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SUSTAINABLE DSM ON DEEP MINE REFRIGERATION SYSTEMS – A NOVEL APPROACH

J VAN DER BIJL

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PROMOTER: **PROF. M KLEINGELD**

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PRETORIA





ABSTRACT

Title:	Sustainable DSM on deep mine refrigeration systems – a novel approach
Author:	Johan van der Bijl
Promoter:	Prof. M. Kleingeld
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The supply and demand of energy have become a world wide concern. It is predicted that world energy usage could increase from 15TW, to 21TW by 2020. In South Africa the peak demand for electrical energy has already outrun the supply. Eskom produces 96% of South Africa's electricity requirements and has launched a Demand Side Management (DSM) program. Its primary target is that of reducing electrical load during the peak demand period.

South African mines are the main "culprits" regarding the intensive use of electricity. Large refrigeration plants supply chilled water which is used to cool deep underground working areas. If these cooling systems could be controlled to operate more intelligently it could help Eskom with its problems during peak supply (from 18:00 to 20:00).

To investigate the potential for Demand Side Management (DSM) in these systems, integrated simulation is required. It has to predict these systems' responses to DSM control strategies and its effect on critical underground conditions. Mathematical models of refrigeration equipment were therefore simplified and integrated into software for simulation purposes. The accuracy of the predictions of the software was verified on the refrigeration system of Kopanang Gold Mine near Orkney in the Free Sate.

New control algorithms were developed to control a refrigeration system for load shift purposes. These algorithms were also combined into a new global control philosophy which can be applied to any refrigeration system to establish a load shift potential. A unique investigation protocol was developed which can also be used to investigate any refrigeration system for a DSM potential.

The only way to sustainably and effectively realise a DSM potential in a refrigeration system, via optimised control, is through the implementation of an Energy Management System (EMS). A Real-Time Energy Management System (REMS) was developed to be applied as a fully automated control software solution. It communicates with a Supervisory Control and Data Acquisition system (SCADA) which in turn controls plant automation infrastructure.

Refrigeration systems in South African mines were investigated and four systems were identified and submitted to Eskom DSM for approval. All four proposals were approved with the required DSM target of 17MW to be removed from the Eskom evening peak period. Eskom DSM supplied all capital funding for the required plant automation infrastructure.

The Real-time Energy Management System (REMS) was installed on the refrigeration systems of Kopanang and Tshepong Gold Mines. The REMS system realised a DSM potential of 3.6MW on Kopanang, and 4.0MW on Tshepong without compromising requirements for plant equipment, process, maintenance or mine health and safety constraints.

Automated and optimised control of mine refrigeration systems is an effective, sustainable and cost effective option for Eskom DSM. The REMS system not only realises the much needed control of the evening peak energy capacity Eskom needs, but also realises electricity cost savings for the mines involved, by effective operation of these systems during cheaper tariff periods.

The REMS system at Kopanang Gold Mine has been operating automatically for more than 20 months, realising cost savings in excess of R2-million for the mine over this period. The projected cost savings for Tshepong Gold Mine are approximately R500-thousand per annum. The methodologies and strategies developed in this study can be utilised to quickly and effectively investigate the untapped 60MW worth of DSM potential in the refrigeration systems of South African mines.

SAMEVATTING

Titel:	Volhoubare DSM op diep-myn verkoelingstelsels – 'n unieke benadering
Outeur:	Johan van der Bijl
Promotor:	Prof. M. Kleingeld
Skool:	Meganiese Ingenieurswese
Fakulteit:	Ingenieurswese
Graad:	Philosophiae Doctor
Sleutelwoorde:	Energie, Demand Side Management (DSM), elektriese las, piek-aanvraag periode, myne, verkoelingsaanlegte, optimale beheer, simulasie, Real-time Energy Management System (REMS), outomaties.

Die voorsiening van energie het wêreldwyd 'n uitdaging geword. Voorspellings dui daarop dat energieverbruik gaan toeneem van 15TW na 21TW teen 2020. In Suid-Afrika het die piek aanvraag vir elektrisiteit reeds die voorsieningskapasiteit verbygesteek. Eskom genereer 96% van Suid-Afrika se elektrisiteit. Aan die verbruikerskant het Eskom 'n DSM-program geloods om te poog om die elektriese las in die piek-aanvraag periode te verminder.

Suid-Afrikaanse myne is groot en oneffektiewe verbruikers van elektrisiteit. Groot verkoelingsaanlegte verskaf verkilde water wat gebruik word om die ondergrondse toestande te verkoel (die verkoelingsvereistes in 'n myn word grootliks beïnvloed deur, en is direk afhanklik van die diepte van die myn). As hierdie stelsels "slimmer" beheer kan word wat elektrisiteitsverbruik betref, sal dit vir Eskom help om die piek elektrisiteitsverbruik tussen 18:00 en 20:00 te verminder.

Om DSM geleenthede in hierdie stelsels te ondersoek moet die stelsel se gedrag (onderhewig aan DSM beheer-strategieë) ondersoek word deur middel van geïntegreerde simulasie. Wiskundige modelle van verkoelingstoerusting is vereenvoudig en in simulasie sagteware geïntegreer. Die akkuraatheid van die simulasie-sagteware se voorspellings is op die verkoelingstelsel van die Kopanang Goudmyn, naby Orkney in die Vrystaat, geverifieer.

Nuwe beheer-algoritmes is ontwikkel om die beheer van 'n verkoelingstelsel vir die verskuiwing van energie te bewerkstellig. Deur hierdie algoritmes te kombineer kon 'n nuwe globale beheer-filosofie ontwikkel word wat op enige verkoelingstelsel toegepas kan word om 'n lasskuif potensiaal te realiseer. 'n Unieke ondersoekmetode is ook ontwikkel wat gebruik kan word om DSM potensiaal in enige verkoelingstelsel te ondersoek.

Die enigste manier om volhoubare DSM resultate in verkoelingstelsels te realiseer, met betrekking tot optimale beheer, is met behulp van 'n Energie Bestuur Stelsel (EBS). 'n Intydse energiebestuurstelsel, REMS (Real-Time Energy Management System), is ontwikkel as 'n sagteware oplossing vir díe doel. Die REMS-stelsel kommunikeer met 'n SCADA-stelsel (Supervisory Control and Data Acquisition) wat dan gebruik word om outomatiese aanlegtoerusting te beheer.

Die verkoelingstelsels van Suid-Afrikaanse myne is ondersoek en vier myne is geïdentifiseer as moontlike voorstelle wat deur Eskom DSM goedgekeur kan word. Die vier voorstelle, met 'n gekombineerde 17MW lasskuif potensiaal vanaf die Eskom aandpiek-periode, is deur Eskom aanvaar. Eskom DSM het al die nodige infrastruktuur ten volle betaal.

Die REMS stelsel is geïnstalleer op die verkoelingstelsels van die Kopanang en Tshepong goud myne. Die REMS stelsel het 'n DSM potensiaal van 3.6MW op Kopanang en 4.0MW op Tshepong gerealiseer. Geen vereistes ten opsigte van aanleg toerusting-, proses-, instandhouding-, mynveiligheid-, of gesondheidsvereistes is oortree nie.

Outomaties en optimale beheer van myn-verkoelingstelsels is 'n effektiewe, volhoubare en koste effektiewe oplossing vir Eskom se DSM aanslag. Die REMS-stelsel genereer nie net die nodige aandpiek elektrisiteitskapasiteit wat Eskom verlang nie, maar ook aansienlike elektrisiteitskoste beparings vir die myne deur die verkoelingstelsels in goedkoper tarief-periodes te bedryf.

Die REMS stelsel te Kopanang beheer die myn se verkoelingstelsels al vir langer as 20 maande, en het die myn al meer as R2-miljoen bespaar. Die geskatte kostebesparing vir die Tshepong projek beloop ongeveer R500-duisend per jaar. Die metodes en strategieë wat ontwikkel is in die studie kan gebruik word om vinnig en doeltreffend die potensiële 60MW DSM potensiaal in myn-verkoelingstelsels in Suid-Afrika te ondersoek en te bewerkstellig.

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Firstly, all thanks to God, for giving me the capabilities and opportunity to complete this study. Thank you Lord, for always being there, thank you for your grace and mercy, thank you for your Son, and thank you for all the things you bless me with.

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- This study is dedicated to my wife, Lynette. Your support and love has always motivated me. Thank you for your patience and for always caring and being there for me. I love you;
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To Lynette...

NOMENCLATURE

ENGLISH LETTER SYMBOLS

A	Exposed area of dam	m^2
a	Correlation coefficients for the K_h versus K_f relation	
a_n	Regression coefficients for cooling capacity	
b	Correlation coefficients for the η_{pump} versus K_f relation	
b_n	Regression coefficients for power	
C	Mass flow constant	
c	Specific heat	J/kgK
Cc	Cooling capacity at the expected operational temperatures of the chiller	kW
D	Rotor diameter	m
dP	Static pressure rise	Pa
f	Active fraction of total capacity	
G	Irradiation	W/m^2
h	Convective heat-transfer coefficient	W/m^2K
K	Dimensionless coefficient for pumps	
k	The number of pumps in cascade	
$\dot{m}$	Mass flow rate	kg/s
$m_{l(cond)}$	Mass flow rate of water through the condenser	kg/s
$m_{l(evap)}$	Mass flow rate of water through the evaporator	kg/s
n	Rotational speed of the pump	rpm
P	Compressor power at the expected operational temperatures of the chiller	kW
Pwr	Power required	kW
Q	Rate of heat gain	kW
Q_e	Cooling capacity	kW
R	Unit thermal resistance	m^2K/W

T	Temperature	K
t	Time interval	s
t_{ci}	Expected temperature of water entering the condenser	°C
t_{ei}	Expected temperature of water entering the evaporator	°C
$t_{le(cond)}$	Temperature of water leaving the condenser	°C
$t_{le(evap)}$	Temperature of water leaving the evaporator	°C
$t_{li(cond)}$	Temperature of water entering condenser	°C
$t_{li(evap)}$	Temperature of water entering evaporator	°C
U	Overall heat-transfer coefficient	W/m^2K
V	Volume	m^3

SUBSCRIPTS

A	Ambient
D	Dam water
f	Flow
h	Pressure head
i	Initial
i	Inward
j	j = 0 to k
l	Liquid
li	Liquid entering at inlet
le	Liquid leaving at outlet
motor	Motor
o	Outside surface
o	Outward
p	Constant pressure
pump	Pump
S	Solar air
t	Time

GREEK LETTER SYMBOLS

α	Absorptance	
Δ	Change in a quantity or property	
ε	Emittance	
η	Efficiency	
ρ	Mass density	kg/m^3

ABBREVIATIONS

BAC	Bulk Air Cooler
COP	Coefficient of Performance
CP	Control Privilege
DME	Department of Minerals and Energy
DSM	Demand Side Management
EE	Energy Efficiency
EEDSM	Energy Efficiency Demand Side Management
EMS	Energy Management System
ESCO	Energy Services Company
GDP	Gross Domestic Product
GW	Gigawatt
GWh	Gigawatt Hour
HMI	Human Machine Interface
IEP	Integrated Energy Planning
IO	Input Output
IRP	Integrated Resource Planning
kW	Kilowatt (Standard unit for power consumption)
kWh	Kilowatt Hour (Standard unit for electricity consumption)
LM	Load Management
LR	Load Reduction
LS	Load Shift
M&V	Measurement and Verification
MD	Maximum Demand
MW	Megawatt
MWh	Megawatt Hour

NERSA	National Energy Regulator of South Africa
NIRP	National Integrated Resource Plan
OLE	Object Linking and Embedding
OPC	OLE for Process Control
PID	Proportional Integral Differential
PLC	Programmable Logic Control
PPP	Purchasing Power Parity
RDP	Reconstruction and Development Programme
REMS	Real-time Energy Management System
RH	Relative Humidity
SAPP	South African Power Pool
SCADA	Supervisory Control and Data Acquisition
SHE	Safety, Health and Environment
SSM	Supply Side Management
TOU	Time of Use
TW	Terra Watt
TWh	Terra Watt Hour
VC	Ventilation and Cooling
VRT	Virgin Rock Temperature

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CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1. THE ELECTRICITY CHALLENGE IN SOUTH AFRICA

ENERGY: A WORLD WIDE CONCERN

As populations grow and economies take off, millions of people in the developing world are enjoying the benefits of a lifestyle that requires increasing amounts of energy [1]. Worldwide, total energy demand trends from 1970 to 2002 have increased from $207x10^{24}$ British thermal units (Btu) to $412x10^{24}$ Btu [2]. The United States Department of Energy predicts that the world primary energy consumption will increase by 59% over the period 1999 to 2020 [3].

Economic activity, as measured by Gross Domestic Product (GDP) in Purchasing Power Parity (PPP) terms, is expected to expand by 5.1% per year in the emerging economies. This is compared with 2.5% per year in the mature market economies and 4.4% per year in the transitional economies [2], [4].

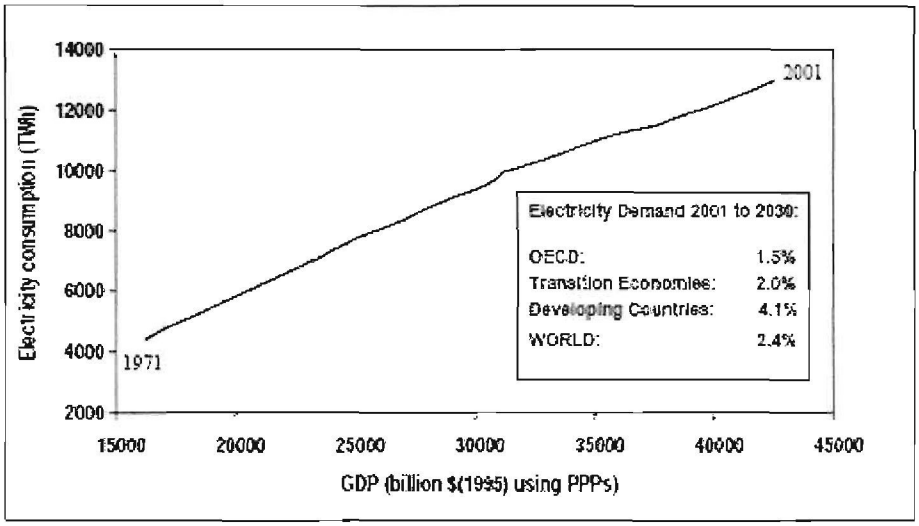


Figure 1-1: World Electricity Consumption vs. GDP 1971-2001 [4].

The US, for example, is home to 4% of the world's population but is consuming 25% of the world's energy [4]. As wealthier countries in general continue to prosper, their energy needs will continue to grow accordingly [4]. The electricity used in developing countries during the 1980s has grown by more than 11% per year and is still increasing [5].

The challenge is to provide clean, affordable energy necessary for rapid economic growth and rising living standards in emerging economies, while also fulfilling demand in the world's more developed economies [6]. This will require a combination of increasing conservation, expanding and diversifying our energy supply, and improving energy efficiency [7].

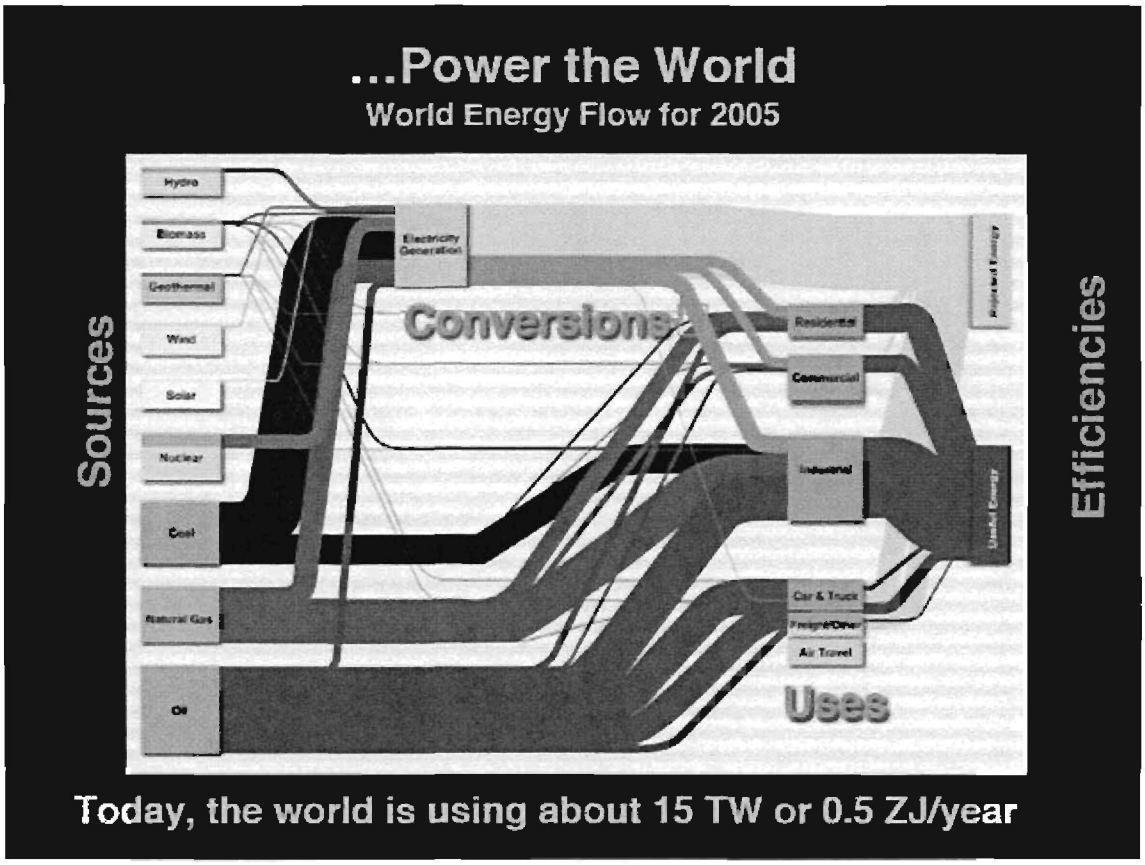


Figure 1-2: World energy flow [8].

