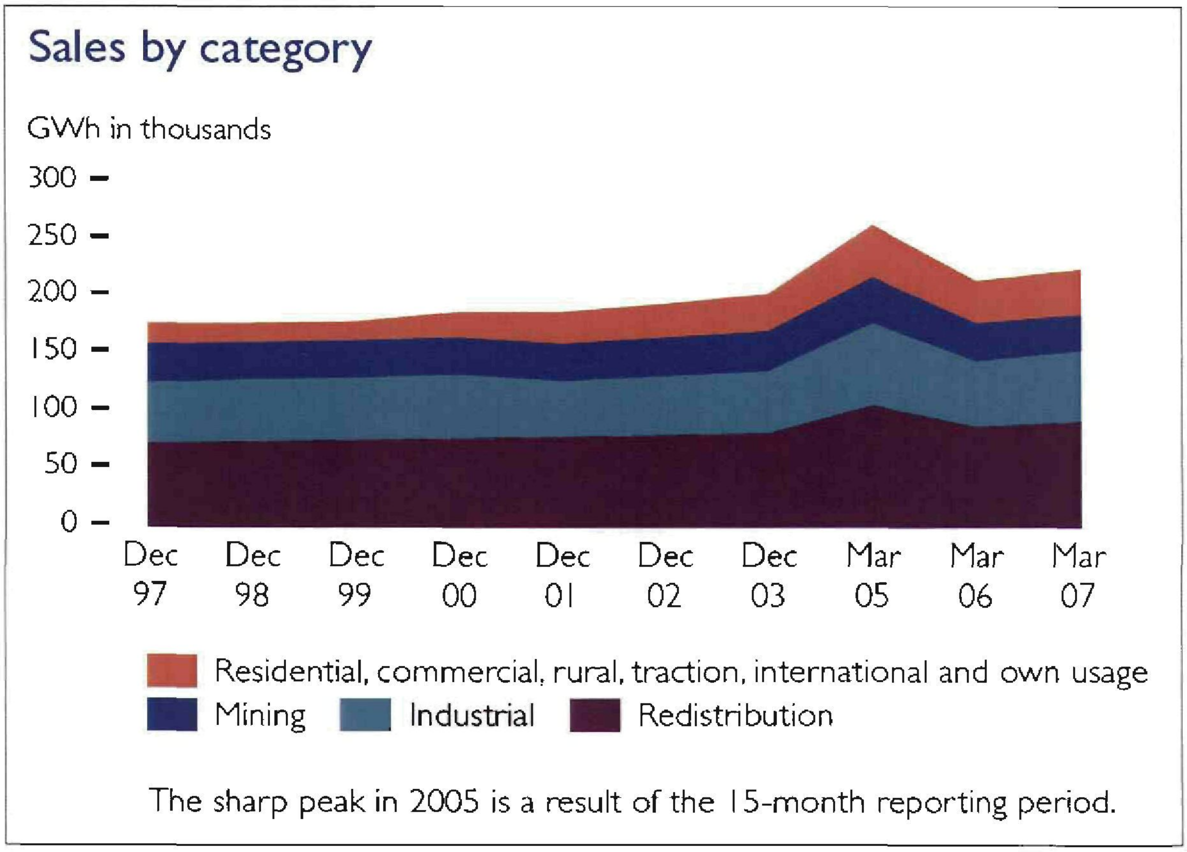


Figure 5 - Sector energy use [9]

There is a relatively high theoretical potential for energy saving. This amounts to 50% of current consumption on a sector by sector basis, compared with international best practice. Notwithstanding this, research has shown that a savings potential of at least 11% is readily achievable using low-cost to medium-cost technical interventions [3].

Furthermore, an additional 5 - 15% energy saving would be achievable by proven no-cost and low-cost techniques of energy management and good housekeeping. It is therefore considered that the prescribed target of 15% is realistic and achievable. Herein lies the potential for the largest savings by replacing old technologies with new ones, and by employing best energy management practices [3].

1.4. Mine surface refrigeration systems

The energy consumption per unit output of gold increases with the depth of the mine. Also, as the quality of the ore decreases, the energy consumption increases [3], as well as the cost per ounce.

Mining at great depths requires surface and underground refrigeration systems. The mine cooling load is determined by the virgin rock temperature (VRT) at mean rock breaking depth. The cooling of the mine relies entirely on its refrigeration system [29]. Owing to the depth, size and temperatures of the mine, a large part of the mining energy goes into refrigeration.

Mine water is used in a semi-closed loop. This lessens the environmental effects of the mining process, because only small amounts of water, compared to the amount of water used, takes form and is discharged into the environment. The blasted ore bearing rock is cooled by heat conduction to cold water and by evaporative cooling. Mine refrigeration systems and cooling strategies are discussed in more detail in chapter two of this dissertation.

Heat is transferred by conduction, convection and radiation.[1] The mine ventilation air is cooled and dehumidified by a BAC which receives its cold water from the refrigeration plant. The cold water for human consumption is also cooled by the mine's refrigeration plant.

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[1] Consultation with A.W. Schutte, Rock Engineering Manager, Kopanang gold mine, Orkney, Tel. (082) 302 5962, May 2007.

The power consumption of a surface refrigeration system depends on the atmospheric conditions and can therefore change with the seasons [8]. The contribution of the surface refrigeration system to the total power consumption of a mine can drop from 25% to 13% when the seasons change from summer to winter.[1]

The cooling load that a deep gold mine's refrigeration system is designed for, is close to 30 MW. The quantity and temperature of water at the shaft head is specific to a mine's cooling load and installed refrigeration layout. The cooling load of a mine is directly proportional to the temperature and amount of water used. For example with a mine outlet water temperature of 28.81 °C, a 30 MW cooling load, the mine will consume 3 °C water at a rate of 277.78 l/s.[2]

1.5. Objectives of this study

This study continues to build on the dissertation and theses of R. Els [29], D.C. Arndt [30] and J. Calitz [8].

R. Els researched the potential for load shifting in ventilation and cooling systems. He used South Deep to verify results of simulations used to investigate the potential of load shifting and other strategies on cooling cycles. [29]

R. Els concluded that using thermal storage is the best way to shift the energy load usage of refrigeration plants. The load shift can be achieved by implementation of new control parameters and strategies on the current system. [29]

It is important that the dams are as full as possible before the load shift occurs. The total amount of energy used remains the same, as the chilled water demand per day stays the same. [29]

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[1] Consultation with R. Mack, Engineering Manager, Kopanang gold mine, Orkney, Tel. (018) 478 9992, April 2007.

[2] Consultation with Q. Crew, Mechanical Engineer, South Deep gold mine, Westonaria, Tel. (011) 411 1469, August 2007.

The chilled water outlet temperature is controlled with the vane position of the refrigerant compressor. Changing the vane position also changes the mechanical work load seen by the compressor.

The chilled water inlet temperature is controlled through back-passing water from the outlet, having mixed with the water in the pipe coming from the dam. A portion of the water is thus re-circulated within the refrigeration machine. This control strategy is indicative of the system's response variation.

D.C. Arndt's purpose was to investigate the potential of load shifting on the cooling system of a deep mine. This could only be done using integrated software capable of doing dynamic simulations to investigate the effect of various load shifting options.

D.C. Arndt suggests that new stable simulation procedures must be developed to solve conditions of complex systems with a large number of closed-loops in an iterated fashion.

D.C. Arndt encountered the problem that it was very difficult to obtain stable solutions when the re-circulation of water was implemented for chilled water temperature control. It was recommended that further work be done on this. [30]

Both R. Els and D.C. Arndt predicted through their research that a load shift potential of 4 MW existed at South Deep's cascade mine surface refrigeration system. In mining terminology, cascade refers to underground distribution strategy. For this study a cascade refrigeration system is defined as a refrigeration system consisting of two interdependent refrigeration systems.

J. Calitz researched and implemented a load reduction system for mine refrigeration systems. J. Calitz proved that DSM can be implemented on a series type mine refrigeration system configuration. The developed controller cannot compensate for all kinds of cooling configurations, but it is the ground work and foundation for further studies. It was recommended by J. Calitz that a universal controller be further researched.

The objective of this study is to further investigate the load shift possibilities on the energy intensive refrigeration systems of South Africa's deep gold mines. This is to help the DSM initiative reduce the national peak power demand.

This dissertation will:

- Investigate cascade mine surface refrigeration systems
- Develop mathematical modelling for cascade mine surface refrigeration systems with back-passing for temperature control
- Simulate a cascade mine surface refrigeration system
- Develop a new control system and specify new parameters that can be implemented on a cascade mine surface refrigeration system
- Test the new control system

Throughout all of the above the mine will be supplied with 24 ML water per day with a temperature between 2 °C and 6 °C.

1.6. Overview of this dissertation

This dissertation commences with an introduction to the energy generation and demand situation in South Africa and explains the need for DSM projects. It broadens the horizon of the reader and shows what has been done in this line of research. The energy demand out-growing the supply in South Africa, is identified as the research problem.

The need for this study will be clearly evident and will bridge the gaps of other research done in this field. It establishes a firm background and overview of the specific research topic. The literature survey reveals methods of dealing with similar problems.

The next section describes the DSM possibilities in mining and mine surface refrigeration systems.

A simulation model and ongoing control system was developed. A case study was done on a cascade mine surface refrigeration system at South Deep. The new control philosophy is developed and implemented.

The effect of the new control system on a case study is captured, verified and results shown. The document is concluded in chapter 5. Recommendations for further research are listed. In the Conclusion, the effect of the study is discussed.

1.7. References

[1] Swart, C., *Integrated simulation of heat transfer networks.* Thesis submitted in partial fulfilment of the requirements for the degree of Master of Engineering, North-West University, November 2001.

[2] Lavine M., Gadgil A., Sathaye J., Stafurid J., Wilbanks T., *Energy Efficiency developing nations and eastern Europe:* A report to the US working group on global energy efficiency, International Institute for Energy Conservation, IIEC-Africa, 67 Fourth Avenue, Melville, Johannesburg, 2092, South Africa, Tel: +27 11 482 5990, June 2001.

[3] Department of Minerals and Energy: *Energy Efficiency Strategy of the Republic of South Africa, March 2005*, Department of Minerals and Energy, Private Bag X 59, Pretoria, 0001, South Africa.

[4] United States Department of Energy, *Energy Highlights*, U.S. Department of Energy, 1000 Independence Ave., SW, Washington, DC, 20580, also available at: http://www.eia.doe.gov/, 2005.

[5] *Economic environment: National State of Environment Report – South Africa*, Blignaut Prof J – Bureau for Economic and Policy Analyses, University of Pretoria, De Wit MP – CSIR, Division of Water Environment and Forestry Technology, also available at: http://www.ngo.grinda.no/soesa/nsoer/issues/economic/pressure.htm.

[6] *NER, An Integrated Electricity Outlook for South Africa*, National Electricity Regulator, Sats Mail 2003, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 2002.

[7] *Integrated Energy Plan for the Republic of South Africa*, Department of Minerals and Energy of the Republic of South Africa, Private Bag X 59, Pretoria, 0001, South Africa, also available at: http://www.dme.gov.za/2005.

[8] Calitz, J., *Research and implementation of a load reduction system for mine refrigeration systems,* Thesis submitted in partial fulfilment of the requirements for the degree of Master of Engineering, North-West University, November 2006.

[9] Eskom Annual report 2007, Chairman and Chief Executive's report, Chairman, Valli Moosa, Chief executive, Jacob Maroga, 2007, Eskom, Megawatt Park, Maxwell Drive, Sunning hill, Sandton, 2157.

[10] Electroserve, Brochure of ESKOM's professional device for commercial services, ESKOM, PO Box 1091, Johannesburg, 2000, 1995.

[11] Pumzile Mlamo-Ngcuka, Minister of Minerals and Energy, *Draft Energy Efficiency Strategy of the Republic of South Africa,* Department of Minerals and Energy of South Africa, Private Bag X 59, Pretoria, 0001, South Africa, April 2004, p14.

[12] National Energy Regulator, *Electricity supply statistics for South Africa 2001,* p.4, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600.

[13] Joffe, H., *Cost of warming to the challenge*, Business Day, Johannesburg, 20 July 2007, Business Day, Johncom House, 4 Biermann Avenue, Rosebank, 2196, also available at: http://allafrica.com/stories/printable/200707200764.html.

[14] Kevin Bennet, *Energy Efficiency in Africa for sustainable development: a South African Perspective*, Energy Research Institute, University of Cape Town, November 2001, also available at: www.eri.uct.ac.za/eri%20publications/nairobi%20paper.pdf, p 2-6.

[15] ESKOM, *ESKOM Load Shedding "What is load shedding"*, July 2006, Postal address: ESKOM, PO Box 1091, Johannesburg, 2000, Gauteng, Tel: +27 11 8000 8111, http://loadshedding.eskom.co.za/, 2007/05/12 or http://www.eskom.co.za/live/content.php?Item_ID=3977&Revision=en/11, 2007/07/26.

[16] Gcabashe, T.S., ESKOM Annual Report 2005, ESKOM, PO Box 1091, Johannesburg, 2001, Key statistic section p.5 & Top utilities section p.194.

[17] Creamer, T., *Energy efficiency takes on renewed urgency following gas-turbine delay*, Engineering News, 21 September 2007, Creamer Media, PO Box 75316, Garden View, 2047, South Africa, Tel: +27(0)11 622 3744, also available at: http://www.engineeringnews.co.za.

[18] Phasiwe, K., *Eskom promises cleaner energy*, Business Day, Johannesburg, 23 July 2007, Business Day, Johncom House, 4 Biermann Avenue, Rosebank, 2196, also available at: http://allafrica.com/stories/printable/200707231401.html.

[19] ESKOM, ESKOM, Postal address: ESKOM, PO Box 1091, Johannesburg, 2000, also available at: http://loadshedding.eskom.co.za/whatis.htm, 2007/05/12.

[20] Clive Beggs, *Energy, management supply and conservation*, Elsevier Publication, 24 September 2002, ISBN 0-75-065096-6, p. 48 & p. 49.

[21] Eskom Annual report 2006, Chief Executive's report, Chief executive, Thulani S Gcabashe, 2006, Eskom, Megawatt Park, Maxwell Drive, Sunning hill, Sandton, 2157.

[22] *South Africa's Demand-Side Management program: a savings opportunity*, 2005, Nortje T., ESKOM DSM, PO Box 1091, Johannesburg, 2000, Gauteng, p.1, p.3, p.5, p.6.

[23] ESKOM, *ESKOM Demand-Side Management, "What is DSM"*, February 2006, Postal address: ESKOM, PO Box 1091, Johannesburg, 2000, Tel: +27 11 800 8111, also available at: http://www.eskomdsm.co.za/whatisdsm.php, 2006.

[24] Creamer, T., *Standards certainty crucial to South Africa saving 8 000 MW by 2025*, Engineering News, 7 September 2007, Creamer Media, PO Box 75316, Garden View, 2047, South Africa, Tel: +27(0)11 622 3744, also available at: http://www.engineeringnews.co.za.

[25] Lane, I.E., *Load audits and simulation to develop DSM potential in the mining sector*, Report for Department of Mineral and Energy Affairs, Report no. ED9206, Department of Minerals and Energy of South Africa, Private Bag X 59, Pretoria, 0001, South Africa, August 1996, p. 16 – 17.

[26] NAESCO, *"What is an ESCO"*, 21 June 2000, online: www.naesco.org, 1615 M Street, NW, Suite 800, Washington DC, 20036, USA, email: info@naesco.org.

[27] NAESCO, *"ESCO"*, February 2006, http://www.naesco.org/about/esco.htm, 1615 M Street, NW, Suite 800, Washington DC, 20036, USA, email: info@naesco.org.

[28] Van der Merwe, C., *Use less or else, mining industry challenged to cut energy consumption by 15% by 2015*, Mining Weekly, Volume 13 No. 20, Creamer Media, PO Box 75316, Garden View, 2047, South Africa, (1Junie – 7 Junie 2007), PP 47.

[29] Els, R., *Potential for load shifting in ventilation and cooling systems*, Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, University of Pretoria, November 2000.

[30] Arndt, D.C., *Integrated dynamic simulation of large thermal systems.* Dissertation presented in partial fulfilment of the requirements for the degree Philosophiae Doctor in the Faculty of Engineering, Department of Mechanical Engineering, University of Pretoria, November 2000.

2

DSM POSSIBILITIES WITH MINE SURFACE REFRIGERATION SYSTEMS

Background on mine refrigeration systems and using them for DSM load shift.

2. DSM POSSIBILITIES WITH MINE SURFACE REFRIGERATION SYSTEMS

2.1. Introduction to the mine refrigeration system

As stated in the previous section, mining is an energy intensive process. At 3000 m below the surface the virgin rock temperatures rise up to 60°C. This is above the acceptable human endurance levels of 27°C and ventilation and cooling are needed for these areas to be mined [31]. Electrical energy is used around the world to drive heat transfer networks [32]; such is the case in most of South Africa's mines [31].

The future of mining at depth will increasingly depend on the mining industry's ability to contend with the environmental control problems by satisfactory ventilation and cooling in an acceptable and cost-effective manner [33].

Ventilation and cooling presents a difficult and potentially dangerous situation, concerning the safety, health and comfort of the workers. Satisfactory ventilation is needed as well as a means to investigate the impact of machines in the event of the ventilation cycle breaking down or performing at lower efficiency [34]. The refrigeration system is one of the many parts involved in supplying satisfactory ventilation.

As mines become deeper and heat loads increase, the future capacity of refrigeration systems will place huge financial burdens on the mines [37]. This is true especially with the possible increase of 18% in the cost of electricity in 2008 and 19% in 2009. Thus the refrigeration system will need to be optimally applied.

One of South Africa's deepest mines is South Deep gold mine, which has surface and underground refrigeration plants. The mine refrigeration system forms part of the water cycle of the mine. The water is cooled by the refrigeration system, either on the surface or underground.

The water is heated when it is used in the mining levels and BAC's. The water is then pumped back to the refrigeration systems for cooling. Figure 6 illustrates a typical mine water cycle.

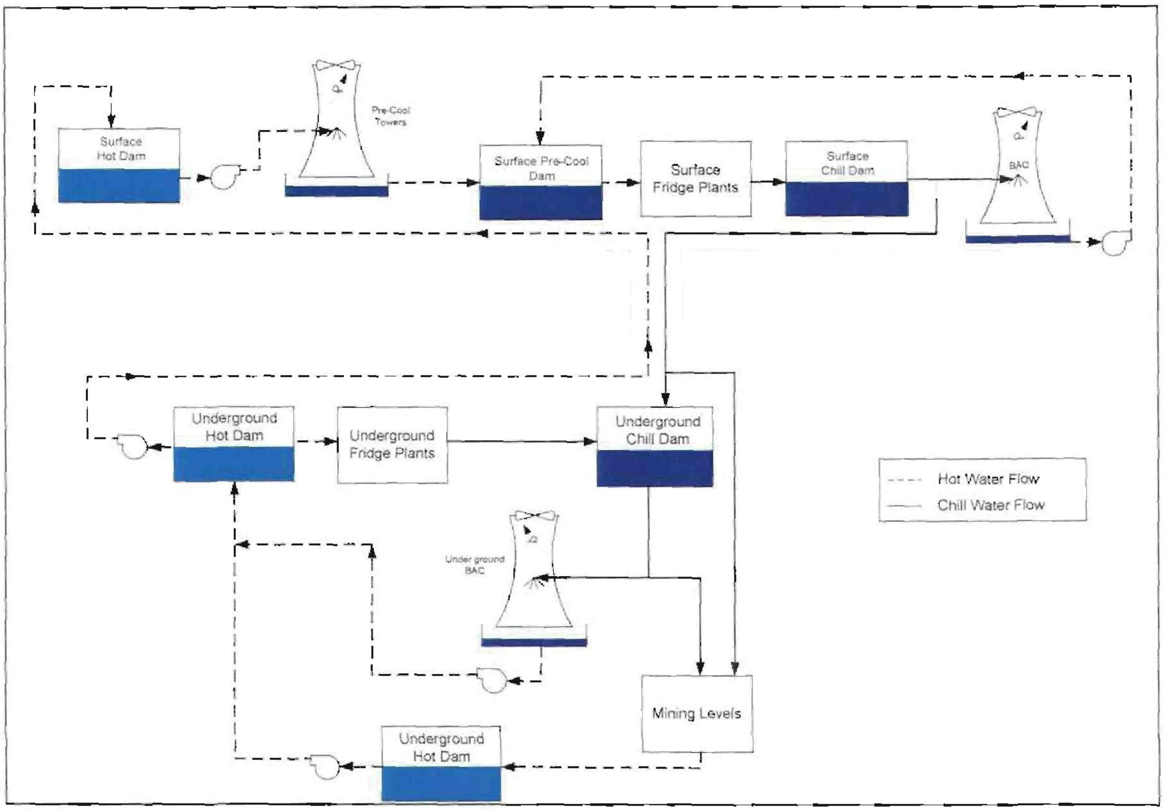


Figure 6 - Mine water cycle

The director of Bluhm Burton Engineering (BBE), Mr. R.E. Gundersen said the following [36] "... The mining industry, South Africa leads the way in terms of mine ventilation and refrigeration systems..."

Due to the competitive nature of the industry and the often high capital cost of heat exchangers, cooling towers and chillers, it is justified to optimise the design for a given cooling capacity, taking into consideration practical limitations as far as possible [37]. An example of load shifting is the optimisation and utilisation of thermal storage capacity [38].

To make load management possible at large electricity consumers (for example the mining industry), the commodity must be identified. One of the most common and easiest commodities used at a mine is water.

The water can be used in the thermal storage appliances, as previously mentioned. Water is not just a working fluid at the mine but can also serve as thermal storage, as well as the ventilation and cooling (VC) systems. [39]

Many VC systems make use of thermal storage (either hot or cold water) to provide a buffer in capacity. The purpose of this buffer is primarily to ensure that all the safety regulations are achieved and that there will be continuity of the production process [40]. Although this is not essential, it is helpful to shift load and clip peaks.

DSM possibilities are created through the correct and appropriate use of a mine's thermal storage capacity.

2.2. Surface refrigeration system configuration

A mine refrigeration system is comprised of surface and underground systems working together to provide the required cooling capacity. The surface fridge plant can be configured in various ways; series, parallel or any combination thereof.

Harmony's Tshepong gold mine in the Free-State, and AngloGold Ashanti's Kopanang gold mine, have parallel configuration surface refrigeration systems. The Tshepong system layout is shown in Figure 7.

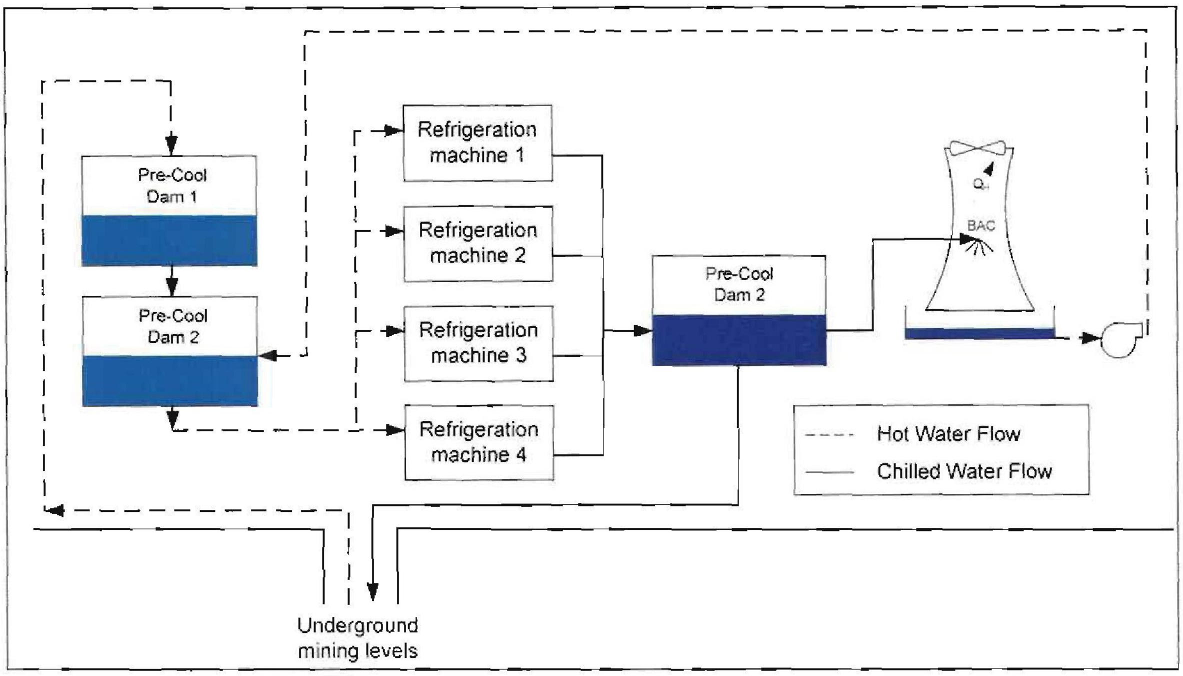


Figure 7 - Parallel layout at Tshepong gold mine

Anglo-Platinum's Amandelbult platinum mine's number two shaft, near Thabazimbi, has a surface refrigeration system in the series configuration as shown in Figure 8.

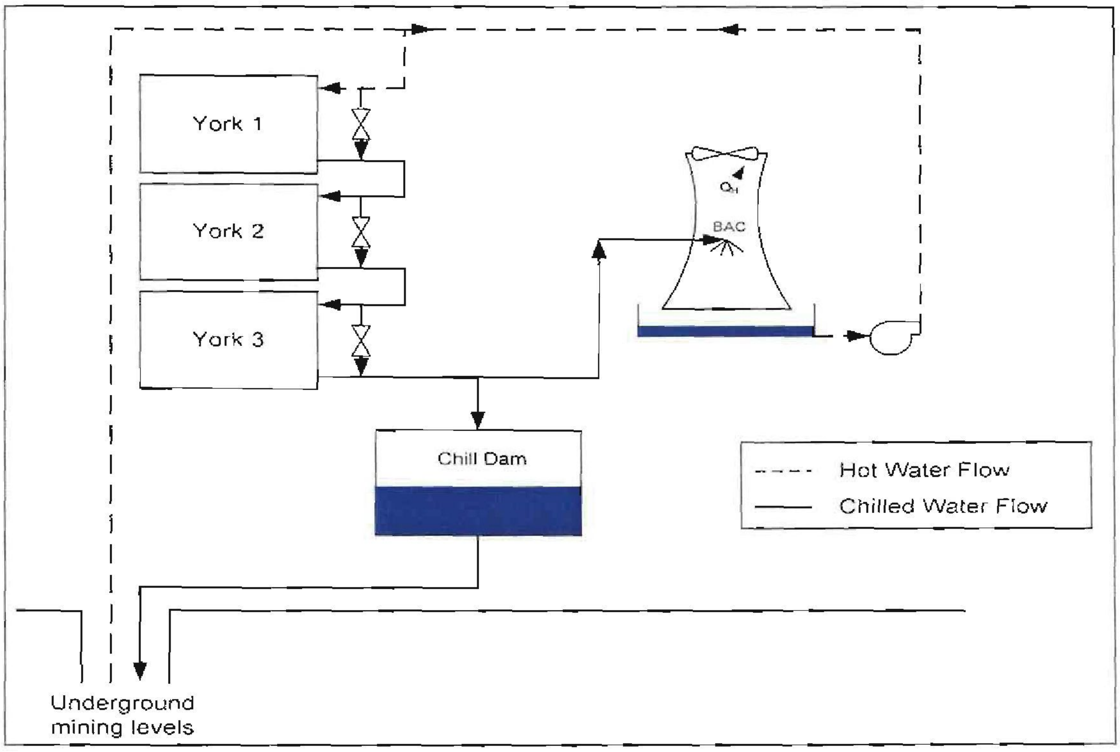


Figure 8 - Series layout at Amandelbult platinum mine

Goldfields' South Deep gold mine near Westonaria has a current cascade surface refrigeration plant layout as depicted in Figure 9.

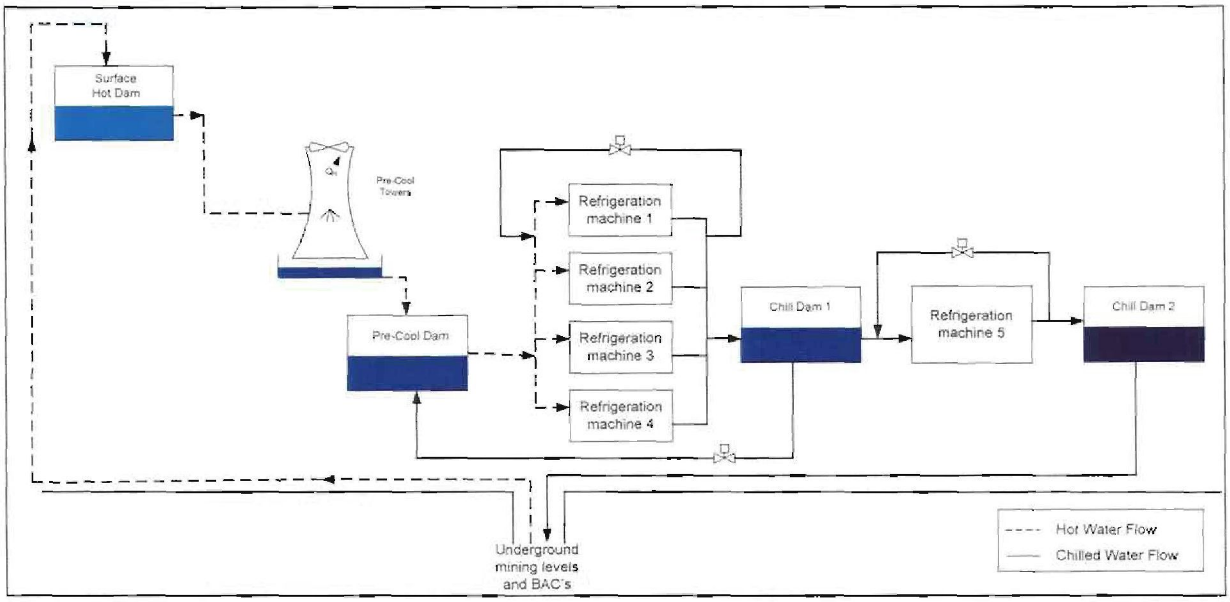


Figure 9 – Multi-stage (cascade) surface refrigeration system layout

This is a cascade or multi-stage surface refrigeration system with a combination of two different and separate sets of refrigeration machines. There are 4 parallel vapour-compression cycle machines in series with a fifth ammonia absorption refrigeration machine.

Water from the underground mining levels is pumped into the Surface Hot Dam. The Surface Hot Dam gravitationally feeds into the pre-cool tower and flows into the Pre-Cool Dam. A portion of the water is cleaned through the sand filters. The water is cooled down by the pre-cool tower to just above ambient temperature. The free cooling done by the pre-cool towers is an important power saving tactic in the mining industry.

From the Pre-Cool Dam, the water is pumped by evaporator pumps through flow control valves and through the evaporators of the parallel refrigeration machines. The water is chilled by the evaporators of refrigeration machines 1-4 from a temperature of between 25°C – 17°C to a temperature of 8°C.

Depending on the water temperature from the pre-cool towers, up to a third of the colder water is routed back to the inlet of refrigeration machines 1-4 evaporators by a back-pass valve. The back-pass valve links into the evaporator inlet pipe before the evaporator pumps.

This controls the inlet temperature to refrigeration machines 1-4 and allows the machines to operate at the highest level of efficiency. The machines then deliver the designed outlet temperature into the first chilled water dam labelled Chill Dam 1 in figure 9.

Water from Chill Dam 1 is sent through refrigeration machine 5, where the water is chilled further to a temperature of 3°C. Again a percentage of the cold water is routed back to the inlet of refrigeration machine 5, through a back-pass valve. The remaining water is sent to the Chill Dam 2.

The evaporator pumps are transfer and circulation pumps, required by the system to operate. These evaporator pumps in turn use electrical energy, but the main electrical energy consumer in the system is the refrigerant compressors.

The storage capacity of Chill Dams 1 and 2, the mine water consumption, and the installed cooling capacity of the refrigeration plants create the possibility for DSM.

From Chill Dam 2, the chilled water is sent to the underground mining levels and bulk air cooler (BAC). A portion of the water in Chill Dam 1 can be back-passed to the Pre-Cool Dam to lower the overall system temperatures.

The cascade surface refrigeration system at South Deep is unique in that it has four York chiller machines in parallel, which are in series with the Howden machine. Depending on the system valve setup, the dams can either be bypassed or act as buffers between the two systems. One needs to observe and control each system individually to control the total system.

2.3. The working of surface refrigeration machines

The mine cooling philosophy plays an important role, and factors such as positioning and type of refrigeration systems (surface only, surface and underground, ice, ammonia, etc.) must be considered [37].

Vapour-compression cycle refrigeration machines

The vapour-compression cycle is the most common way in which refrigeration is done. It has low maintenance and is effective for cooling substances, such as water to about 3 - 5 °C.

In accordance with the Montreal Protocol, the R12 gas is replaced with R134A gas, as the refrigerant in most refrigeration systems. The machine's compressor blade angles and compressor pressures are not designed for R134A. The machine can be converted to work on R134A by changing the compressor blades with blades designed for R134S.

The gear ration is also changed by speeding up the gearbox for the machine to run at higher revolutions per minute. The machine can then achieve the needed compression pressure. These are expensive changes to make and the machine still works at lower efficiency. This makes it important to use these machines optimally.

Figure 10 illustrates the typical vapor-compression refrigeration system electrical energy using components while an industrial PID is attached in appendix A.

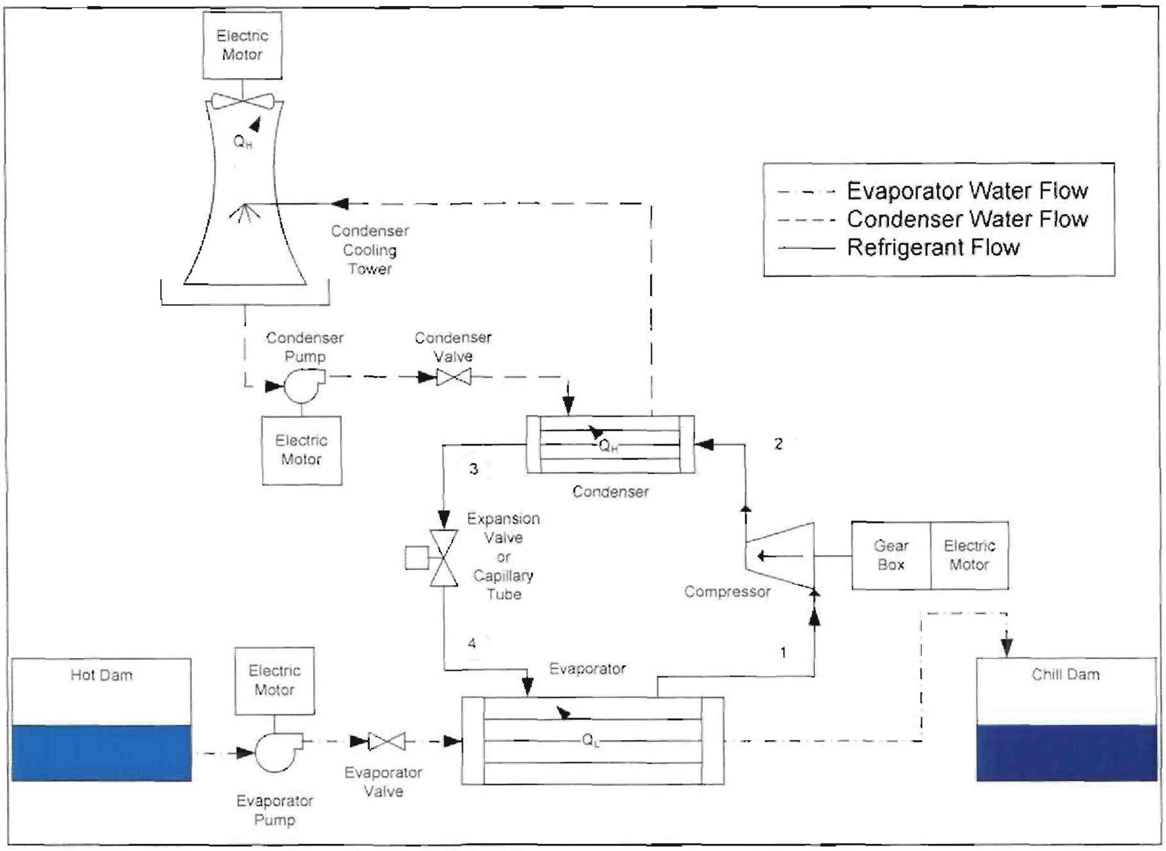


Figure 10 - Typical York refrigeration system

The evaporator water flows from a Hot Dam at a high temperature (25 - 35°C) through the evaporator where it is cooled or chilled. The chilled water is then stored in a Chill Dam. From the Chill Dam, the water can undergo a second stage chilling until the water is at the desired low temperature (3 - 6°C). As stated in the previous section, the chilled water is used for the BAC's and for underground mining operations.

The common vapour-cycle refrigeration or air-conditioning system has an evaporator where heat is absorbed, and a condenser where heat is rejected [41].

The refrigerant (Freon, R12 or R134A) undergoes an adiabatic compression from state 1 to a high-temperature, high-pressure state 2. The heat is rejected at a constant pressure and the condenser cools down the refrigerant. At state 3, the refrigerant is at a high pressure and lower temperature, and leaves the condenser as a liquid [42].

The refrigerant is expanded through an adiabatic throttling process. The temperature decreases accordingly and the refrigerant exits in a two-phase form. At state 4, the refrigerant flows through the evaporator at a constant low pressure and temperature. In the evaporator, the evaporator water heats up the refrigerant to state 1 where it is at low pressure and warm temperature [42].

In the condenser, heat is transferred to the condenser cooling water and the refrigerant is cooled down. In the evaporator, heat is transferred from the evaporator water to the refrigerant. The refrigeration heats up, which in effect chills the evaporator water.

The South Deep York 1-4 refrigeration machines use R12 gas. The R12 gas contributes to the hole in the ozone and to global warming. South Deep monitors the machines continuously to prevent gas leaking into the atmosphere.

The process explained above is not the only process that can be used to cool large amounts of water. Another cooling process is the absorption refrigeration cycle. There are various absorption processes such as LiBr and ammonia.

The Howden refrigeration machine at South Deep operates on the ammonia absorption process. This process is described in the section below.

Ammonia absorption refrigeration machines

The mechanical vapour compression refrigeration system, described in the previous section, is an efficient and practical method. However, the required energy input is shaft work power, which is high-grade energy and expensive. The relatively large amount of work required is because of the compression of vapour that has a large volume and requires a large compressor [43].

It is possible to replace the vapour-compression process with a series of processes where the refrigerant vapour is absorbed by a liquid and then the liquid solution is pumped to a higher pressure [43].

Custom-engineered ammonia refrigeration systems often have design conditions that span a wide range of evaporating and condensing temperatures. Ammonia is the refrigerant of choice for many industrial refrigeration systems [44].

The use of ammonia (R717) for refrigeration systems has received renewed interest, owing in part to the scheduled phase-out and increasing cost of chlorofluorocarbon (CFC) and hydro chlorofluorocarbon (HCFC) refrigerants [44].

The ammonia absorption refrigeration cycle differs from the vapour-compression cycle in the manner in which compression is achieved [45].

In the absorption cycle the low-pressure ammonia vapour is absorbed in water in the absorber. The liquid solution is pumped to a higher pressure by a liquid pump. The high pressure liquid is pumped through a heat exchanger into the generator. The typical ammonia system layout can be seen in Figure 11 [45] while an industrial PID is illustrated in Appendix B.

The low-pressure ammonia vapour leaving the evaporator, enters the absorber where it is absorbed in the weak ammonia solution. This process takes place at a temperature slightly higher than that of the surroundings [45].

Heat must be transferred to the surroundings during this process. The strong ammonia solution is then pumped through a heat exchanger to the generator where higher pressure and temperature are maintained [45].

Under these conditions, ammonia vapour is driven from the solution as heat is transferred from a high-temperature source. The ammonia vapour goes to the condenser where it is condensed, as in a vapour-compression system, and then to the expansion valve and evaporator [45]. In the evaporator, the evaporator water is chilled in the same manner as a vapour-compression system.

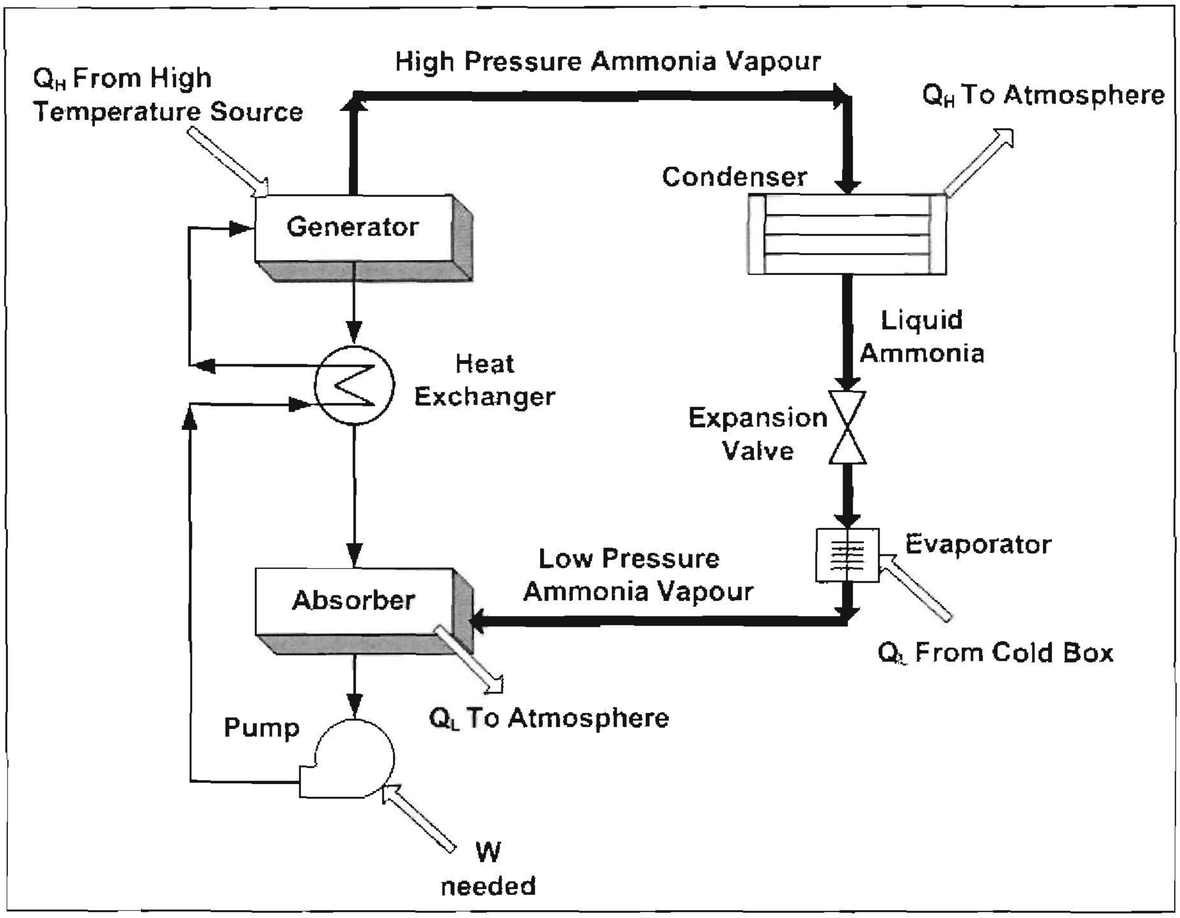


Figure 11 - Typical ammonia absorption refrigeration cycle [45]

The weak ammonia solution is returned to the absorber through the heat exchanger. The distinctive feature of the absorption system is that very little work input is required because the pumping process involves a liquid.

Standardising on one type of refrigeration cycle will not result in a quantifiable power saving. Standardisation will make maintenance easier.

Understanding the working of the refrigeration machines alone will not result in DSM. There are necessary changes to be made to the system as discussed in the next section.

2.4. Necessary changes needed for DSM on cascade refrigeration system

The configuration of the cascade mine surface refrigeration system and the existing infrastructure determine what changes are needed for DSM. The machines must be fully automated, remotely viewed and controlled. The valves and flows must also be remotely viewed and controlled. The dam levels and temperatures must be remotely viewed.

The above listed components must be remotely viewed and controlled so that the entire system can be controlled from a central point.

Currently, on older mines such as South Deep, the refrigeration machines are manually started. The valve status, dam level and flows are remotely viewed and only the critical valves and flows are remotely controlled.

Changes to the infrastructure and a communication network are required. Upgrading the infrastructure will allow the system to be controlled in such a way that will make DSM possible. The ESCO assists the mine with the appropriate infrastructure needed to do DSM.

Due to the uniqueness of the system, a new separate and overhead control strategy will be developed for the refrigeration systems. This is to ensure that DSM is done automatically and optimally.

An optimised load-shift profile cannot be achieved by only rescheduling the necessary equipment of the current system at the mine, using the commodity. The safety regulations and all the other mine constraints must be taken into account as well. An experienced energy specialist for that specific system must therefore do the investigation and installation of a load-management system [46].

2.5. Conclusion

DSM with mine surface refrigeration systems is possible because of thermal storage of electrical energy within the refrigeration system.

Upgrading the system infrastructure and installing a communication network together with the development of the optimal control strategy, enables the optimised use of mine surface refrigeration systems.

When investigating the energy saving possibilities at a mine, it is important to determine what the present power consumption of the specific mining process is, and whether it will result in a feasible DSM project.

The DSM energy saving potential is a factor of a mine's water consumption, chill water storage capacity, and installed refrigeration capacity. The energy savings potential of the mining process will be determined.

2.6. References

[31] Shone, R.D.L. and Sheer, T.L., *An overview of research into the use of ice cooling deep mines*, Fourth International Mine Ventilation congress, MVS SA, PO Box 403, Wilgeheuwel, 1736, July 1988.

[32] Swart, C., *Integrated simulation of heat transfer networks*, November 2001 Ultra Deep Mines. Journal of the Mine Ventilation Society of South Africa, MVS SA, PO Box 403, Wilgeheuwel, 1736.

[33] Marx, W.M., 1990. *Providing an Acceptable Working Environment in Ultra Deep Mines*. Journal of the mine Ventilation Society of South Africa, MVS SA, PO Box 403, Wilgeheuwel, 1736.

[34] Viljoen, R.P., *Deep-Level Mining – A Geological Perspective*, Technical Challenges in Deep-Level Mining, (1990), pp 411-427.

[37] Rawlins, C.A. and Phillips, H.R., *Mine cooling strategies and insulation of chilled water pipes*, Proc. 7th Int. Mine Ventilation Congress, Cracow, 17-22 June 2001, pp. 371-380, MVS SA, PO Box 403, Wilgeheuwel, 1736.

[36] Khalid Patel, Engineering News, 19 May 2006, *Business booming despite dwindling engineering numbers*, B2B Coupon No. MW28-04-2006E84545, also available at: http://www.engineeringnews.co.za/eng/news/features.

[37] Kröger, D.G., *Air-cooled heat exchangers and cooling towers, thermal-flow performance evaluation and design*, Department of Mechanical Engineering, Stellenbosch University, Private bag X1, Matieland, 7602, South Africa, Tel: +27 21 808 4958, e-mail: dgk@maties.sun.ac.za.

[38] *Indiana Electricity Projections: The 1999 Forecast*, State Utility Forecasting Group Purdue University, A.A. Potter Engineering Centre, Chapter 8, p 1-2, also available at: https://engineering.purdue.edu/IE/Research/PEMRG/SUFG//PUBS/1999-Forecast.

[39] Lace, W., *Kloof – Africa's hydropower power house*, Mining Weekly, Vol.8, no.4, pp.2-3, February 2002, Creamer Media, PO Box 75316, Garden View, 2047, South Africa.

[40] Jansen van Vuuren, S.P., *A thermal storage system for surface refrigeration plants*, Journal of the Mine Ventilation Society, 36, pp. 45-52, MVS SA, PO Box 403, Wilgeheuwel, 1736, May 1983.

[41] Mills, A.F., *Basic heat and mass transfer*, Irwin, 1995, ISBN: 0-256-16388-X.

[42] Stoecker W.F. and Jones J.W., *Refrigeration and air conditioning*, second edition, Mc Graw Hill, 1982, ISBN: 0-07-066591-5.

[43] McQuiston F.C. and Parker J.D., *Heating, Ventilating, and Air Conditioning*, Analysis and design, Third Edition, John Wiley and Sons, 1988.

[44] American Society of Heating, *Refrigerating and Air-Conditioning Engineers*, Ashrae handbook, refrigeration, SI edition, 2002,1791 Tullie Circle, N.E.,Atlanta, GA 30329 (http://www.ashrea.org).

[45] Sonntag, R.E., Borgnakke, C., Van Wylen, G.J., *Fundamentals of Thermodynamics*, sixth edition, John Wiley & Sons, 2003, ISBN 0-471-42883-3.

[46] Calitz, J., *Research and implementation of a load reduction system for mine refrigeration systems*, Thesis submitted in partial fulfilment of the requirements for the degree of Master of Engineering, North-West University, November 2006.

3

DEVELOPING A NEW CASCADE REFRIGERATION SYSTEM SIMULATION MODEL

Chapter 3 is concerned with the development of an optimal surface refrigeration system setup and control strategy.

3. DEVELOPING A NEW CASCADE REFRIGERATION SYSTEM SIMULATION MODEL

3.1. Introduction

A new simulation model for a cascade surface refrigeration system is needed. The model is created to research the possibilities and effect of a DSM project. The model is created through the collection of specific mining data, such as electrical and thermal data from the refrigeration system, along with additional technical data such as dam sizes, flow rates, temperatures, layouts, valves, back-pass etc.

The data is received in a log book format, or in electronic format. The data is then filtered, processed and summarised in a number of 24-hour profiles. A report is written on the thermal energy and electrical energy consumption findings. The findings are considered as the energy baselines against which a DSM project is measured.
A report of the energy baseline findings is handed over to Measurement and Verification (M&V). They are an independent group of researches that verify the findings. An example of the report can be seen in appendix C.

This chapter starts with the refrigeration system constraints and variables. The chapter will then describe the data filtering and processing methods along with the resultant modelling of the system. The model is optimised and results are verified. The controller is developed to accomplish the optimised results within the constraints. The results from the controller are verified and this chapter explains general refrigeration efficiency.

3.2. Surface refrigeration system constraints and variables

The cascade surface refrigeration system of interest is investigated. The installed capacity and physical system constraints were researched and are summarised in the tables in appendix D [47].

The most important constraints with regards to DSM are:

- Dam or storage capacity
- The required mine water consumption
- Cooling capacity of refrigeration machines
- The water processing capacity of the transfer pumps

The most important variables with regards to DSM are:

- System inlet temperature
- The amount of back-pass water
- System efficiency

In order to obtain an accurate simulation of the refrigeration plant the entire process is modelled using flows and temperatures. The result from the simulation is then verified against the 24-hour profiles obtained from the data. The simulation is then optimised for DSM while keeping within the constraints. The optimisation is aimed to shift load during the peak Eskom times.

3.3. Data processing

The following important criteria were kept in mind while gathering data. This increases the accuracy and relevancy of the information.

Bias is the difference between the average result of the measurement of an object/entity, and the actual value of the entity. Bias can typically be rectified through calibration. Measuring instrumentation should be calibrated to limit potential errors.

Variability is the inherent difference that occurs when measuring the same object on more than one occasion. This can be attributed to variability in the measuring device, as well as changes in the environment. When measuring an entity, one should always do more than one measurement.

The data collected from the mines is usually in the form of logbooks, in which case they are converted to an electronic copy. The data in logbooks are logged hourly or half hourly by mine personnel. In cases where the system is already automated, the project data is acquired electronically from the SCADA system. The electronic data received from the SCADA system is logged in two minute intervals.

The data is received in monthly bundles. The following data is in a monthly bundle:

- Hot Dam temperature
- Cooling tower water temperature
- Pre-cool Dam temperature
- Chill Dam 1 temperature
- Water temperature to underground
- York flow
- Howden flow

An hourly average data point of the above is calculated for each day of the month. These data points are used to calculate the hourly average thermal energy needed to reduce the inlet temperature to the outlet temperature for the amount of water (mass flow) for each day. The thermal energy absorbed by the refrigerant from the water is calculated with the following equation.

$$Q = \dot{m} C_p \Delta T \qquad (1)$$

List of symbols:

Q – Thermal energy

$\dot{m}$ – Mass flow

C_p – Specific heat

T_i – Evaporator water inlet temperature

T_o – Evaporator water outlet temperature

The number (x) of refrigeration machines running is calculated with the following equation using the hourly average data point mass flow and installed evaporator mass flow of the refrigeration machines from Appendix D.

$$x_{Refrigeration\ Machine} = \frac{\dot{m}_{Data\ Point}}{\dot{m}_{Refrigeration\ Machine}} \tag{2}$$

With an automated system the controller could get the number of plants in operation from status feedback. Using the number of refrigeration machines running, the hourly average data point auxiliary power is calculated with the following equation. The condenser fan status is governed by the condenser water flow.

$$E_{Auxiliary} = x_{Refrigeration\ Machine}(E_{Evap.Pump} + E_{Cond.Pump} + E_{Cond.Fan}) \tag{3}$$

The thermal and auxiliary data are filtered and processed to obtain a 24-hour energy profile for the month's weekdays, Saturdays and Sundays. The following is a typical software function used to filter and process data.

$$Q_{24hour} = {sumif(DataHour, WantedHour, Q_{DataRange})}\Big/{countif(DataHour, WantedHour)} \tag{4}$$

$$Aux_{24hour} = {sumif(DataHour, WantedHour, Aux_{DataRange})}\Big/{countif(DataHour, WantedHour)} \tag{5}$$

The weekday 24-hour thermal and auxiliary power are then summarised in a table. The same is done for the Saturday and Sunday 24-hour average thermal and auxiliary power. Table 1 is the weekday summary for the month of July 2005 for the South Deep York and Howden cascade surface refrigeration system.

July 2005							
Thermal				Auxiliary			
weekday	York energy (kW)	Howden energy (kW)	Total Thermal (kW)	weekday	York energy (kW)	Howden energy (kW)	Total Auxiliary (kW)
weekday 01:00	7753.12	7717.84	15470.96	weekday 01:00	388.33	227.81	616.14
weekday 02:00	10002.49	8523.86	18526.34	weekday 02:00	489.32	255.20	744.52
weekday 03:00	10918.54	9009.09	19927.63	weekday 03:00	541.25	264.79	806.04
weekday 04:00	9889.45	9156.85	19046.30	weekday 04:00	493.82	267.39	761.20
weekday 05:00	8599.82	9023.54	17623.36	weekday 05:00	426.16	269.38	695.54
weekday 06:00	9196.97	8077.70	17274.67	weekday 06:00	445.02	254.67	699.69
weekday 07:00	9096.26	6976.34	16072.60	weekday 07:00	430.94	246.90	677.84
weekday 08:00	10082.13	7203.41	17285.54	weekday 08:00	478.30	245.88	724.18
weekday 09:00	12886.11	7220.85	20106.96	weekday 09:00	590.30	233.63	823.92
weekday 10:00	13415.30	7889.64	21304.94	weekday 10:00	612.92	256.99	869.91
weekday 11:00	10994.31	7575.26	18569.57	weekday 11:00	519.15	246.90	766.05
weekday 12:00	9796.57	7835.66	17632.24	weekday 12:00	459.48	256.33	715.81
weekday 13:00	9933.63	7503.48	17437.11	weekday 13:00	453.63	251.29	704.92
weekday 14:00	11879.61	7719.34	19598.95	weekday 14:00	536.40	254.64	791.04
weekday 15:00	10605.52	8061.65	18667.17	weekday 15:00	502.05	258.90	760.95
weekday 16:00	10033.05	7646.04	17679.09	weekday 16:00	473.38	246.14	719.52
weekday 17:00	9944.18	7294.27	17238.45	weekday 17:00	480.69	227.24	707.92
weekday 18:00	9613.62	7618.34	17231.96	weekday 18:00	453.10	242.91	696.01
weekday 19:00	9062.46	7467.46	16529.92	weekday 19:00	437.74	233.50	671.23
weekday 20:00	8251.90	7829.07	16080.96	weekday 20:00	404.95	235.07	640.02
weekday 21:00	8139.87	8067.37	16207.24	weekday 21:00	393.85	238.89	632.74
weekday 22:00	8050.45	7873.32	15923.77	weekday 22:00	399.52	231.31	630.84
weekday 23:00	12680.14	7490.01	20170.14	weekday 23:00	654.74	222.49	877.23
weekday 00:00	8096.64	8495.21	16591.84	weekday 00:00	410.27	245.81	656.08
Sum	238922.14	189275.56	428197.70	Sum	11475.27	5914.07	17389.34
Ave	9955.09	7886.48	17841.57	Ave	478.14	246.42	724.56

Table 1 - Thermal and auxiliary summary table for July 2005

The above table was made for three winter months and for three summer months. The winter and summer 24-hour average weekday profile was then calculated as shown in the following two tables.

Winter 2005							
Thermal				Auxiliary			
Weekday	York energy (kW)	Howden energy (kW)	Total Thermal (kW)	Weekday	York energy (kW)	Howden energy (kW)	Total Auxiliary (kW)
weekday 01:00	10245.32	7801.51	18046.83	weekday 01:00	448.48	240.83	689.31
weekday 02:00	10876.61	8011.75	18888.36	weekday 02:00	474.78	250.22	725.00
weekday 03:00	10921.52	8336.54	19258.06	weekday 03:00	484.66	258.68	743.33
weekday 04:00	10992.11	8419.39	19411.50	weekday 04:00	478.06	268.24	746.30
weekday 05:00	10892.08	8433.42	19325.50	weekday 05:00	472.96	271.65	744.61
weekday 06:00	10801.51	7850.16	18651.67	weekday 06:00	465.78	265.99	731.76
weekday 07:00	10998.93	6940.90	17939.83	weekday 07:00	477.96	251.51	729.48
weekday 08:00	10004.23	7174.46	17178.69	weekday 08:00	441.33	253.50	694.83
weekday 09:00	10778.16	7451.34	18229.49	weekday 09:00	466.27	245.80	712.07
weekday 10:00	11125.95	7690.73	18816.68	weekday 10:00	480.40	253.19	733.58
weekday 11:00	11293.16	7624.96	18918.11	weekday 11:00	483.46	250.59	734.05
weekday 12:00	11214.62	7581.72	18796.33	weekday 12:00	472.77	258.48	731.25
weekday 13:00	11434.59	7751.27	19185.86	weekday 13:00	477.16	264.42	741.58
weekday 14:00	12592.31	7666.05	20258.36	weekday 14:00	524.81	261.20	786.02
weekday 15:00	12123.35	7572.00	19695.35	weekday 15:00	507.26	257.74	765.00
weekday 16:00	12096.42	7523.40	19619.82	weekday 16:00	496.07	249.47	745.53
weekday 17:00	11317.25	6974.81	18292.06	weekday 17:00	470.70	232.92	703.62
weekday 18:00	11065.15	7220.98	18286.13	weekday 18:00	454.76	239.59	694.35
weekday 19:00	10236.32	8674.40	18910.72	weekday 19:00	434.66	232.74	667.40
weekday 20:00	9624.00	7460.67	17084.66	weekday 20:00	411.05	234.76	645.81
weekday 21:00	9988.06	7272.73	17260.79	weekday 21:00	418.47	234.28	652.75
weekday 22:00	9977.60	7559.51	17537.11	weekday 22:00	425.34	236.98	662.32
weekday 23:00	11500.95	7410.56	18911.51	weekday 23:00	507.10	231.63	738.73
weekday 00:00	10564.93	7853.08	18418.01	weekday 00:00	455.19	242.71	697.90
Sum	262665.13	184256.32	446921.44	Sum	11229.46	5987.11	17216.57
Ave	10944.38	7677.35	18621.73	Ave	467.89	249.46	717.36

Table 2 - Thermal and auxiliary summary table for winter 2005

Summer 2005							
Thermal				**Auxiliary**			
Weekday	York energy (kW)	Howden energy (kW)	Total Thermal (kW)	Weekday	York energy (kW)	Howden energy (kW)	Total Auxiliary (kW)
weekday 01:00	12527.02	9743.02	22270.04	weekday 01:00	524.52	314.68	839.20
weekday 02:00	11158.33	9849.72	21008.05	weekday 02:00	475.33	318.80	794.13
weekday 03:00	11714.05	10040.75	21754.81	weekday 03:00	506.12	319.57	825.68
weekday 04:00	11843.93	11964.83	23808.76	weekday 04:00	513.36	319.58	832.95
weekday 05:00	12445.68	10798.99	23244.66	weekday 05:00	538.58	349.40	887.98
weekday 06:00	9862.30	7772.46	17634.76	weekday 06:00	440.48	246.46	686.95
weekday 07:00	10223.96	6894.58	17118.54	weekday 07:00	443.77	243.19	686.96
weekday 08:00	9720.65	6987.20	16707.85	weekday 08:00	425.44	241.79	667.23
weekday 09:00	9420.35	8613.20	18033.55	weekday 09:00	400.13	234.09	634.22
weekday 10:00	10852.22	8877.04	19729.26	weekday 10:00	454.54	238.53	693.07
weekday 11:00	13118.01	11152.15	24270.16	weekday 11:00	537.18	295.56	832.74
weekday 12:00	12683.52	9106.89	21790.41	weekday 12:00	514.49	303.24	817.73
weekday 13:00	12900.96	9078.02	21978.98	weekday 13:00	520.73	305.45	826.18
weekday 14:00	14303.81	10899.04	25202.86	weekday 14:00	562.89	288.57	851.46
weekday 15:00	13806.11	8758.55	22564.66	weekday 15:00	539.42	281.65	821.08
weekday 16:00	13517.52	8613.62	22131.14	weekday 16:00	517.55	278.69	796.24
weekday 17:00	12641.62	8238.14	20879.76	weekday 17:00	485.47	265.38	750.85
weekday 18:00	12163.35	9088.81	21252.16	weekday 18:00	477.45	286.77	764.22
weekday 19:00	11518.64	8799.11	20317.75	weekday 19:00	459.54	278.41	737.95
weekday 20:00	11493.85	9183.24	20677.08	weekday 20:00	473.43	280.13	753.56
weekday 21:00	11674.24	9691.82	21366.06	weekday 21:00	479.34	304.42	783.76
weekday 22:00	12083.69	9613.03	21696.71	weekday 22:00	500.81	302.90	803.70
weekday 23:00	11683.23	9111.09	20794.32	weekday 23:00	481.30	296.13	777.43
weekday 00:00	12267.68	9323.81	21591.49	weekday 00:00	501.10	308.49	809.59
Sum	285624.71	222199.11	507823.82	Sum	11773.00	6901.87	18674.87
Ave	11901.03	9258.30	21159.33	Ave	490.54	287.58	778.12

Table 3 - Thermal and auxiliary summary table for summer 2005

Three months of the year are classified as winter by Eskom and nine as summer. A yearly 24-hour average weekday, Saturday and Sunday profile was made by taking the weighted values from the summer and winter months' averages. The weighted average thermal equation is as follows.

$$Q_{yearly} = \frac{(9\times Q_{summer}) + (3\times Q_{winter})}{12} \qquad (6)$$

Replacing the thermal energy with the auxiliary energy gives the weighted auxiliary equation. The 2005 yearly 24-hour thermal and auxiliary profiles are shown in the table 4.