Most scientists now agree that global warming is real and that we have changed the world's climate by our energy conversion activities. We need to change our approach to the supply and use of energy or our planet will eventually force us to.

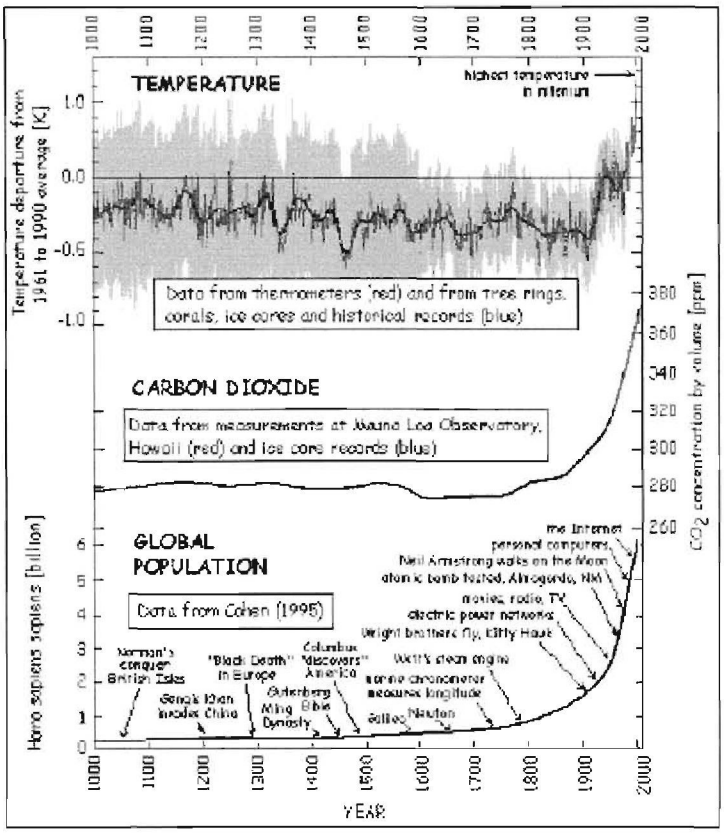


Figure 1-3: The impact that burning of fossil fuels have on our planet [8].

THE PROBLEM SOUTH AFRICA IS FACING

In South Africa a large portion of the primary energy is provided through the generation of electricity from coal (87%), hydro pumped storage (6%) and nuclear (5%). This can be seen in Table 1-1. These figures exclude imported electricity, for example from the Cahora Bassa hydro scheme in Mozambique.

Energy Source	Capacity / MW
Coal	32,202
Nuclear	1,840
Hydro Pumped Storage	1,580
Hydro	667
Gas Turbine	662
Bagasse	105
TOTAL	**37,056**

Table 1-1: South Africa's electricity generation capacity (MW) [9].

Eskom produces 95.9% of South Africa's electricity requirements [10], the remainder being provided through local authorities, industry and imports via the South African Power Pool (SAPP). Eskom's generation capacity, assuming a 50 year life per plant, is indicated in Figure 1-4.

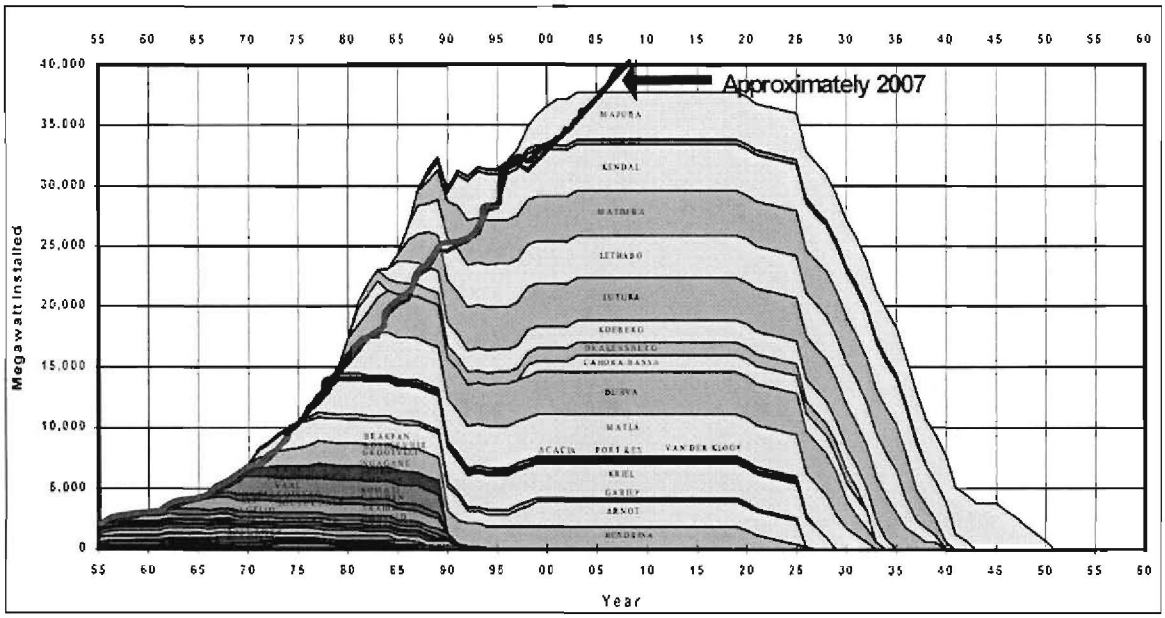


Figure 1-4: Eskom electricity generating capacity as a function of time [9].

The capacity is primarily from coal-fired power stations and the graph indicates that current plants are scheduled to be operational until at least the year 2020. The red demand line in the figure indicates that further electricity generation plants will be required by approximately year 2007 [11], [12].

It is important to note that whilst current concerns relate to new capacity to accommodate growth in demand, after the year 2020 and for the following three decades, generating capacity to replace the existing 37,000MW will need to be urgently addressed. Current concerns may seem trivial when compared with the foreseen energy requirements after the year 2020.

Figure 1-5 shows the trends in generation plant capacity by Eskom and the peak demand for electricity during the period 1995-2005 [13]. Peak demand showed an upward trend from 2000 onwards after being depressed since 1997.

The average growth in peak demand over the period 1990 to 2003 was 3.3% [10]. This means that electricity demand in South Africa is currently estimated to be growing approximately 1000MW per annum [14].

However, when looking at the figure it is interesting to note that a peak demand (for the period 2004 to 2005) of 34,195MW was recorded (13 July 2004). It was substantially higher than the peak demand of 31,928MW that was recorded in 2003. There was a substantial decrease in the generation reserve margin from 16.9% in 2003 to 8.5% in 2004 [13].

Figure 1-5 shows how the electricity demand by all consumers in South Africa simultaneously changes depending on the time of day. During the winter months the average demand is higher than during the summer months. In winter both the morning and evening peak demands are more pronounced than in summer, while there is a significant increase in the evening peak demand due to the need for heating.

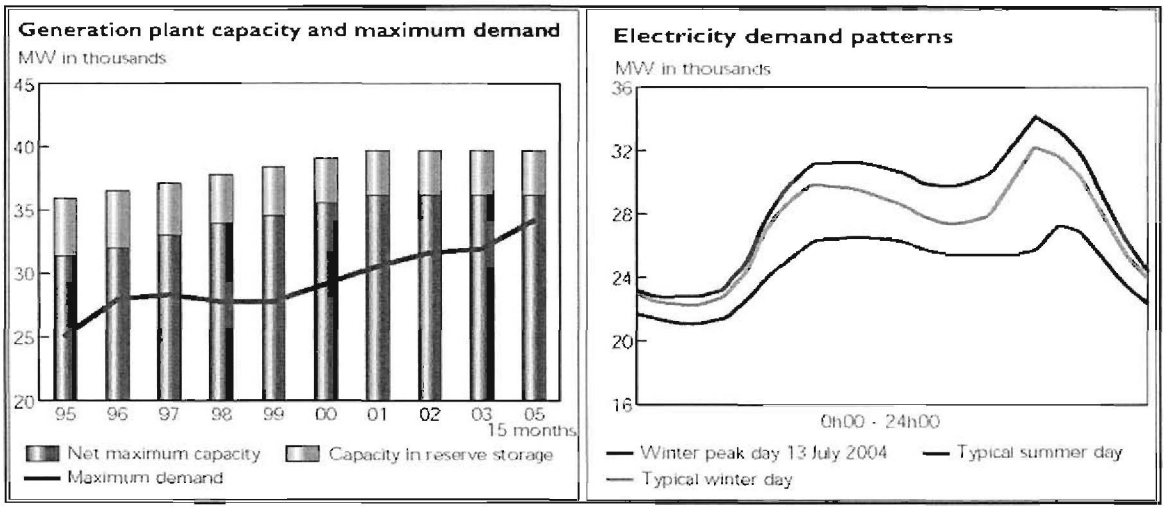


Figure 1-5: Eskom generation capacity, maximum demand, and 2004 demand profiles.

At night the demand decreases to an average of about 69% of the peak demand (78% in summer and 70% in winter) [13]. From Figure 1-5 it is evident that electricity supply in South Africa faces a major challenge. One of the main reasons for this is because of the commendable mass housing and electrification programmes of the Reconstruction and Development Programme (RDP).

More than 1.3 million new electricity connections have been established between 1994 and 1996, bringing urban electrification to 79% at the end of 1996 [15].

Electricity demand in low-income urban areas, however, tends to be heavily skewed towards the peak periods of power demand in the mornings and evenings, even though total electricity usage is often low. Moreover, the poor quality of RDP homes means that much of the energy used for heating is wasted.

The rapid increase in electrified homes soaks up much of the surplus capacity in South Africa, especially during the peak times [16]. Therefore, Eskom estimates that a high-growth scenario might require a new power generation plant by the year 2007 [11], [12].

Given the time to commission a new plant, the current electricity generation network could soon be viewed as vulnerable. As growing power shortages in South Africa threaten its continued economic growth, it becomes more important than ever to find effective ways to use energy more efficiently.

1.2. DSM IN SOUTH AFRICA

SUPPLY SIDE MANAGEMENT

As was clearly seen in the previous section, Eskom is running out of electricity supply options. They should have started building new power stations 10 years ago to cater for the growing electricity demand, as well as to replace base load capacity. If this was done there would not have been an electric power shortage.

However, Eskom has announced an investment programme of at least R200-billion over the next 25 years that will ensure that South Africa has enough electricity to power its fast growing economy [17]. Eskom's programme is divided into two phases.

The first phase deals with the immediate electricity needs for the next five years, which will require Eskom to add 1,000MW of capacity every year from 2005 to 2009 to avoid shortages during peak times. The second phase deals with the replacement of old power plants with new generating possibilities that will add to the base load of its network.

This is the long term phase of Eskom's programme, where big investment decisions are required. Most of Eskom's current power plants will only be operational until 2020 and new generating possibilities will have to replace them [11]. Eskom has many long term projects running to meet the base load capacity.

These include Braamhoek pumped storage scheme; Steelpoort pumped storage scheme; a new gas turbine near Coega; adding three power units to the existing six at Mathimba power station; as well as a new greenfields coal fired power station. But these are long term projects and at the earliest electricity is only expected to be delivered by 2012 [17].

On the supply side a lot of new projects are in operation. This is called Supply Side Management (SSM). SSM is however a long term solution and Eskom will be running out of power shortly. Demand Side Management (DSM) provides a solution, or at least alleviation, to the problem. DSM aims to reduce peak load (specifically between 18:00 and 20:00) and projects can deliver immediate results in a fairly short time.

HISTORY OF DSM IN THE WORLD

DSM refers to measures sponsored, funded, and/or implemented by utilities that modify end-use electrical energy consumption, either reducing overall consumption through energy efficiency (EE) or using load management (LM) to reduce demand at times when the cost of reducing demand is less than the cost of servicing it.

Cost-effective efficiency and load management measures could significantly improve the reliability of national electric systems and close the gap between supply and demand, while lowering the economic and environmental costs of electric service [18].

More than 30 countries around the world have successfully applied DSM to increase electricity savings, reduce the need for new power plants, improve economy and reliability in power network operation, control tariff escalation, lower consumer electricity expenses, save energy resources, and improve environmental quality [19].

The USA – mastering DSM

DSM has become an important strategy for achieving sustainable energy and electricity development. Specific applications differ in each country according to local conditions. DSM has made a tremendous contribution to the economic growth of the United States since the Arab oil embargo of 1973.

In 2000, the total U.S. primary energy use per capita was almost identical to that of 1973. Yet over the same time period, economic output (GDP) per capita increased by 74% [20]. By 2000, reduced "energy intensity" (compared with 1975) provided 40% of all U.S. energy services.

This made DSM (energy efficiency) America's largest and fastest growing energy resource—greater than oil, gas, coal, or nuclear power. Since 1973, the United States has received more than four times as much "new energy" from savings, as from all net expansions of domestic energy supply, combined [21].

In 2000, U.S. consumers and businesses spent more than US$600-billion for total energy use. Had the United States not drastically reduced its energy intensity since 1973, they would have spent at least US$430 per capita more in energy purchases in 2000 [20].

Over the last two decades in the United States, many states used Integrated Resource Planning (IRP) to compare the benefits and costs of DSM with the costs of additional generation. These IRP programs led estates to generate a network of utility DSM programs that together avoided the need for about 100 power plants with a combined capacity of 300MW [22].

The average initial cost of improved efficiency was less than one-half the cost of building new power plants. Utilities report that their average cost of implementing electricity savings of all kinds has been about 2 cents per kWh.

In comparison, each kilowatt-hour generated by an existing power plant costs more than 5 cents. Delivered power from a nuclear plant can cost as much as 20 cents per kWh [21]. In the late 1980s, more than 1,300 DSM programs were conducted in the United States, which together curtailed 0.4% - 1.4% of peak load, corresponding to a demand growth rate of 20% to 40%.

Between 1985 and 1995, more than 500 utilities conducted DSM programs, curtailing 29GW of peak load. Up to the mid 1990s, U.S. utilities increased their investment in DSM each year, from US$900-million in 1990 to US$2,700-million in 1994, corresponding to 0.7% - 1% of average sales revenue. The uncertainty brought on by impending electric industry restructuring caused DSM spending to drop dramatically during the 1990s. Yet a total of US$1.4-billion was still spent on utility energy efficiency programs in 1999, due primarily to the adoption of system benefit charges [23].

A number of other new approaches to DSM have emerged since restructuring. Texas, for example, is pioneering the idea of an "energy efficiency portfolio standard," analogous to a renewable portfolio standard, whereby utilities are required to derive a certain percentage of their energy from renewable sources, such as solar or wind. Texas requires regulated utilities to acquire energy efficiency equivalent to 10% of each year's growth in electricity demand.

The European Union – taking the lead on directives

The Council of the European Union is in the process of drafting a Directive on Energy Efficiency-Demand Side Management (EE-DSM). This directive would require each member state to achieve a certain minimum level of energy efficiency improvements through EE-DSM programs. Each state would be free to determine which policy mechanisms to adopt to meet that target [24].

The draft directive recommends a minimum target energy savings level of one percent per year below the consumption in each member state the previous year, expressed in TWh/year per member state. The target also includes a recommended minimum level of investment for EE-DSM programs from each member state of 2% of the total net revenue in that member state, from electricity and natural gas sales to final consumers.

The EE-DSM program investments must be additional to energy efficiency activities financed from the state budget at present. The member states should also support the development of a market for EE-DSM services [24].

The United Kingdom – innovative approaches to DSM

In 1992, following electric sector restructuring, the United Kingdom established an independent, non-profit Energy Saving Trust (EST) to design and oversee DSM programs. Its primary mandate was to reduce carbon dioxide emissions through DSM and energy efficiency [25].

During the first four years of the DSM program, the UK power sector collected US$165-million from a wire surcharge, or system benefit charge, and invested it in more than 500 energy efficiency projects. Estimated electricity savings totalled more than 6800GWh, which is equivalent to the annual electricity consumption of 2 million UK households.

Under the UK Utilities Act of 2000, both gas and electricity suppliers are required to meet specific energy efficiency targets and encourage or assist domestic customers to implement energy efficiency measures. The overall energy savings target (known as the Energy Efficiency Commitment) is 62TWh, with half of the savings targeted at consumers receiving benefits or tax credits.

The UK government regulator is responsible for administering the commitment, apportioning the overall target to each supplier and monitoring suppliers' performance against their targets [25]. Table 1-2 lists most of the world wide countries that successfully apply DSM programs [19].

LIST OF COUNTRIES WITH DSM PROGRAMS			
Argentina	Hong Kong	Netherlands	Spain
Australia	India	New Zealand	Sri Lanka
Belgium	Indonesia	Norway	Sweden
Brazil	Ireland	Peru	Taiwan
China	Italy	Philippines	Thailand
Denmark	Japan	Singapore	United Kingdom
France	Malaysia	South Africa	USA
Greece	Mexico	South Korea	Vietnam

Table 1-2: List of world countries with DSM programmes.