Yearly 2005							
Thermal				Auxiliary			
Weekday	Summer (kW)	Winter (kW)	Yearly (kW)	Weekday	Summer (kW)	Winter (kW)	Yearly (kW)
weekday 01:00	22270.04	18046.83	21214.24	weekday 01:00	839.20	689.31	801.73
weekday 02:00	21008.05	18888.36	20478.13	weekday 02:00	794.13	725.00	776.85
weekday 03:00	21754.81	19258.06	21130.62	weekday 03:00	825.68	743.33	805.09
weekday 04:00	23808.76	19411.50	22709.44	weekday 04:00	832.95	746.30	811.28
weekday 05:00	23244.66	19325.50	22264.87	weekday 05:00	887.98	744.61	852.14
weekday 06:00	17634.76	18651.67	17888.99	weekday 06:00	686.95	731.76	698.15
weekday 07:00	17118.54	17939.83	17323.86	weekday 07:00	686.96	729.48	697.59
weekday 08:00	16707.85	17178.69	16825.56	weekday 08:00	667.23	694.83	674.13
weekday 09:00	18033.55	18229.49	18082.54	weekday 09:00	634.22	712.07	653.68
weekday 10:00	19729.26	18816.68	19501.11	weekday 10:00	693.07	733.58	703.20
weekday 11:00	24270.16	18918.11	22932.15	weekday 11:00	832.74	734.05	808.07
weekday 12:00	21790.41	18796.33	21041.89	weekday 12:00	817.73	731.25	796.11
weekday 13:00	21978.98	19185.86	21280.70	weekday 13:00	826.18	741.58	805.03
weekday 14:00	25202.86	20258.36	23966.73	weekday 14:00	851.46	786.02	835.10
weekday 15:00	22564.66	19695.35	21847.33	weekday 15:00	821.08	765.00	807.06
weekday 16:00	22131.14	19619.82	21503.31	weekday 16:00	796.24	745.53	783.57
weekday 17:00	20879.76	18292.06	20232.83	weekday 17:00	750.85	703.62	739.04
weekday 18:00	21252.16	18286.13	20510.65	weekday 18:00	764.22	694.35	746.75
weekday 19:00	20317.75	18910.72	19966.00	weekday 19:00	737.95	667.40	720.31
weekday 20:00	20677.08	17084.66	19778.98	weekday 20:00	753.56	645.81	726.62
weekday 21:00	21366.06	17260.79	20339.75	weekday 21:00	783.76	652.75	751.01
weekday 22:00	21696.71	17537.11	20656.81	weekday 22:00	803.70	662.32	768.36
weekday 23:00	20794.32	18911.51	20323.62	weekday 23:00	777.43	738.73	767.75
weekday 00:00	21591.49	18418.01	20798.12	weekday 00:00	809.59	697.90	781.67
Sum	507823.82	446921.44	492598.23	Sum	18674.87	17216.57	18310.29
Ave	21159.33	18621.73	20524.93	Ave	778.12	717.36	762.93

Table 4 - Thermal and auxiliary yearly summary table for 2005

From the thermal power, the electrical power used by the refrigeration machine's compressor is calculated by using the coefficient of performance (COP) of the refrigeration machines. The relation between the thermal energy, compressor electrical energy and COP is given in the equation below.

$$COP = \frac{Thermal\ Energy\ (kW\ )}{Comp.Electrical\ Energy\ (kW\ )} = \frac{Q}{E_{Comp}} \qquad (7)$$

The baseline thermal, auxiliary and electrical energy for the surface cascade refrigeration system are given in Table 5.

Baseline 2005				
Weekday	Thermal energy (kW)	Comp. electrical energy (kW)	Auxiliary energy (kW)	Total electrical energy (kW)
weekday 01:00	21214.24	5056.50	801.73	5858.23
weekday 02:00	20478.13	4753.51	776.85	5530.36
weekday 03:00	21130.62	4904.97	805.09	5710.07
weekday 04:00	22709.44	5271.46	811.28	6082.74
weekday 05:00	22264.87	5168.26	852.14	6020.40
weekday 06:00	17888.99	4152.50	698.15	4850.65
weekday 07:00	17323.86	4021.32	697.59	4718.92
weekday 08:00	16825.56	3905.66	674.13	4579.79
weekday 09:00	18082.54	4197.43	653.68	4851.11
weekday 10:00	19501.11	4526.72	703.20	5229.92
weekday 11:00	22932.15	5323.15	808.07	6131.22
weekday 12:00	21041.89	4884.38	796.11	5680.49
weekday 13:00	21280.70	4939.81	805.03	5744.84
weekday 14:00	23966.73	5563.31	835.10	6398.41
weekday 15:00	21847.33	5071.34	807.06	5878.40
weekday 16:00	21503.31	4991.48	783.57	5775.05
weekday 17:00	20232.83	4696.57	739.04	5435.61
weekday 18:00	20510.65	4761.06	746.75	5507.81
weekday 19:00	19966.00	4634.63	720.31	5354.94
weekday 20:00	19778.98	4591.22	726.62	5317.84
weekday 21:00	20339.75	4721.39	751.01	5472.40
weekday 22:00	20656.81	4794.99	768.36	5563.35
weekday 23:00	20323.62	4717.65	767.75	5485.40
weekday 00:00	20798.12	4827.79	781.67	5609.46
Sum	492598.23	114477.11	18310.29	132787.41
Ave	20524.93	4769.88	762.93	5532.81

Table 5 – 2005 thermal, compressor, auxiliary and total electrical baseline

By processing the data and studying the system interaction as described in chapter 2, a mathematical model of the surface cascade refrigeration system can be constructed.

3.4. Mathematical modelling

Numerical modelling is a mathematical model to describe the behaviour of a system. It is used to evaluate the dependence between variables or dependants. It is a representation attempting to describe the structure of an object or event in the real world through mathematics. Mathematical models are extensively used in computer simulations such as in this dissertation.

Normally a system can be described by a series of mathematical equations, because a system is made up of a series of interactive elements. By varying an input to the system between pre-determined ranges, its effect on the system can be observed (experimentation). When these equations have been identified, the system can be simulated. The accuracy of the simulation depends on the accuracy of the model's mathematical equations.

The following steps of mathematical modelling were followed:

1. Create the mathematical models: First, the main focus of the investigation must be identified. The model always attempts to describe a real-life situation. Simplify the physical situation, so that only the main focus remains. This is done through various assumptions. Remember that too many assumptions can lead to errors in the model, but that it may be difficult to obtain answers from an overly complicated model. Assumptions may include geometrical simplifications and assumptions, phenomenological simplifications and assumptions, etc.

2. After the key issue has been identified, the mathematical model must be established. Determine the important variables and constants, and group them together in terms of input variables, output variables, and constants. The equations that describe the process can then be derived. This is often the most time-consuming and difficult part of the process.

3. Solve the models (simulate): The results of the simulation can have an exact solution, or the solution must be obtained from numerical techniques, or a combination of both.

4. Verify the results: When the model has been created and used, it must be verified to determine the validity of the model. This can be done by comparing it to basic principles, like the conservation of mass and energy. The researcher can analyse the results logically. Another method is to verify the model experimentally. This is typically done in a case study, where the outputs of the model are compared to measured values of the actual system.

The South Deep cascade surface refrigeration system is used as the basis for the development of the new simulation model for cascade surface refrigeration systems. The simulation model can thus be used on any cascade surface refrigeration system by changing the names of the dams, valves and refrigeration machines.

The 24-hour energy baseline and the overall schematic layout of the refrigeration system are obtained from data processing. The baseline and cascade refrigeration system layout is verified with the mine.

The schematic layout of the surface cascade refrigeration system is used to obtain an overall picture of the typical flows through the chiller machines. The key elements of the model can be identified in the schematic layout of the surface cascade refrigeration system in Figure 12.

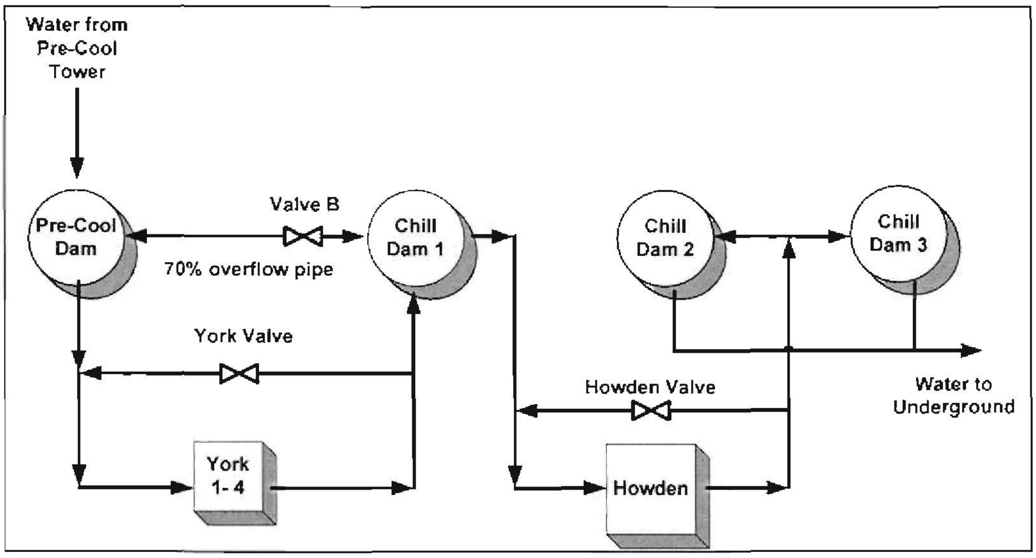


Figure 12 - Schematic layout of the cascade refrigeration system

The pipe between the Pre-Cool Dam and Chill Dam one is situated at seventy percent of the height of both dams and is thus named the seventy percent overflow pipe. Valve B is part of this pipe and allows for the overflow to be opened or closed.

The mathematical modelling starts with the inputs into the system. From the data discussed in the previous section the following water flows and temperatures go into the system.

Input		
Time	Flow (l/s)	Temp (°C)
01:00	247.56	20.54
02:00	293.44	20.09
03:00	300.24	20.09
04:00	286.02	20.47
05:00	275.72	20.33
06:00	272.41	20.31
07:00	261.80	20.23
08:00	286.41	20.22
09:00	276.61	19.19
10:00	283.46	19.61
11:00	277.14	19.81
12:00	293.89	19.93
13:00	274.51	20.93
14:00	298.79	21.22
15:00	297.49	20.58
16:00	288.69	21.42
17:00	283.89	21.35
18:00	283.27	21.26
19:00	265.37	21.19
20:00	262.94	21.11
21:00	264.00	20.90
22:00	239.09	20.90
23:00	286.33	20.69
00:00	286.33	20.75
Sum	6685.37	
Ave	278.56	20.55

Table 6 - Mathematical model inputs

These inputs change the Pre-Cool Dam's levels and temperature. There are also inflow into or outflow from the Pre-Cool Dam through the Chill Dam 1 overflow, and an outflow of the Pre-Cool Dam through the York chiller machines.

The following equations and examples are how the new dam level and temperature of the Pre-Cool Dam are calculated.

$$New\ Dam\ Level\,\% = \frac{\left[\left(\frac{previous\ Dam\ Level\,\%}{100}\right)\times Dam\ Volume + (\dot{m}_{in} - \dot{m}_{out})\times 3.6\times t\right]\times 100}{Dam\ Volume}$$

(8)

Example of a dam level calculation:

$$previous\ Dam\ Level\% = 50\%$$
$$Dam\ Volume = 2700\,m^3$$
$$\dot{m}_{in} = 322.77L/s$$
$$\dot{m}_{out} = 278.56L/s$$
$$t = 1hr$$

$$New\ \ Dam\ \ Level = \frac{\left[\left(\frac{50\%}{100}\right)\times 2700\,m^3 + (322.77L/s - 278.56L/s)\times(3.6\frac{kg/hr}{L/s})\times 1hr\right]}{\left[2700\,m^3\right]}\times 100$$

$$New\ \ Dam\ \ Level = 55.89\%$$

The new temperatures of the dam are similarly calculated:

$$New\ Dam\ Temp = \frac{\left[\left(\frac{previous\ Dam\ Level\,\%}{100}\right)\times Dam\ Volume\times previous\ Dam\ Temp + (\dot{m}_{in}\times T_{in} - \dot{m}_{out}\times T_{out})\times 3.6\times t\right]}{\left(\frac{previous\ DamLevel\%}{100}\right)\times Dam\ Volume + \dot{m}_{in} + \dot{m}_{out}}$$

(9)

Example of calculating dam water temperature:

$$previous\ Dam\ Level\,\% = 50\%$$
$$Dam\ Volume = 2700\,m^3$$
$$previous\ Dam\ Temp = T_{out} = 18.06\,^{o}C$$
$$T_{in} = 18.11\,^{o}C$$
$$\dot{m}_{in} = 322.77\ L/s$$
$$\dot{m}_{out} = 278.56\ L/s$$
$$t = 1\,hr$$

$$New\ DamTemp = \frac{\left[\left(\frac{50\%}{100}\right)\times 2700\,m^3 \times 18.06\,^{\circ}C + (322.77L/s \times 18.11^{\circ}C - 278.56\,L/s \times 18.06^{\circ}C)\times(3.6\frac{kg/hr}{L/s})\times 1\,hr\right]}{\left[\left(\frac{50\%}{100}\right)\times 2700\,m^3 + (322.77\,L/s - 278.56\,L/s)\times\left(3.6\frac{kg/hr}{L/s}\right)\times 1\,hr\right]}$$

$$New\ DamTemp = 18.098^{\circ}C$$

Note that this is an iterative process and the calculation is updated as the variables (York outflow and Chill Dam 1 overflow) change. The dam level and temperature must stay within the mine's specified parameters. And the calculation is done for each hour of the day.

The flow through the York machine is partly from the Pre-Cool Dam and partly from the back-pass. The following equation gives the total flow through the York machines, and the inlet temperature.

$$\dot{m}_{York} = \dot{m}_{pre-Cool} + \dot{m}_{Back-pass} \tag{10}$$

$$T_{Inlet} = \frac{T_{pre-Cool}\dot{m}_{pre-Cool} + T_{Back-pass}\dot{m}_{Back-pass}}{\dot{m}_{pre-Cool} + \dot{m}_{Back-pass}} \tag{11}$$

Refrigeration machines are programmed to give a set output temperature when the cooling load is within its design parameters. The back-pass valve reduces the inlet temperature and contributes to the machine's ability to give the correct outlet temperature.

The thermal energy is calculated with equation (1). Because the outlet temperature is constant, and inlet temperature and flow vary, the thermal energy of the refrigeration machine varies.

Example of calculating the thermal energy required to cool the water:

$$Q = (115 kg\ / s)\left(4.183 \frac{kJ}{kg\ .K}\right)(8^{\circ}C - 16.4^{\circ}C)$$

$$Q = -4040.78\, kW$$

Note:

- The water mass flow unit in the calculation is kilogram per second. The following relationship holds true: (1 l/s = 1 kg/s)
- The temperatures are not converted from degrees Celsius to Kelvin because [(xoC+273.15K)-(y oC+273.15K)] = [xoC - yoC].
- Q is negative because energy was removed from the system

The electrical energy required by the machine for the given thermal energy is calculated with equation (7). The auxiliary power is calculated with equations (2) and (3). An average COP of 6.11 is assumed for the example.

Example of calculating the electrical energy from the thermal energy:

$$E = \frac{4040.78 kW}{6.11}$$

$$E = 661.34 kW$$

The water from the York refrigeration machines flows into the Chill Dam 1. Chill Dam 1's change in level and temperature is calculated with equations similar to equation (8) and (9). Chill Dam 1 has an inflow from or outflow to the Pre-Cool Dam and an outflow to the Howden refrigeration machine.

The water flow and temperature through the Howden, taking the back-pass into consideration, are done with equations similar to equations (10) and (11). Again the Howden is programmed to give a set output value and the back-pass assists by lowering the inlet temperature.

The thermal and compressor electrical energy are also calculated with equations (1) and (7). The auxiliary is calculated with equations similar to equations (2) and (3).

Changes in dam level and temperature for Chill Dams 2 and 3 are also calculated with equations similar to equations (8) and (9). Chill Dams 2 and 3 receive water from the Howden. The outflow is the water that goes to the BAC and underground mining activities.

Once the simulation is complete and the overall kW power from the simulation represents the baseline, the system mathematical model simulation is ready to be optimised.

3.5. Optimisation of cascade refrigeration system

The mathematical model simulation developed in the section above is optimised to use the least amount of thermal and electrical energy during the Eskom peak times. The following Eskom Mega Flex time of use (TOU) structure is used in the calculation for the most cost and energy effective way to do the required cooling with the South Deep cascade surface refrigeration system.

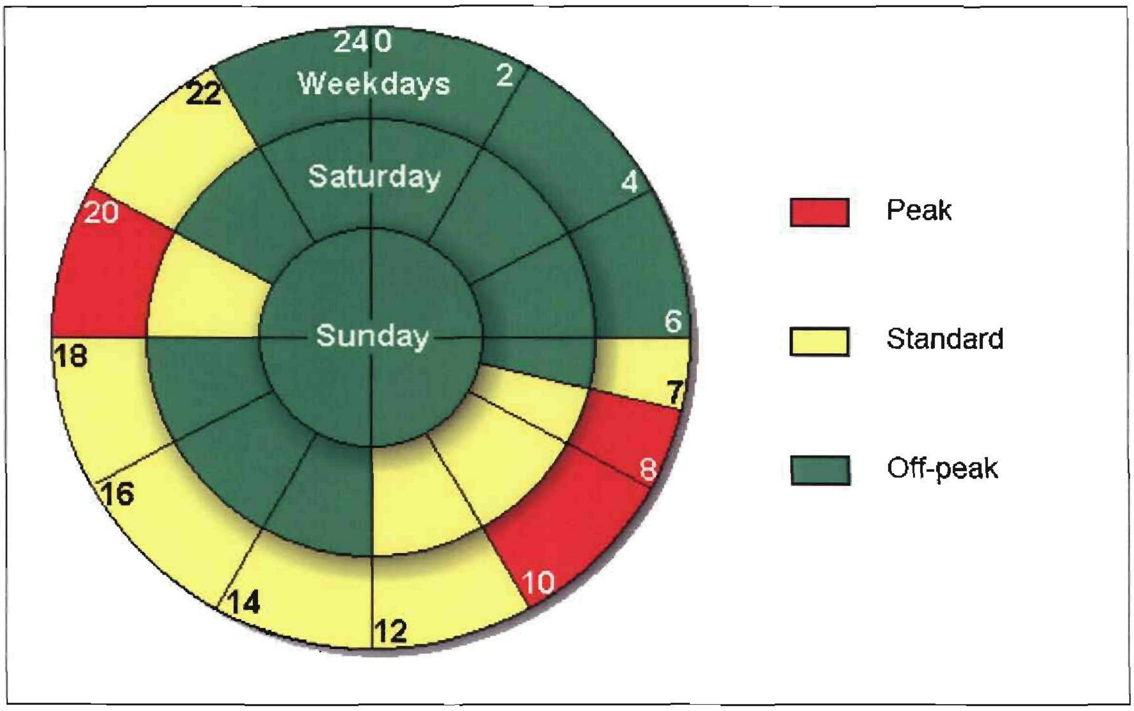


Figure 13 - Eskom Mega Flex TOU [48]

High-demand season (June – August)		**Low-demand season (September – May)**
52,22c + VAT = **59,53c/kWh**	Peak	14,82c + VAT = **16,89c/kWh**
13,81c + VAT = **15,74c/kWh**	**Standard**	9,20c + VAT = **10,49c/kWh**
7,51c + VAT = **8,56c/kWh**	Off-peak	6,52c + VAT = **7,43c/kWh**

Table 7 - Eskom Mega Flex TOU price index [48]

The optimisation cost function is to minimise the amount of cooling required during Eskom peak times while keeping the supply of chilled water underground unchanged.

From equation (1) it can be seen that the thermal energy is reduced when the temperature difference across the evaporator of the refrigeration machine is reduced to a minimum. The thermal energy is also reduced when the mass flow through the evaporator nears zero. The mass flow is zero after the controlled shut down of the entire refrigeration machine.

Thus the system is optimised by minimizing the water mass flow through the refrigeration machines during the Eskom peak times and having the maximum water flow through the refrigeration machines during the Eskom off-peak period.

This doesn't influence the mine chilled water demand because the chilled dam is filled with chilled water during the Eskom off-peak period. The chilled dam is used as a buffer to supply the mine peak chilled water demand throughout the day.

Optimisation is achieved through an iterative process while keeping all the simulation variables within the mine specified range.

3.6. Verification of new simulation models

Verification is the process whereby inspection and reviews are carried out to ensure that requirements were addressed and that objectives were met. This ensures that the system was built correctly. Validation is the process whereby testing and comparisons are carried out to ensure that the results are applicable to the initial intention and that they are accurate. It ensures that the right system was built.

In theory, in order to perform validation and verification (V&V) of a calculation result, V&V work must be performed on the following:

- The input data
- The software used
- The calculation model that was created
- The calculation that was performed using the model

The input data used in the simulation model came from processing the data received from the mine as described in section 3.3. The input data was V&V by mine personnel. The software used for the simulation model is MS-Excel. The calculations of the mathematical model created are discussed in section 3.4.

The electrical energy profile from the mathematical model is compared with the baseline electrical energy from the processed data in Figure 14.

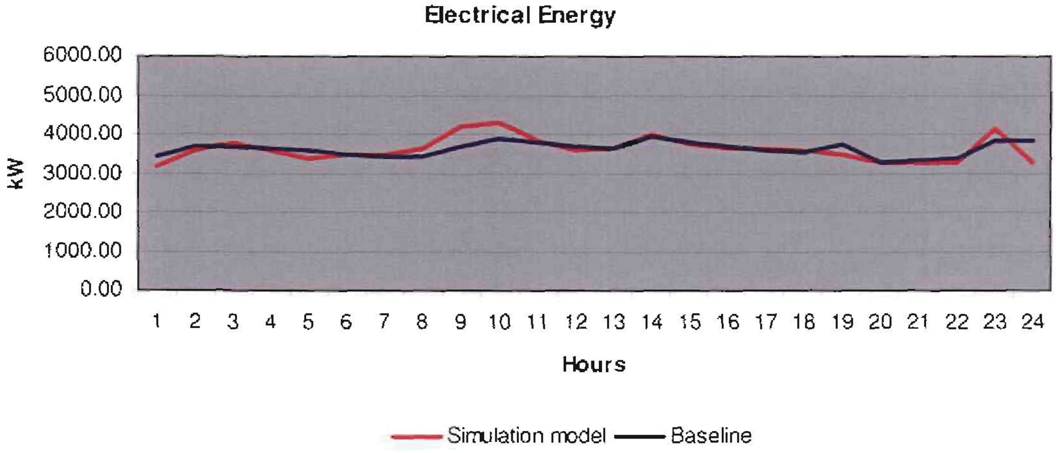


Figure 14 - Simulation model and baseline comparisons

Taking an energy efficiency component of 0.9503 into account the electrical energy profile from the mathematical model closely matches the baseline profile.

The mathematical model was used to perform optimisation calculations keeping within mine-specified parameter constraints. A control specification is made from the optimisation process.

3.7. Developing new controllers to meet system constraints

Understanding the PLC – SCADA control (internal control) of the cascade surface refrigeration system helps to understand the DSM specific control. In Appendix E the flow diagram of the internal control of the machine is given and explained. It is thus not necessary to develop an entirely new PLC – SCADA control system for the DSM application.

The new controller is a supervisory control system working on top of the PLC-SCADA system. The new controller takes into account the flow, dam levels, temperatures and especially time of the day for its decisions. This section discusses the control philosophy executed by the REMS3 FP controller for each component illustrated in Figure 12 of section 3.4.

3.7.1. Howden Controller

The Howden controller evaluates the water level and temperature of Chill Dams 2 & 3 as well as the water level and temperature of Chill Dam 1. Note that Chill Dams 2 & 3 will have precedence over Chill Dam 1. The control protocol is to keep Chill Dam 2 & 3 filled with Chilled water. Figure 15 illustrates the water and information flow with a summary of the main components of the controller.

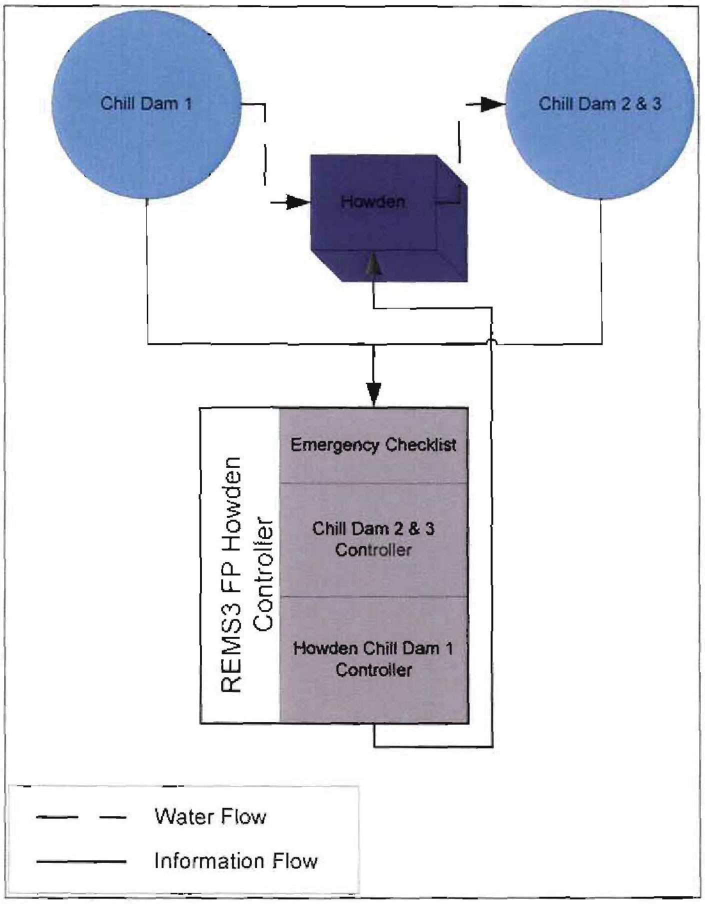


Figure 15 - Howden controller with water and information flow

Figure 16 shows the Emergency Checklist that the Howden controller will go through continuously before going to the control system. The inputs from Chill Dam 1 and Chill Dams 2 & 3 are in the starting block of the diagram.

If the system clears all the Emergency Checks the controller moves onto the Chill Dams 2 & 3 controller. The mine can also have its own emergency checklist and only send REMS a system-healthy signal, which enables REMS to control the system. The mine emergency checklist, for example, takes the machines oil pressure into account.

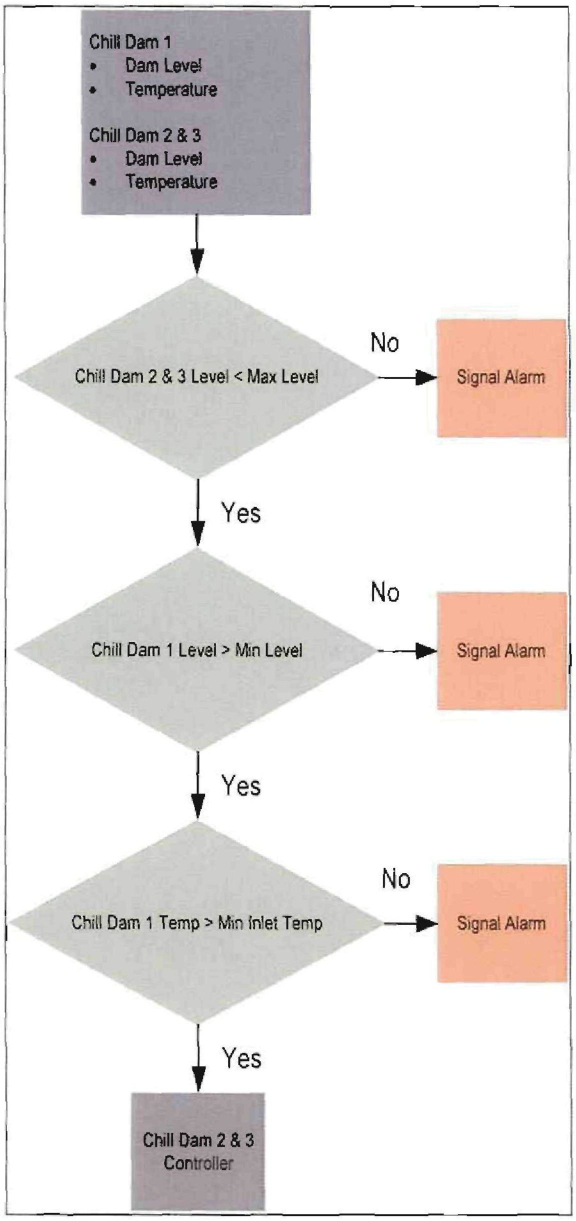


Figure 16 - Howden Emergency Checklist

The Chill Dams 2 & 3 controller ensures that Chill Dams 2 & 3 are at the correct set point temperature and set point level for a given time of the day.

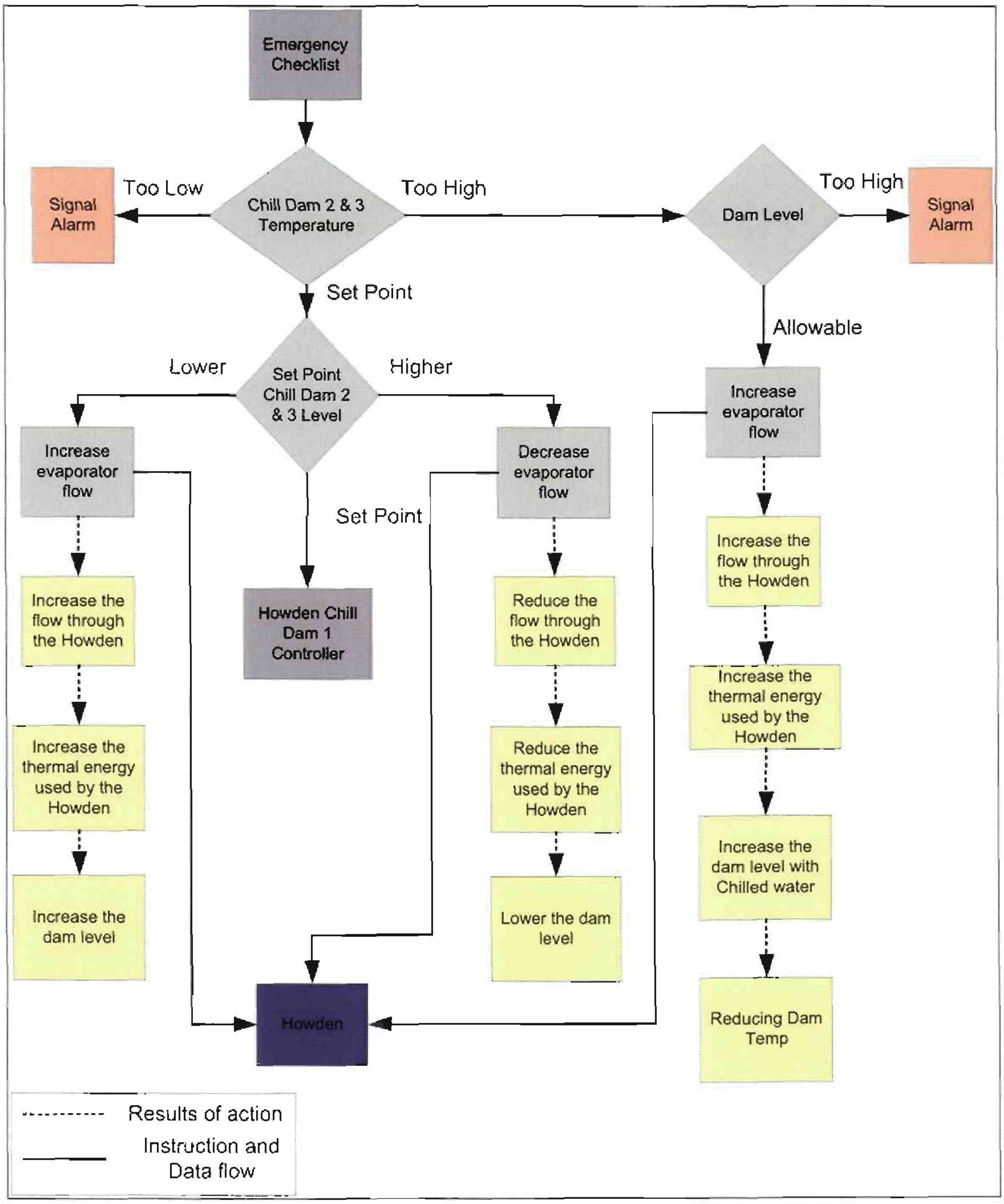


Figure 17 - Howden Chill Dams 2 & 3 controller

Following a decision route, the controller either gives a command to the Howden PLC, signals an alarm or moves on to the Howden Chill Dam 1 controller illustrated in Figure 18.

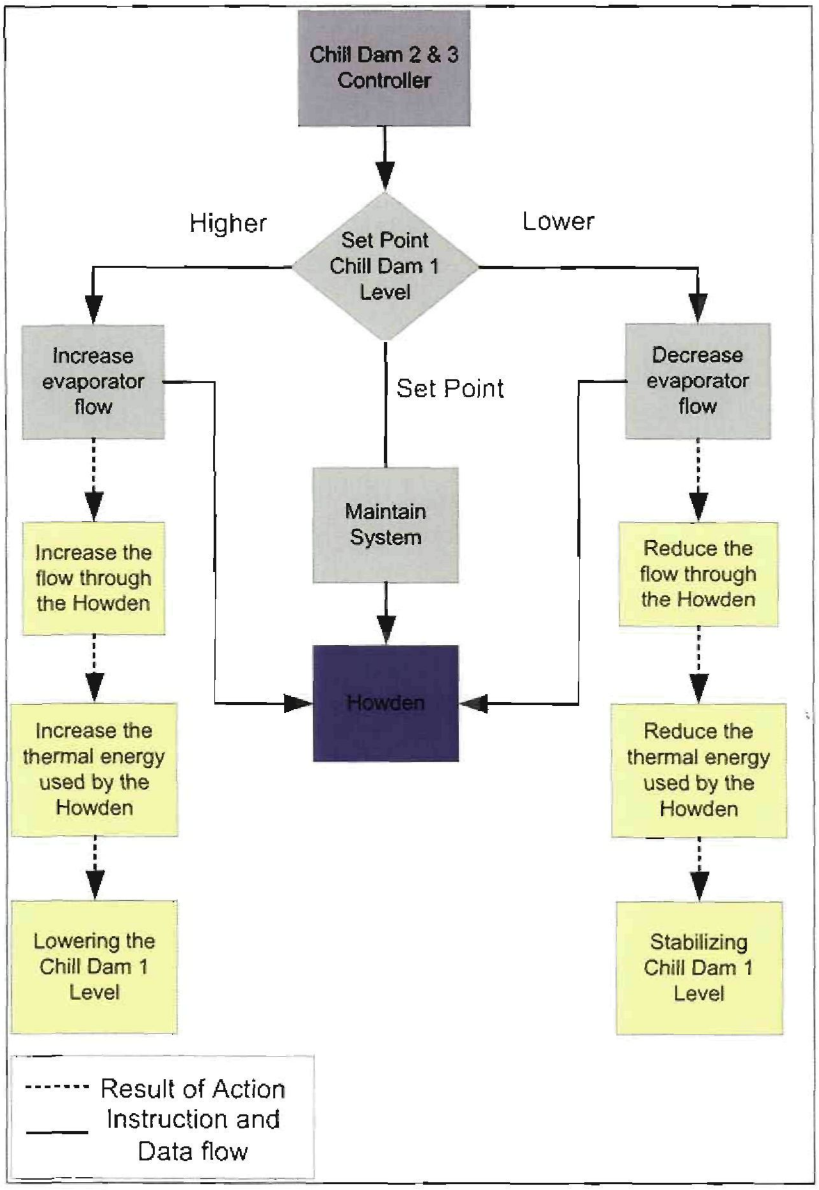


Figure 18 - Howden Chill Dam 1 controller

The Howden Chill Dam 1 controller ensures that the Howden doesn't empty Chill Dam 1. The Howden controller's main objective is to ensure that there is enough chilled water in Chill Dams 2 & 3 to supply to the underground mining levels at any time of the day.

3.7.2. Howden Back-Pass Valve Controller

The Howden back-pass valve controller will control the inlet temperature into the Howden by opening or closing the Howden Back-pass valve. Figure 19 illustrates the information and water flow.

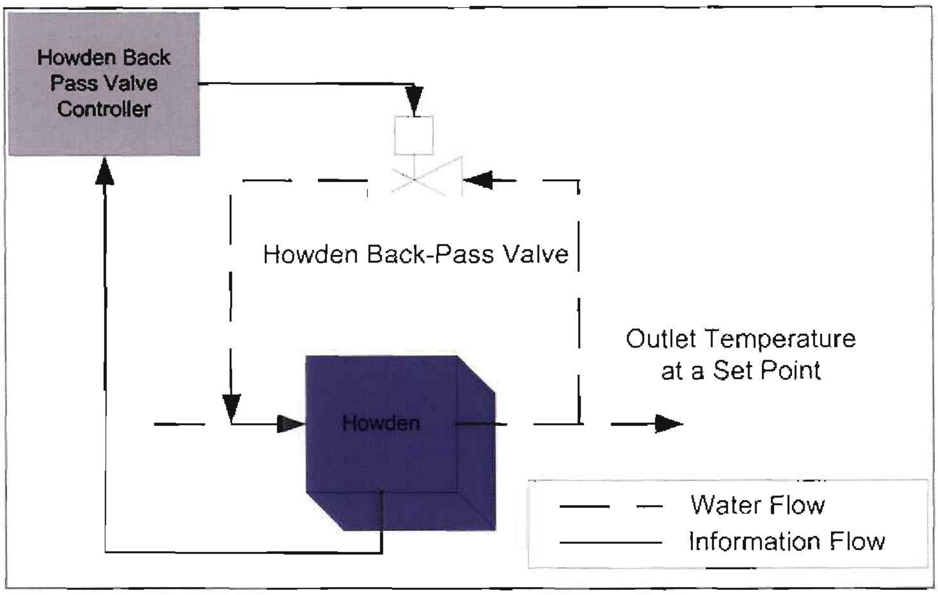


Figure 19 - Howden back-pass valve controller water and information flow

The Howden back-pass valve controller will use the data supplied by the SCADA system to determine the percentage opening of the valve according to the predetermined set points. These set points are calculated using the time of day, Chill Dam 1 temperature and flow.

Note that the developed control strategies work together to manipulate the power consumption of the refrigeration system. The impact of the strategy with all the controllers working together is evaluated later in this study.

Figure 20 is a flow diagram of the Howden back-pass valve controller.

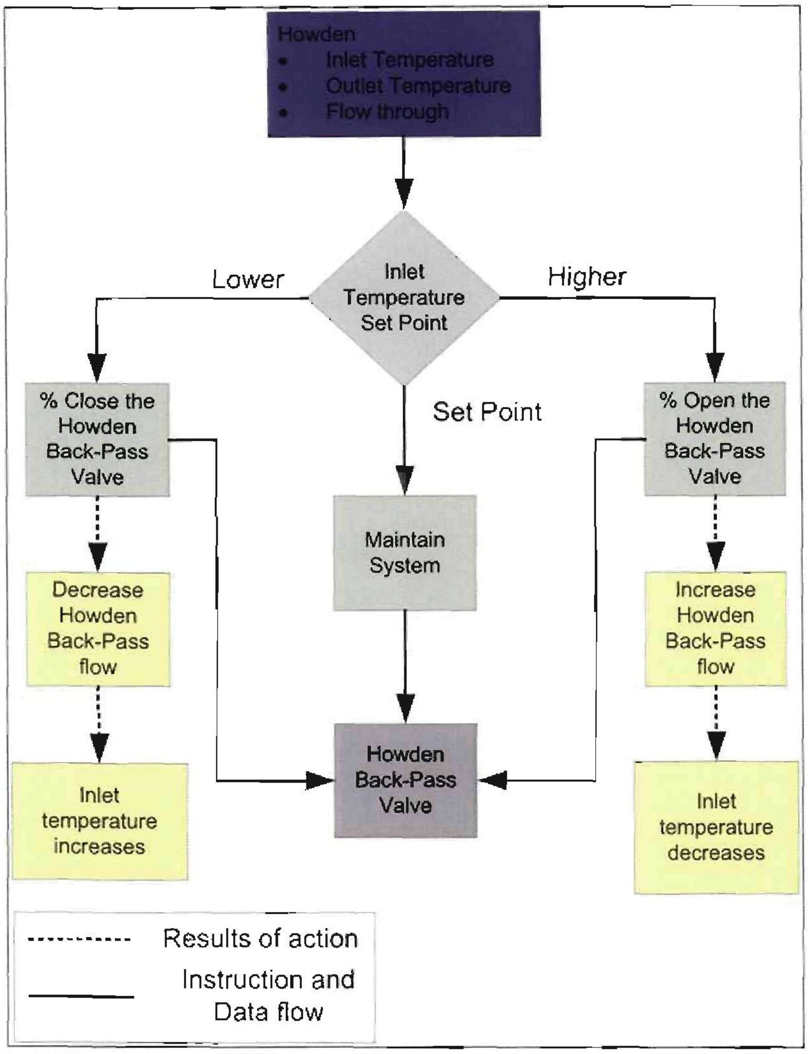


Figure 20 - Howden back-pass valve controller diagram

3.7.3. York Controller

The York controller looks at the water level and temperature of Chill Dam 1 as well as the water level and temperature of the Pre-Cool Dam. Note that Chill Dam 1 level and temperature will have precedence above the Pre-Cool Dam level and temperature. The York controller is similar to that of the Howden, and Figure 21 illustrates the water flow and information flow. The three main parts of the York controller are an Emergency Checklist, Chill Dam 1 controller and Pre-Cool Dam controller.

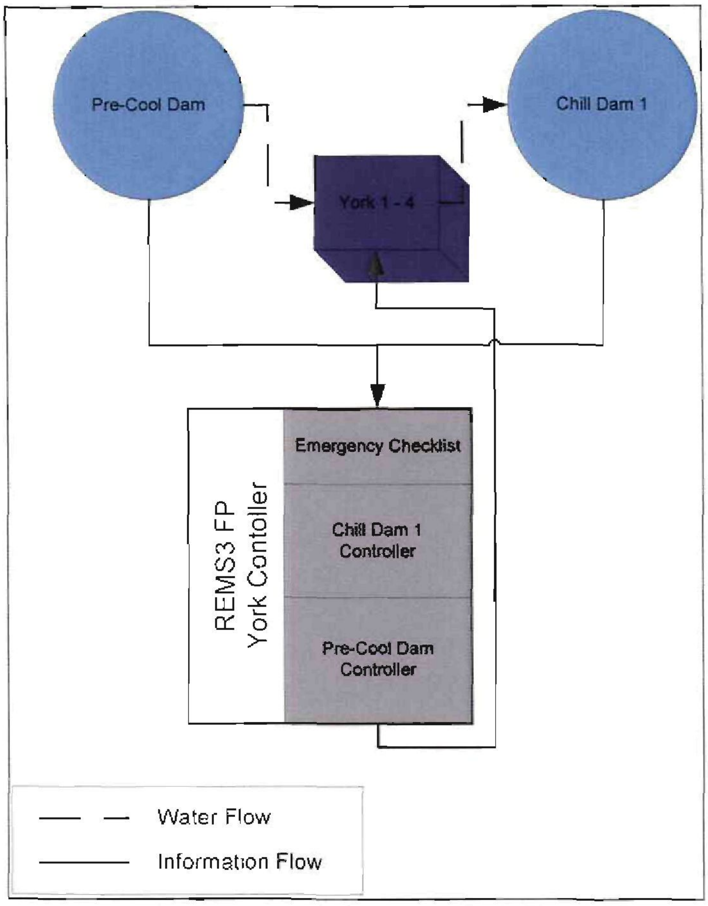


Figure 21 - York controller with water and information flow

The York controller will acquire the dam level and temperature of the Pre-Cool Dam and Chill Dam 1 via tags from the PLC and SCADA systems. This data will be weighed against the check list and will signal an alarm if an alarm criterion is encountered. Figure 22 illustrates the working of the Emergency Checklist for the York controller.

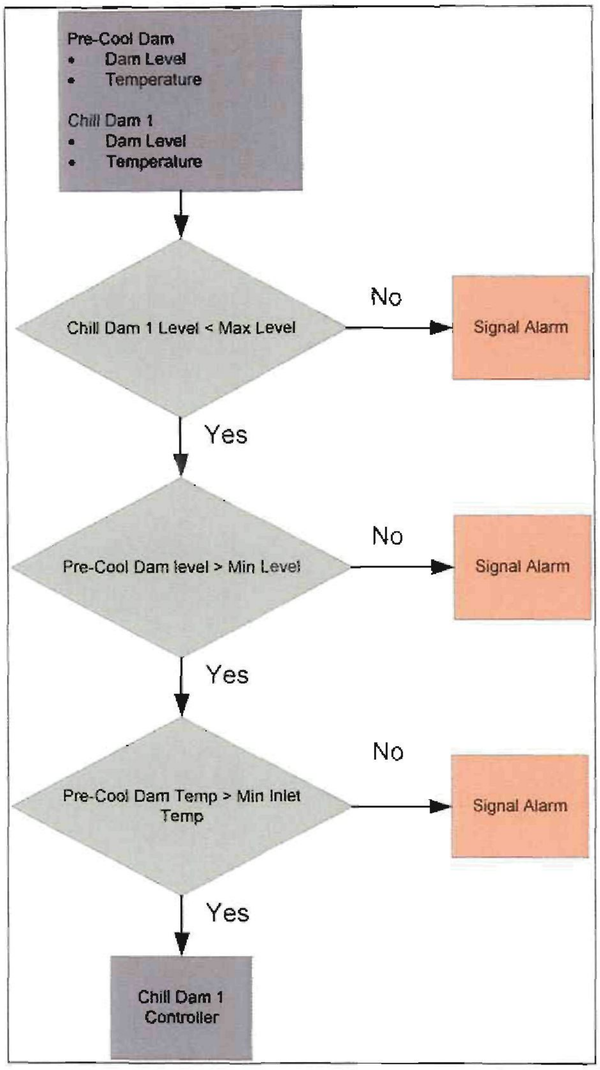


Figure 22 - York emergency checklist

The York controller goes onto Chill Dam 1 controller if no alarm is signalled. The Chill Dam 1 controller is illustrated in Figure 23. The first priority is the Chill Dam 1 temperature and then the dam level.

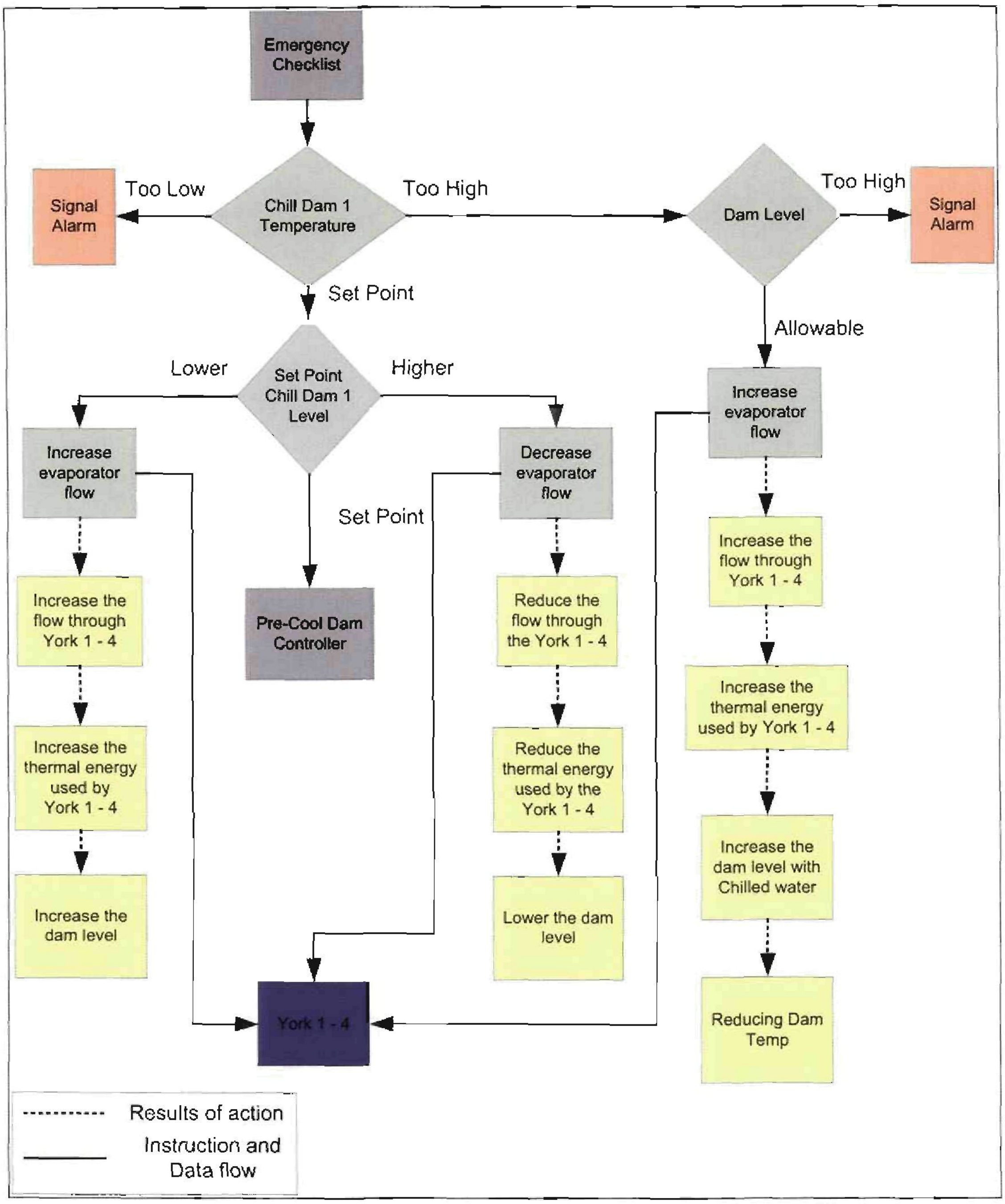


Figure 23 - Chill Dam 1 controller

Depending on the decision course followed through the controller, a signal to the individual York machine PLC or the York controller goes onto the Pre-Cool Dam controller shown in Figure 24.

The required water flow through the system is average 280l/s. The controller uses the dam's current level and change in level over a period of time to achieve the target flow and temperature with the 4 York machines.

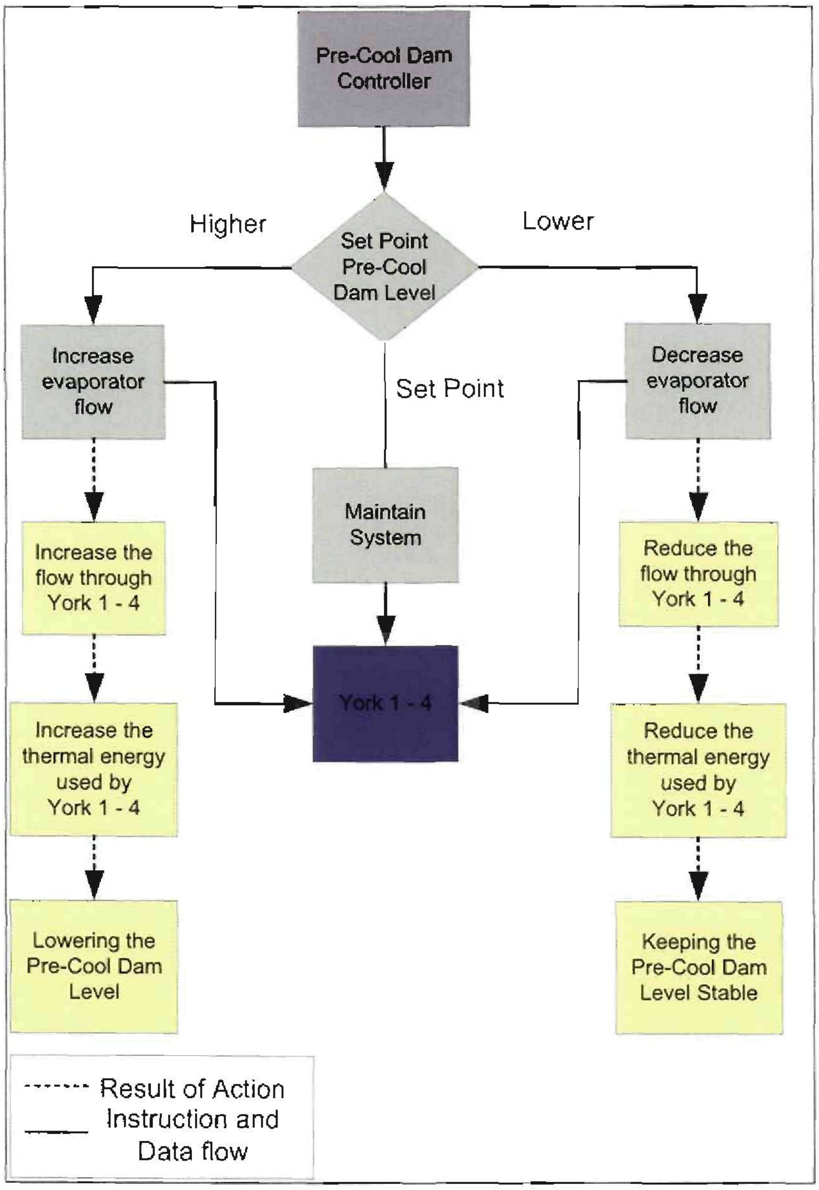


Figure 24 - Pre-Cool Dam controller

The Pre-Cool Dam controller will ensure that there is enough volume in the Pre-Cool Dam to accommodate the inflow of warm water at any time of the day.

3.7.4. York Back-Pass Valve Controller

The York back-pass valve controller will control the inlet temperature into the York through opening or closing the valve. The control is similar to the Howden back-pass valve controller, and Figure 25 illustrates the system layout with information and water flow.

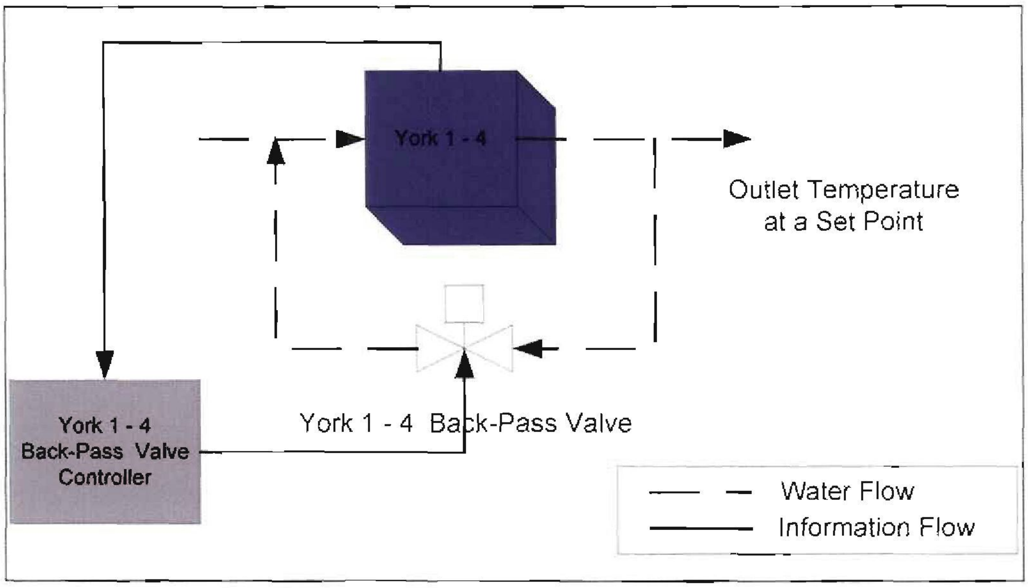


Figure 25 - York back-pass valve layout

The percent opening will be determined by the predetermined set points of the inlet temperature weighed against the actual inlet temperature of the York machines. The outlet temperature and flow rates will be taken into account by the controller.

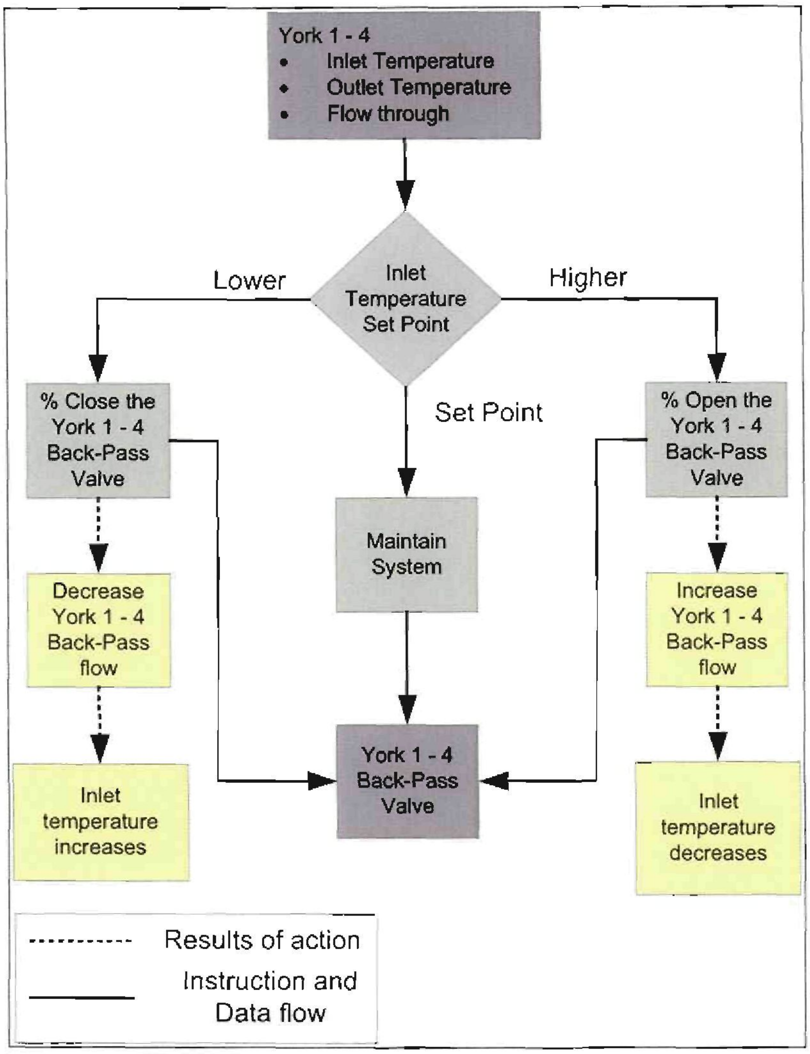


Figure 26 - York back-pass valve controller

If the inlet temperature is at its set point, the system is maintained as is and no changes occur.

3.7.5. Valve B Controller

Valve B is situated in the seventy percent overflow pipe between the Pre-Cool Dam and Chill Dam 1. The valve allows chilled water from Chill Dam 1 to overflow into the Pre-Cool Dam. This cools the Pre-Cool Dam temperature and allows the system more thermal storage.

During the Eskom evening peak time the valve allows pre-cooled water to flow into the Chill Dam 1 until the maximum Chill Dam 1 temperature or level is reached. The control is illustrated in the block diagram shown bellow.

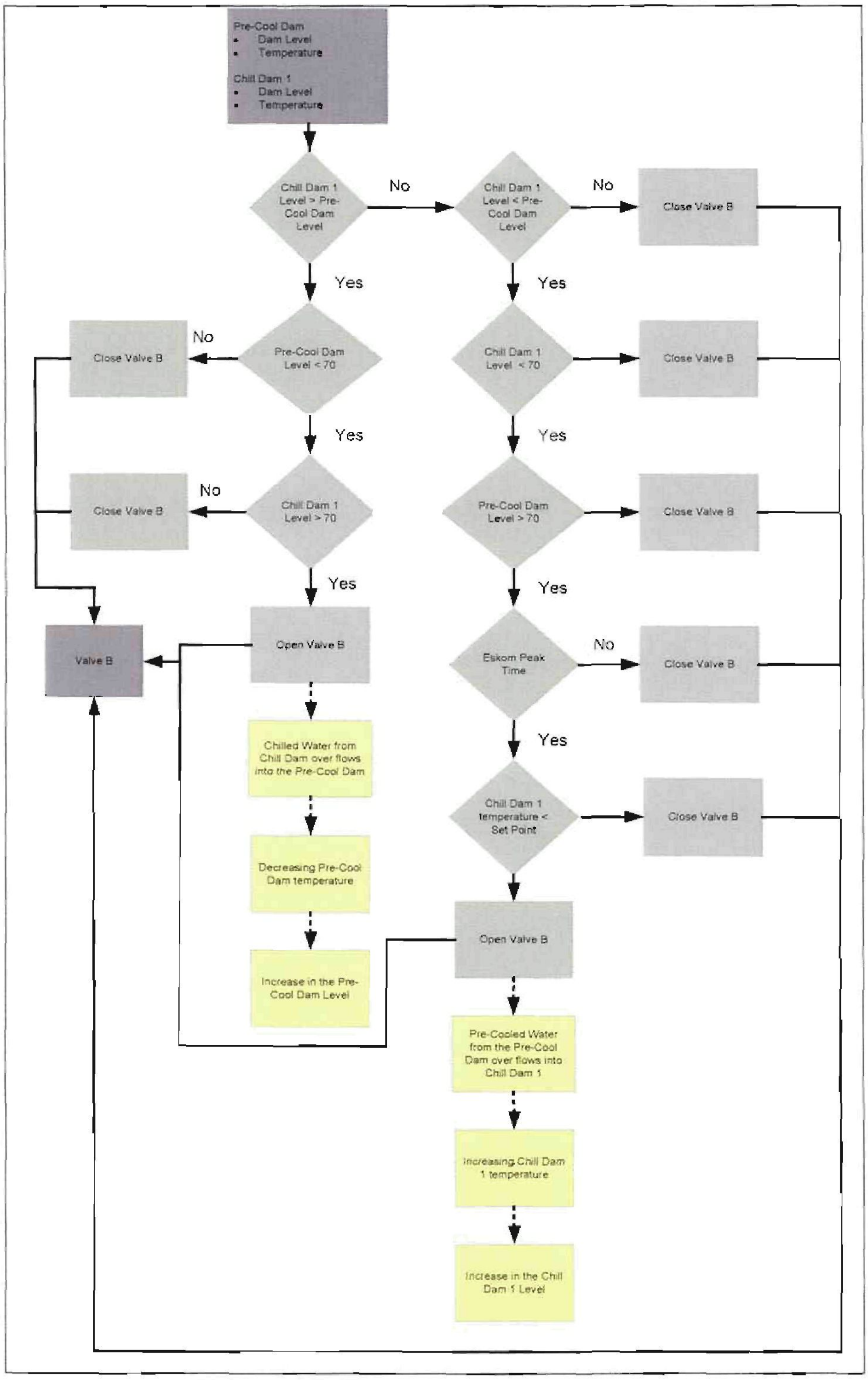


Figure 27 - Valve B controller

The control systems described above are programmed into the REMS simulation and control system. The set-up or set point parameters are case-study specific and unique for each case study. The control system described above is first tested on a simulation of the case study.

3.8. System simulation

The mathematical modelling and optimisation completed proves that it is indeed possible to optimise the system within safe operational limits. The controllers for the system developed in the previous section are then tested on the system simulated in a real-time software environment.

The REMS Platform (Real-time Energy Management System) is then used to simulate the whole process in real time. In Figure 28, a REMS Platform layout of the South Deep cascade surface refrigeration system is shown.