A SOLUTION FOR SOUTH AFRICA

DSM aims to reduce electricity demand during peak periods, when Eskom's supply capability is limited. The greater the co-operation between Eskom and consumers in reducing demand during peak periods, the longer Eskom will be able to delay inevitable investment in new power stations and the accompanying price impact on energy users [26].

From the Minister of Minerals and Energy [27]

In the foreword to the March 2005 Energy Efficiency Strategy of the Republic of South Africa, the former Minister of Mineral and Energy and current vice-president, Phumzile Mlambo-Ngcuka states [27]:

"In South Africa we take energy for granted, with the consequence that our energy consumption is higher than it should be.

Whilst our historically low electricity price has contributed towards a competitive position, it has also meant that there has been little incentive to save electricity. So in many respects we start with a clean slate with little energy efficiency measures having taken place, apart from many years of work by universities and other research institutions that have pointed the way.

The White Paper on Energy Policy (1998) recognized that standards and appliance labelling should be the first measures to put in place in implementing energy efficiency. Indeed such perspective-type measures provide the framework on which energy efficiency strategy is based.

At the same time consumers of energy also need to perceive the cost benefits they can derive from energy savings measures and it is here that demonstrations are essential. The Industrial and Mining Sector are the heaviest users of energy, accounting for more than two-thirds of our national electricity usage. Here lies the potential for the largest savings by replacing old technologies with new, and employing best energy management principles."

Existing programs and technologies used to realise DSM potential

DSM is realised through implementation of activities to influence the time - pattern and electricity usage in such a way that it produces a change in the electricity load profile of the industry, while still maintaining consumer satisfaction [28]. This will assist the supply utilities to reduce or shift electricity peaks and therefore reduce the cost of generation.

Existing programs and technologies can be categorised into the two legs of DSM namely load management and energy efficiency. Some of the programs and technologies are specific to a DSM leg and some are overlapping. First the differences between the two DSM legs are discussed.

Energy Efficiency (EE)

EE is a term used in the DSM field for the efficient use of electrical energy. It is said that energy conserved is energy generated. Energy conservation and efficiency measures are the best alternative energy sources. Figure 1-6 (left) shows DSM through increasing energy efficiency (EE). This implies that less energy will be consumed and therefore the area under the load curve will decrease.

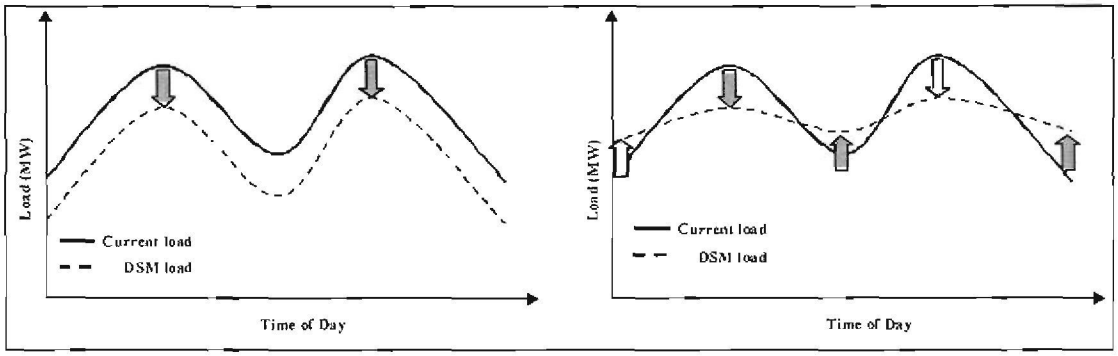


Figure 1-6: Illustrations of energy efficiency and load management.

There are various opportunities and techniques available for reducing electricity consumption such as efficient lighting, variable speed drives, solar hot water systems, etc. These technologies reduce demand, help in lowering high peak prices and also reduce greenhouse gas emissions due to less stress on generating plants.

Investing in energy efficiency is often cheaper, cleaner, safer, faster, more reliable, and more secure than investing in new supply [21]. In addition to reducing the need to construct new generation, transmission and distribution facilities, improving efficiency also reduces maintenance and equipment replacement costs, as many efficient industrial technologies have longer lifetimes than their less efficient counterparts.

Relying on efficiency also avoids a number of costly risks associated with generation, such as lack of demand, cost overruns, interest rate risk, volatile fuel costs, technological obsolescence, catastrophic failure and political and national security risks. Retrofitting motors and pumps, adding insulation to buildings, or even changing a light bulb takes much less time than constructing a new power plant [18].

Load management (LM)

LM programs involve reducing loads on a utility's system during periods of peak power consumption or allowing customers to reduce electricity use in response to price signals. Figure 1-6 (right) depicts DSM through load shifting / clipping.

This implies that by optimised planning (scheduling) the electricity usage is moved to some of the lower demand periods which will decrease peak demands.

It is very important to note that with load management the electricity load is moved, and not reduced. Therefore, the area under the electrical load profile will remain the same. Load management programs use mechanisms like interruptable load tariffs, time-of-use rates, real-time pricing, direct load control and voluntary demand response programs.

Although load management programs are largely short-term responses, it has a major impact on the reduction of peak load, which in turn helps to reduce utility operational costs as well as lower electricity rates. Load management also extends the point at which when new power generation utilities will be necessary due to increasing demand. Therefore it buys valuable time for new power stations to be built.

Load management also reduces the customer's electricity bill (because electricity usage is reduced during expensive peak periods). Using the example of a gold mine the cost per ton gold produced or ton reef mined is reduced, making such projects attractive because of its quick implementation potential.

Regulatory programs

DSM programs can increase compliance with regulatory programs such as new building or appliance standards, by helping consumers bear the costs. These programs can also help develop the market for efficient (DSM) technologies more quickly, demonstrate the feasibility of tightening existing efficiency standards, and initiate next-generation DSM measures once the current generation has been broadly commercialised and is understood [29].

For example, refrigerators were the largest residential user of electricity in 1972 in the United States, but their energy consumption declined fourfold over the next 30 years as a result of policy, at the same time the size and features were increasing and the price to the consumer decreased in real dollars. Much of the momentum for this improvement came from regulatory DSM programs [30].

Another example is energy efficient lights in South Africa. The compact fluorescent lamps (CFLs) were originally priced between R60 and R80 per lamp and in 2004 the price was dropped to between R13 and R20 [31]. This was possible because of a jointly funded programme between the Global Environmental Facility and Eskom.

In South Africa the Department of Mineral and Energy (DME) has outlined the following targets [27]:

- Nationally – final energy demand reduction of 12% by 2015;
- Industry and Mining sector – final energy demand reduction of 15% by 2015.

Electricity tariffs

In many cases, load management can be encouraged with properly designed and progressive tariffs, such as time of use and interruptable tariffs. These tariffs work on the "supply and demand"- concept. During a 24 hour profile, the electricity price is high when the demand is high and low when the demand is low. Some tariff structures also vary seasonally if the demand is higher during certain seasons of the year.

To improve load management, suppliers must further expand the price differential between the peak and valley hour tariffs in order to encourage load shifting. This means greater electricity cost savings for those clients that participate in load management and higher electricity costs for those clients that still use high electricity load during the peak times.

In South Africa the MegaFlex tariff structure is available to electricity intensive industrial clients. The price difference in high demand season (winter) between peak and off–peak times differ almost 7 times, and between high demand season peak and low demand season peak 3.5 times [32].

Energy Services Companies (ESCos)

Experience in a number of countries, including the United States, New Zealand, Chile and Argentina, indicates that neither a restructured electricity sector nor the market itself will automatically deliver energy efficiency. In fact, DSM will generally be a casualty of restructuring unless active steps are taken to include it [19].

When the United Kingdom began to restructure its electric industry, for example, no special provisions were made for energy efficiency or DSM. It was assumed that market forces would meet demands for energy efficiency measures as they arose. Experience proved otherwise, and three years later the United Kingdom established an independent Energy Saving Trust (EST) which, with the help of ESCos, realised DSM targets [33].

Energy Service Companies (ESCos) are private companies which help to realise DSM goals. Normally they operate in a three way partnership between themselves, the electricity supplier or regulatory body responsible for DSM and the electricity consumer [34]. They make use of DSM programs, technologies and optimisation packages to determine and realise DSM results at the electricity consumer.

In South Africa, an ESCo will typically approach a client and offer to carry out a no-cost energy survey to determine whether a DSM project is feasible. If the survey has positive results, the ESCo will draw up a project proposal, which will indicate clearly the DSM results to be delivered as well as the turnkey cost of the project.

The proposal is submitted to the electricity supplier, or regulatory body responsible for DSM and they determine if funds will be made available to the ESCo to implement the project and deliver the proposed DSM targets. The roles of ESCos prove to be successful. Currently the ESCo industry in North America facilitates $2-billion annual investment in energy efficiency [35].

Yet experience in other countries has shown that while the ESCo industry provides a very valuable role in delivering DSM results to large industrial and commercial markets, it has been less successful in serving other market segments, particularly residential and small commercial and industrial customers.

In market segments where ESCos have been most successful, DSM funding programs have played a major role in creating and supporting the ESCo industry, and continue to do so today [36].

The Department of Minerals and Energy stated in its Draft Energy Efficiency Strategy that [37]:

"It is accepted that the ESCo model does have an important role to play in the delivery of energy management services in South Africa. Indeed Eskom's own Demand Side Management programme uses the ESCo concept as its key delivery mechanism. There is, therefore, merit in supporting and strengthening this service delivery mode given the potential to achieve energy savings at minimum cost to the Fiscus."

On reflection, it is clear that Eskom's EE-DSM programme has no hope of succeeding without the existence of a strong ESCo industry to make it happen.

THE CURRENT ESKOM DSM PROGRAM IN SOUTH AFRICA

South Africa is in a fortunate position where it can learn from over thirty years of experience of developed markets. We are still faced with the challenge of tailor-making an initiative for our unique environment.

DSM is implemented through collaboration with the Department of Minerals and Energy (DME) and the National Electricity Regulator of South Africa (NERSA).

It also includes the DME's White Paper on Energy Policy, the department's Energy Efficiency Strategy and NERSA's Energy Efficiency and Demand Side Management Policy.

The White Paper identifies energy efficiency as one of the areas that needs to be developed and promoted whilst NERSA is mandated to ensure the installation of sufficient generation capacity to meet the needs of future electricity demand [26].

In South Africa Eskom's DSM strategy comprises a dual approach: to reduce electricity demand at peak periods (07:00-10:00 and 18:00-20:00) by shifting load to off-peak periods and by overall electricity consumption reduction (24-hour reduction) by installing energy efficient equipment and optimising industrial processes.

Sustainable DSM projects often involve a combination of both methods. The frameworks of DSM supporting mechanisms that have already been established in South Africa include:

- Integrated energy planning (IEP) with DSM as part of the integrated energy supply portfolio;
- Government support to drive DSM and EE (energy efficiency) from a national benefit perspective, irrespective of the industry structure, in particular through periods of industry transformation;
- Clear legal framework to regulate, promote and enforce DSM implementation, clarify roles of variable stakeholders, set targets, determine technology requirements and provide environmental conservation legislation, among other things;
- Introduction of a policy framework for guiding and promoting efficient technology use and appliance labelling, and enabling spot trading;
- A viable funding mechanism for overcoming disincentives to utilities for implementing DSM;
- Agreement on set price structures that convey to consumers the implications of the timing of energy consumption;
- Establishment of 106 Energy Services Companies (ESCos) to effectively realise DSM [14];
- Ongoing education and awareness campaigns to maintain public participation and market transformation, among other things;
- Research and development focusing on the successful application of technologies and programmes within the South African context; and

- Independent monitoring and evaluation to assess and evaluate sustainability and influence informed decision-making for the future.

DSM activities

The DSM programme includes the following various programme themes:

- Residential, commercial and industrial programmes: The main objective of this programme is to transform the South African electricity market into creating an energy efficiency industry;
- Public education: The primary objective of this programme is to increase awareness about energy efficiency. The programme includes a broad range of marketing and public relations activities, and feeds directly into programmes in different income segments as well as residential, commercial, industrial and institutional programme activities; and
- Schools' programme: The objective of this programme is to highlight the benefits and importance of using electricity efficiently, to learners. DSM seeks to increase the awareness of learners and faculties on energy efficient measures through providing participating institutions with resources packs, including teacher and learners and electricity audit guides.

DSM benefits

- Reduced electricity demand during peak periods, thus delaying additional capital investment to further increase electricity supply;
- Improved value of electricity service to customers by reducing costs - customers have a wide range of energy efficient options and financial benefits;
- Conservation of the environment by reducing emissions and water consumption at power stations; and
- Support of macro-economic development through job creation and improved productivity.

DSM funding

In South Africa the DSM profitable partnership programme offers financial assistance for approved projects:

- For viable load management projects; designed to shift electricity consumption to off peak periods in order to reduce peak loads; Eskom funds all capital expenditures. One can see why these kinds of projects are attractive to consumers and ESCos; and
- For viable energy efficiency projects; designed to make businesses and buildings more electricity efficient and reduce electricity consumption; Eskom will make a 50% contribution towards the project implementation cost.

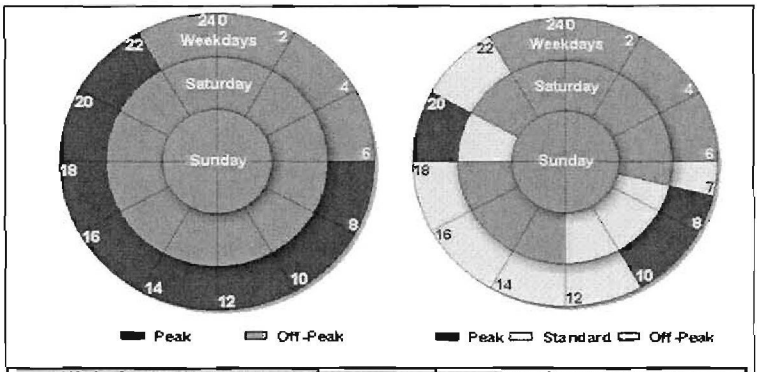
Eskom's time of use tariffs [32]

Eskom currently supplies the cheapest electricity in the world [38].

For large electricity consumers they provide alternative pricing structures. The five main tariffs available to them are NightSave, MegaFlex, MiniFlex, RuraFlex and Wholesale Electricity Pricing (WEP). WEP is still in a testing phase at various pilot sites.

MegaFlex is more suitable for large consumers that need a supply of 1MVA and above. The TOU period is exactly the same as MiniFlex as shown in Figure 1-7 (right). This is ideal for large consumers capable of shifting load for long periods (4 to 5 hours per day). The only disadvantage is that this tariff is very rigid with little room for innovative scheduling.

Most of the mines in South Africa make use of the MegaFlex tariff structure.



High-demand season (June - August)		Low-demand season (September - May)
49,69c + VAT = 56,65c/kWh	Peak	14,10 + VAT = 16,07c/kWh
13,14c + VAT = 14,98c/kWh	Standard	8,75c + VAT = 9,98c/kWh
7,15c + VAT = 8,15c/kWh	Off-peak	6,20c + VAT = 7,07c/kWh

Figure 1-7: Time-of-use for NightSave (left) and MiniFlex, RuraFlex and MegaFlex (right).

DSM targets and results

Eskom has set an annual target of 153MW load shift out of the evening peak period since 2003 [13]. Thus, at the end of 2005 the accumulated target load to be shifted was 612MW. The aim over the next 20 years is to save an accumulative total of 4255MW, representing the capacity of one six-pack coal-fired power station [14].

Measurement and Verification (M&V), the independent monitoring and evaluation team for Eskom DSM projects, has indicated that an accumulated total load of 181MW would be shifted at the end of 2005. This means that since 2003 the Eskom DSM programme only achieved 30% of the targeted 612MW. These results are shown in Figure 1-8 [39].

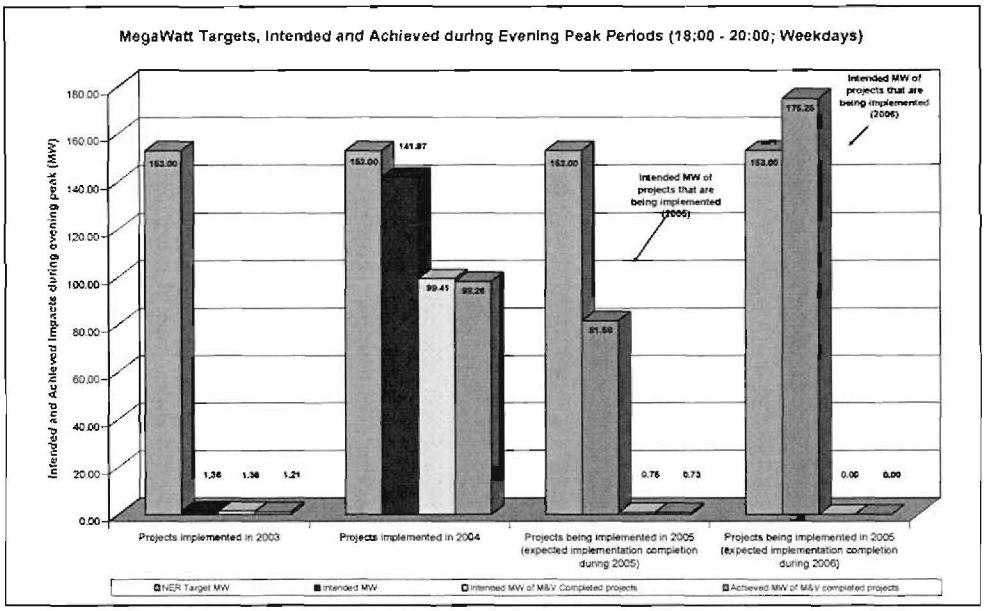


Figure 1-8: Eskom DSM target and results since 2003.