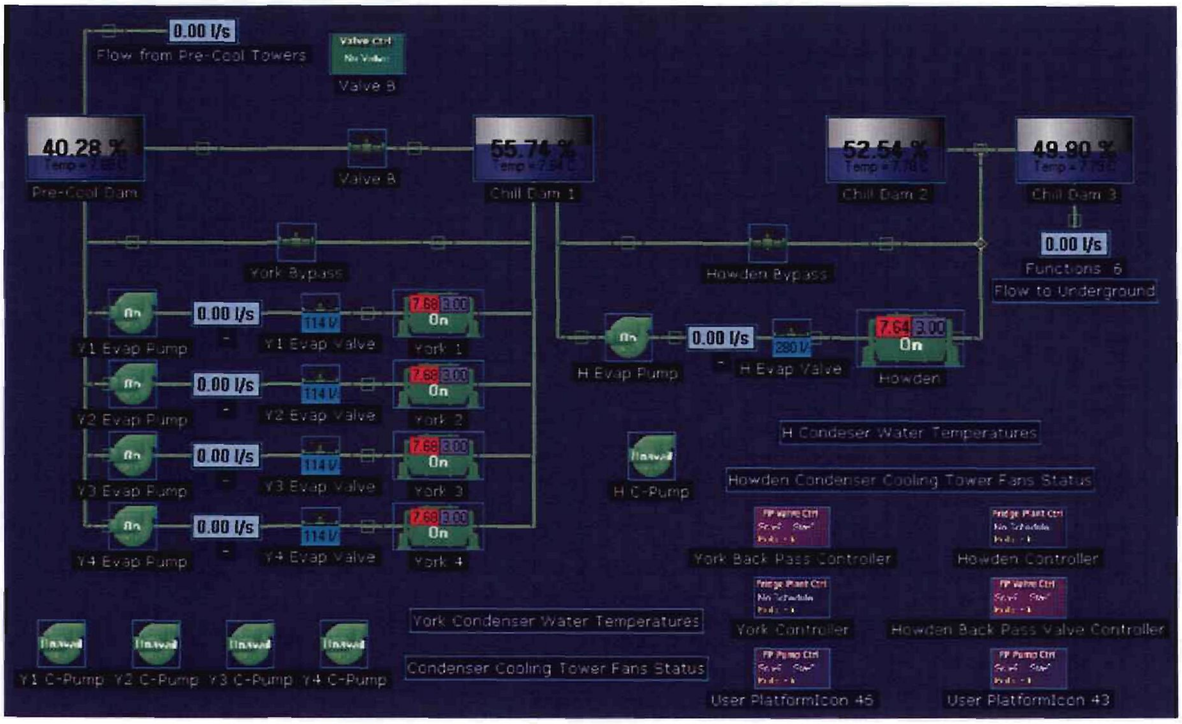


Figure 28 - REMS simulation model software

All the components on the platform are interfaced once the layout is completed. Then the different controllers for each component are programmed to control the entire system within the mine-specified limits.

This is a real-time simulation and it provides a clear picture of what the actual situation at the mine will be.

3.9. Verification of new system constraint controllers

Verification of the simulated system with new controllers is necessary before testing the controllers on the case study.

This section discusses the result of the previous section's controllers with a varying inflow and inlet temperature on the system. Figure 29 illustrates the varying inflow and inlet temperature.

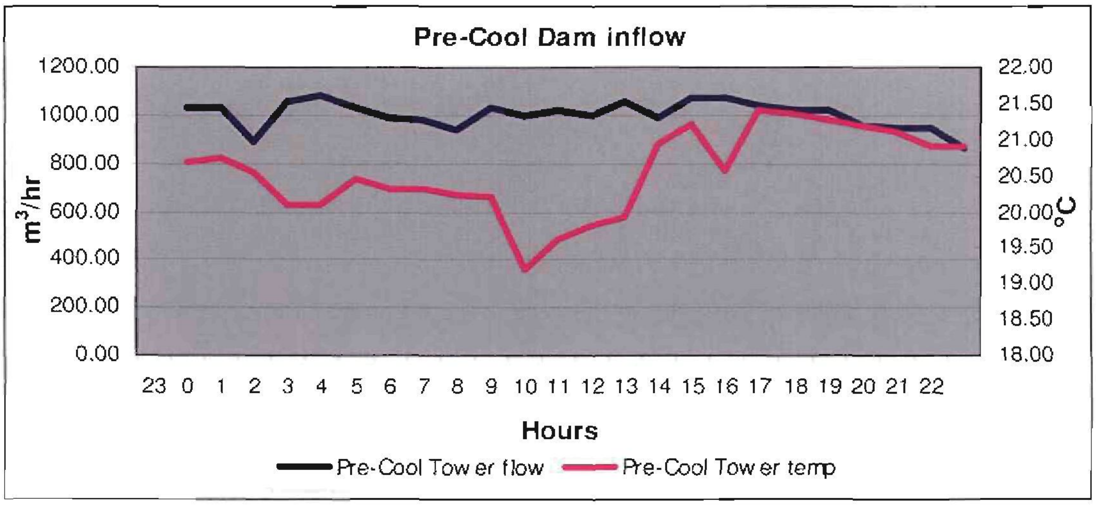


Figure 29 - Pre-Cool Dam inflow

The decrease in inlet temperature will be reflected in the thermal energy usage of the York as can be seen in Figure 30. The York back-pass will be used mainly to control the inlet temperature going into the York and will also be used during the morning peak period to reduce the energy consumption for the period.

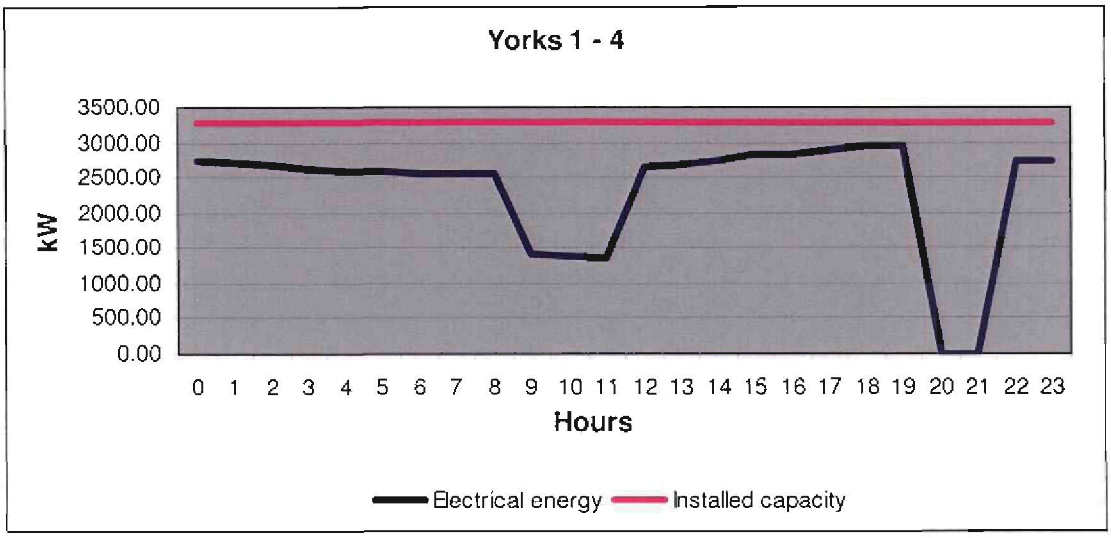


Figure 30 - York 1 - 4 energy curve

In Figure 31 the effect of the Howden back-pass valve is also apparent in the predicted power usage of the Howden refrigeration machine.

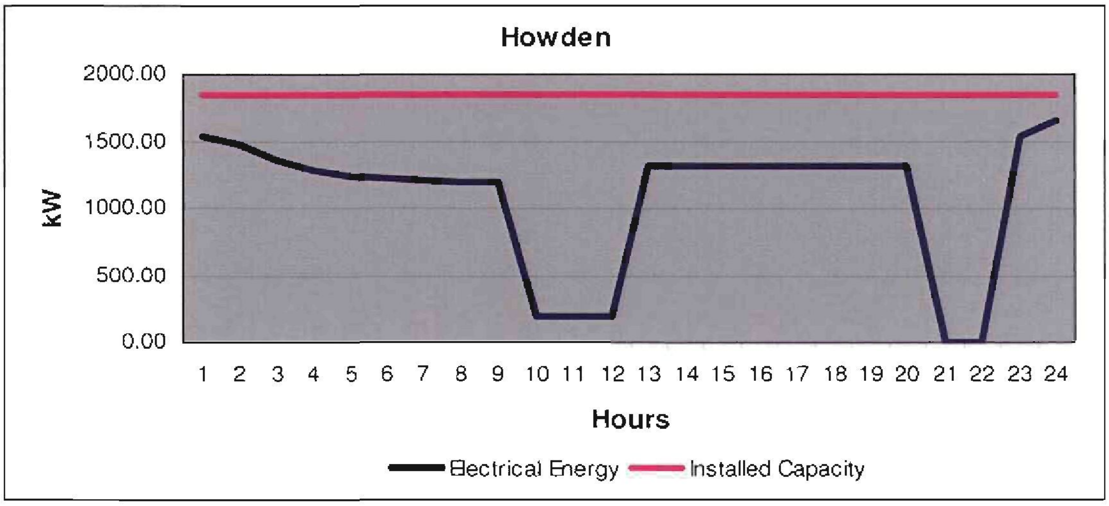


Figure 31 - Howden power curve

In Figure 32 the effects of the York back-pass valve on the York refrigeration machine inlet temperature can be seen.

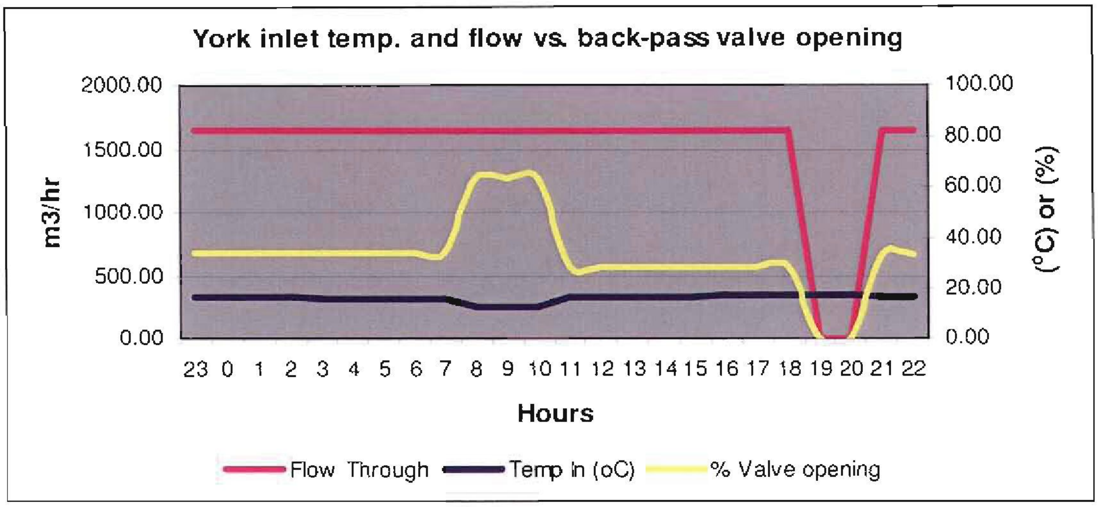


Figure 32 - York inlet temp and flow vs. back-pass valve opening

The effect of the Howden back-pass valve on the inlet temperature is shown in Figure 33 along with the flow through the Refrigeration Machine and the percent valve opening.

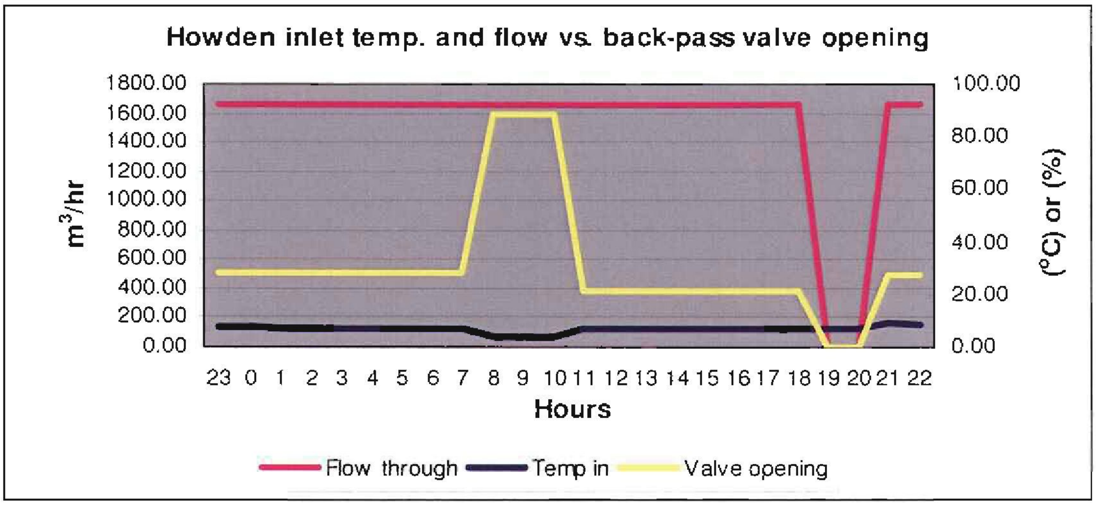


Figure 33 - Howden inlet temp and flow vs. back-pass valve opening

Optimising the controller will enable the Pre-Cool Dam temperature and level to follow the curves illustrated in Figure 34. This will ensure enough dam capacity so that all the York FP can be shut down during the Eskom evening peak period without exceeding the mine's constraints.

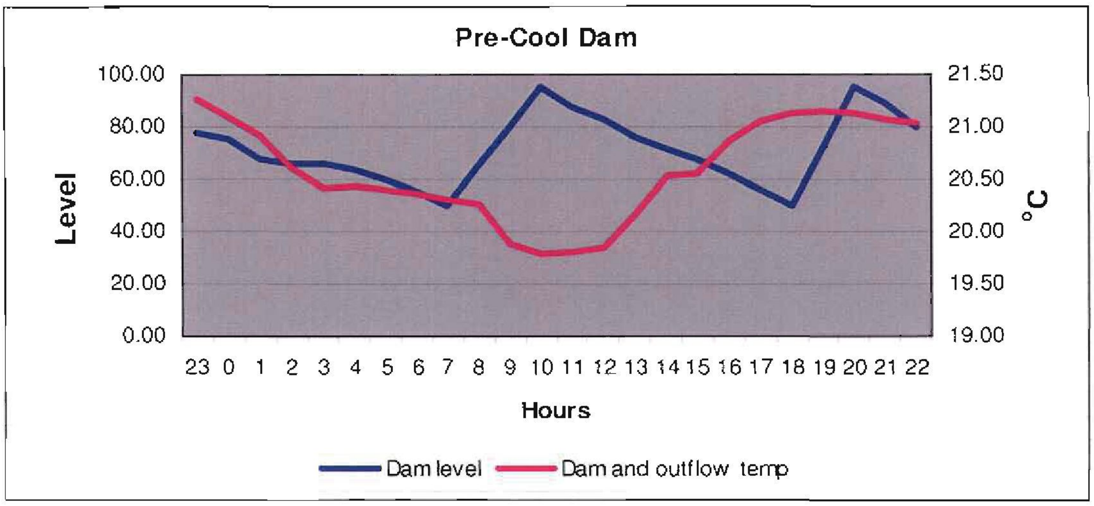


Figure 34 - Pre-Cool Dam

In Figure 35 the Chill Dam 1 level and temperature can be seen. It must be noted that the temperature will rise slightly during the Eskom evening peak period. The rise is due to Valve B and the accompanying controller. The rise in temperature is within the constraints of the mine.

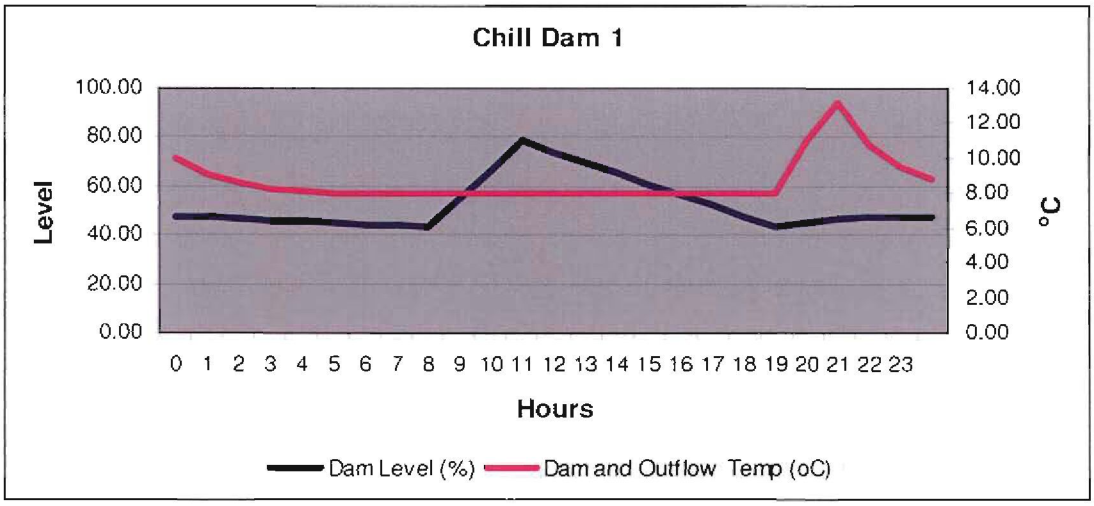


Figure 35 - Chill Dam 1 temperature and level

The effect on the dam level and temperature of Chill Dam 2 & 3 supplying water to underground with the implemented system is shown in Figure 36. From this figure it can be seen that there will be a slight increase in temperature. The rise in temperature is within the mine's constraints.

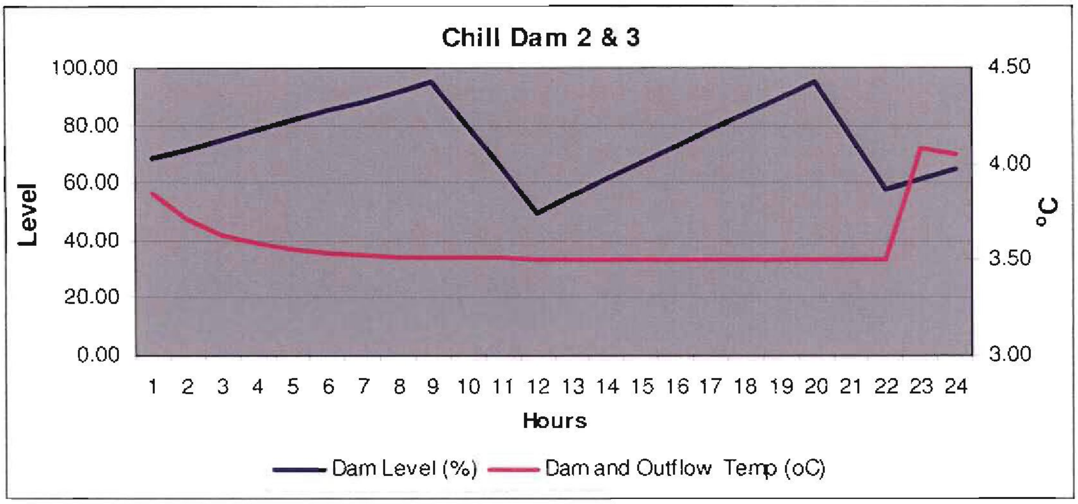


Figure 36 - Chill Dam 2 & 3 water level and temperature

3.10. General refrigeration efficiency optimisation

This is not a complete guide or list to optimise the efficiency of a refrigeration system, but it provides ideas which can be used.

The general efficiency of the refrigeration system is optimised by: [49]

- Keeping heat transfer surfaces of evaporators and condensers clean, thus ensuring optimal heat transfer
- Insulating the system and thus preventing heat loss
- Calibrating controls and checking performance regularly
- Maintaining specified design refrigerant charge as well as design refrigerant
- Ensuring unrestricted air movement around condensing units

3.11. Conclusion

Section 3 started with the constraints and variables of a surface refrigeration system. Data was captured and analysed. From the data a mathematical model was constructed. The model was optimised and verified with the data and system constraints.

From the optimised model a new controller was developed to meet the system constraints. The system was simulated and the newly developed controller verified. The section ended with general refrigeration efficiency optimisation.

Verification of the model was done by comparing the baseline values from the captured data and energy kW values from the model as illustrated in Figure 14. The simulation was verified by showing that the results of the simulation were within the system constraints. The dams did not overflow. The machines did not exceed their installed cooling capacity and the temperature going underground is under 5°C.

The baseline data was captured hourly for six months and summarised in a 24 hour profile. For the model verification, one set of hourly data for a 24 hour period was used. The simulation verification also used one set of hourly data for a 24 hour period. The hourly data point for a 24 hour period from the model and simulation could be duplicated time and time again. Thus no specific data set was used for the verification process and the data was taken at any time.

The conclusion of this section is that simulation and control of the cascade model was successfully done. The projected saving is 4.2MW.

3.12. References

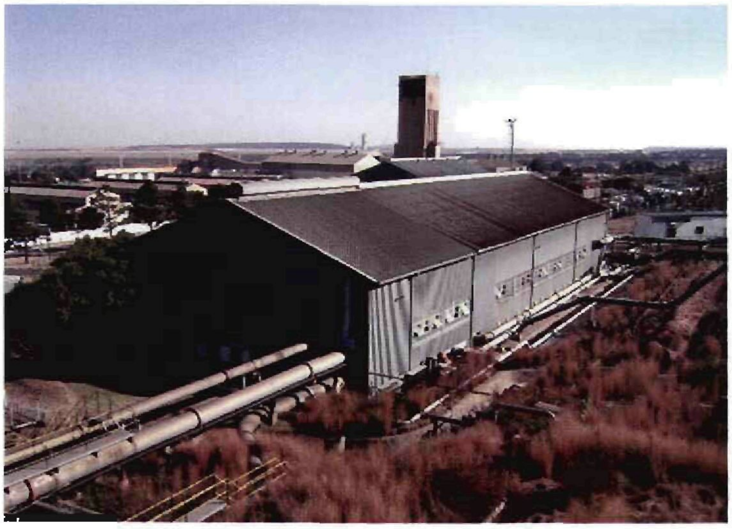
[47] Els, R., *Potential for load shifting in ventilation and cooling systems*, Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, University of Pretoria, November 2000.

[48] Eskom, *Tariffs and Charges*, Effective from 1 April 2006 to 31 March 2007, Postal address: ESKOM, PO Box 1091, Johannesburg, 2000, Gauteng, Tel: +27 11 800 8111.

[49] 3E Strategy , *How to save energy and money*, Guide Book 4, Refrigeration, The Energy Research Institute, Department of Mechanical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, Cape Town, South Africa, www.eri.uct.ac.za.

4

CASE STUDIES: VERIFICATION OF THE SIMULATION ON SOUTH DEEP MINE



The procedures developed in chapter 3 are verified on the South Deep cascade mine surface refrigeration system.

4. CASE STUDIES: VERIFICATION OF THE SIMULATION ON SOUTH DEEP MINE

4.1. Introduction

In this case study the control system is observed in its real life environment. The case study is used to gather information by applying the controllers to the actual environment and observing the results. The case study is used to verify the simulation model and the results obtained from the research.

The South Deep gold mine is situated about 42 kilometres southwest of the city of Johannesburg in the Gauteng province, near the town of Westonaria. The mine is owned by Gold Fields and has mining activities exceeding a depth of 2 000 metres.

The mine uses a surface refrigeration system to provide chilled water for ventilation, mining activity and underground refrigeration systems. The surface chilled water provides an acceptable underground working environment.

The surface refrigeration system at South Deep chills the water through two consecutive refrigeration systems. The first is the York system that uses R12 and the second system is a Howden system that makes use of ammonia as refrigerant.

Chilling the water through two systems using separate refrigerants makes the South Deep surface refrigeration system a cascade refrigeration system. The simulation and controllers were developed on a basis of a cascade mine surface refrigeration system that closely resembles South Deep. South Deep is thus the ideal case study for the demand-side energy management controller.

4.2. Implementation on cascade refrigeration system

The success of load management depends on the tariff rates, operation strategy, thermal storage capacity and climatic conditions [50]. Load management adjustments must take safety of the mine personnel and continuity of production into account before the implementation can start [51].

The layout of the South Deep cascade mine surface refrigeration system is shown in the figure below.

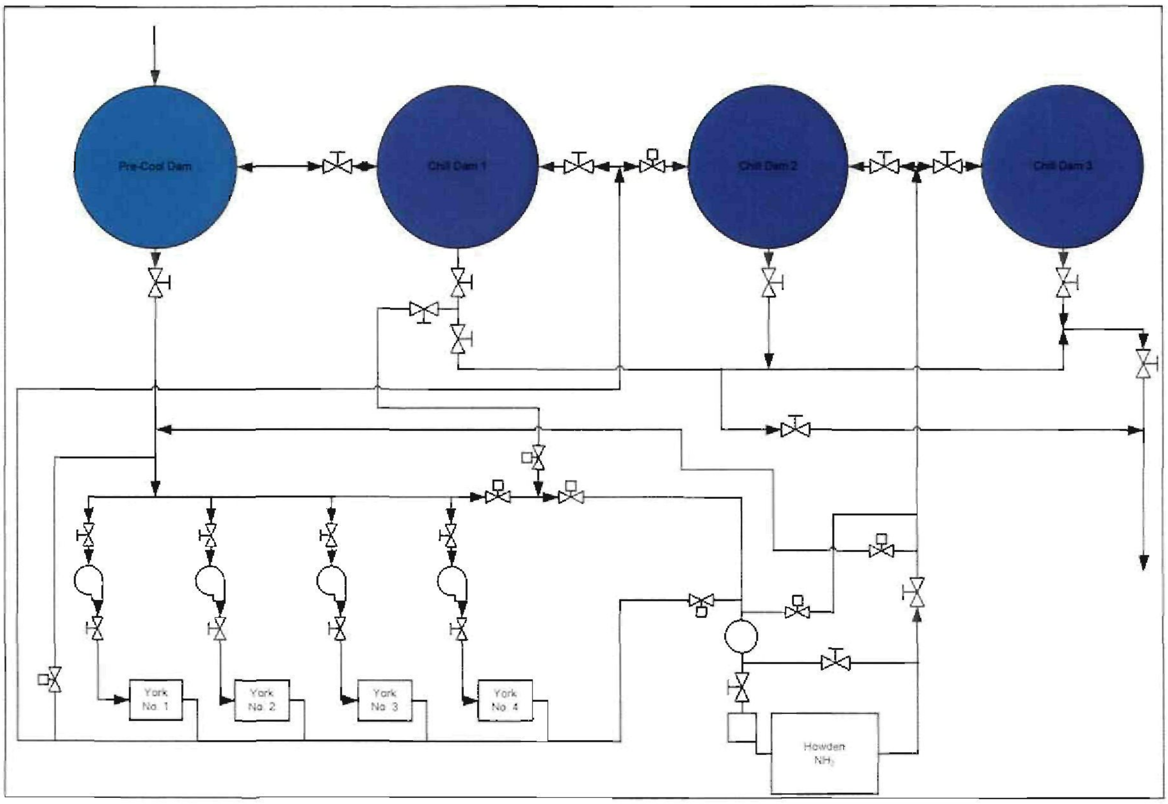


Figure 37 – South Deep cascade surface refrigeration system layout

Figure 12 from section 3.4 of this document is a diagram of the system that highlights the important features needed for demand-side energy management.

For the energy management to be efficient, all the highlighted features need to be viewed and controlled automatically from a central point. A network and SCADA system allows just that. A risk assessment on the automation of the machines, the effects thereof and the proposed new control system and parameters were done to insure that the case study adheres to industrial safety standards.

Each machine is controlled with its own PLC. The five refrigeration machine PLC's are connected to the Plant PLC. The Plant PLC is also called the supervisory PLC and the remaining plant valves and other field instrumentation tie into the system at this point.

The SCADA system shows all the information on the supervisory PLC and the individual refrigeration PLC. Commands are given through the SCADA system for the plant to execute. The SCADA is also set up in such a manner that the DSM controller can be bypassed by a refrigeration plant operator. This allows operators to do maintenance on the plant.

The SCADA system and inherent PLC control systems are aimed at gold pre-production and don't take electrical time of use (TOU) into account. Thus, a Real-time Energy Management System (REMS) is installed on top of the mine SCADA system to control the system within the mine production operation constraints. REMS looks specifically at electrical TOU and energy efficiency.

The Real-time Energy Management System interacts with the mine SCADA system as shown in Figure 38.

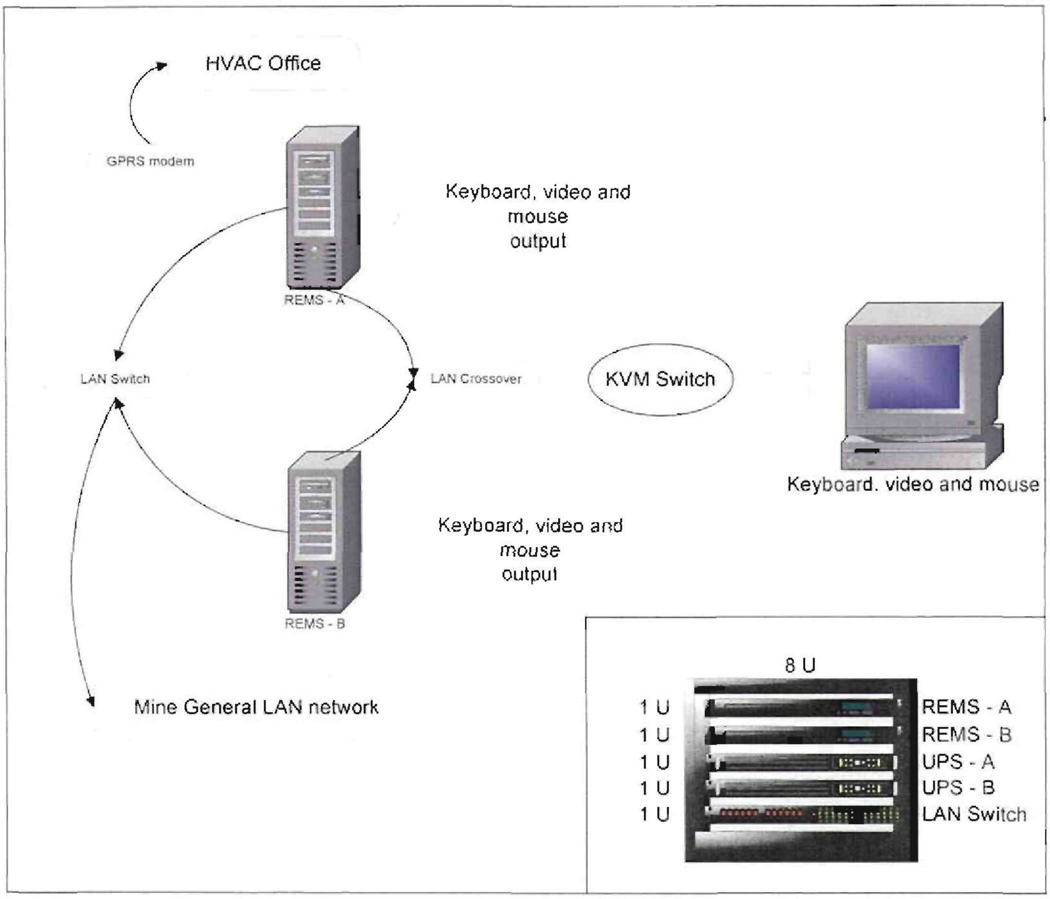


Figure 38 - REMS system layout for implementation

From Figure 38 it can also be seen that REMS can be viewed and controlled via the internet. REMS is installed and the developed control strategy is implemented on the system. First the communication with the SCADA and PLC via an OPC connection is tested through monitoring dam levels, flows, running statuses and switching refrigeration machines on and off from the SCADA and REMS platform.

When communication from and to all parts of the plant is established, the decisions the controller makes are logged and evaluated. The plant achieves load shedding at this stage by switching the refrigeration plants off manually.

The system goes over to the fully automated mode when it becomes evident that the controller is making the right control decisions. The system is then monitored and evaluated, making minor plant specific adjustments until the system runs fully automated.

The system receives data; makes the control calculations and executes the decisions in real time. The plant is controlled accordingly and prepared for the evening peak load shift. The data is logged every two minutes for a typical production day.

This is an adequate resolution because of the size of the dams and the amount of flow going through. Any change in temperature or dam level takes longer than two minutes to realise. It takes five minutes for a refrigeration machine to complete the controlled start up sequence and four minutes for the controlled stop sequence.

The preparation of the refrigeration machine, back-pass valve and dam level is discussed in the following sections of this dissertation. The effect of control will also be highlighted.

4.3. Refrigeration machine control

The refrigeration machine controllers developed in section 3.7.1 and 3.7.2 are programmed into the REMS.

Figure 39 is a picture of one of the four York refrigeration machines. The result of controllers on the York refrigeration machines is shown in Figure 40. The figure is a summary of the installed capacity of the four York refrigeration machines, baseline electrical energy usage, expected results and the real-time observed results.

The results captured every two minutes are processed and averaged into hourly intervals. The hourly averaged results give an adequate picture of the plant and what happened during the Eskom evening peak time. A better resolution will not give a better insight into the results.

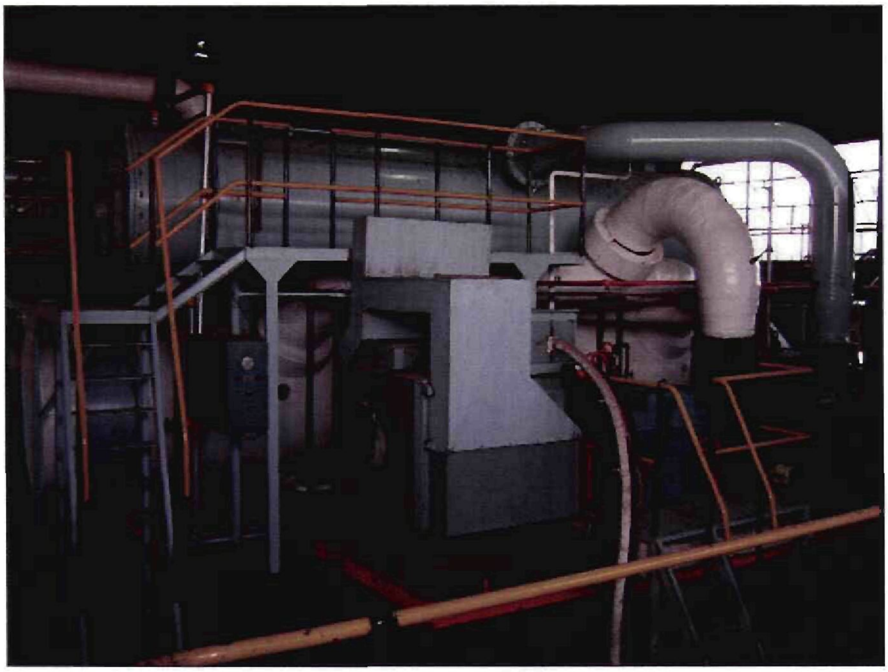


Figure 39 - York refrigeration machine

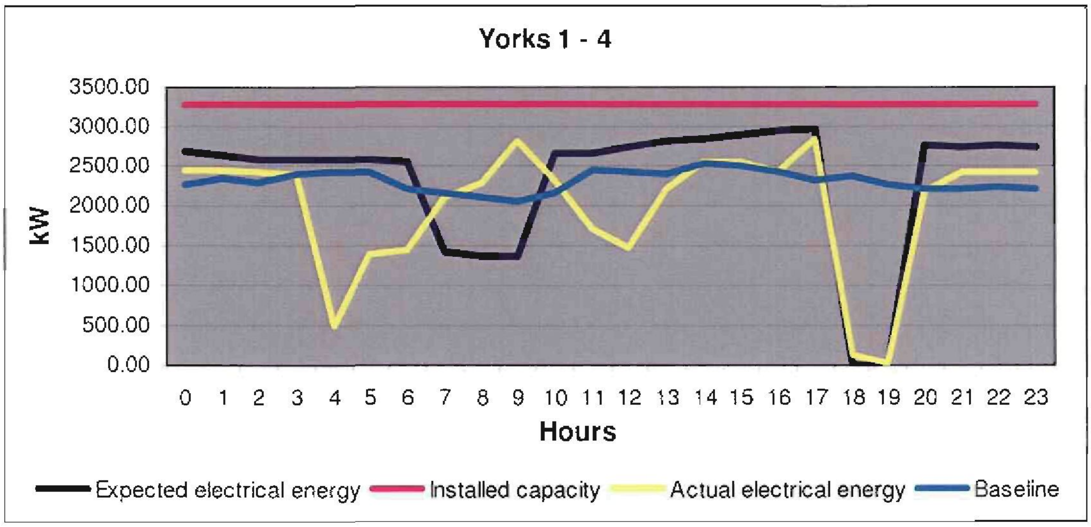


Figure 40 - York 1 - 4 energy curves

The decrease before the Eskom morning peak in the actual data is due to the fact that the four machines tripped. Two of the machines tripped again at 12:00. The data is verified by noting that all the data is under the installed capacity. During the Eskom evening peak time the expected data and the actual data are almost identical.

From the above figure it can be seen that an evening load shift is indeed possible for the York machines. The baseline is adjusted to have the same area under both the actual data graph and baseline graph. This makes the load shift energy neutral.

The area under the actual electrical energy graph and expected electrical energy graph is not the same. This can be due to the plant not processing the amount of water that was predicted or the machine inlet temperature is lower than expected, or the machine outlet temperature is higher than what was expected.

The above figure illustrates a 2.15 MW electrical energy load shift for the York refrigeration machines.

Figure 41 is a picture of the Howden Ammonia refrigeration machine. The result of the controller on the Howden refrigeration machine is shown in Figure 42. The figure is also a summary of the installed capacity of the Howden refrigeration machine, baseline energy usage, expected results and the real time observed results.

Figure 41 - Howden refrigeration machine

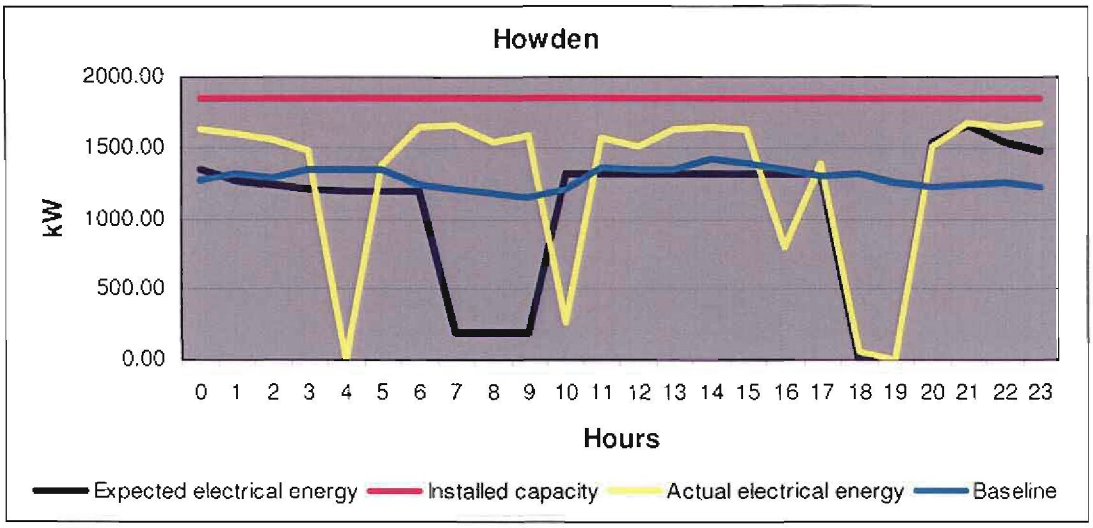


Figure 42 - Howden Power Curve

Again there is evidence of the Howden refrigeration machine tripping at 04:00 and again around 10:00. A faulty vibration sensor caused the trips. The sensor was replaced.

The data is under the installed capacity and again the actual electrical energy and expected electrical energy are similar during the Eskom evening peak. The baseline is also adjusted with the area under the actual electrical energy and base line being the same.

The area under the actual electrical energy graph is more than the area under the expected electrical energy graph. This shows that the Howden machine did more cooling than what was expected. This can be due to an increase in flow or increase in evaporator inlet temperature, or the machine outlet temperature set point was made lower. The change in water temperature is discussed later in this chapter.

Figure 42 illustrates a 1.26 MW electrical energy load shift for the Howden machine. By adding all of the auxiliaries power (1.09MW) to the refrigeration machine compressor power a total load shift of 4.5MW was achieved.

4.4. Back-pass valve control

Figure 43 is a picture of the York back pass valve. It is also known as the York mixing valve and is a top to bottom flow valve with the chilled evaporator water flowing through the pipe on top.

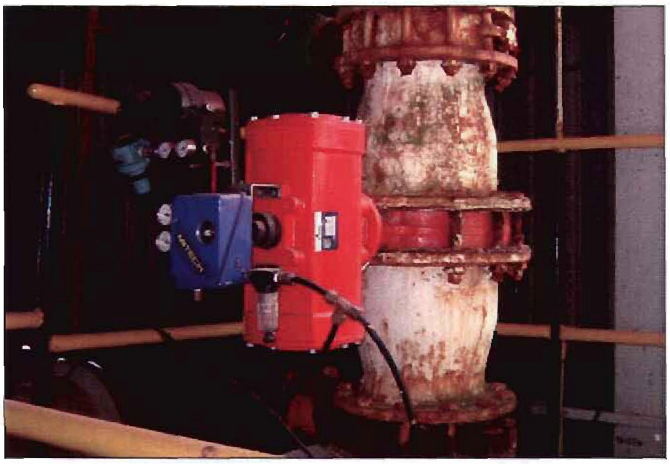


Figure 43 - York back-pass valve

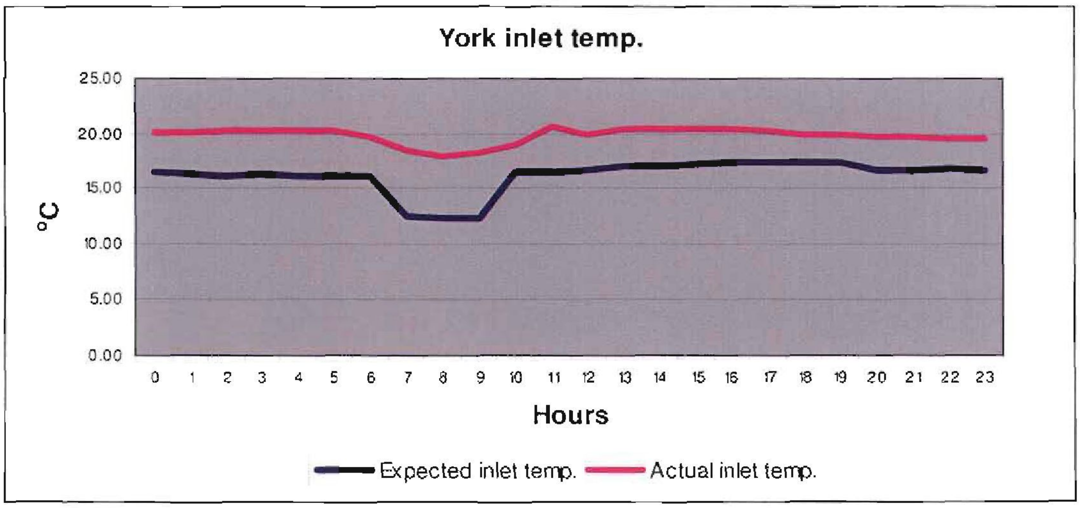


Figure 44 - York Inlet Temp

There is no visible effect on the inlet temperature in the above figure because the part of the SCADA and PLC controlling the York Back-pass valve had an error during testing.

Thus, the back-pass valve controller could not be evaluated in the case study. The actual temperature is also much higher than expected and can be due to the Pre-Cool towers not working efficiently enough. However, the temperature remains fairly constant between 18°C and 20°C.

Figure 45 is a picture of the Howden back-pass valve at South Deep.

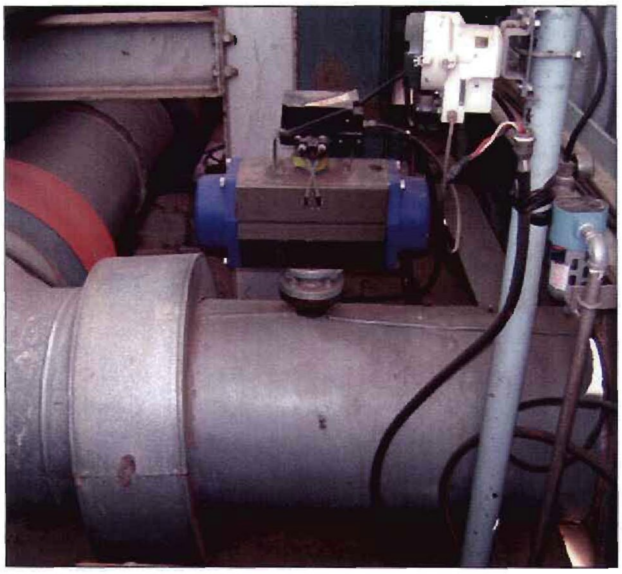


Figure 45 - Howden back-pass valve

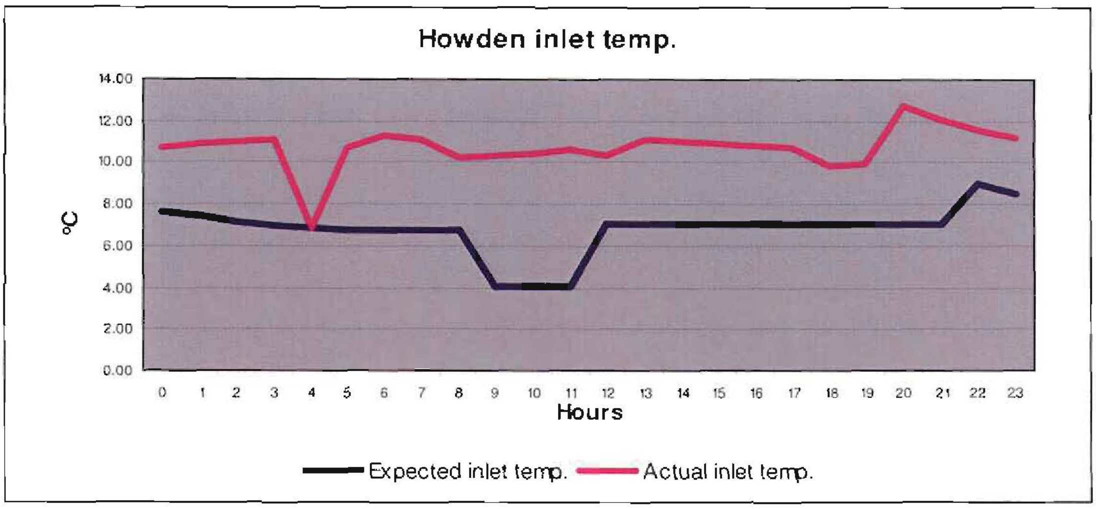


Figure 46 – Howden inlet temp.

There is no visible effect on the inlet temperature in the above figure because there is no flow meter to indicate the amount of water being back-passed. Thus the back-pass valve controller can be tested only after the additional flow meter is installed. The actual temperature is again much higher than expected and can be the result of not using the York back-pass valve.

Thus, the higher energy usage of the Howden machine is due to the higher evaporator inlet and the machine still trying to reach the set point outlet temperature.

4.5. Dam level control

The temperature inputs shown in table 8 into the system remained the same for the baseline determined in section 3 and the actual measured data. The actual measured flow shown in the below is the flow through the Pre-Cool towers and it was assumed that this would be the flow into the Pre-Cool dam, but the system is able to circulate the water through the Pre-Cool Towers.

Figure 47 is a picture of the four Chill Dams at South Deep.

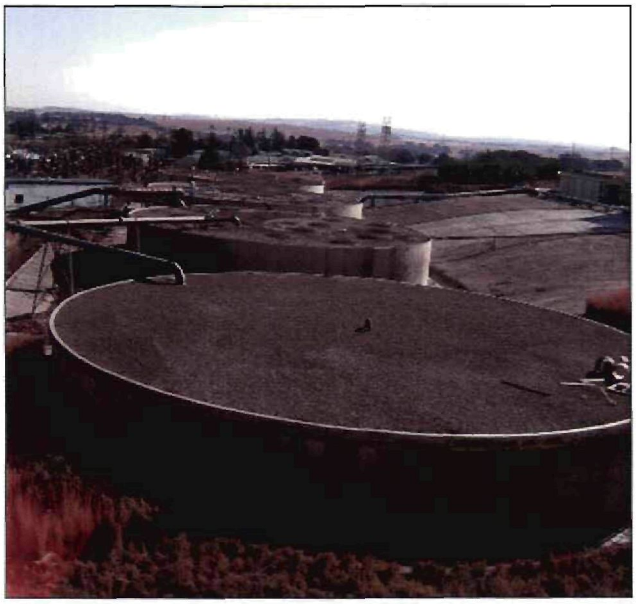


Figure 47 - South Deep Chill Dams

	Baseline inputs		Actual measured inputs	
Time	Flow (l/s)	Temp (°C)	Flow (l/s)	Temp (°C)
00:00	286.33	20.69	397.53	20.48
01:00	286.33	20.75	392.14	20.60
02:00	247.56	20.54	389.70	20.66
03:00	293.44	20.09	388.49	20.58
04:00	300.24	20.09	233.55	20.11
05:00	286.02	20.47	173.18	19.51
06:00	275.72	20.33	293.12	19.10
07:00	272.41	20.31	347.97	19.58
08:00	261.80	20.23	357.61	20.44
09:00	286.41	20.22	503.95	21.57
10:00	276.61	19.19	497.57	22.12
11:00	283.46	19.61	342.06	21.91
12:00	277.14	19.81	303.02	19.92
13:00	293.89	19.93	670.86	19.94
14:00	274.51	20.93	700.00	20.65
15:00	298.79	21.22	700.00	21.08
16:00	297.49	20.58	640.14	20.92
17:00	288.69	21.42	700.00	20.60
18:00	283.89	21.35	637.70	20.29
19:00	283.27	21.26	700.00	19.77
20:00	265.37	21.19	700.00	20.01
21:00	262.94	21.11	700.00	19.67
22:00	264.00	20.90	700.00	19.50
23:00	239.09	20.90	700.00	19.34
Sum	6685.37	493.15	12168.60	488.34
Ave	278.56	20.55	507.02	20.35

Table 8 – Baseline inputs vs. implemented inputs

The result of the REMS on the Pre-Cool Dam temperature and level is illustrated by the curves in figure 48. The Pre-Cool Dam is kept full by the SCADA system using the Pre-Cool Tower and Sand Filter pumps. The predicted capacity, where the water is captured, moved up the system to the Mine Surface Dam 1 & 2.

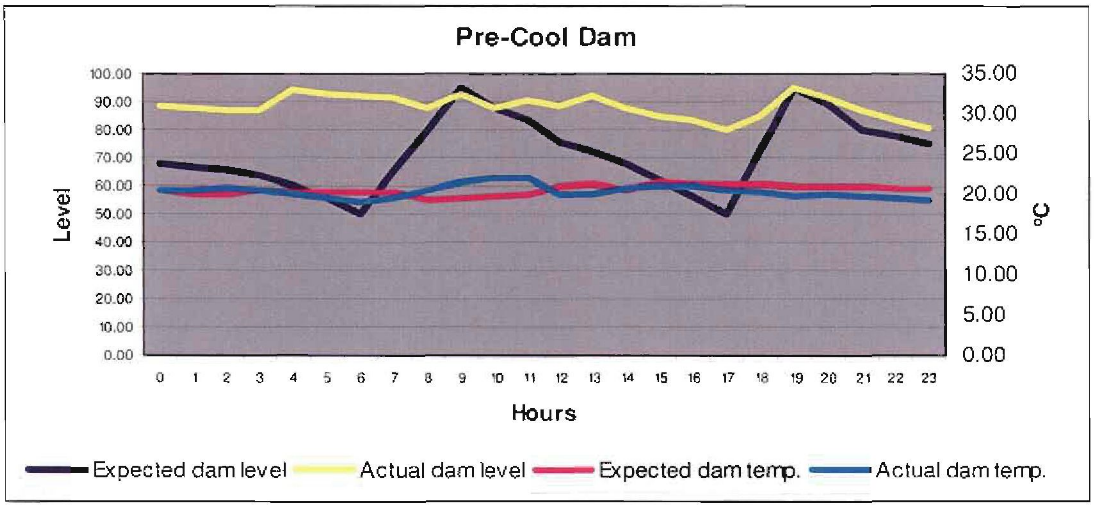


Figure 48 - Implemented Pre-Cool Dam

Figure 49 shows the Chill Dam 1 level and temperature. As the capacity to capture water moved up in the system to the Mine Surface Dam 1 & 2, the Chill Dam level was also kept nearly full. The Chill Dam 1 temperature is higher because the York Back-pass valve was not used.

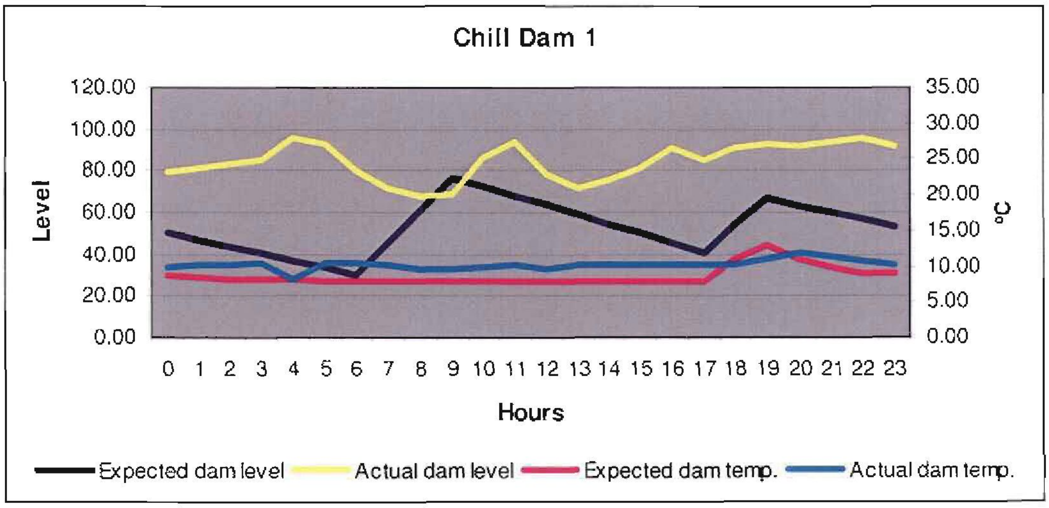


Figure 49 - Chill Dam 1 temperature and level

The effect on the dam level and temperature of Chill Dam 2 & 3, which supplies water underground with the implemented system, is shown in Figure 50. From this figure it can be seen that there is a slight increase in temperature during the Eskom evening peak period. This is due the Howden evaporator pump filling up the dam level with warmer water from Chill Dam 1.

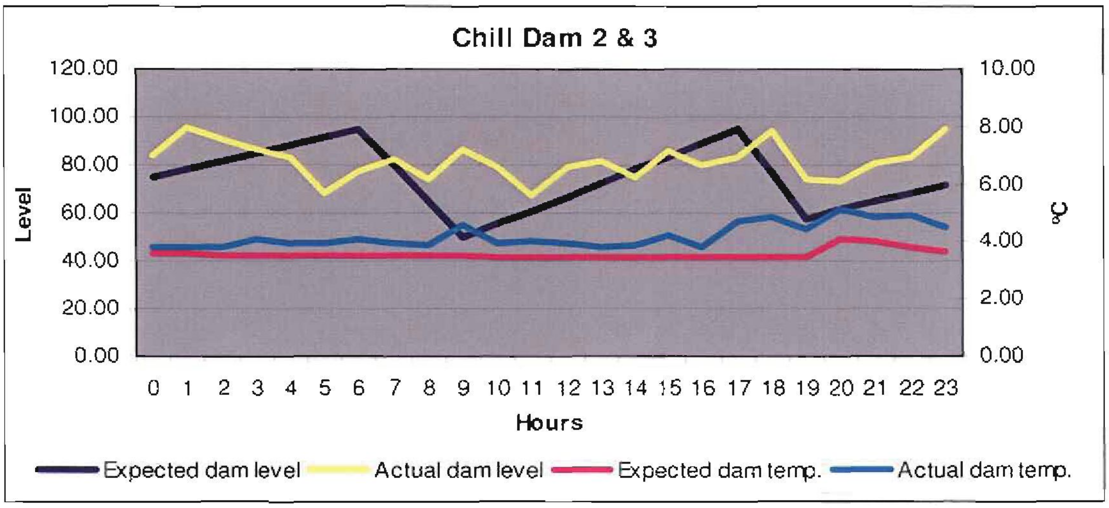


Figure 50 - Chill Dam 2 & 3 water level and temperature

The Chill Dam 2&3 level is kept above 70% due to the fact that the mine consumption is greater than what the Howden machine can supply. The mine water consumption is not at an average 340 l/s throughout the day but is rather a pulse of 400 l/s as shown in the figure bellow.

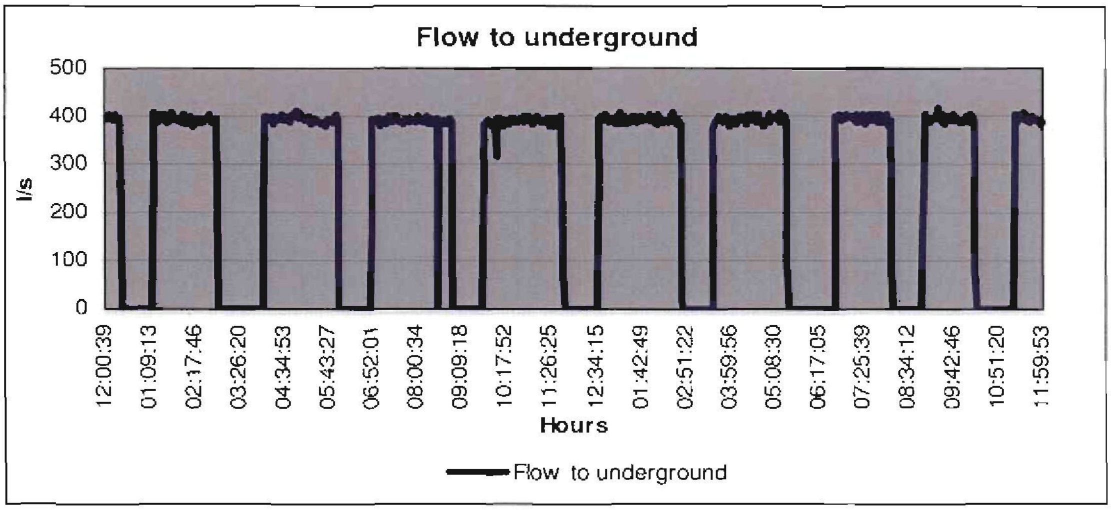


Figure 51 - Flow to underground

It was found in the risk assessment that it is a big hazard not having enough water in Chill Dam 2&3. The chilled water flows down a pipe 700m to an under ground chill dam and if the Chill Dam 2&3 level goes too low, a vortex forms. The vortex can cause air to be sucked into the pipe.

Having a section of air moving down the pipe is a serious hazard, because the water will fall across the section of air due to a lack of back-pressure. There is also the potential that if enough water falls across an air pocket, it will exert enough force to tear the pipe apart, or worse, dislodge the pipe and have it falling down the shaft.

It is thus better in terms of the fridge plant operation to fill the Chill Dam 2&3 with hot water and send hot water down the mine, than having the dam drain while trying to fill it with chilled water. This is not ideal from an environmental perspective and would indicate that the water management strategy is flawed. But sending hot water down the mine is an emergency condition. It is best to keep the dam filled with ice cold, chilled water.

4.6. Benefits of energy management on refrigeration systems

The benefits of energy management on refrigeration systems are:

- Selective time of use of work
- Most cost effective way to run energy intensive system
- Enhanced plant monitoring
- Improved controllers and actuators
- Calibrated instrumentation and tested information paths
- Improved energy efficiency
- Improved stability of operation
- Reducing maintenance and the cost thereof.
- Flexible in that the system can be set up for any required energy-demand Profile

4.7. Conclusion

The cascade surface refrigeration system of South Deep South Shaft was used for the case study. The system had to be fully automated for it to work. This was not the case and the back-pass valves could not be evaluated.

The conclusion of the case study in this chapter is that the refrigeration machine controller developed in the previous section, can be used for DSM projects on cascade mine surface refrigeration systems. An evening load shift of 4.2 MW was recorded by adjusting the base line and making the system energy neutral. This was a bad day due to the back-pass valves not working.

Although the desired dam levels and temperatures were not reached, as expected; the refrigeration machines and auxiliary power can be shut down for two hours with adequate water supply to underground from Chill Dam 2&3.

The daily amount of water processed by the plant remained the same, as well as the inlet temperature of the water.

By not using the York back-pass valve the, Howden machine was forced to do more cooling. Not using the Howden back-pass valve increased the temperature sent underground. The real time actual data remained within the installed capacity of the plant. The mine did not lose any notable production due the increased water temperature sent underground and the correct temperature will be achieved with back-passing.

It was also found that the water flowing underground did not follow a good average daily profile, and was rather pulsed. With the Chill Dam 2&3 at a maximum level and at a minimum temperature the dam has enough capacity to supply water throughout the pulse profile for the duration of the Eskom evening peak. The pulsed profile increases the complexity of the system, but the controller will be sufficiently capable.

The implementation of this system is recommended. The results are repeatable and sustainable.

4.8. References

[50] Ashok, S., Banerjee, R., *Optimal cool storage capacity for load management*, Energy systems Engineering, Indian Institute of technology Bombay, Mumbai 400076, India, August 2001.

[51] Jansen van Vuuren, S.P., *A thermal storage system for surface refrigeration plants*, Journal of the Mine Ventilation Society, 36, pp. 45-52, May 1983 , MVS SA, PO Box 403, Wilgeheuwel, 1736.

5. CONCLUSIONS

5.1. Summary of contributions

Eskom's capacity to generate the maximum demand needed to power South Africa is at a critical stage. This dissertation contributed to expanding the research into the DSM possibilities of surface cascade refrigeration systems aimed at reducing the maximum demand.

Investigation of mine surface cascade refrigeration systems was done and the key aspects identified. This dissertation developed a mathematical model of the cascade mine surface refrigeration system that can be used as a basis for further research in this field. The simulation of mine surface cascade refrigeration systems can be modified and applied to all industrial cascade refrigeration systems.

Researching the mine water consumption, chill water storage capacity and installed refrigeration capacity makes DSM with mine surface refrigeration systems possible. Investigating the energy saving possibilities at a mine, it is important to determine what the present power consumption of the specific mining process is, and whether it will result in a feasible DSM project. In other words, the energy savings potential of the mining process will be determined.

South Deep, a typical cascade surface refrigeration plant, was selected to investigate the application of DSM technology in mine refrigeration systems. The operating constraints and system variables were identified. Data was captured, processed into 24 hour profiles and analysed. From the data a mathematical simulation model was developed. The model was optimised and verified with the data and system constraints.

5

CONCLUSION

Limitations and suggested solutions are highlighted for future research.

From the optimised model a new automated real–time controller was developed to meet the system constraints. The system was simulated and the newly developed controller verified. The section ended with general refrigeration efficiency optimisation.

Upgrading the system infrastructure and installing a communication network along with the development of the optimal control strategy, enable the optimised use of the mine surface refrigeration systems.

The developed control system was tested along with new operational parameters. The conclusion of this section is that simulation and control of the cascade model was successfully done.

The automated real-time controller implemented on the South Deep surface cascade refrigeration plant realised a 4.5 MW load reduction during the Eskom evening peak demand period. This is 0.3 MW more than the initial predicted impact. This was achieved without influencing either the flow underground, or the total daily cooling load. Only the temperature of the water going underground increased.

The pilot tests were performed over a typical production day. Therefore similar load shifting results can be expected during summer months. The cooler ambient temperature during winter reduces the amount of cooling done by the surface plant.

5.2. Recommendations

It is recommended that mine refrigeration systems be further studied in the field for DSM projects. This is applicable to underground refrigeration machines, surface refrigeration machines and the interaction between surface and underground refrigeration systems.