1.3. DSM IN THE SOUTH AFRICAN MINING INDUSTRY

SOUTH AFRICA'S ELECTRICITY ECONOMY AND THE MINING INDUSTRY

The discovery of diamonds and gold towards the end of the 19th century fundamentally changed the history of the South African economy and began the long dominance of mining in the industry. South Africa has vast mineral wealth, including the world's largest reserves of gold, chromium, manganese, platinum, titanium and vanadium, and huge amounts of copper, iron ore, lead, silver, fluorspar, uranium and coal [40].

The mining sector as a whole used 18% of South Africa's electrical energy in 2003 [14]. Deep level mines (mostly gold and platinum mines) accounted for 15% of all electrical energy consumed in 2003 [41]. Thus, total electrical energy for gold and platinum mines was 28,559GWh in 2003. Mainly electricity is used for hoisting, milling, cooling, pumping and ventilation.

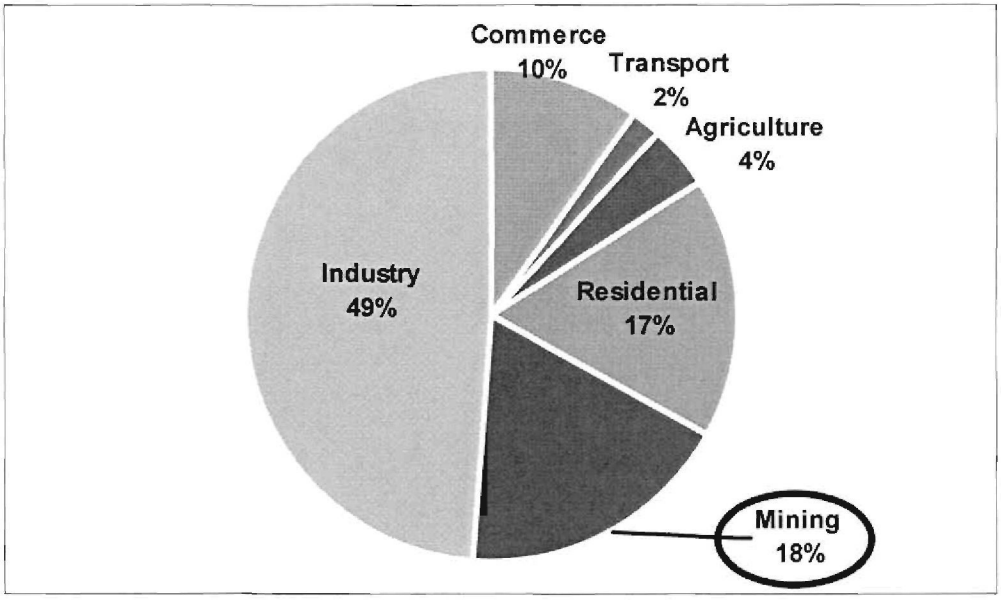


Figure 1-9: Electricity consumption by sector with total 190 396 GWh, (2003 data).

In 2005, the mining and quarrying sector contributed R94.3-billion (US$14,8-billion) or 7% to Gross Value Added, an increase of R6.83-billion or 7.8% over the previous year's Gross Value Added, and 6.1% or R15.9-billion to Total Fixed Capital Formation, some 11% percent below the contribution to Total Fixed Capital Formation in 2004 [42].

Although total primary mineral sales earnings increased an impressive 14.1% year-on-year, their contribution to total South African export revenue increased only marginally to 29.3% from 28.7% in 2004. The contribution of gold to total annual primary mineral export sales value, decreased to 18.6% in 2005, from 23.7% in 2004 [42].

Gold was South Africa's top mineral earner in 2003, but slipped into second place behind platinum-group metals in 2004. Platinum-group metals consolidated their position as the main contributor to South African primary mineral sales revenue in 2005, accounting for 26.9% of total mineral sales, followed by coal with 24.9%, with gold in third place [42].

During 2005, the mining industry employed 2.6% of South Africa's economically active population, or 5.1% of all workers in the non-agricultural, formal sectors of the economy.

The average number of workers employed in the mining industry decreased by 5,609, or 1.3%, from 448,909 in 2004 [42].

Gold is however by far the biggest electrical energy user in mining. Although the tonnage of South African gold production is decreasing, the energy needed for each ton of gold is increasing.

This is because the gold mines are becoming deeper and deeper, needing more energy for pumping, cooling, lifting and transporting. As the gold content in the ore decreases, more tons of ore have to be mined, lifted and processed for each ton of gold recovered, and this uses more electricity [40].

The total amount of electricity used for mining gold increased from 1967 to 1988 and after that declined slightly. The electricity used in gold mining as a percentage of the electricity used in all mining declined from 88% in 1967 to 67% in 1995. Since then it has declined further. However, it still uses more electricity than all other mining activities put together [41].

South Africa has an abundance of mineral reserves for which there will be international demand, and nearly 80% of earnings from minerals come from exports. In the special case of gold, production is likely to decline, but with increasing depths and poorer ores the energy demand will remain the same or increase.

The one possibility that could change the future for gold mining is ultra-deep mining, to depths down to 5000m, which could once again extract almost as much gold as has been mined in the past [43]. This is only likely to happen with a large and sustained increase in the price of gold.

DSM TECHNOLOGIES IN THE MINING INDUSTRY

Many mines make use of ventilation systems, refrigeration plants and underground pumping systems.

These can typically contribute approximately 25% of the electricity used in underground mines [44]. The industrial sector contributes 52% to Eskom's peak demand and the contribution of refrigeration approximately 3 to 4% [14].

This means that mine refrigeration systems alone contribute approximately 600MW to the 34,000MW electricity peak in South Africa [44]. A case study by Lane in 1996 on a typical deep mine in South Africa showed that a 27% reduction in coincident system peak demand could be achieved by using optimised scheduling of energy systems [44].

Figure 1-10 lists the processes in the industrial sector and their contribution to Eskom's peak demand.

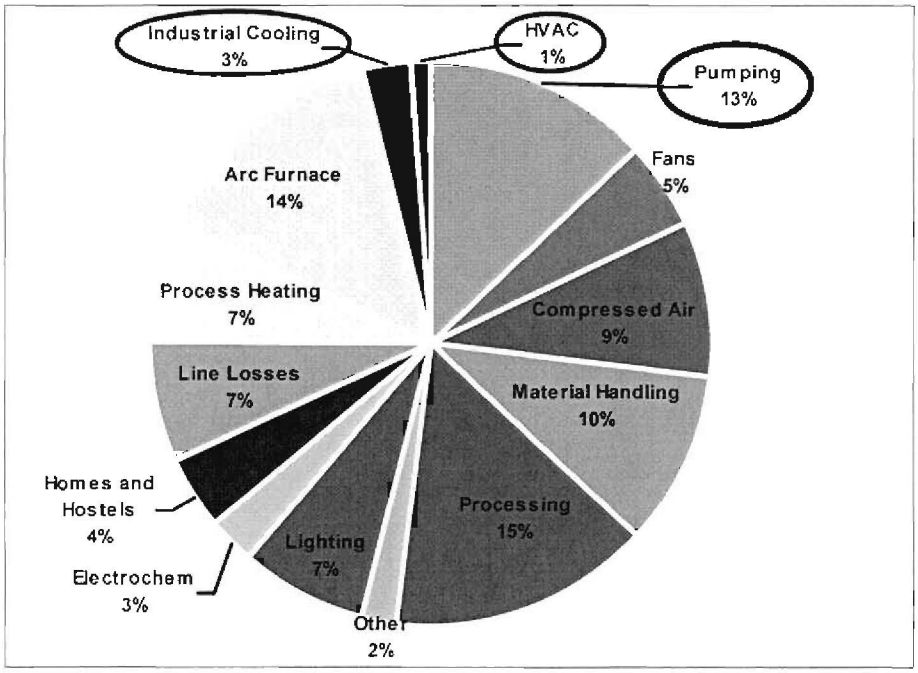


Figure 1-10: Contribution in the industrial sector to Eskom's peak demand, (2003 data).

It seems that most of the ESCo industry in South Africa involved in the mining industry and focussing on large energy users, focuses on load shifting possibilities in mine pumping systems.

DSM in mine pumping systems

Clear water pumping systems can usually be well controlled with storage built into the entire system through the use of dams. Therefore these systems offer an ideal business opportunity if they can be utilised correctly. Load shift on clear water pumping systems can be realised without influencing the mining operations, because the pumping of water is not directly coupled to the production of the mine.

The excess water from mining operations in the surrounding area, as well as the ground water underground is caught-up in dams. Normally, this hot water is cleaned, pumped out to surface and cooled, to be used again in underground mining operations. Thus, a continuous water cycle from shaft bottom to surface, back to shaft bottom again exists throughout the day.

Many mines are not fully aware of opportunities available on their systems and the possible benefits to them with regard to the Demand Side Management (DSM) program. By optimising mining systems according to Eskom's TOU tariffs, huge electricity cost savings can be realised through load management.

Underground dams which are part of the clear water pumping system can be used cleverly as storage capacity in order to realise DSM (load shift) during peak periods of the day. This is almost similar to pumped storage systems used in Supply Side Management (SSM). A good example of this is the Drakensberg and Palmiet pump storage schemes.

If the dams in clear water pump systems can be used to store the continuous incoming water during Eskom's peak periods, electrical intensive pumps can be switched off. Then, after peak period, the pumps can be started up and the stored water will be pumped out to attain the water balance in the mine.

The use of the electrical pumps outside Eskom's peak period results in peak load reduction. Because the electricity tariff is lower in off peak periods, the mine realises electricity cost savings through rescheduling their pumps out of peak times. Thus, the mine uses more, cheap, off peak electricity and less, expensive, peak electricity.

The capacity of the dam and the flow rate into the dam determine how long the pumps can remain switched off. Higher dam levels on shaft bottom also mean higher risk for the mine (risk of a pump failing to start with the dam already at a high level). Because the clear water system is a complex system with many variables, mine managers will not stop pumps during peak times.

Technologies available to realise peak load reduction in pumping systems

A good example of a company that provides a system for automated energy metering and reporting in the mining environment is *IST Otokon (Pty) Ltd* in South Africa [45]. The *IST Otokon* system does remote energy metering via a data collection network. A user can access the data with their *ecWin*^{TM} software.

The system is used to:

- Reconcile the readings from the various energy meters of the installation with the reading of the utility that supplies the energy;
- Allocate energy costs to sub-sections of an installation;
- Identify billing problems;
- Identify overall trends; and
- Warn users of peak prices.

The *IST Otokon* system only does energy metering in the mining industry and does not perform simulation, optimisation and realisation of electrical load shift. Recently they have extended the metering system to control the pumping system of Midvaal Water Company to reduce the peaking energy used [46].

Midvaal supplies portable water to municipalities and has large reservoirs and pumps that serve an area of about 900km² [47]. *IST Otokon* has not implemented a load management system on a clear water pump system in the mining industry.

Another company that claims to do load management on clear water pump systems in mines is *National Power Contractors cc* [48]. However, their approach is to implement the optimised control software inside the PLC of each pump station.

Available software to realise DSM potential in mine pumping systems

The first software system for the optimisation of water distribution systems is *H20NET Scheduler* [49]. This system is part of a larger suite of programs that are used by several water utilities to analyse and optimise the design and operation of residential water distribution systems.

The specific aim of *H20NET Scheduler* is to optimise daily pump operations (daily pump scheduling) for maximum performance and energy savings. The program uses generic algorithms to determine the lowest energy cost on a daily basis. It also takes hydraulic operational constraints into account like pressure, velocity, head loss and desired tank trajectory curves.

A second system is *MISER-PS* [50]. It is used for the derivation of least-cost pumping schedules for optimisation of energy usage and the exploitation of electricity tariff structures. It is used to plan day-to-day system operation, to identify emergency responses to failures and for tariff management, with the potential for on-line pump scheduling to deliver further cost-savings.

A third system is *Derceto 3.0* by *Beca Technologies* of New Zealand [51]. *Derceto* optimises pump schedules to minimise distribution costs of large water distribution networks. On-line data collection allows *Derceto* to choose the lowest cost source of water. By predicting future consumption, it calculates the thousands of possible pump schedule combinations to meet the day's evolving demand, in real-time.

A fourth system is *PumpView* by *MultiTrode Industrial Solutions* [52]. This system is a web-based pump station management system that provides control and monitoring of a network of water and wastewater pump stations. Similar to most systems it was specifically designed for municipality pump stations.

TEMM International has developed an Energy Management System (EMS) that was implemented on Kopanang mine [53]. This system was a "one-off" system, specifically developed for the clear water pumping system of Kopanang mine.

DSM in mine refrigeration systems

Some ESCos focus on installing additional refrigeration equipment to establish a DSM potential in these systems, e.g. ice storage. These systems are expensive and maintenance intensive (more detail is given in Chapter 2).

The previous section showed various control systems available to realise DSM potential (specifically load shifting) on pumping systems. In theory the same control strategy used for DSM purposes in pumping systems, namely water storage, can be applied to refrigeration systems (chilled water storage in the case of refrigeration systems).

As for pumping systems, a detailed integrated dynamic, simulation and control system is needed to realise DSM control strategies in refrigeration systems to ensure that constraints are adhered to. In the case of refrigeration systems no deviation from normal chilled water temperature or flow rate is allowed.

1.4. DEEP MINE REFRIGERATION

TYPICAL MINE VENTILATION AND COOLING SYSTEM

Most mines use relatively standard ventilation and cooling layouts (see Figure 1-11). A conventional way of cooling the intake air is by placing bulk air coolers (BACs) at the intake or down shaft. This is satisfactory for mines that are not too deep. When the mine becomes too deep, the air speed needed to convey the cold air to the stopes becomes too fast and uncomfortable.

For most mines these layouts consist of a surface cooling plant and an underground plant. The underground plant is typically between 1000m and 2000m below the surface. The surface plant contains the chillers or icemakers, water storage dams and cooling towers. The underground plant consists of a thermal storage dam and cooling coils or spray chambers.

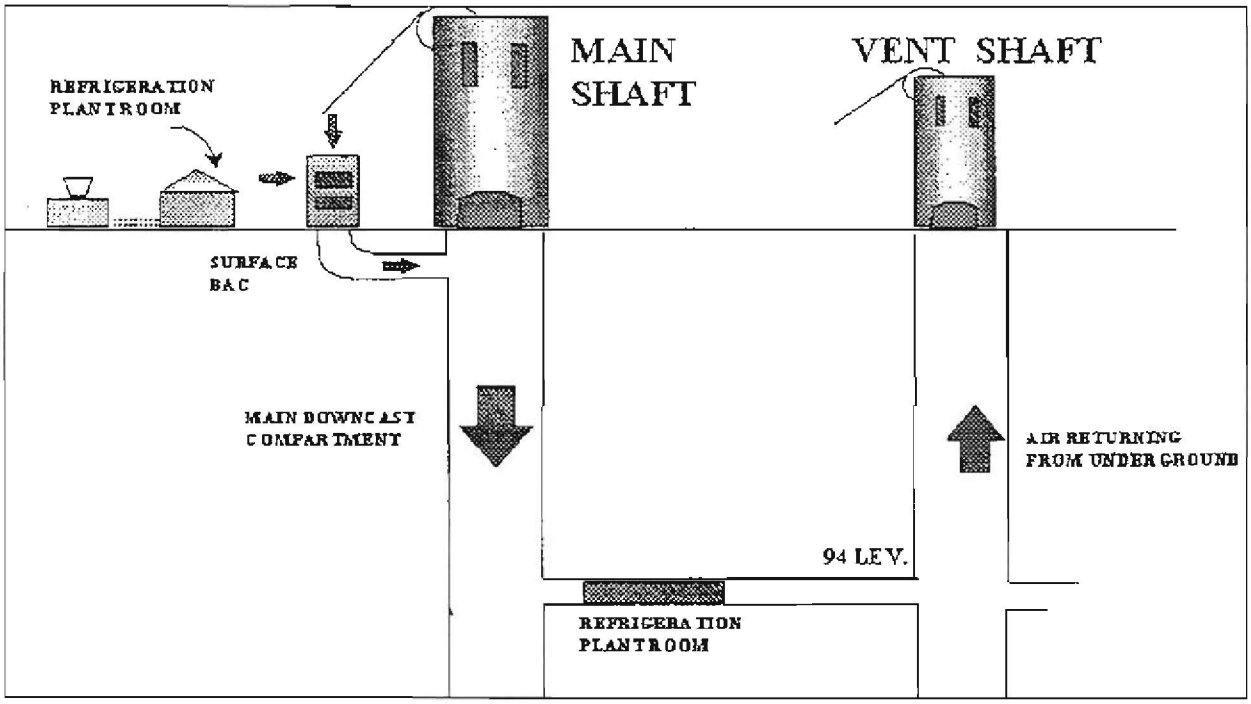


Figure 1-11: Typical layout of a mine's ventilation and cooling system.

If extra cooling is needed a further cooling plant or mobile plant can be installed below the surface. The warm intake air, heated by internal loads and the virgin rock, passes through the cooling coils or the chambers. Extraction fans, placed in the return airways, extract the warm air. Producing satisfactory cooling and ventilation for deep mines is a precise and necessary task.