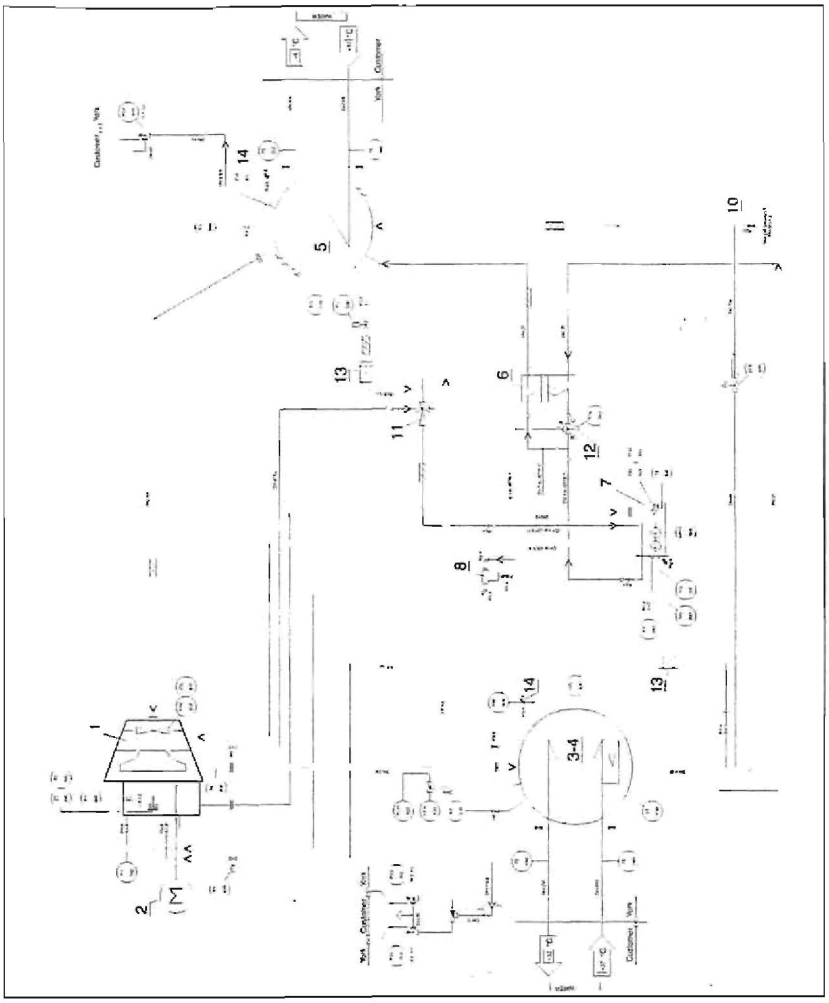
It is also recommended that a further study is conducted on efficiency of the mine cooling system:

- The efficiency of water used during non-mining times of the day at mining levels.
- Installing flow control valves to reduce the amount of water sent to the mining levels during non-mining times of the day.
- Controlling the amount of water that leaks from the water supply system, which can reduce the cooling load of a mine.

The effect of switching off the BAC on the mining environment deserves further investigation. Mine ventilation is designed using a node system of connected shafts and stopes. Predicting the time-related effect on the mining environment of stopping a BAC cannot be simulated on the node system currently used to design mine ventilation systems.

APPENDIX A: YORK REFRIGERATION MACHINE PID DRAWING

REFRIGERANT FLOW DIAGRAM



LEGEND							
PT30	CONDENSER PRESSURE	LCV	EXPANSION VALVE	1	COMPRESSOR	8	FILTER
PT41/42	OIL PRESSURE	PCV	PRESSURE CONTROL VALVE	2	MOTOR	9	ORIFICE
PT10	COOLER PRESSURE	TCV	TEMP. CONTROL VALVE	3	CONDENSER	10	CHARGE
PSH31/32	HIGH PRESSURE CUTOUT	MPH	OIL MOTO-PUMP	4	SUB-COOLER	11	EDUCTOR
TE	TEMPERATURE SENSOR	OH	OIL HEATER	5	COOLER	12	3 WAY VALVE
PRV	PRE-ROTATION	PSV	SAFETY VALVES	6	OIL COOLER	13	FILTER DRYER
XY/OY/PY	SOLENOID VALVE	TT	HIGH SPEED DRAIN TEMP.	7	OIL RECEIVER	14	TRANSFER
LT	LEVEL TRANSMITTER	TCV03	HOT GAS BY-PASS				
SG	SIGHT GLASS	PGD	PROX. GAP DISTANCE				

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Figure 52 - York process and instrumentation drawing

APPENDIX B: HOWDEN AMMONIA REFRIGERATION MACHINE PID DRAWING

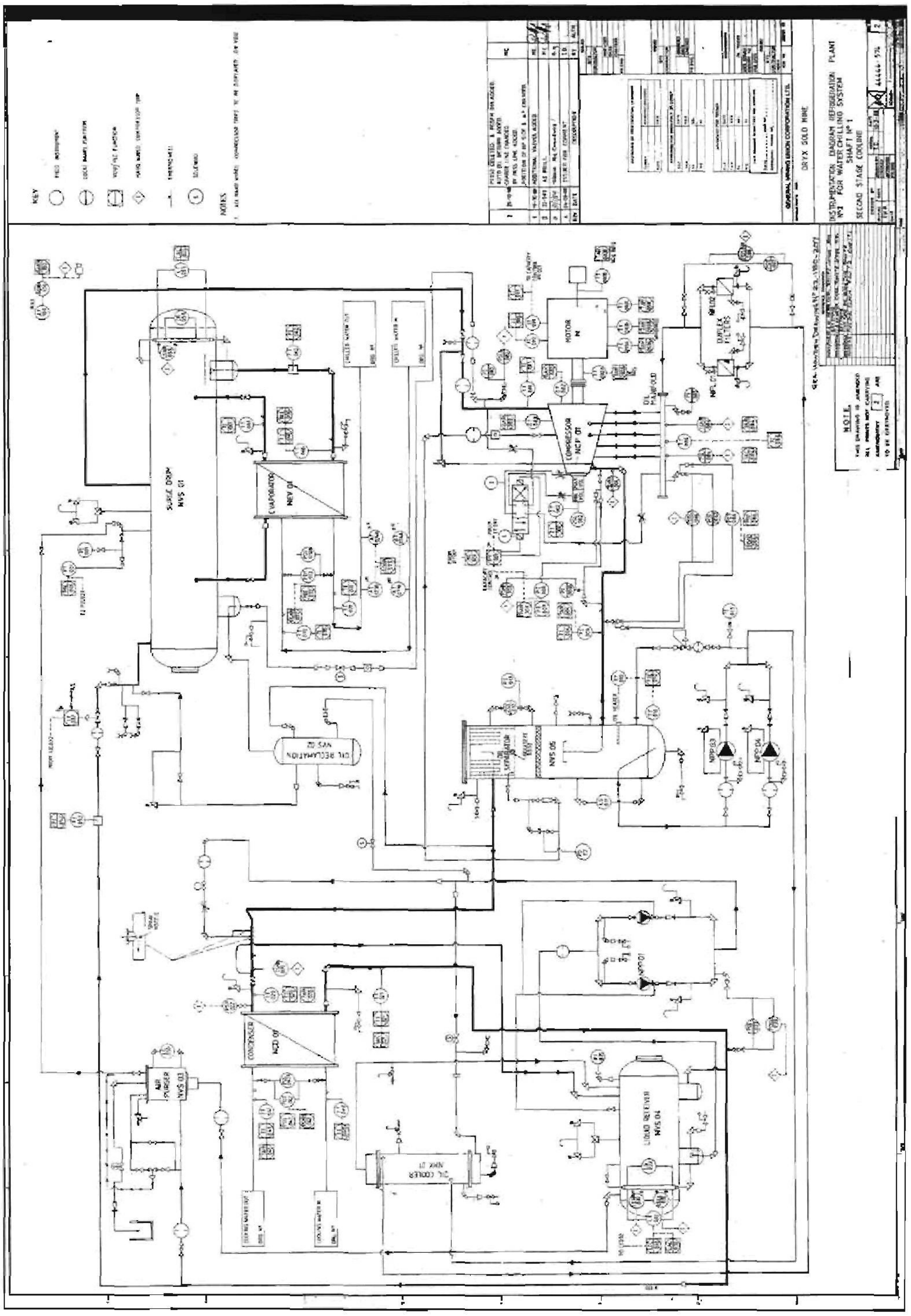


Figure 53 - Howden ammonia process and instrumentation drawing

APPENDIX C: M&V OVERVIEW

M&V Overview:

South Deep Cascade Surface Refrigeration System

Project overview

South Deep is a gold mine owned by Gold Fields. The mine uses a surface refrigeration system to provide chilled water for ventilation use underground. The chilled water helps to provide acceptable underground working conditions.

The project includes complete system automation and the implementation of REMS 2 FRIDGE PLANTS technology and software. After commissioning, REMS 2 FRIDGE PLANTS will log data, and simulate and control the integrated *refrigeration system with all its components in real time. The aim is to shift load* from the Eskom evening peak on mine working weekdays, without influencing mining activities.

Location

South Deep gold mine is situated near Westonaria and it is approximately 170 km from Pretoria, and 90 km from Potchefstroom.

Technology

REMS 2 FRIDGE PLANTS technology is a proprietary, patented on-site energy management system that optimises and controls mine refrigeration systems.

Simplified system layout

The refrigeration machines listed in the table 9 below are centrifugal compressors. Figure 54 is a screen shot of the simulation setup in the REMS 2 FRIDGE PLANTS software and illustrates the layout of the South Deep surface cascade refrigeration system.

Refrigeration machine	Electrical capacity (kW)	Cooling capacity (kW)
York #1	820	5 011
York #2	820	5 011
York #3	820	5 011
York #4	820	5 011
Howden	1 850	9 600
Total	**5 130**	**29 664**

Table 9 - Surface refrigeration machines at South Deep gold mine

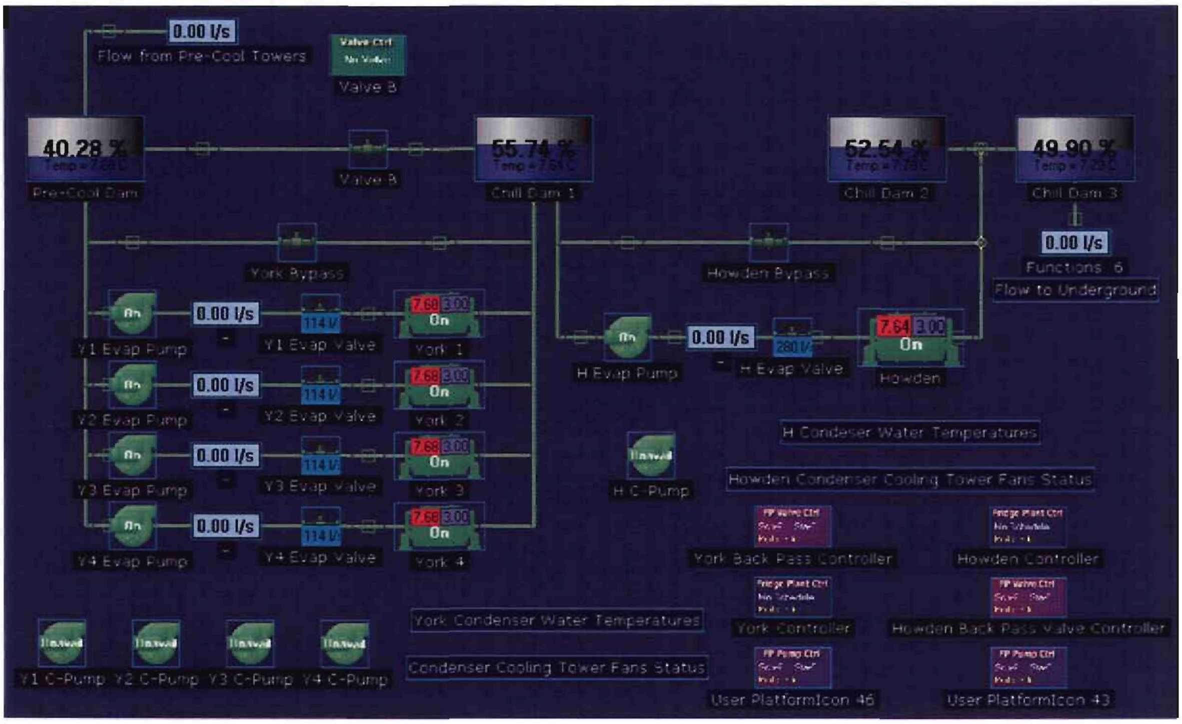


Figure 54 - Surface refrigeration system layout at South Deep

Auxiliary power

The electrical capacity stated above is that of the refrigerant compressor that drives the refrigerant cycle. The evaporator and condenser cycles are auxiliary systems that also use electricity. Table 10 summarises the equipment that provides auxiliary functions on the refrigerant compressors.

Auxiliary equipment	**Pump Type**	**Electrical capacity (kW)**	**Quantity**	**Total (kW)**
York evaporator pump	Salweir SDB 200/250	55	4	220
Howden evaporator pump	Salweir SDB 350/450	160	1	160
York condenser pump	Salweir SDB 10/12	132	4	528
Howden condenser pump	Salweir SDB 350/450	185	1	185
Total				**1093**

Table 10 - Auxiliary system controlled at South Deep

Thermal baseline

The Thermal baseline was calculated out of data logged hourly over a 3 month period for the summer and winter.

The thermal baseline for the four York machines and one Howden machine was calculated using the inlet and outlet temperatures as well as the flow rates through each fridge plant. The following variables are used:

$Q - Thermal\ energy$
$\dot{m} - Mass\ flow$
$C_p - Specific\ heat$
$T_i - Evaporator\ water\ inlet\ temperature$
$T_o - Evaporator\ water\ outlet\ temperature$

The required thermal energy of a refrigeration machine is calculated by:

$$Q = \dot{m}C_p\Delta T$$

Example:

Assuming a water flow of 115l/s, an evaporator inlet temperature of 16.4°C and outlet temperature of 8°C, the thermal energy absorbed is given by:

$$Q = (115kg\ /s)\left(4.183\frac{kJ}{kg\ .K}\right)(8^{\circ}C - 16.4^{\circ}C)$$

$$Q = -4040.78kW$$

Note:

- The water mass flow unit in the calculation is kilogram per second. The following relationship holds true: (1 l/s = 1 kg/s)
- The temperatures are not converted from degrees Celsius to Kelvin because [(x°C+273.15K)-(y °C+273.15K)] = [x°C - y°C].
- Q is negative because energy was removed from the system

THERMAL BASELINE			
SUMMER BASELINE		**WINTER BASELINE**	
Hour	kW	Hour	kW
1	22 270	1	18 047
2	21 008	2	18 888
3	21 755	3	19 258
4	23 809	4	19 411
5	23 245	5	19 326
6	17 635	6	18 652
7	17 119	7	17 940
8	16 708	8	17 179
9	18 034	9	18 229
10	19 729	10	18 817
11	24 270	11	18 918
12	21 790	12	18 796
13	21 979	13	19 186
14	25 203	14	20 258
15	22 565	15	19 695
16	22 131	16	19 620
17	20 880	17	18 292
18	21 252	18	18 286
19	20 318	19	18 911
20	20 677	20	17 085
21	21 366	21	17 261
22	21 697	22	17 537
23	20 794	23	18 912
24	21 591	24	18 418

Table 11 - Thermal baseline for South Deep surface refrigeration

The summer and winter thermal baselines of the mine are shown in Table 11. The thermal baseline is a 24 hour summary of the demand cooling load of the mine surface refrigeration system before the study.

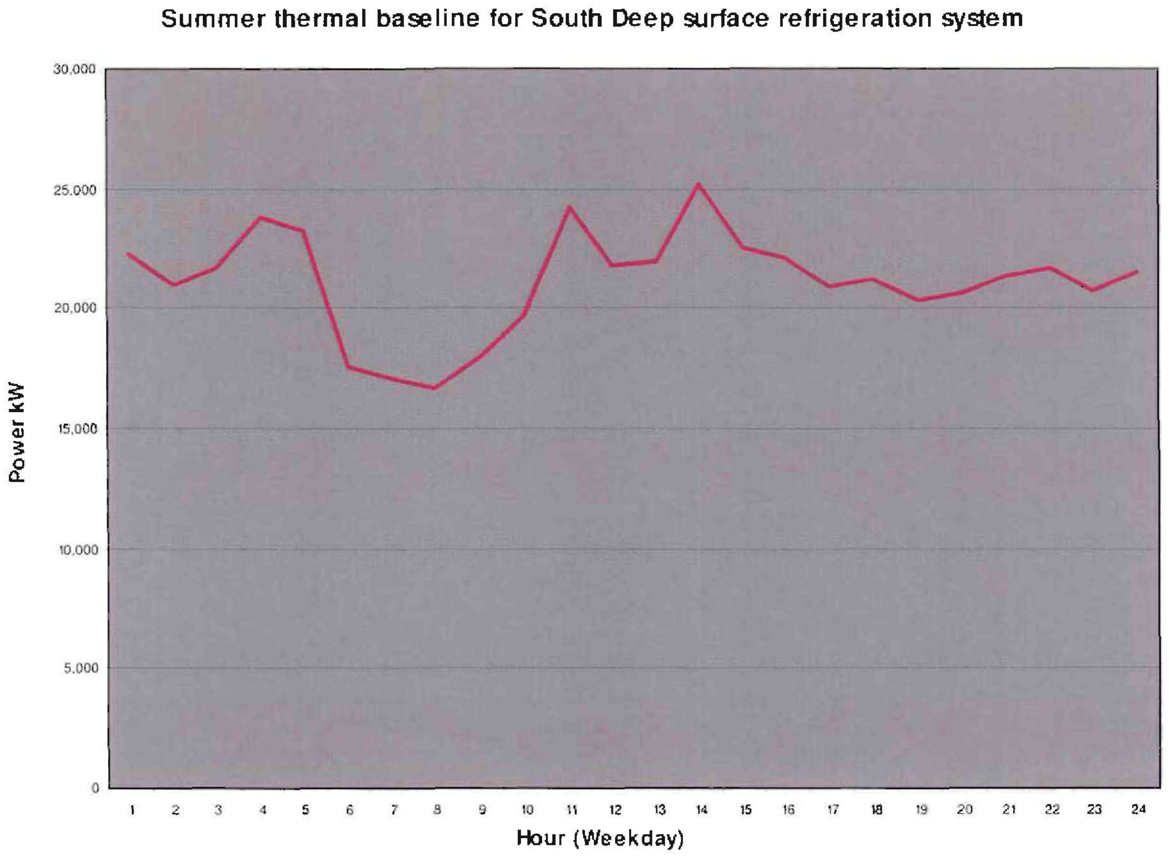


Figure 55 - Summer thermal baseline for South Deep surface refrigeration

Figure 55 is a graph of the summer thermal baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily cooling load carried out by the machines for an average summer day.

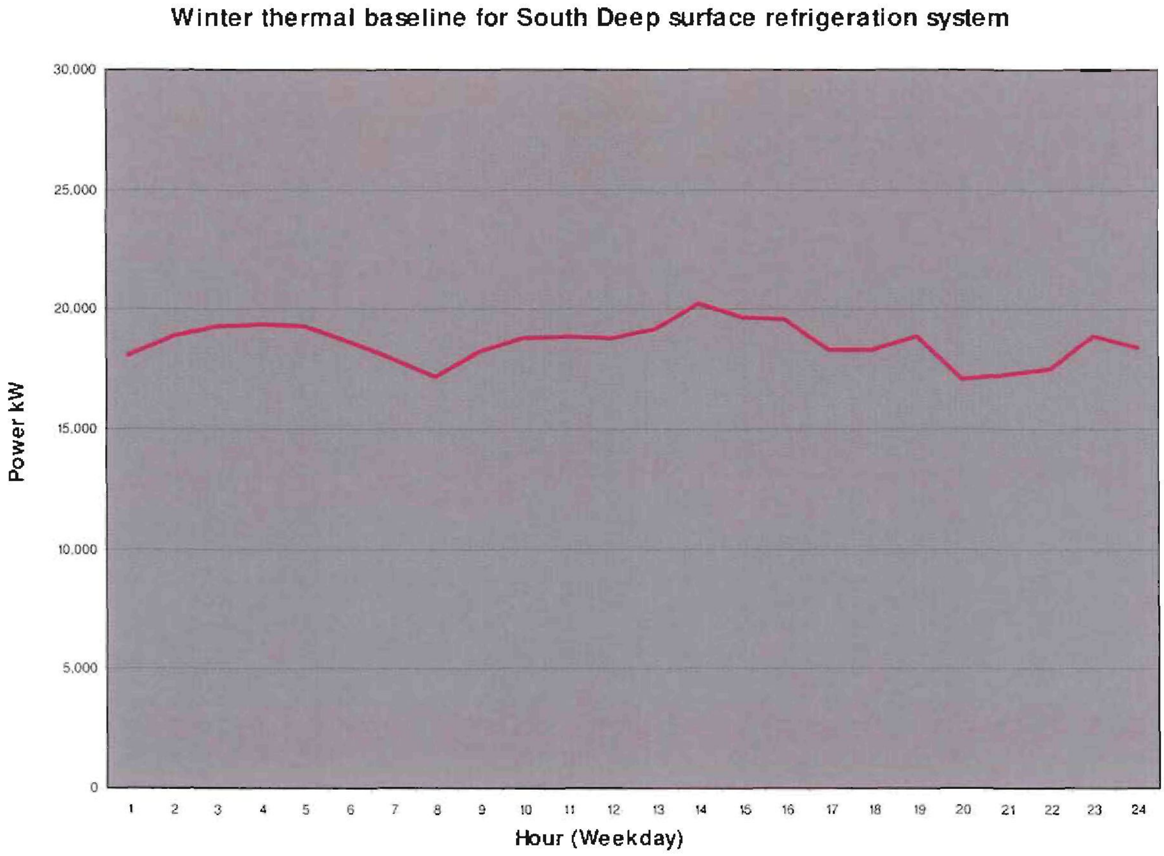


Figure 56 - Winter thermal baseline for South Deep surface refrigeration

Figure 56 is a graph of the winter thermal baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily cooling load carried out by the machines for an average winter day.

Electrical baseline

A conversion factor, or Coefficient Of Performance (COP), is used to convert the thermal energy used by a refrigeration machine, to the electrical power used. The COP is also seen as a ratio of thermal energy to electrical energy.

An estimate average for the COP can be obtained from the fridge plant operating manuals or can be calculated, if the designed cooling capacity and the compressor's installed electrical capacity are known. The COP is not constant and varies with the ambient temperature and with the cooling load required from the refrigeration machine.

The formula used to calculate the COP is the following:

$$COP = \frac{Cooling\ Capacity(kW)}{Compressor(kW)}$$

The estimated COP of a York machine is 3.96. The COP of the Howden machine is 5.7. The estimated values are used due to the machines not being fully automated. The machines are designed to give a diverse performance to meet conditions that range in daily and seasonal cycles.

The estimated weighted COP average is:

$$\frac{(3.96\times 4)+(5.70\times 1)}{(4+1)} = 4.31$$

The electrical energy of the four York machines and one Howden machine was calculated from the thermal energy. The following variables were used in the calculation:

$Q - Thermal Energy$
$E - Electrical Energy$
$COP - Coefficient\ Of\ Performance$

The electrical energy of a refrigeration machine is calculated by:

$$E = \frac{Q}{COP}$$

Example:

The refrigeration machine absorbed 4040.78 kW of cooling at a COP of 4.31.

$$E = \frac{Q}{COP}$$

$$E = \frac{4040.78kW}{4.31}$$

$$E = 937.53kW$$

Therefore requires 937.53kW of electrical power.

ELECTRICAL BASELINE			
SUMMER BASELINE		WINTER BASELINE	
Hour	kW	Hour	kW
1	5 169	1	4 189
2	4 877	2	4 384
3	5 050	3	4 470
4	5 527	4	4 506
5	5 396	5	4 486
6	4 093	6	4 330
7	3 974	7	4 164
8	3 878	8	3 988
9	4 186	9	4 232
10	4 580	10	4 368
11	5 634	11	4 391
12	5 058	12	4 363
13	5 102	13	4 454
14	5 850	14	4 702
15	5 238	15	4 572
16	5 137	16	4 554
17	4 847	17	4 246
18	4 933	18	4 245
19	4 716	19	4 390
20	4 800	20	3 966
21	4 960	21	4 007
22	5 036	22	4 071
23	4 827	23	4 390
24	5 012	24	4 275

Table 12 - Electrical baseline for South Deep surface refrigeration

The summer and winter electrical baselines of the mine are shown in Table 12. The electrical baseline is a 24 hour summary of the electrical energy demanded for the cooling load of the mine surface refrigeration system before the study.

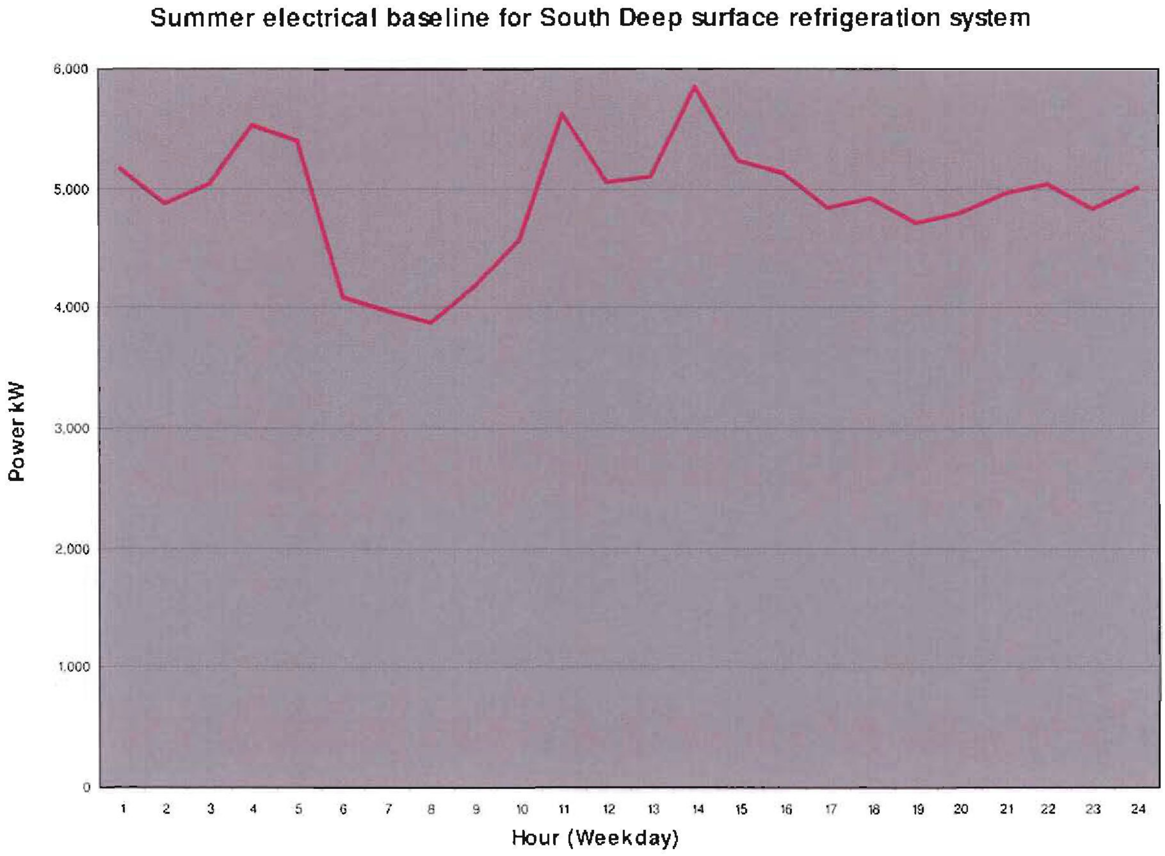


Figure 57 - Summer electrical baseline for South Deep surface refrigeration

Figure 57 is a graph of the summer electrical baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily electrical energy used for the cooling load by the machines for an average summer day.

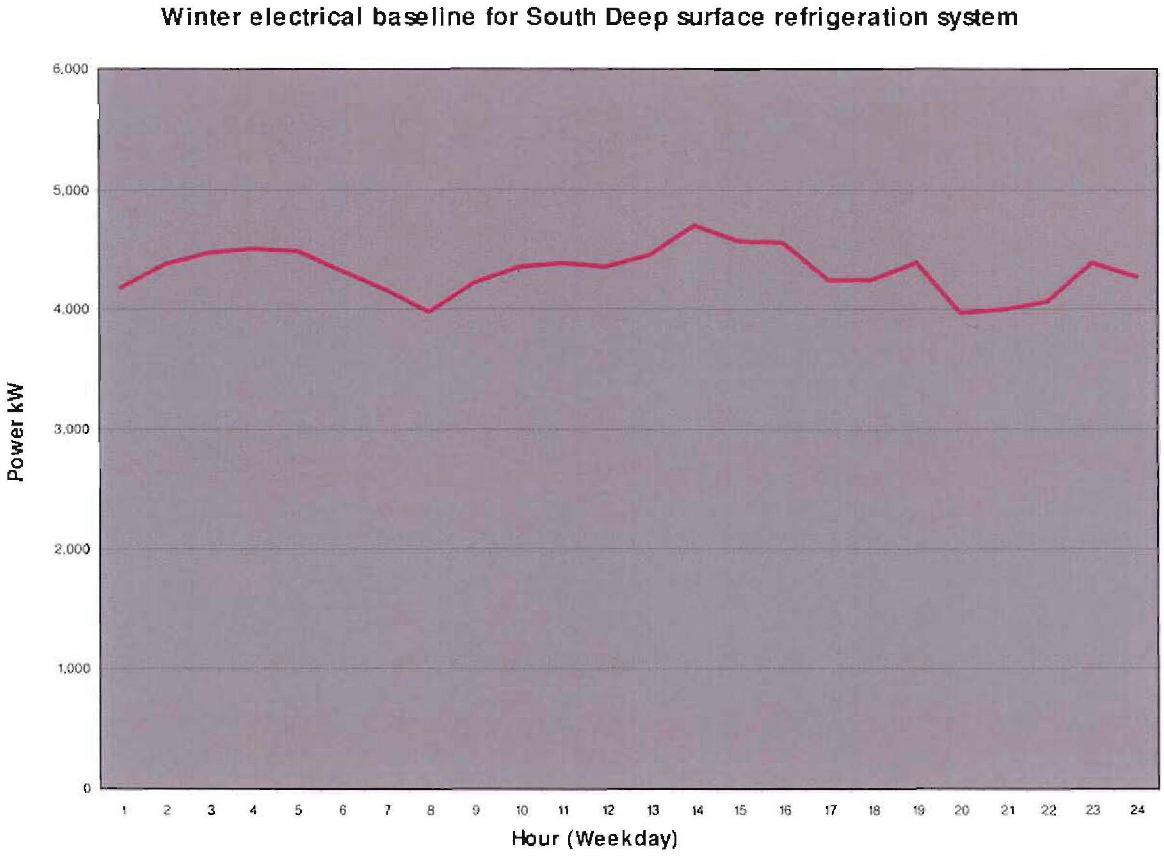


Figure 58 - Winter electrical baseline for South Deep surface refrigeration

Figure 58 is a graph of the winter electrical baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily electrical energy used for the cooling load by the machines for an average winter day.

Auxiliary electrical baseline

The auxiliary electrical baseline for the four York machines and one Howden machine was calculated using the mass flow through the refrigeration machines.

AUXILIARY BASELINE			
SUMMER BASELINE		WINTER BASELINE	
Hour	kW	Hour	kW
1	839	1	689
2	794	2	725
3	826	3	743
4	833	4	746
5	888	5	745
6	687	6	732
7	687	7	729
8	667	8	695
9	634	9	712
10	693	10	734
11	833	11	734
12	818	12	731
13	826	13	742
14	851	14	786
15	821	15	765
16	796	16	746
17	751	17	704
18	764	18	694
19	738	19	667
20	754	20	646
21	784	21	653
22	804	22	662
23	777	23	739
24	810	24	698

Table 13 - Auxiliary electrical baseline for South Deep surface refrigeration

The summer and winter auxiliary electrical baselines of the mine are shown in Table 13. The electrical baseline is a 24 hour summary of the electrical auxiliary energy demanded for the cooling load of the mine surface refrigeration system.