THE NEED FOR UNDERGROUND COOLING

The exploitation of the reef body was initially achieved by developing footwall inclines from surface outcrops. These inclines were later replaced by first-generation vertical shafts and finally by second-generation shafts. Later, sub-inclines or sub-shafts [54] augmented the inclines.

Virgin rock temperature

Naturally, with the increase in depth, there is a correlated increase in the VRT (virgin rock temperature) [55]. The correlation between depth below surface and VRT can be seen in Figure 1-12 (also showing the effect of the specific strata).

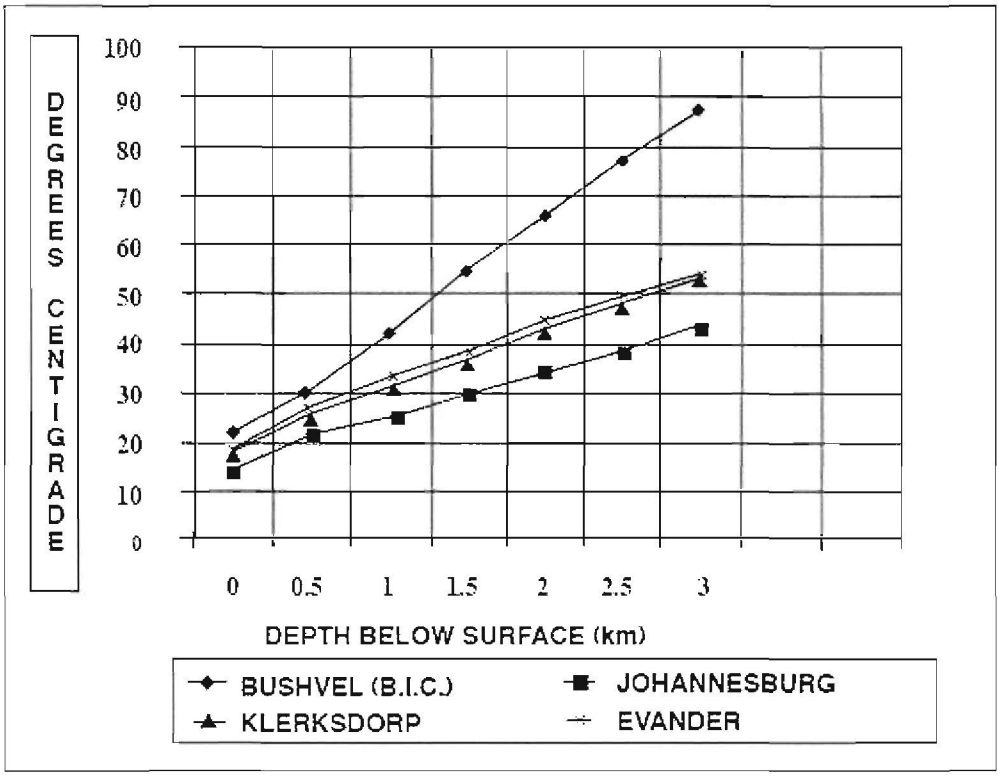


Figure 1-12: Virgin rock temperatures [55].

The challenges presented by the gradual increase in average working depths are especially significant in the area of mine environmental control. The single dominant challenge in this context is the heat problem, which is aggravated at depth, mostly, but not exclusively, due to the increased virgin rock temperatures.

The ultimate future of mining at great depth will increasingly depend on the industry's ability to contend, in an acceptable and cost-effective manner, with the environmental control problems related to the provision of satisfactory ventilation and cooling [56].

Human Tolerances

Humans possess a well-developed perspiration mechanism and our skin is practically devoid of insulative hair. In addition, our thermoregulatory system has a greater reserve of heat elimination than of heat conservation capacity. These facts indicate that hot conditions present a greater threat to us than cold conditions [57].

Air-cooling and ventilation are needed in deep underground mines to minimise the stress associated with heat [58], [59]. One of the primary aetiologies of heat stroke is excessive environmental heat loads [60].

Table 1-3 summarises actions required for different ranges of temperature exposure within the underground environment.

Temperature Range	Interpretation	Action
wb > 32.5°C db > 37.0°C	Unacceptable risk of heat disorders for routine work	No routine work allowed
25°C < wb < 32.5°C db < 37.0°C	Environment conducive heat disorders	Routine work may take place if a mandatory Heat Stress Management system is in place

Table 1-3: Actions required at various temperatures [57].

The general conclusion with regard to the management of heat stress is that there is no precedent that dictates a uniform approach to the problem [57]. The absolute solution however would be to cool the underground environment to below 27.5°C wet bulb.

Studies have revealed that at low heat stress levels behavioural changes, such as depression, aggression, irritability and other psychological problems occur. This results in a loss of concentration, and a decrease in efficiency in both mental and skilled tasks.

At mild to moderate heat stress, the Index of Heat Stress includes "subtle to substantial decrements" involving intellectual input, dexterity and alertness. At higher levels of heat stress, the impact appears to become physiological in nature. A progressive decrease in physical working capacity and ultimately the development of heat disorders are apparent [57].

Of importance is that heat stress adversely affects mental performance much sooner than any deterioration in physical working capacity. A large number of observations made by the Human Sciences Laboratory of the Chamber of Mines of South Africa have resulted in two graphs that clearly indicate that the thermal environment is directly linked to productivity and health and safety [61], [57].

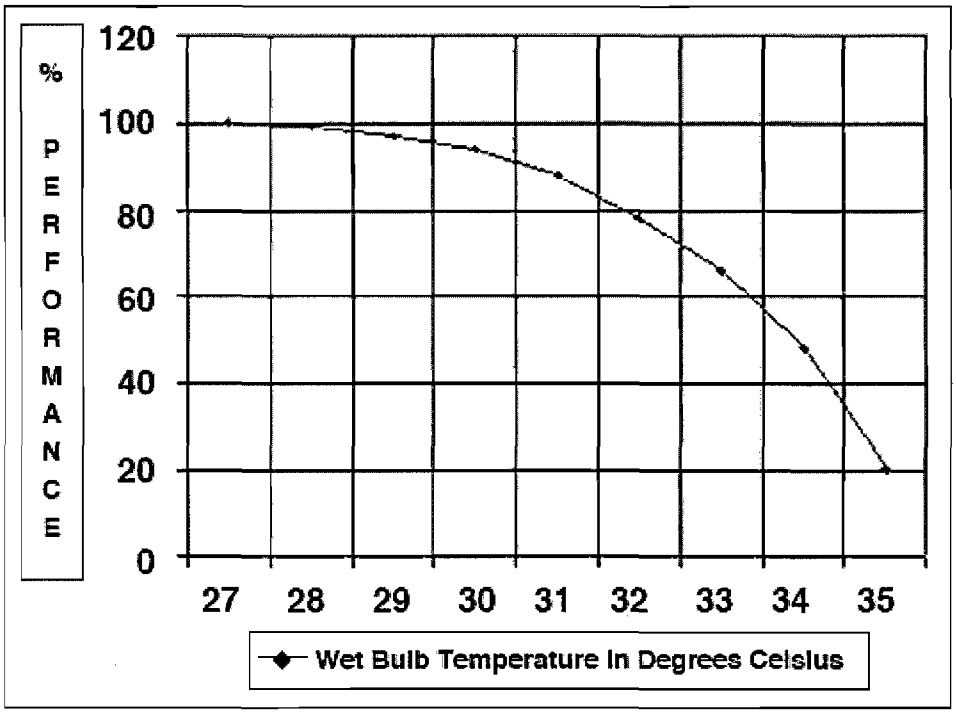


Figure 1-13: Changes in production rate [62].

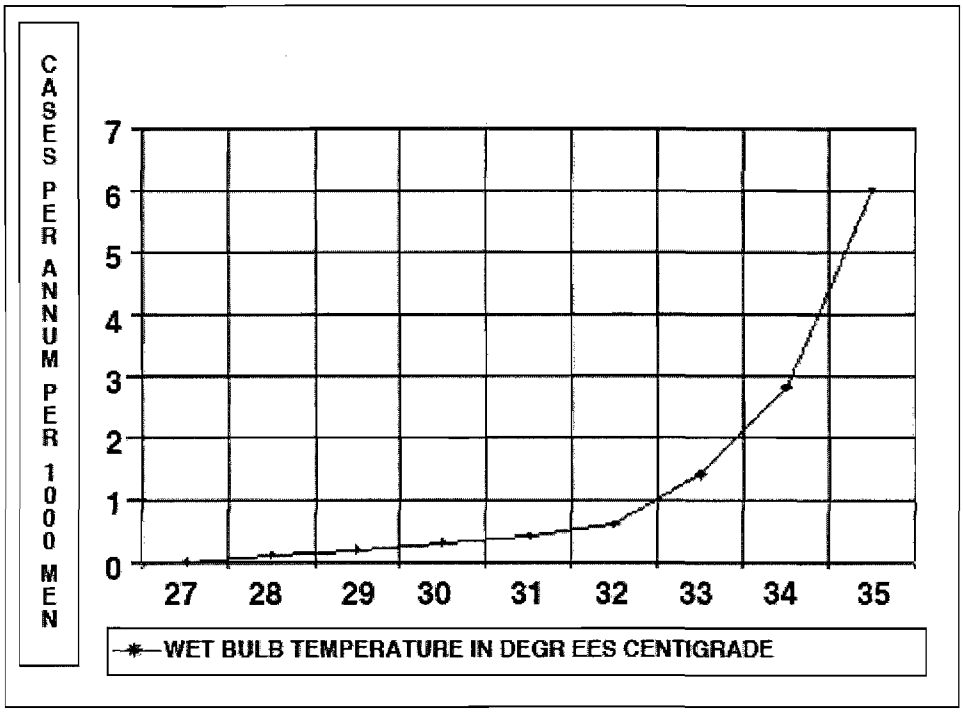


Figure 1-14: Estimated heat stroke risk [62].

1.5. NEED FOR THIS STUDY

From the information provided in this chapter, the need for this study can be summarised as follows:

- The peak power demand in South Africa will exceed the available generation capacity by 2007;
- Eskom is addressing this problem by the implementation of a DSM programme. The DSM programme has, however, only reached 30 % of its targets by the end of 2005;
- Currently load shift projects are funded 100% by Eskom – this makes these kinds of projects really attractive to consumers and ESCos. It makes sense to target load shift projects as the proverbial "low hanging fruit" of possible DSM projects;
- Deep level mines account for 15% of all annual electrical energy consumed. It makes sense to focus on this industry to investigate DSM opportunities;
- Most deep level mines make use of ventilation systems, refrigeration plants and underground pumping systems. These systems typically contribute in the order of 25% of the electricity used in underground mines;

- The ESCo industry serving the South Africa mining industry has been focussing largely on applying DSM strategies in the pumping systems of mines (mainly load shifting strategies) and lighting projects;
- No examples of successfully implemented DSM (load shift) projects in the refrigeration systems of deep level mines could be found (largely because of mine ventilation professionals saying it could not be done);
- Some ESCo companies focus on installing additional refrigeration equipment to establish a DSM potential in these systems, e.g. ice storage;
- No examples could be found of DSM projects where the focus is on optimised control of existing systems. In theory the same DSM strategy (load shifting) applied to pumping systems; water storage, could be applied to refrigeration systems (chilled water storage in the case of refrigeration systems). This can however only be predicted through simulation;
- Compliance with active constraints for load shift projects in refrigeration systems is strict, i.e. no change in the supply temperature or flow rate of chilled water is allowed at any time. This means that production or underground ventilation requirements may not be influenced in any way. Novel control algorithms are needed to shift load from a refrigeration system without violating system constraints. None could be found in industry;
- No simulation software could be found to quantify DSM potential and demonstrate that constraints are adhered to; and
- For pumping systems, a detailed integrated dynamic, simulation and control system will be needed to realise DSM control strategies in these systems. No such systems could be found for the control of existing refrigeration systems for DSM purposes.

1.6. CONTRIBUTIONS OF THIS STUDY

The contributions of this study can be summarised as follows:

New DSM concept

- The energy cost saving concept of shifting electrical load of a mine refrigeration system through optimised control vs. installation of additional refrigeration capacity, is new;
- No one has ever attempted to shift load from a refrigeration system in this manner (partly due to the stringent constraints applicable to these systems) through existing system control regimes;
- Other companies (ESCos) in the mining industry focus on installing new equipment (which also uses electricity) to realise savings (e.g. ice storage systems);
- This study focussed on the automatic optimised control of existing equipment to realise savings. This makes it possible to identify more systems in industry on which these control strategies can be applied;
- The DSM concept proved in this study is much cheaper and faster to implement; and
- Refrigeration equipment is not replaced or added, current existing equipment is just controlled better or smarter.

Simplified integrated simulation model

- Existing mathematical models were simplified and incorporated into a new integrated plant simulation model. Such integrated models for refrigeration plants could not be found;
- Model parameters and inputs of this integrated model were simplified to enable fast and accurate simulation of refrigeration equipment and systems;
- The simulation model can predict system response to load shift control strategies and most importantly, test if active constraints (no change in temperature or flow rate of chilled water supply are allowed at any time) are adhered to; and

- This simulation model can be used to quantify load shift potential in mine refrigeration plants.

Control algorithms and a global control philosophy

- New control algorithms to realise DSM potential (specifically load shifting) in refrigeration systems were developed and were incorporated into the simulation model; and
- These algorithms were incorporated into a global DSM control philosophy to successfully establish load shifting in refrigeration systems.

DSM investigation methodology

- A DSM investigation method was developed to determine DSM potential in refrigeration systems.

Simplified and easy to use tools

- The new simplified model can be used by less skilled persons to simulate the equipment and chilled water cycle of any refrigeration plant;
- The global DSM control philosophy can be applied by less skilled persons to any refrigeration system;
- The new investigation protocol can be used by less skilled persons to determine a load shift potential in refrigeration systems;
- The simulation model and control algorithms were further simplified and developed into an investigation tool which can be used by less skilled persons; and
- The investigation tool can supply an accurate and fast investigation result.

Automated software control solution

- A new software solution (incorporating the new control algorithms and strategy) was developed to realise identified DSM potential in refrigeration systems in a fully automated and sustainable manner;
- The software system communicates with a mine SCADA system to automatically control the plant equipment;
- The software solution was implemented on case study mines to demonstrate its effectiveness;
- No commercially available automated software control solution to realise load shifting in refrigeration systems could be found;
- A fully automatic control solution was developed to realise the DSM opportunities in refrigeration systems; and
- Infrastructure requirements were identified for each case study mine and solutions designed to enable full automatic system control.

Added benefits of the new control solution

- Other companies (ESCos) attempt to save energy in refrigeration systems through increasing plant cooling capacities. This is normally done by the addition of ice making chillers, ice storage dams and complex reticulation systems. These add-on systems are not only expensive to install, but also expensive to maintain;
- The control solution proposed in this study controls existing equipment to ensure they operate within design and plant constraints; and
- The control system proposed in this study has the added benefit of offering a monitoring system. Through monitoring machine and system parameters, preventative maintenance opportunities and capabilities are added to the plant operation.

1.7. BRIEF OVERVIEW OF THIS THESIS

As far is possible, the chapters in this dissertation have been written so that they can be read independently of one another. Each has its own abstract, introduction, conclusion and list of references where required. This has the advantage of greatly enhancing readability. However, some repetition of important concepts may occur. A brief overview of each chapter is given below.

Chapter 1

The energy situation in South Africa is discussed. An overview of Demand Side Management is given, with current DSM applications in the South African mining industry. A brief overview of the need for refrigeration in deep level mines is also given.

Chapter 2

This chapter gives background to refrigeration systems and practices currently used in the mining industry. It discusses current energy saving options in refrigeration systems and gives an overview of the challenges of implementing load shift strategies in these systems.

Chapter 3

Commercially available simulation products are researched. The need for a generic simplified model to simulate refrigeration systems are discussed in this chapter. Verification results of simulation predictions are discussed. This simulation model is necessary to confirm that constraints are adhered to while load is being shifted from the plant's operation.

Chapter 4

The new control algorithms necessary to realise the load shift potential in the systems are discussed. The DSM control strategy is explained. The DSM investigation method is formalised in this chapter. DSM potential in various refrigeration systems is quantified. Necessary plant infrastructure is discussed.

Chapter 5

The development of a real-time energy management system for refrigeration systems and its end result; an integrated software solution, is shown. Business cases were identified and developed using the real-time energy management system as a platform. A cost analysis forms part of the business case exercise.

Chapter 6

Verification results of the real-time energy management system are shown in this chapter with the new control system actually implemented on four case study mines.

1.8. CONCLUSION

The energy challenge in South Africa has become a reality already in 2007. One of the initiatives to help manage this challenge, DSM, can be applied in industry. The mining industry has large energy sapping systems, which can be targeted for DSM strategies. Possible DSM potential exists in one of these systems; the refrigeration system.

To successfully realise any DSM potential in these systems a detailed integrated dynamic, simulation, investigation, and control system will be needed. This investigation and control system will have to be verified on actual case study mines to confirm its application possibilities.

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CHAPTER 2

BACKGROUND TO DEEP MINE REFRIGERATION

2. BACKGROUND TO DEEP MINE REFRIGERATION

2.1. PREAMBLE

Mine refrigeration requirements increase dramatically with underground depth. Large refrigeration plants (surface and sometimes underground) supply chilled water which is used to cool underground conditions. These plants typically utilize two refrigeration cycles: the vapour compression cycle and/or the absorption refrigeration cycle.

The primary source of mine cooling is by normal ventilation air. Temperatures have, however, increased due to the geothermal gradient, which increases with depth, as well as the auto-compression heat added per vertical meter of depth. This has resulted in the development of specific underground cooling strategies.

Chilled water from the refrigeration plants is reticulated through surface bulk air coolers, underground station bulk air coolers, crosscut coolers and in-stope coolers. Chilled water is also utilised as service water. Currently the only cost saving strategies employed in mine refrigeration systems are ice systems (although the main purpose of these systems in the mining industry is to add thermal energy to existing systems).

When refrigerator systems are located on surface the warm water has to be pumped back from underground, at great cost. One of the advantages of using ice sent down from surface to absorb the heat load is that the quantity of water to be pumped back out of the mine can be reduced to about a quarter of that for an all-water cooling system, thus giving cost savings. But these systems are very expensive to install and to maintain.

Refrigeration plays an important role in mine processes – but it comes at a price in the form of large electricity costs.

2.2. REFRIGERATION CYCLES

TYPES OF CHILLED WATER SUPPLY SYSTEMS

Vapour compression cycle

The majority of refrigeration systems are driven by a machine, which compresses and circulates refrigerant (typically R-22, R134-a, etc.) vapour in a sealed circuit [1], [2], [3], [4], [5]. Heat is absorbed and rejected through heat exchangers. These systems work on what is called a vapour compression cycle.

There are other types of cycles which can be used to obtain a cooling effect, such as absorption cycle systems, but these are not commonly used and are only economically viable where there are large supplies of waste heat.

Heat can only flow naturally from a hot to a colder body. In refrigeration systems the opposite must occur. This is achieved by using a substance called a refrigerant, which absorbs heat and hence boils or evaporates at a low pressure to form a gas.

This gas is then compressed to a higher pressure, such that it transfers the heat it has gained to ambient air or water and turns back into a liquid (condenses). In this way heat is absorbed, or removed, from a low temperature source and transferred to one at a higher temperature.

There are a number of factors, which make the operation of the vapour compression cycle possible:

- The temperature at which refrigerant boils varies with its pressure; the higher the pressure, the higher the boiling point;
- When refrigerant liquid boils, changing its state to a gas, it absorbs heat from its surroundings;

- Refrigerant can be changed back from a gas to a liquid by compression and cooling it, usually by using air or water to transfer the heat to.

Note: In the refrigeration industry the term evaporation is used instead of boiling. Also, if a gas is heated above its boiling point it is said to be superheated and if liquid is cooled below its condensing temperature it is sub-cooled.

To enable the refrigerant to be condensed it has to be compressed to a higher pressure, and it is at this point that energy has to be used to drive the machine that performs this task. The machine is called a compressor and it is usually driven by an electric motor.

The operation of a simple refrigeration system is shown in Figure 2-1. The diagram shows the refrigerant pressure (kPa) and its heat content (kJ/kg).

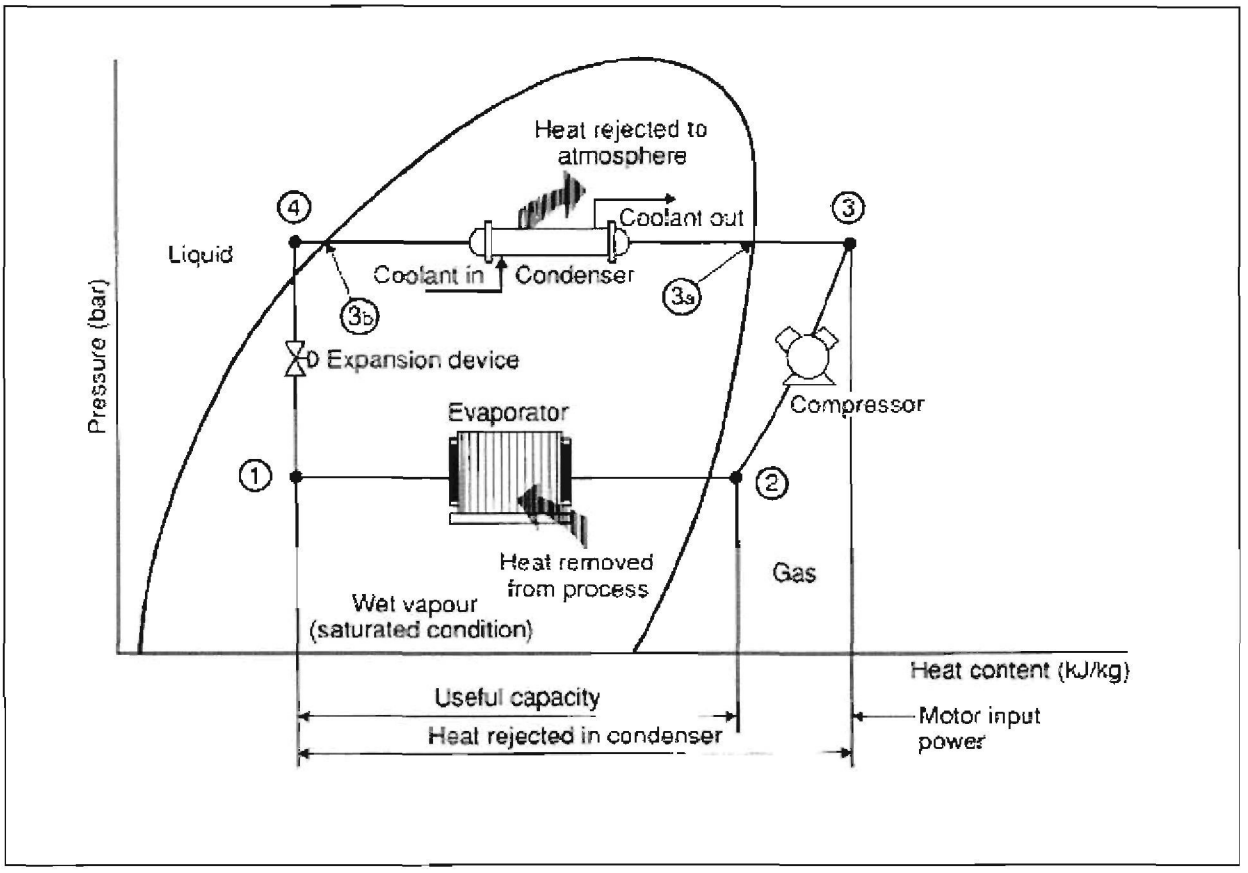


Figure 2-1: Single stage vapour compression circuit and pressure enthalpy diagram [5].

The refrigeration cycle can be broken down into the following stages:

1-2: Low pressure liquid refrigerant in the evaporator absorbs heat from its surroundings, usually air, water or some other process liquid. During this process it changes its state from a liquid to a gas, and at the evaporator exit the gas is slightly superheated.

2-3: The superheated vapour enters the compressor where its pressure is raised. A big increase in temperature will also occur because a portion of the compression energy is transferred to the refrigerant in the form of heat.

3-4: The high pressure superheated gas passes from the compressor into the condenser. The initial part of the cooling process (3 - 3a) de-superheats the gas before it is then turned back into liquid (3a - 3b). The cooling for this process is usually achieved by using air or water.

A further reduction in temperature happens in the pipe work and liquid receiver (3b - 4); so that the refrigerant liquid is sub-cooled as it enters the expansion device.

4-1: The high pressure sub-cooled liquid passes through the expansion device, which both reduces its temperature and pressure and controls the flow into the evaporator.

It is clear that the condenser has to be capable of rejecting the combined heat inputs of the evaporator and the compressor; i.e. (1 - 2) + (2 - 3) has to be the same as (3 - 4). There is no heat loss or gain through the expansion device.

Absorption refrigeration cycle

Ammonia is normally used as refrigerant in these types of systems and many mines make use of such systems. The ammonia absorption refrigeration cycle differs from the vapour-compression cycle in the manner in which compression is achieved [5], [6].

In the absorption cycle the low-pressure ammonia vapour is absorbed in water (sometimes oil is used, as is the case for one of the systems discussed in Chapter 4), and the liquid solution is pumped to a higher pressure by a liquid pump. The typical ammonia system layout is shown in Figure 2-2.

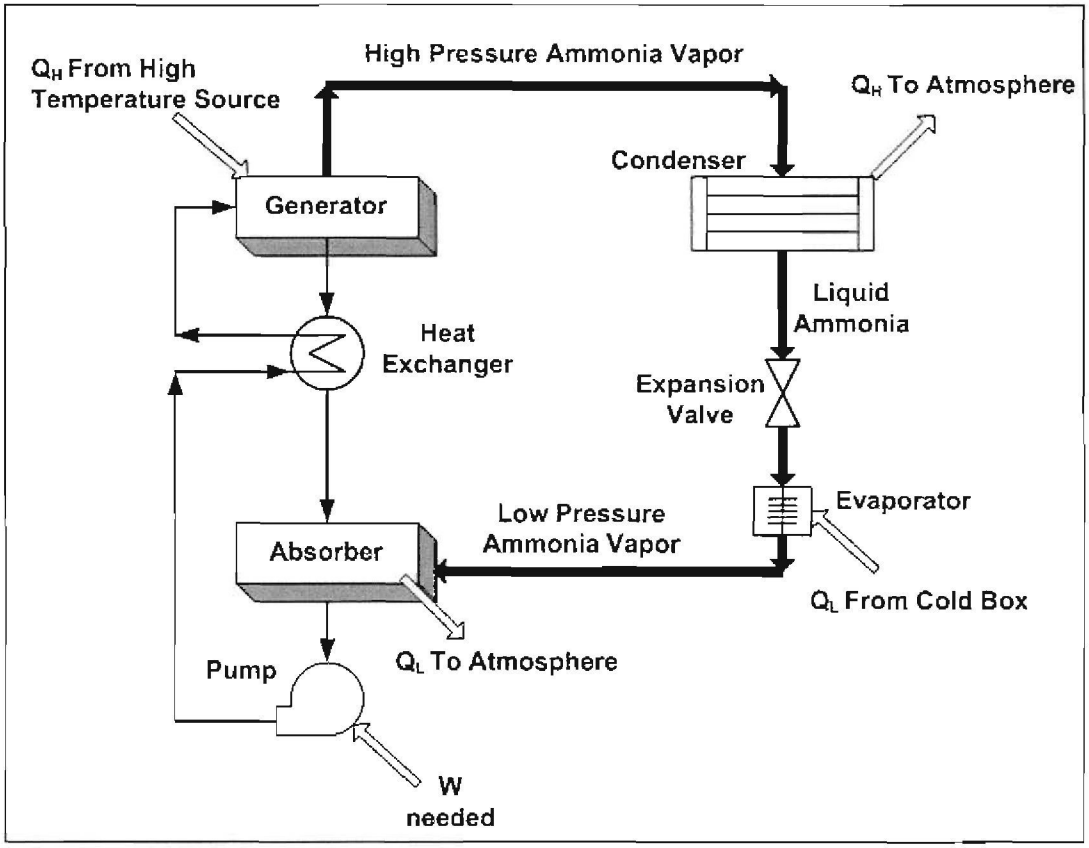


Figure 2-2: The typical ammonia absorption refrigeration cycle [6].

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. 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.

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. 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. In order to understand this refrigeration process better, the oil and ammonia circuits, as well as the major parts of an ammonia chiller are discussed in more detail.

- **Ammonia Circuit**

  Ammonia gas is drawn into the compressor from the surge drum by the two rotating rotors of the compressor, where it is compressed. During compression the gas is cooled by means of injecting oil.

  The discharge temperature is maintained by injection of liquid ammonia into the compressor chamber at a constant rate. The control valve on the liquid injection maintains the preset temperature. During certain operational conditions this valve is assisted by means of a solenoid valve which operates upon a rise in temperature.

  The discharge gas–oil mixture flows through the oil separator, where the oil is separated from the ammonia. The ammonia gas is condensed in the condenser and the liquid now continues to flow to the expansion valve (the liquid receiver acts as a surge vessel and assists in the maintaining of the liquid seals).

  From the expansion valve, the cold ammonia liquid (which has been cooled as a result of expansion i.e. pressure difference) flows to the surge drum where it is sprayed evenly over the surge drum area. This cold liquid ammonia is used to cool the mining water in the evaporator, causing the liquid ammonia to evaporate. The ammonia is collected in the surge drum and the cycle is completed.

- **Oil Circuit**

  Oil at discharge temperature is drawn from the oil separator by an oil pump. The oil is passed through an oil filter into the manifold, where it is fed to the bearings, balance piston, shaft seal, compression chamber, and hydraulic chamber. At the compression chamber, the oil is used to cool the ammonia gas; from there it is pumped to the oil separator.

  A small amount of oil is always carried over from the separator with the ammonia. This oil normally accumulates at the "cold" side of the system (usually in the surge drum); it is usually returned automatically to the hydraulic cylinder.

- **Compressor**

  The compressor is the heart of the refrigeration cycle. A positive displacement, capacity controlled oil flooded rotary screw machine is usually used for compression.

- **Electrical Motor**

  The compressor is directly coupled to an electrical motor. The motor is normally air cooled, and is fitted with a heat exhaust air ducting. The motor is also fitted with an anti-condensation heater.

- **Oil Separator**

  The oil separator vessel contains the lubricating oil, which will always be at discharge pressure. In the separator vessel the lubricating oil is separated from the hot high pressure ammonia gas. The initial separation is by means of impingement and directional change, where most of the large droplets of oil fall down into the oil reservoir. The gas mixture then flows through a knitted wire pack. The pack has an extensive wire surface area, with high free volume.

As the gas flows through the wire pack, small oil droplets form on the wires. Seeing that the density of the oil is much higher than that of the ammonia gas, only oil droplets will form. As the larger oil droplets form on the wires, it falls into the reservoir.

The remaining oil-gas mixture flows through the coalescer elements, where the remaining fine oil droplets are removed. The oil droplets are collected upstream of the coalescer elements and are returned to the suction of the compressor via a siphon line, control valve and sight glass.

To ensure that the ambient oil temperature is kept between 35°C and 40°C, the oil separator is equipped with a heater. The heater is controlled from the PLC, via the temperature element. A magnetic type level gauge is fitted to the oil separator tank in order to monitor the oil level and provide additional oil if necessary.

- **Surge Drum**

The surge drum is positioned at an elevated position above the evaporator plate heat exchanger. In the surge drum cold liquid ammonia and ammonia gas are stored. From here the liquid ammonia is fed into the evaporator, and the gas produced during evaporation is returned to the surge drum. (Thermo-siphon system)

The gas produced during expansion (in the expansion valve) along with the ammonia gas in the surge drum is fed into the compressor through a non-return valve and strainer. The surge drum also contains demister packs, to prevent liquid droplets from entering the compressor; liquid distribution manifold and oil drain pot.

- **Liquid Receiver**

The liquid receiver is designed to hold the whole ammonia charge. It is situated behind the condenser. This vessel is also fitted with a similar level gauge used in the oil separator.

- **Expansion Valve**

  The expansion valve is located between the condenser/liquid receiver and the surge drum. The expansion valve is controlled by a PLC.

- **Evaporator**

  In the evaporator, the water flow is highly turbulent. This prevents freezing and the water can thus be cooled to temperatures as low as 0.5°C.

- **Condenser**

  Highly turbulent water flowing through the condenser is used to assist in the prevention of fouling. The incoming ammonia gas is at compressor discharge temperature. The gas is condensed to a liquid in the condenser.

Practical mine applications of the cycles discussed in this section will be discussed in more detail in Chapter 4.

Coefficient of Performance

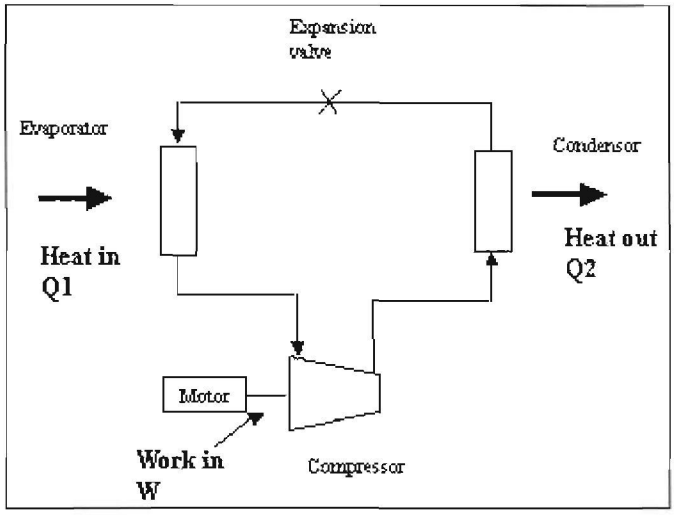


Figure 2-3: Typical refrigeration cycle.

Energy is conserved so that:

$Q2 = Q1 + W$

The coefficient of performance is defined as [5]:

$$COP = \frac{Q1}{W} \tag{2.1}$$

For example, at a COP of 3, one watt of motor power input will produce 3 watts of cooling at the evaporator and 4 watts of heating at the condenser. A higher COP is a measure of "better" efficiency.

Another way of thinking of the COP is:

$$COP = \frac{Output}{Input}$$

2.3. MINE COOLING REQUIREMENTS

MINE ISOTHERMALS

Figure 2-4 shows how refrigeration requirements increase dramatically with increase in underground depth [7].