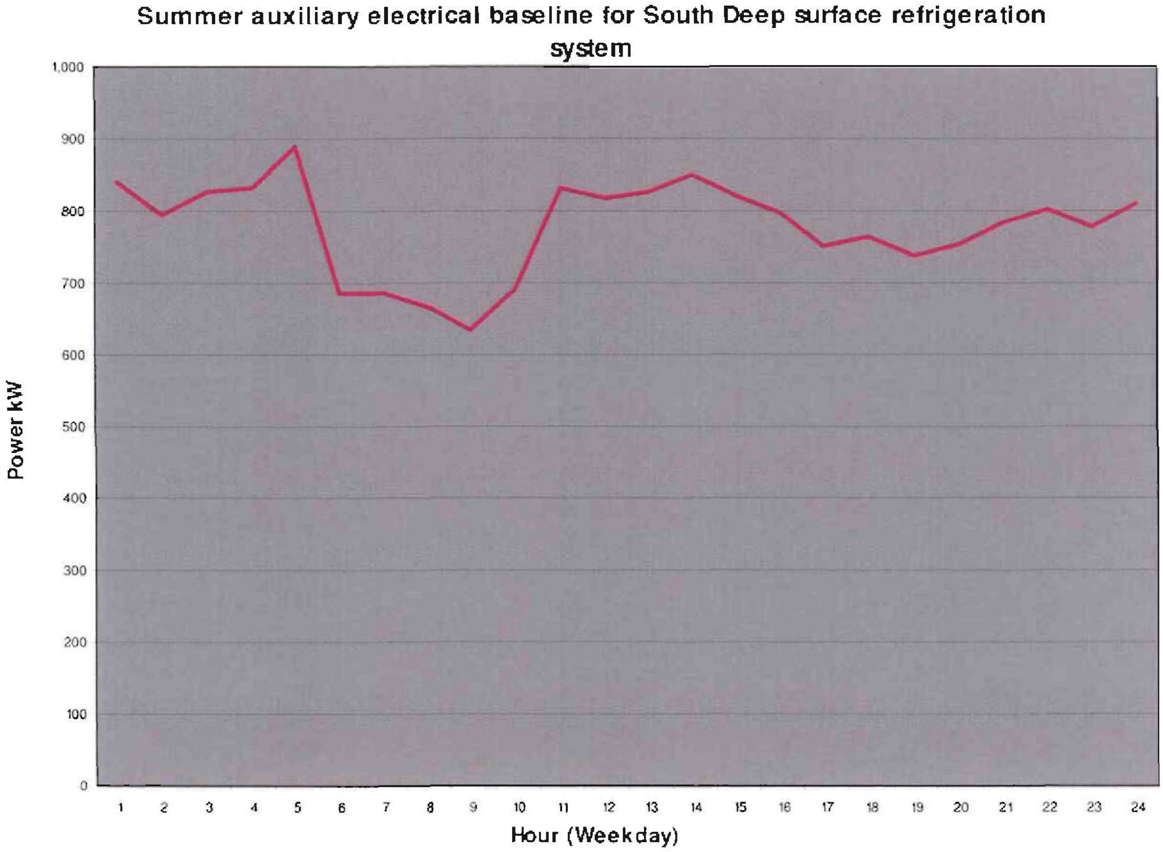


Figure 59 - Summer auxiliary electrical baseline for South Deep refrigeration

Figure 59 is a graph of the summer auxiliary electrical baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily electrical auxiliary energy used for the cooling load by the machines for an average summer day.

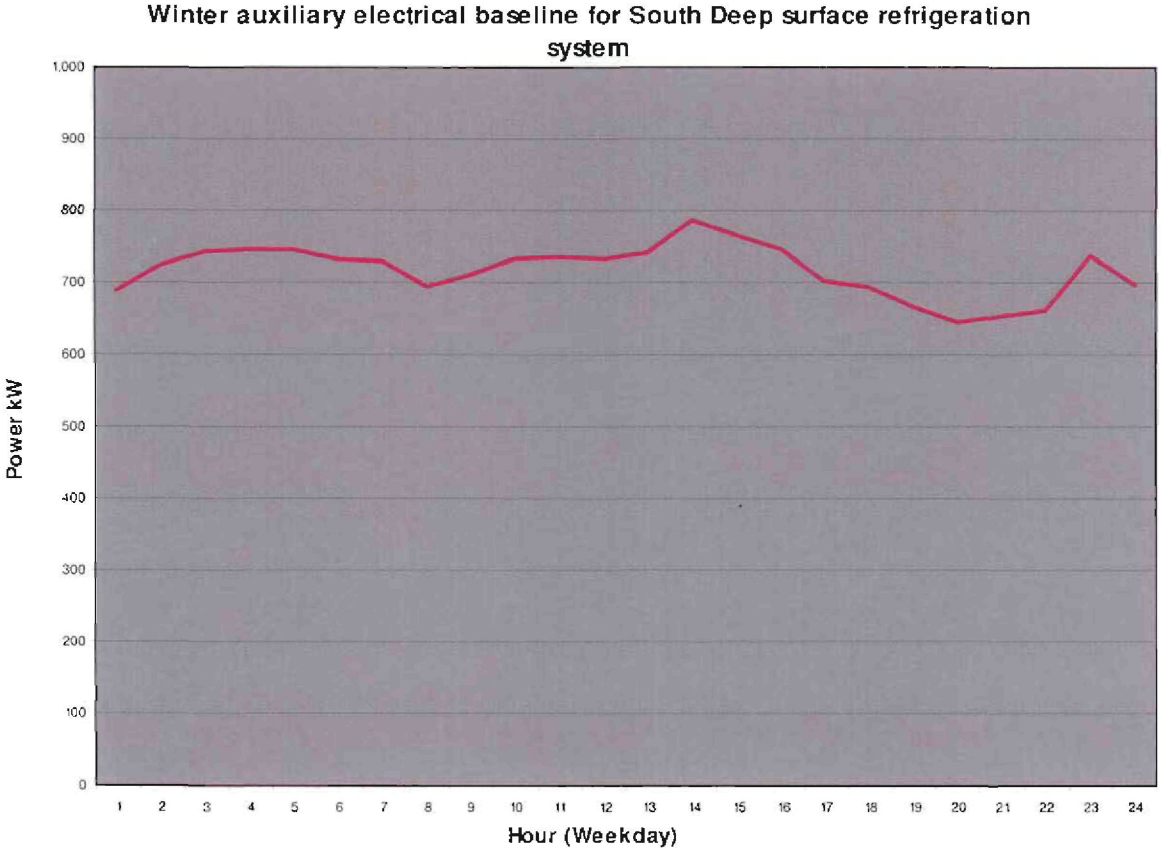
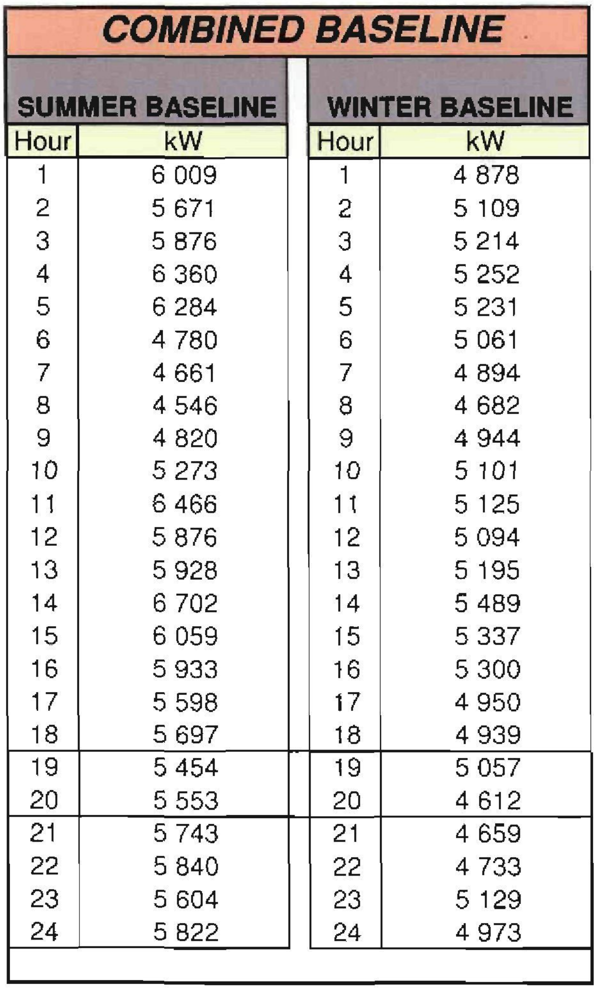


Figure 60 - Winter auxiliary electrical baseline for South Deep refrigeration

Figure 60 is a graph of the winter auxiliary electrical baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily electrical auxiliary energy used for the cooling load by the machines for an average winter day.

Combined electrical baseline

The combined electrical baseline for the four York machines and one Howden machine is the sum of the calculated electrical baseline and the auxiliary electrical baseline.



COMBINED BASELINE			
SUMMER BASELINE		**WINTER BASELINE**	
Hour	kW	Hour	kW
1	6 009	1	4 878
2	5 671	2	5 109
3	5 876	3	5 214
4	6 360	4	5 252
5	6 284	5	5 231
6	4 780	6	5 061
7	4 661	7	4 894
8	4 546	8	4 682
9	4 820	9	4 944
10	5 273	10	5 101
11	6 466	11	5 125
12	5 876	12	5 094
13	5 928	13	5 195
14	6 702	14	5 489
15	6 059	15	5 337
16	5 933	16	5 300
17	5 598	17	4 950
18	5 697	18	4 939
19	5 454	19	5 057
20	5 553	20	4 612
21	5 743	21	4 659
22	5 840	22	4 733
23	5 604	23	5 129
24	5 822	24	4 973

Table 14 - Combined electrical baseline for South Deep surface refrigeration

The summer and winter combined electrical baselines of the mine are shown in Table 14. The combined electrical baseline is a 24 hour summary of the machine and auxiliary electrical energy demanded for the cooling load of the mine surface refrigeration system.

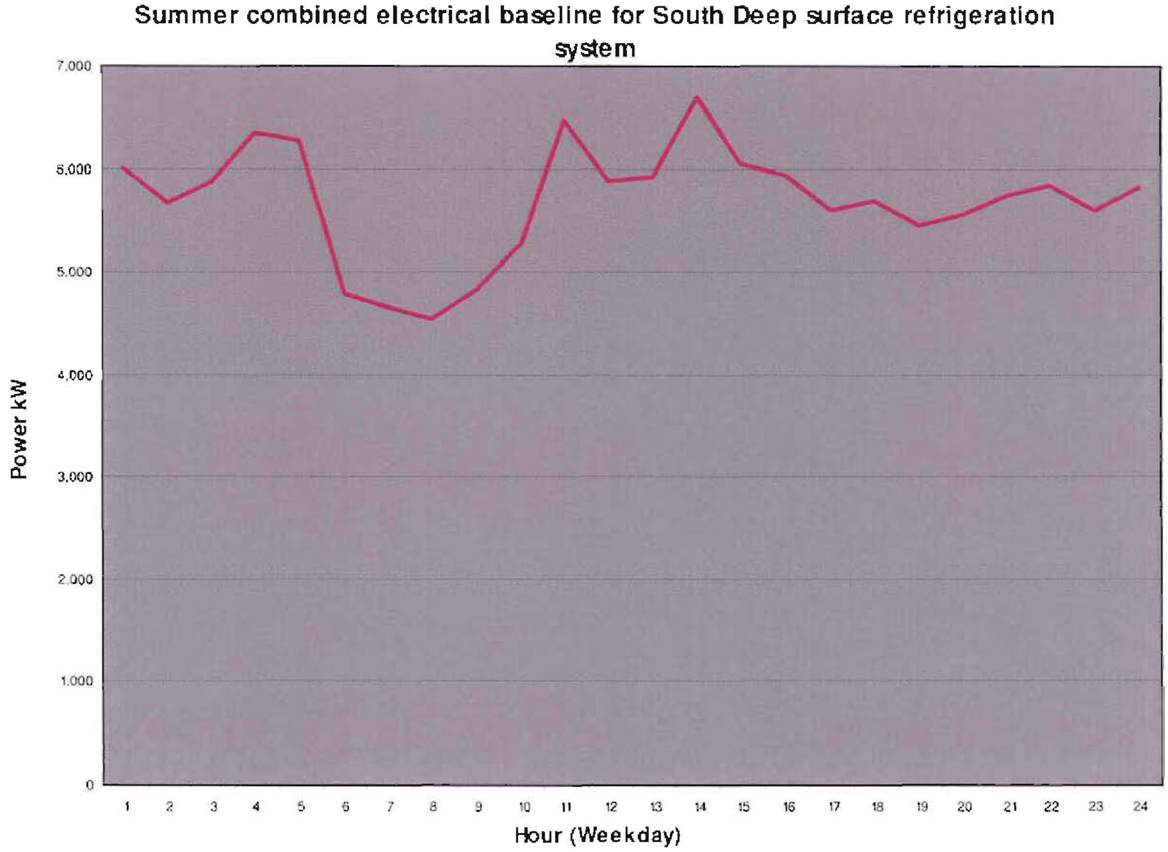


Figure 61 - Summer combined electrical baseline for South Deep refrigeration

Figure 61 is a graph of the summer combined electrical baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily machine and auxiliary, counted together electrical energy used for the cooling load by the machines for an average summer day.

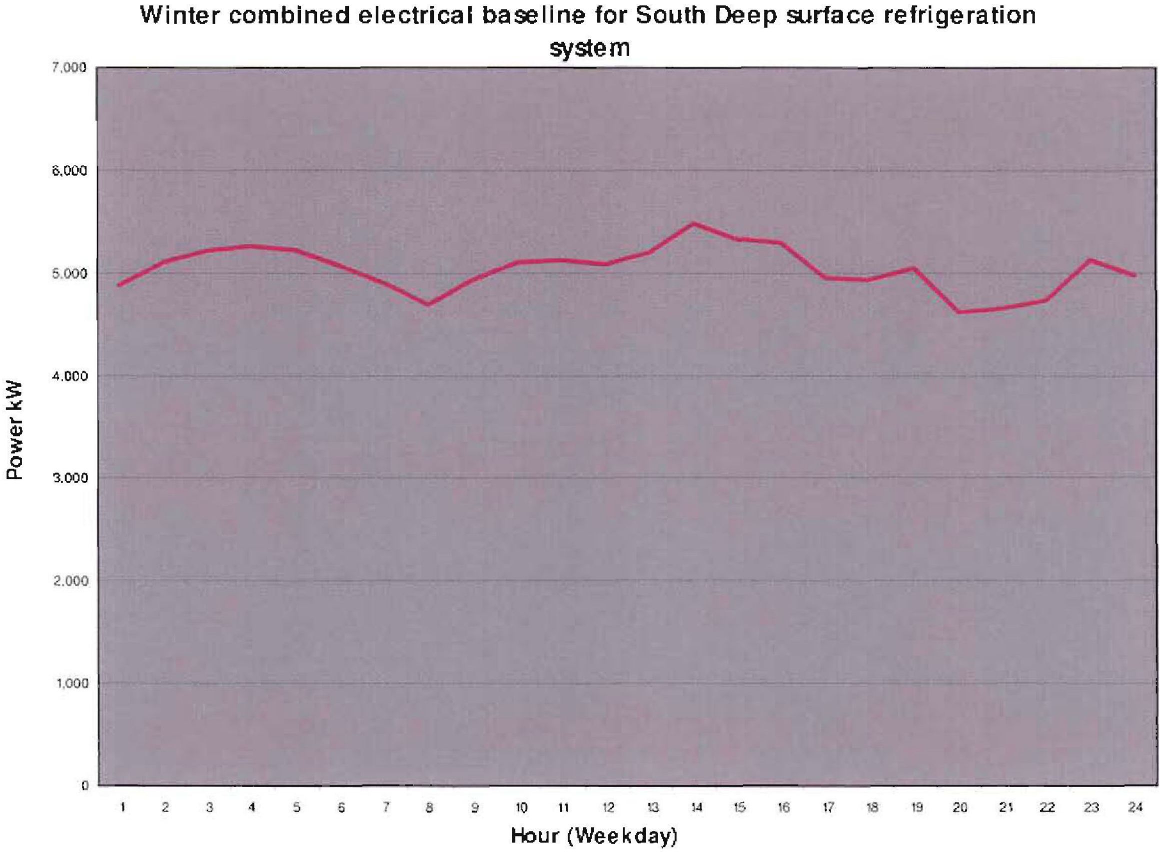


Figure 62 - Winter combined electrical baseline for South Deep refrigeration

Figure 62 is a graph of the winter combined electrical baseline of the South Deep surface refrigeration system. This can be seen as a plot of the daily machine and auxiliary, counted together electrical energy used for the cooling load by the machines for an average winter day.

Proposed value

Shifting a total of 3.8 MW from of the evening peak on mine working weekdays during the winter months and a total of 4.4 MW during the summer months, is proposed. The annual target for the South Deep surface refrigeration system project is a weighed average of 4.2 MW. This target is calculated as follows:

{(4.4 x 9) + (3.8 x 3)}/12 = 4.2 MW.

This is feasible because the average evening peak for summer lies at 5.5 MW and the average evening peak for winter lies at 4.8 MW,.

APPENDIX D: SPECIFICATION, CONSTRAINTS AND VARIABLES OF THE EQUIPMENT AND SITE

The physical system constraints from section 3.2 are listed in the following tables.

Dam	Purpose	Volume (m^3)	Open or closed[1]	Control variable(s)[2]	Control level (%)	Control temp. (^oC)
Mine water dam	Collect water from mine	3 817.7	Open	-	30 - 95	-
Hot water Dam	Hot water pumped from mine water dam	2 709	Open	Level	30 - 95	-
Pre-Cool Dam	Collect water from pre-cool towers	318.1	Open	Level	30 - 95	-
Cool water Dam	Store water from pre-cool towers	2 709	Closed	Level	30 - 95	19 - 25
Chill Dam 1	Store water after York chiller machines	2 709	Closed	Level/temp.	30 - 95	9 - 12
Chill Dam 2	Store water after York or Howden chiller machines	2 709	Closed	Level/temp.	30 - 95	3 - 5
Chill Dam 3	Store water after Howden chiller machines	2 709	Closed	Level/temp.	30 - 95	3 – 5

Table 15 - Surface refrigeration system dam constraints [52]

Pump description	Pump (Type)	Impeller diameter (m)	Flow (l/s)	Power (kW)	Controlled by:
Mine Water	KSB ETA 250/50	0.41	300	200	Hot Dam level
Filter pumps – A	Sulzer AZS 200/250	0.25	75	15	Cool Dam level
Filter pumps – B	Allis-Chalmer	0.3	120	30	Cool Dam level
York Evaporator	Salweir SDB 200/250	0.32	114	55	Chill Dam 1 level
York Condenser	Salweir SDB 10/12	0.36	280	132	Chill Dam 1 level
Howden Evaporator	Salweir SDB 350/450	0.415	420	160	Chill Dams 2&3 level
Howden Condenser	Salweir SDB 350/450	0.475	420	185	Chill Dams 2&3 level

Table 16 - Surface refrigeration system pump constraints [52]

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[1] Indicates whether the dam is open or closed on top. A closed dam is better insulated from the environment.

[2] Indicates if the surface refrigeration system can influence the specific dam's level, temperature or both.

1. Performance Data	
Inlet Water Temp. (°C)	28
Outlet Water Temp (°C)	18.5
Inlet B Air Temp. (°C)	16
Outlet WB Air Temp. (°C)	23.3
Pressure (kPa)	85
Water Flow (m^3/s)	1 728
Air flow/cell (m^3/s)	525.8
Static pressure drop (Pa)	136.8
Heat Exchange (MW)	19.06
2. Fan details	
Diameter (m)	7.315
RPM	1 480
Number of blades	6
Pitch of blades (°)	16.3
Manufacturer	Howden
Type	ENF
3. Motor Details	
Power per motor (kW)	132
RPM	1 480
Manufacturer	ZEST/WEG
4. Construction details	
Number of cells	2
Total Plot area (m^2)	14.85 x 28.75
Fill Area (m^2)	14.34 x 14
Induced draught	
Air opening (m^2)	80
Pitch of fill (m)	0.25
Fill Depth (m)	3.25
Height to bottom of fill (m)	3

Table 17 - Surface refrigeration system cooling towers information [52]

Design Details	
Voltage (V)	11 000
Amps (A)	85.5
Bearing Temp. – DE (°C)	60
Bearing Temp. – NDE (°C)	60
Barometric Pressure (kPa)	84
% Vane opening	100
Oil Temp. (°C)	60
Oil Press. (kPa)	450
Differential oil Press. (kPa)	210
Suction Temp. (°C)	2
Suction Press. – Gauge (kPa)	240
Suction Press. – Absolute (kPa)	324
Discharge Temp. (°C)	50.5
Condenser Press. – Gauge (kPa)	670
Condenser Press. – Absolute (kPa)	754
Corresponding Temp. (°C)	30.52
Discharge superheat (°C)	20.5
High pressure liquid Temp. (°C)	30
Chilled water inlet temp. (°C)	14.5
Chilled water outlet temp. (°C)	4
Chilled water ΔT (°C)	10.5
Chilled water flow (l/s)	114
Evaporator duty (kW)	5 012
Condenser water outlet temp. (°C)	27.5
Condenser water inlet temp. (°C)	22
Condenser water ΔT (°C)	5.5
Condenser water flow (l/s)	270
Condenser duty (kW)	6 217
Compressor shaft power (kW)	1 264
Coefficient of performance	3.96
Carnot COP	9.5
Cycle efficiency (%)	41.71
Power to cooling ratio	0.25
LMTD Condenser	4.73
LMTD Evaporator	6.21

Table 18 - Surface refrigeration system York chiller machines constraints [52]

Design details (normal running)	
Voltage (V)	11 000
Amps (A)	160
Bearing Temp. – DE (°C)	45
Bearing Temp. – NDE (°C)	34
Barometric Pressure (kPa)	84
% Vane opening	100
Oil Temp in Separator (°C)	40
Oil Temp. in Manifold (°C)	40
Oil filter diff. Press. (kPa)	10
Differential oil Press. (kPa)	440
Suction temp. (°C)	3
Surge drum press. (kPa)	417
Surge drum level (%)	7
Discharge temp. (°C)	40-50
Discharge press. (kPa)	1 230
Evap. ammonia inlet Temp. (°C)	1
Evap ammonia outlet Temp. (°C)	10
Evap. Water inlet temp (°C)	11
Evap. Water outlet temp. (°C)	5
Chilled water ΔT (°C)	5.5
Chilled water flow (l/s)	360
Evaporator duty (kW)	8 300
Cond. ammonia Inlet temp. (°C)	40
Cond. ammonia Outlet temp. (°C)	28
Cond. Water outlet temp. (°C)	30
Cond. Water inlet temp. (°C)	21
Cond. Water ΔT (°C)	9
Cond water flow (l/s)	350
Cond. Duty (kW)	11 340
Coefficient of performance	5.7
Carnot COP	13.434
Cycle efficiency (%)	42.3
Power to cooling ratio	0.1761

Table 19 - Surface refrigeration Howden chiller machine constraints [52]

APPENDIX E: PLC – SCADA REFRIGERATION MACHINES INTERNAL CONTROL

Appendix E gives background knowledge on the control flow diagrams of the cascade refrigeration system PLC and SCADA system.

i. Refrigeration machine outlet temperature

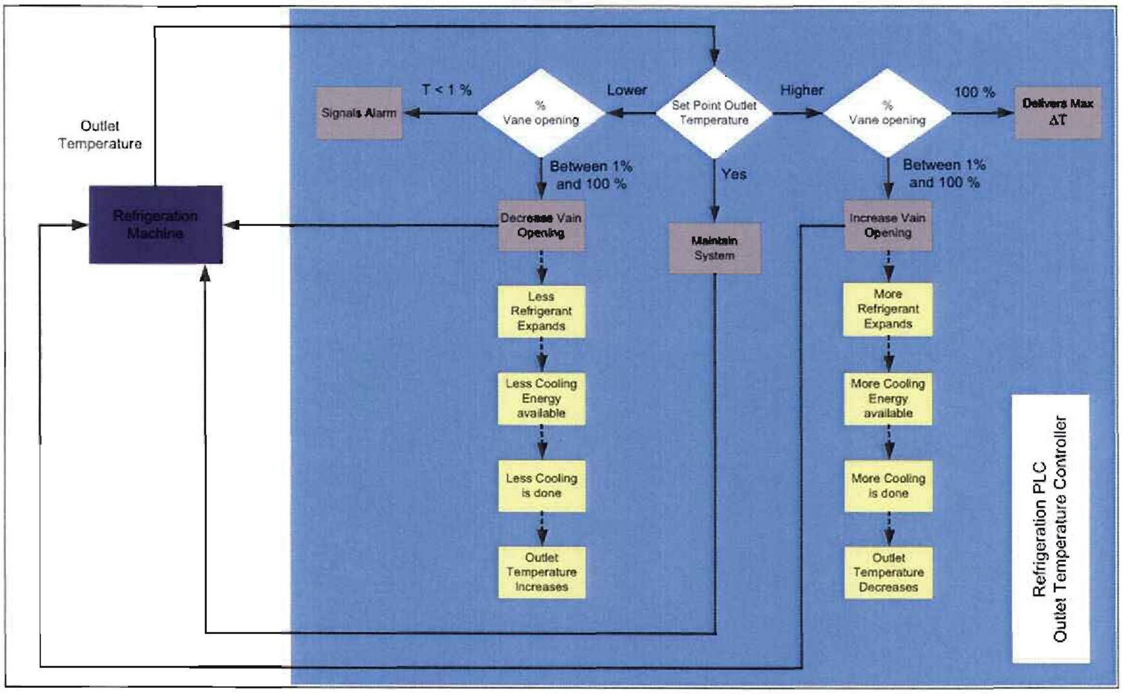

Figure 63 – Outlet temperature control flow diagram

The above control flow diagram shows that the refrigeration system will deliver chilled water at a set temperature if the difference between the inlet and outlet temperature does not exceed the design ΔT.

ii. Flow through

An evaporator valve that controls the flow through the fridge plants and can be in the following configuration.

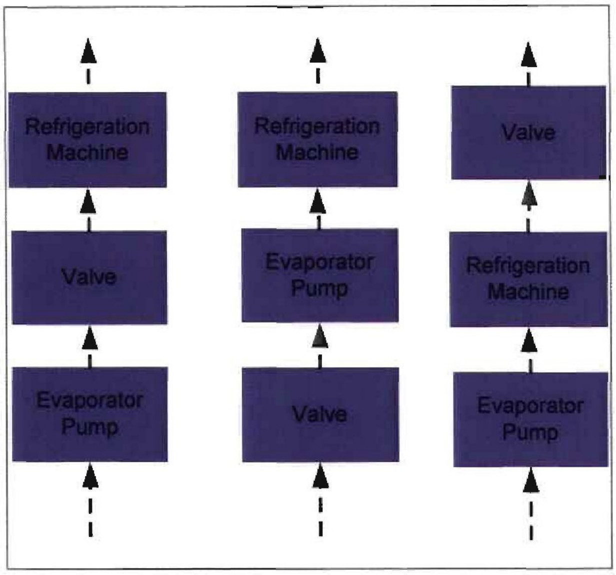

Figure 64 - Evaporator pump, valve and refrigeration machine configurations

The estimated working of the evaporator valve control is shown in the block diagram below:

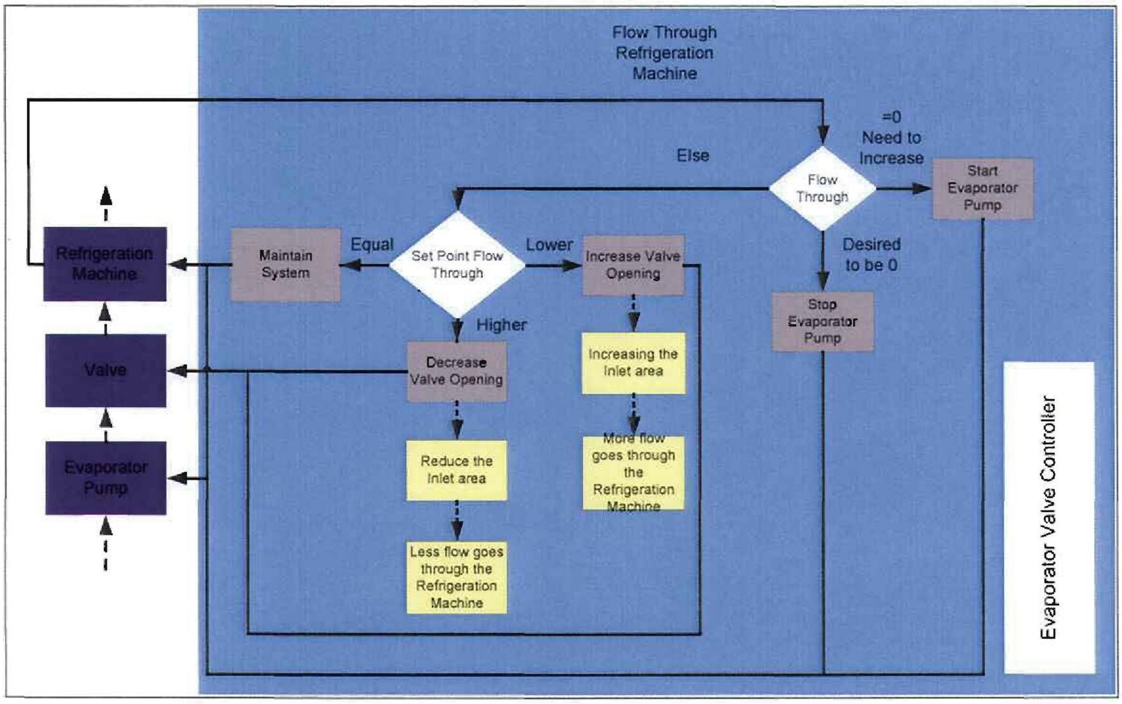

Figure 65 – Evaporator valve control flow diagram

iii. Evaporator pump control

On the South Deep cascade surface refrigeration system, the evaporator pump initiates flow through the machine which is specifically controlled by the evaporator valve as described in the previous section. The following diagram illustrates evaporator pump control.

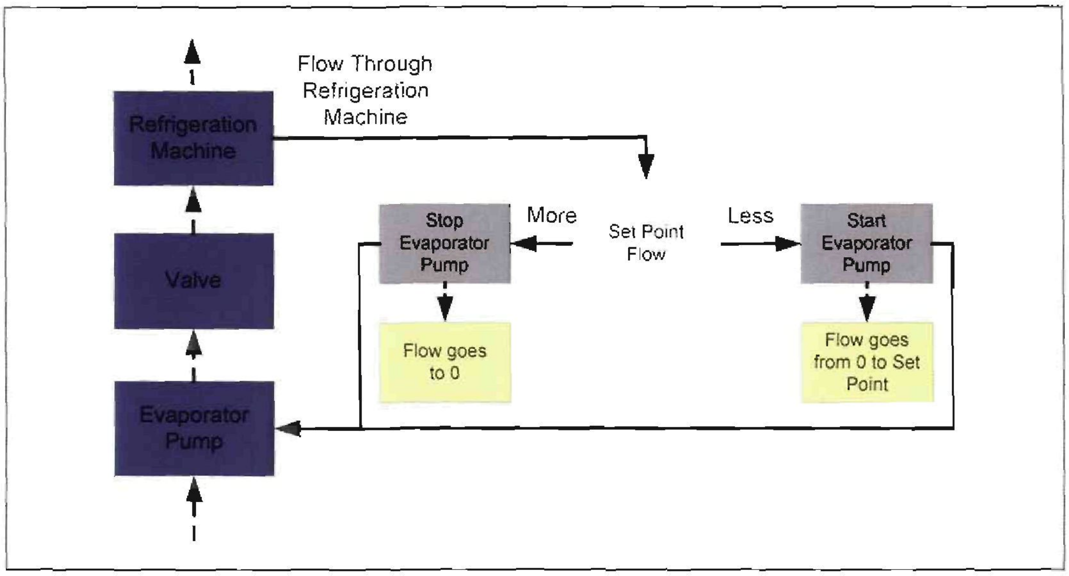

Figure 66 – Evaporator pump control flow diagram

Thus the amount of water flowing through the machine, is controlled by the evaporator valve and the variable speed drive on the evaporator pump motor.

Using the back-pass valves, chilled water is re-circulated and the amount of un-chilled water flowing through the refrigeration machine is lowered. The constraint on the amount of chilled water that can be back-passed is the inlet temperature set point.