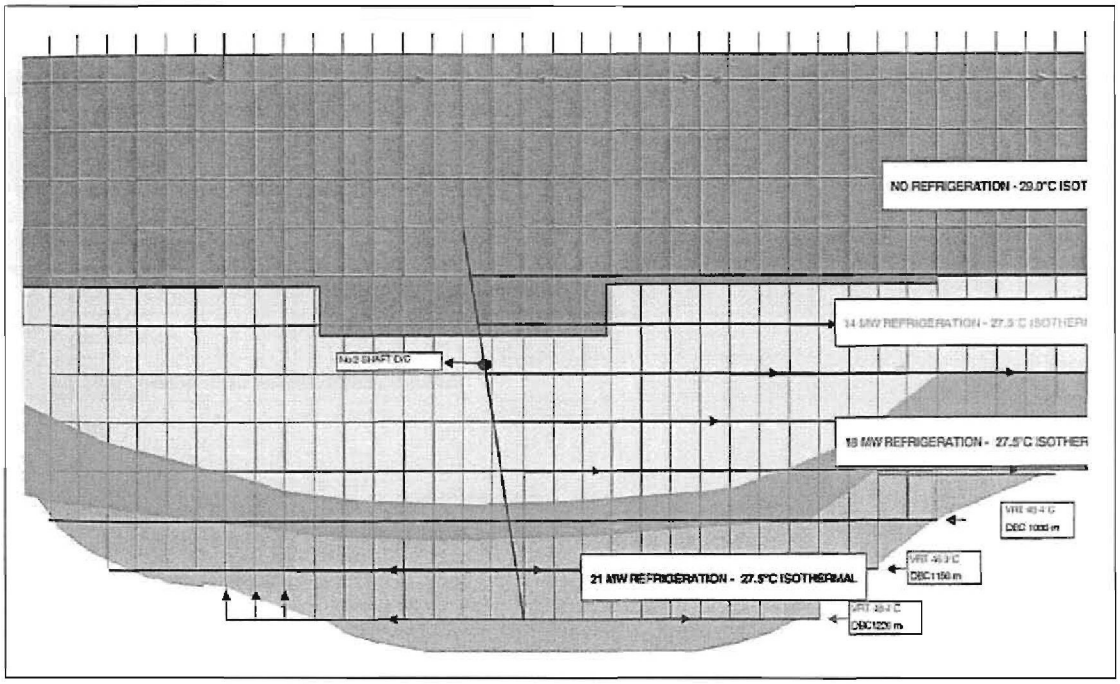


Figure 2-4: Mine isothermal profile with various cooling capacities required.

2.4. METHODS OF REFRIGERATION

TYPICAL MINE REFRIGERATION SYSTEM

The following figures represent typical mine refrigeration cycles. Water used for mining purposes is cooled and sent back to the mining levels. Normally a surface bulk air cooler (BAC) is also supplied with chilled water in a closed loop set-up. The BAC is used to cool ambient air entering the mine.

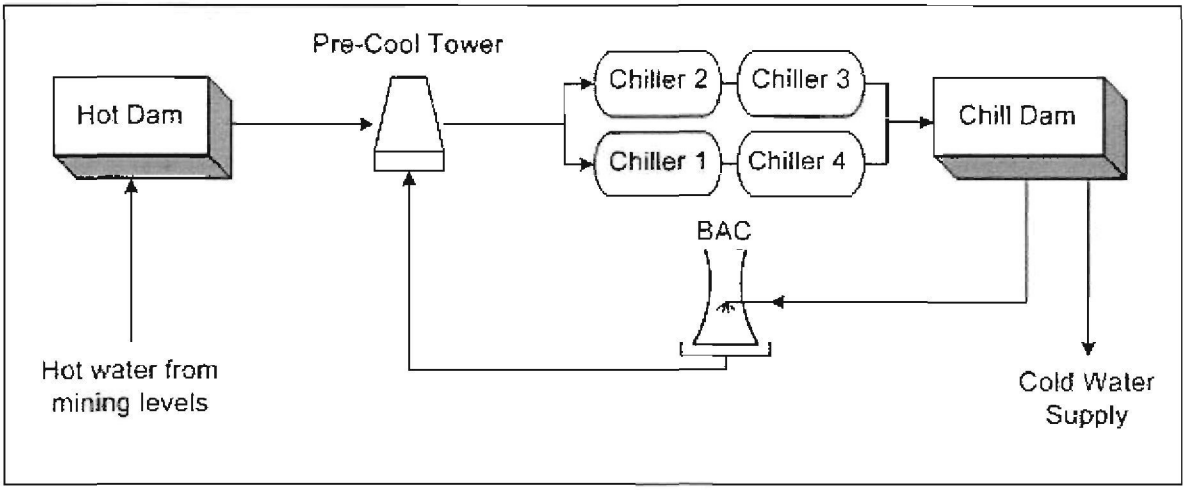


Figure 2-5: Typical open cycle refrigeration system.

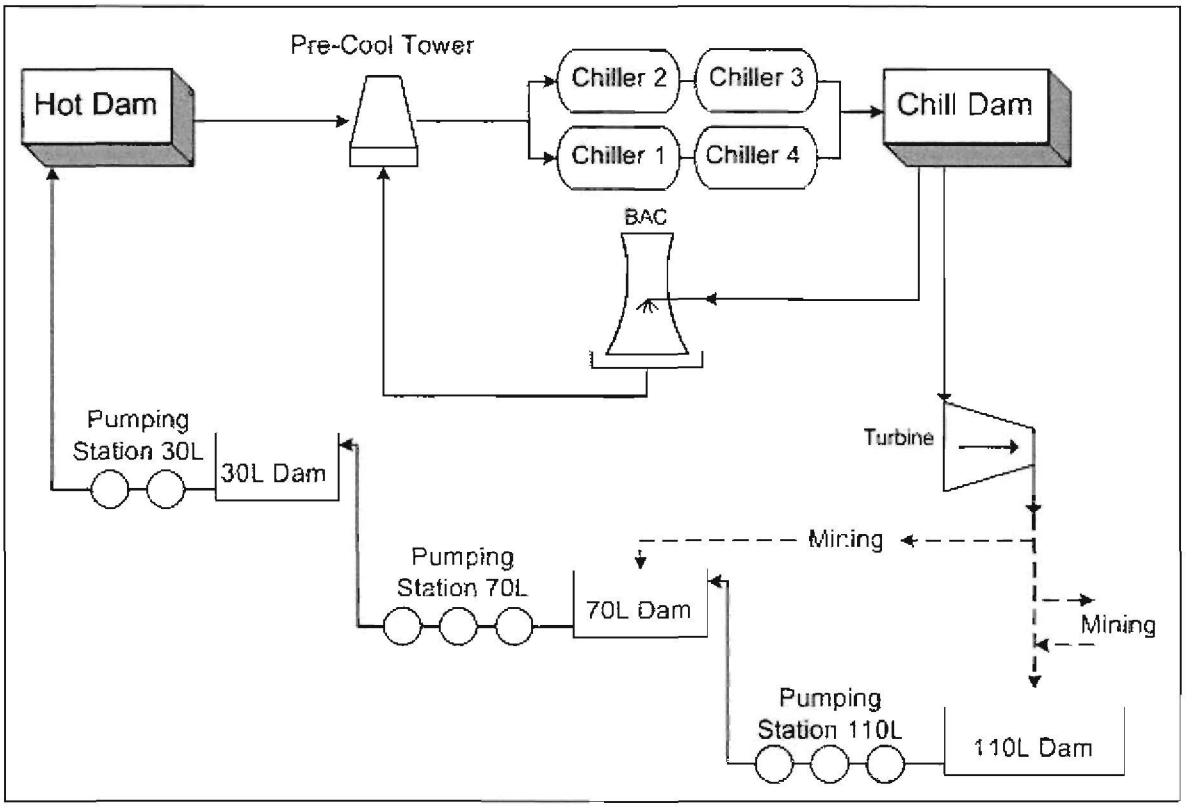


Figure 2-6: A typical mine chilled water cycle.

Note: 30L = 30 Level; 70L = 70 Level; 110L = 110 Level.

MINE COOLING STRATEGIES

The primary source of mine cooling is by normal ventilation air. Temperatures have, however, increased due to the geothermal gradient, which increases with depth, as well as the auto-compression heat added per vertical meter of depth. This has resulted in the generic strategies discussed below, which are used in the following configuration, depending on the actual application or need.

The prime reason for this configuration is the cost of cooling; the cost of surface bulk air-cooling (BAC) being the cheapest [8]. Current strategies include:

- Surface bulk air-cooling;
- Underground station bulk air-coolers;
- Chilled service water;
- Crosscut coolers;
- The use of ice; and
- In-stope cooling.

Surface bulk air-cooling

This has traditionally been used solely for cooling the shafts and haulages where people travel or work, to an acceptable level, and had no direct bearing on the in-stope cooling requirement. It did, however, assist somewhat in reducing the approaching temperature to the secondary or tertiary cooling [9]. This statement is only true for deep-level mines where the VRT and auto-compression play a major role in the heat flow equation.

Within the shallower mines with high VRT, like the platinum mines within the Bushveld Igneous Complex, the heat pick-up due to auto-compression plays a lesser role due to the relatively shorter shafts, even though steeper VRT gradients are experienced. In these instances, depending on the installed capacity, there remains sufficient residual cooling to be used within the stope horizon.

Therefore, once the initial thermal inertia has been overcome, adequate cooling via surface bulk air-cooling, within the reef plane can be achieved as a 'first phase' cooling strategy. This cooling is the cheapest and easiest application of refrigeration, but suffers from poor positional efficiency [10].

Underground bulk air-coolers

Underground bulk air coolers are introduced when the temperature in the shaft is acceptable but the temperatures in the haulages, which lead to the working places, are not. These coolers are placed at strategic sites to cool the ventilation air whenever the air temperature increases above the maximum design value [11].

This form of cooling is then designed to ensure that the thermal environment, where people have to travel and work on the infrastructure leading to the working places, is acceptable. The thermal duties of these units are typically between 0.5 and 20MW [12].

This form of cooling results in a better positional efficiency than surface cooling, and because of the warmer conditions, the plant tends to run at full load throughout the year [8].

Cross-cut coolers

Cross-cut coolers augment the previous cooling strategies to ensure that the air entering the actual working places is in line with accepted norms. This results in an even better positional efficiency, as the water passes through a heat exchanger (which resembles the radiator of a car). Air is blown through the cooler by means of a small fan. The air is cooled and delivered directly to the working face [8].

Chilled service water

The cooling of service water plays an important role in the overall cooling strategy of mines, since the chilled service water is distributed to the working faces where it is traditionally difficult to install and maintain air coolers [12].

This form of cooling results in the best positional efficiency, but suffers from not being continuous (cooling only occurs when water is used, and this is intermittent) [13].

The use of ice

Ice in this context is used to reduce the temperature of the underground service water in mines, and has some distinct advantages [14], [15]. Experimental results from a pilot installation for conveying ice in pipelines down into a mine, is well documented and constitutes no problem [16].

In terms of its usefulness underground, the primary feature of this system is the heat exchange during the latent heat of fusion of ice, which is 335kJ/kg. Simply put, if ice at –5°C is used to chill water underground to 4°C, the water involved is about one quarter of the total circulating underground [17]. This relates to further savings in terms of the consequent reduction in pumping requirements [18].

In-stope cooling

It has been shown that in high thermal environments, subsequent cooling has to be taken into the working face [7], [19]. It is evident that refrigeration technology has progressed dramatically over the last decade. When account is taken of the increase in capacities required and the enormous costs of operating systems, the importance of further improvements is clear [17].

2.5. CURRENT LARGE-SCALE COST SAVING OPTIONS

ICE SYSTEMS

Ice is used in some deep Southern African mines as a heat transfer substance to transport refrigeration to underground working areas from ice-making installations located on the surface level. Three full-scale systems are currently in operation and economic studies indicate that further installations are possible in future.

Two general types of ice have been used: 'hard' ice in the form of fragments and 'slush' ice resembling wet snow. The ice conveying systems are based on long pipelines connecting the ice plants to underground melting dams. Pipeline routes may include horizontal and vertical sections and may in future extend over total distances of up to five kilometres.

Ice slurries have been a popular choice of energy storage because of its high energy density. This is due to the latent heat of phase change. Phase changing materials (PCM) can be used but in most technical applications, mixtures are used.

Chilled water systems are used to absorb and transport much of the heat, using refrigerators located either on surface or underground (and often both). When refrigerators are located on surface the warm water has to be pumped back from underground, at great cost.

One of the advantages of using ice sent down from surface to absorb the heat load is that the quantity of water to be pumped back out of the mine can be reduced to about a quarter of that for an all-water cooling system, giving very large cost savings [21].

If a PCM is dispersed in a carrier fluid, phase change slurry is obtained. Ice slurry is the oldest in the phase change slurries group. Figure 2-7 is a graphical representation of an ice slurry system.

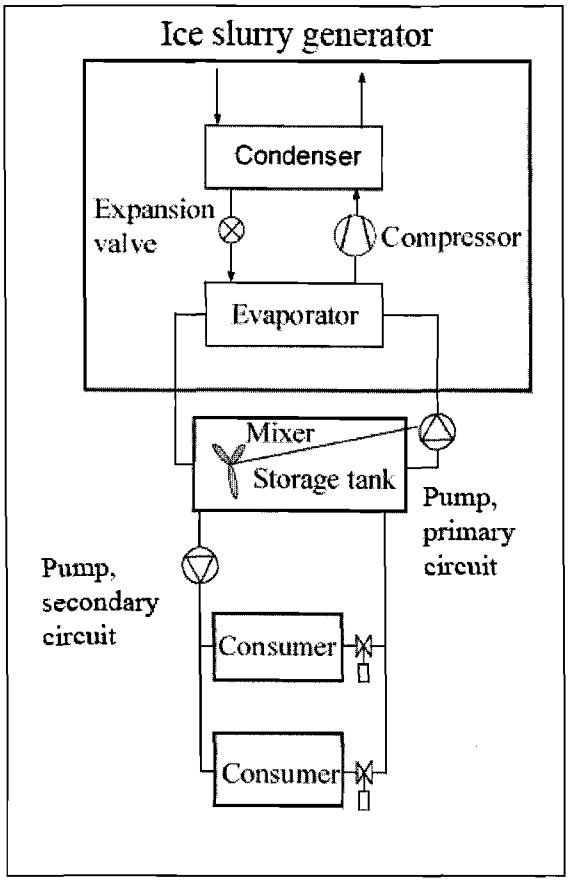


Figure 2-7: Ice slurry system [20].

The ice fed into the conveying pipeline at the surface level of a mine needs to be in as dry a state as possible, consistent with the ice-making process employed, in order to minimize the return water pumping requirement. The design of a complete ice conveying system commences with a given ice flow rate, ice type, and pipeline route from the ice plant down to one or more underground melting dams.

The route could include several vertical and horizontal sections. The following aspects require careful consideration by the designer: the pipe diameter, pipeline construction (including material, couplings, contraction arrangements, bends and supports), a system to transport the ice on surface from the plant to the mineshaft and to inject it into the vertical pipeline in the shaft, and system control.

The primary design criterion is the system reliability and availability. This necessitates the avoidance of flow blockages or pipeline failures. A detailed evaluation of cooling generation systems for ultra-deep level gold mining has recently been carried out as part of a collaborative research program (entitled 'Deepmine') sponsored by certain South African mining companies.

The full cost implications of using several alternative types of cooling systems were determined, for various mining depths down to 5,000m below surface and for various mine designs. The study showed that the most economical form of cooling system for great depths is a hybrid system with a combination of underground and surface refrigeration machines.

Additional refrigeration would generally need to be installed on surface because the maximum refrigeration capacity installed underground (presently in the form of conventional R-134a water chillers, although water vapour refrigeration could become attractive in future), would be limited by the combined heat rejection capacities of the air and water streams returning to surface.

The comparative evaluations confirmed that for depths below about 3,000m ice systems would be the least expensive option for the surface plant at the present time, in spite of the high costs of making ice. Hydrolift systems (of which the three-chamber pipe feeder is one variant) also have attractive potential and are currently also being evaluated [22].

Ice manufacture

Current ice installations produce ice in one of two forms: 'slush' ice (typically having 70 to 75% of ice by mass) formed by dewatering a dilute ice slurry [23], or irregular 'hard', essentially dry, particulate ice [24]. The feasibility of both types of ice has been demonstrated in large mine installations (see Table 2-1).

The total costs (capital plus operating) of the two types of systems generally seem to be comparable for a depth of 3,000m. Slush ice plants have higher coefficients of performance [23] but they incur higher water pumping costs because of the wetness fraction of the ice sent underground.

In the slush ice installation at the Mponeng shaft of Western Deep Levels Gold Mine, dilute ice slurries (about 17% ice crystals by mass) are first generated by means of vacuum evaporation at the triple point of water, dosed to have a salt concentration of about 0.35% [25].

The refrigerant is the water itself and the direct boiling process is inherently efficient, with no thermal resistance from any freezing surfaces in the evaporator. The dilute slurry is thereafter concentrated in gravity drain columns, the effectiveness of which is important (it is hoped to achieve ice mass fractions of over 80% in future).

The development of large slush ice plants, such as those at Mponeng gold mine (where four 3 MW(R) machines are currently operating, each producing more than 800t/d of concentrated slush ice), has required solutions to several challenging problems.

The greatest of these has been the development of special water vapour compressors, with volumetric duties (for each Mponeng unit) of 320m^3/s over a compression ratio of 8:1 in two stages [25]. Hard ice is made in more conventional installations with extensive freezing surfaces, using defrosting cycles for harvesting. The large installation at ERPM employs screw compressors with ammonia refrigerant [24].

Mains water is used to make the ice and one uncertainty in future applications would be whether using mine water as the feed would cause corrosion or fouling problems on the freezing surfaces. Water quality and brine management are also very important issues with vacuum ice machines, for other reasons [25].

Conveying research

A clear fundamental understanding of the multiphase flow in the various sections of a mine ice pipeline is required in order to formulate a pressure gradient model for design purposes and to design for flow reliability.

As the ice, in whatever form, flows down the pipeline it melts progressively at a rate of typically 5 per cent of the initial mass of solid per 1,000m of vertical descent. However air occupies the largest volume fraction in the pipeline and the flow may appropriately be analyzed as a two-phase flow of wet solids with air. Initial ice conveying research was based on the use of hard particulate ice while more recent work has considered slush ice.

Hard Particulate Ice

Most of the existing research information was obtained from tests carried out on a pilot ice conveying installation located at ERPM [26]. This installation incorporated a pipeline that could be extended to depths down to 2,407m below surface level, with a total length of up to 3,905m (with two vertical and three horizontal sections).

The ice, which had an initial average particle size of approximately 34mm, was injected into the 136mm inner diameter pipeline using a blow-through rotary valve. Initial tests showed that steel piping was unsuitable for ice conveying, but an important finding was that plastic (in this case uPVC) piping was very successful.

Wet ice is both highly cohesive and adhesive to carbon steel (and, to varying extents, to other metallic surfaces) and blockages resulted very readily. Hydrophobic surfaces such as uPVC, on the other hand, exhibit no adhesion with wet ice (and very low coefficients of sliding friction) and no blockages were experienced during a program of over a hundred tests.

Low-pressure uPVC piping could be used because the static pressures encountered during conveying were very low, given the absence of blockages. A typical maximum pressure was 20kPa at the foot of the 1,770m vertical section down the mine shaft; this was for an ice flow rate of 7.4kg/s. Photographic observations and pressure recordings at various points along the pipeline showed clearly that the nature of the flow changed significantly from one section of the pipeline to the next.

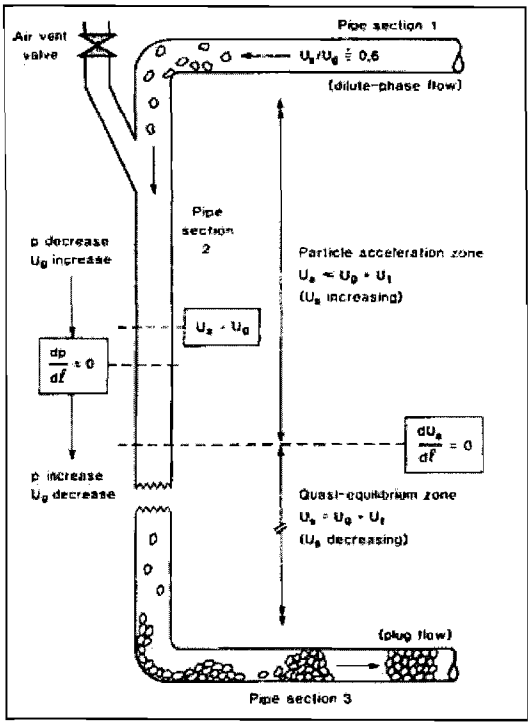


Figure 2-8: Ice-air flow regimes [26].

Slush Ice

Pilot testing was undertaken some years ago at the Western Deep Levels Gold Mine to investigate the flow of slush ice, containing about 30% of water by mass, through various pipelines [27].

A rotary valve was again used as the ice feeder and the pipeline incorporated a surface section 365m long with pneumatic conveying (diameters of either 105mm or 250mm), a vertical section 1,200m long (250mm diameter) fed via an open funnel arrangement, and an 80m horizontal section underground.

The tests confirmed that reliable flow could be achieved using uPVC piping but detailed measurements were not recorded for the purpose of evaluating friction factors. The experience gained was nevertheless useful in the design of the full-scale installation for the same mine. While experience to date suggests that the underground pipeline flow characteristics of slush ice are generally similar to those from hard particulate ice, a number of issues require resolution.

These include quantitative descriptions of the flow conditions that would cause blockages to occur, and the formulation and verification of complete models for the prediction of pressure gradients. Experimental data is required for various pipe sizes in order to develop reliable scaling laws. One of the differences between flows of slush ice and particulate ice concerns the conditions under which transition occurs between different flow-regimes.

In particular, plug flow occurs more readily with slush ice than with hard ice. The transition point depends, however, upon the water content of the ice. (Notwithstanding the different transition characteristics, plug flow will always prevail underground with all ice in horizontal sections.)

Mine operating experience

Significant quantities of ice have been conveyed from surface level to underground dams at four mine installations, in addition to the pilot plants already mentioned. Table 2-1 summarizes the salient data for all these installations up to the beginning of the year 2000.

Mine	Type of ice	Flow rate (kg/s)	Pipe ID (mm)	Ice mass velocity (kg/s per m^2)	Total length (m)	Final depth (m)
ERPM (pilot)	Hard	7,4	136	500	3 900	2 400
Harmony	Hard	10	200	320	1 180	1 100
ERPM *	Hard	44	270	770	2 650	2 500
WDL (pilot)	Slush 70%	5	216	140	1 570	1 200
Mponeng *	Slush 70%	32	216	870	2 760	2 600
Selebi Phikwe*	Slush 65%	23	300	325	390	390

Table 2-1: Particulars of ice conveying pipelines in mines (installations marked * are currently operating) [28].

The flow rates given in this table are neither necessarily the total ice plant production capacities at the respective mines, nor the maximum carrying capacities of individual pipelines, but rather values for flows achieved routinely through single pipelines up to that time.

(In the case of the ERPM pilot plant the maximum pipeline capacity could not be determined because of limitations in the ice feed rate).

With reference to Table 2-1, the installation at Harmony is no longer in operation because of closure of the shaft. The largest mine ice system is at ERPM, which has had ten years of successful operation. The total system capacity is 53kg/s and the ice is normally conveyed underground to two different levels through two separate pipelines of equal diameter (the figures above represent the greatest recorded flow rate for a single pipeline).

The transportation system between the ice machines and the mineshaft includes a combination of short screw conveyors, conveyor belts (200m long) and, lastly, pneumatic conveying pipelines (50m long) that connect directly to the vertical pipelines in the shaft. The uPVC pipes in the shaft have spigot and belled-end joints to accommodate thermal contraction and expansion.

The joints are not airtight in this installation but there is no need to build up the pressure in the pipelines because the underground discharge points are shortly downstream of the final bends out of the shaft. In retrospect it is believed that flanged couplings would nevertheless have been more suitable, for various practical reasons.

The operation of this ERPM system has provided a wealth of valuable information, applicable to any other mine ice conveying system. One important issue in any such system is the mechanical design of the pipeline. As in the other systems mentioned in Table 2-1, it was found that ice plugs form along the pipeline (probably initiated in this case at intermediate deviations during the descent) and these are discharged violently at the pipe outlet.

The movement of the plugs causes the pipelines to shake severely and results in high impact forces at the pipe supports, especially if there is excessive clearance between the pipe and its supports. When using low-pressure plastic piping it is clearly important to minimize impact forces that can shatter the pipes, through careful support design.

Another important issue concerns blockages. In this system (and at two other mines) blockages have occurred mainly at the ends of the pipelines because of overfilling of the underground ice dams into which they discharge; this can be avoided through suitable monitoring and control measures.

Mponeng mine operates the largest slush ice conveying system. Up to the beginning of 2000 the ice was fed into the top of a 216mm inner diameter vertical pipeline through a funnel, into which four ice streams converged from four separate ice concentrators. The top of the funnel had a diameter of 1,500mm and the included angle was 20°.

Occasional blockages occurred in the funnel, due to interference between the four ice streams (three were pneumatically conveyed, and the fourth was a gravity flow down a chute), until the feed pipes were rearranged. The piping used is once again uPVC, with spigot and belled-end joints. The conveying system has operated reliably for some three years since inception.

The only problems experienced were similar to those mentioned above for ERPM; there have been pipe breakages, probably due to unrestrained pipeline movement caused by the rather violent plug flow. Plugs formed during descent because of a diversion in the pipeline in the shaft. The ice-making installation will be expanded in the next phase to a capacity of 64kg/s of ice (5,500t/d).

To accommodate this future flow the shaft pipeline was replaced during 2000 by an uPVC pipeline of 431mm internal diameter. The pipe joints are once again the bell-end and spigot type, with rubber O-rings for sealing. The installation at Selebi Phikwe is interesting in that the slush ice is produced by vacuum evaporation, but using steam ejectors instead of mechanical compressors [29].

In this case steam was available at low cost from elsewhere. The conveying route is simple, comprising a single vertical pipe section.

Energy cost saving strategies

Listed below are various methods of energy cost saving by ice storage [30]:

- Full storage system – in which the chillers do not operate during the day because the system generates and stores enough ice to cool adequately during the on-peak period;
- Partial storage system – the chillers operate continuously during the day but get part of the energy from the ice storage system;
- Demand limiting system – the system turns the chillers off during peak periods and relies on the ice stored to do the cooling when the rates are the highest.

The third system is the one that is usually most effective.

Practicalities

Experience to date with ice cooling systems in Southern African gold mines demonstrates that ice can be manufactured in large quantities and that reliable flow can be sustained to great depths through long gravity-driven pipelines, with ice in the form of either hard particles or slush. The flow underground is mainly intermittent in nature with the ice plugs or slugs separated by long air pockets.

Plastic piping such as uPVC must be used, with steel sheathing in areas where pipes are vulnerable to external physical damage. Because of the intermittent nature of the flow and the violent discharge at the end of a pipeline, particular care must be taken in the design of pipe supports to restrain the pipe and withstand dynamic loads.

Flanged pipe couplings are preferable in order to maintain a smooth bore and to prevent air leakage, but provision must be made for thermal contraction and expansion. There must be no reductions in pipe cross-section, or diversions or off-takes, or any misalignment or protrusions at couplings.

Large-radius bends must be used. The method presently favoured for injecting ice into the top of a vertical pipeline is to feed it into a funnel mounted directly onto the pipe. Further research is in progress to complete the formulation and verification of general mathematical models for multiphase flow through ice pipelines, and to incorporate these into general design guidelines.

It should also be noted that the main goal of these ice systems is to help solve the cooling challenges for deep mine initiatives. These systems are very expensive and maintenance intensive, and are only accessible options for mines with low and competitive production (R/t) figures. These systems will probably not be viable solutions for some of the "struggling" mines in South Africa.

2.6. LOAD SHIFT POTENTIAL IN REFRIGERATION SYSTEMS

Through utilisation of available storage capacities in a system, it can be manipulated to operate in cheaper daily tariff periods (according to a time-of-use electricity structure). The largest energy consuming systems (pumping, refrigeration) in mines make use of water; therefore it makes sense to focus on the storage of this commodity [31].

Although there will also be utilisation of the storage capacities in cooling and pumping systems, load shift in a cooling system is very much different from load shift implementation on a pumping system. The challenge is to utilise the available thermal storage capacity in these systems within system constraints (the mine requires a specific chilled water flow rate and temperature at all times).

To better understand thermal storage in these systems, it can be assumed that cold dams react the same way as an electrical capacitor [32]. This "capacitor" needs to be filled up with enough chilled water during the cheaper tariff periods. The stored chilled water can then be utilised during expensive tariff periods (hence unloading of machines during these periods).

The "capacitor" in the system can be filled by extra loading (if extra cooling power is available off course) of the refrigeration machines during cheaper periods. Inlet temperatures of the machines can also be controlled through back-pass strategies, which also create a decrease in compressor absorbed power [33].

It can be shown that load shift potential in refrigeration systems is dependant on electricity tariff rates, plant operation strategy, chilled storage capacity and climatic conditions [34]. Load shift strategies may not violate any mine or personnel safety, production and maintenance constraints [35].

The climatic conditions during winter cause the refrigeration system to use less power. This effect will cause a reduced load reduction potential during winter and an increased potential during summer. This can be a virtue for Eskom, for maintenance of power plants is usually conducted in the summer months.

2.7. OBSTACLES FOR IMPLEMENTING A LOAD SHIFT SYSTEM

To implement a sustainable load shift program on a refrigeration plant, the following issues need to be addressed:

- Plant personnel's and ventilation specialists' mindsets and resistance to change;
- Environmental conditions;
- Plant equipment conditions;
- Infrastructure requirements;
- Water reticulation network;
- Base load electrical energy profile;
- Storage capacity;
- Seasonal operation;
- Closed loop vs. open loop systems;
- Process requirements;

- Chilled water supply requirements; and
- Machine utilisation.

A simulation system is needed to simulate a refrigeration system's response to a load shift regime, only then can the obstacles above be addressed adequately.

2.8. CONCLUSION

Refrigeration systems play an important role in deep mining. Currently the only cost saving strategy utilised in these systems is that of ice storage. These systems are expensive and face various operational and maintenance constraints which raises the question:

Isn't there a cheaper cost saving option to roll out in these systems?

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CHAPTER 3

SIMULATION OF DEEP MINE REFRIGERATION SYSTEMS

3. SIMULATION OF DEEP MINE REFRIGERATION SYSTEMS

3.1. PREAMBLE

Mathematical models of refrigeration plant equipment, e.g. chillers, pumps, cooling towers, etc. were simplified and incorporated into simulation software. The integrated simulation model was then applied to the surface refrigeration system of Kopanang Gold Mine, and model predictions were verified.

Extensive research into commercially available simulation software was conducted. Findings showed that none of the available simulation models focus on the simulation of refrigeration plant equipment or water reticulation systems. To investigate load shift potential in refrigeration systems, it is necessary to simulate the response of the rest of the system to make sure constraints are adhered to.

The surface refrigeration plant of Kopanang gold Mine was simulated and simulation predictions compared with actual plant measurements (the mine has an extensive SCADA system in place). The model was calibrated and the potential to shift load from the system's operation was investigated.

Verification results showed above 95% accuracy for simulation predictions made. System constraints were identified and the primary constraints were found to be the minimum and maximum dam levels of the confluence dam, the temperature of the chilled water section of this dam, the chilled water flow rate to the BACs and the chilled water flow rate to underground.

The simulation proved its accuracy and could be further used to predict system responses to load shift strategies.

3.2. THE NEED FOR AN INTEGRATED PLANT SIMULATION MODEL

As a general rule, a mine's underground working areas are cooled to the maximum operational capacity of the mine's ventilation and refrigeration equipment. In this way, electrical energy is wasted by supplying a "too good" underground environment. The challenge is to supply only the minimum acceptable underground environment, thus using the minimum electrical energy.

Environmental control systems are complicated. Simulation systems currently available focus on underground monitoring, simulation and control. Current environmental control systems focus on the demand side of the refrigeration cycle (reticulation of chilled water and cooled ventilation air).

Mines need to start focussing on the effective control of their refrigeration plants. An easy-to-use simulation, optimisation and control model needs to be developed to assist mines to effectively control their refrigeration systems to ensure optimal supply of chilled water for cooling requirements.

3.3. SIMULATION SYSTEMS CURRENTLY AVAILABLE

A literature survey was conducted of systems that claim the ability to optimise the electrical energy cost for energy systems. It focused on three areas: patents, commercial software and scientific literature.

Patented systems

There are many patents that claim the ability to manage and optimise the energy cost of HVAC systems in mines, buildings and industries. One such system is disclosed in U.S. Patent Nr.6366889 by Zaloom [1].

According to the inventor the system enables the user to visually analyse energy consumption trends in large facilities to determine operating errors, equipment faults or billing errors. Woolard et al. patented a similar system [2]. This system has an extensive web-based communication capability for real-time energy data.

It is clear that this approach does not represent mathematical optimisation but rather act as an aid for the user to identify areas of inefficient energy usage. A second approach to energy management can be labelled a real-time low-level control approach.

With this approach a controller apparatus is used to control individual components in such a way that the energy consumption is optimised. Cascia et al. patented a digital controller that implements a control strategy for a cooling and heating plant [3]. The control strategy provides for the calculation of near-optimal global set points for all the main components in real-time.

The controller seeks to optimise the instantaneous power consumption of an installation, while ensuring that the heating or cooling load is satisfied. It is clear that the system described in this patent is in general unable to optimise the energy cost of an HVAC system since it does not attempt to shift the electrical load.

The third approach to energy management involves the measurement, reporting and optimising of the total energy cost of an integrated energy system. The invention disclosed by Irvin et al. monitors and controls variable speed pumps, as well as constant speed pumps [4]. Real-time operating cost parameters are calculated.

Based on these parameters the control system suggests the optimum combination of pumps and/or the optimum speeds of the pumps to a plant operator. The system does not use short-term price and fluid demand information to optimise energy costs for a certain future time-horizon; instead, it only uses current data.

In a similar vein, the patented control system of Ehlers et al. uses price data to compute a suitable dead band range for residential heating and cooling systems [5]. This system does not attempt to shift load by making use of some thermal capacitance of the cooling/heating system. It simply relaxes the set point dead band as the energy price increases.

Commercially available software

In Chapter 1 various software packages for the simulation of pumping systems were shown. Two commercially available software simulation packages (applicable to mine refrigeration systems) were found:

- *ENVIRON*;
- *VUMA*;
- *RTP Control*^{TM}.

The most commonly used simulation software package in the mining industry is *ENVIRON* [6]. This software concentrates more on the design of mining systems and the solving of the airflow strategies below ground. It also specifies the cooling capacity that needs to be installed. This is not a dynamic or integrated software package.

VUMA is a recently developed program for the simulation of mine ventilation networks. *VUMA* is an interactive program that allows the simultaneous modelling of air flow, as well as contaminant and thermodynamic behaviour in an underground mine network [7].

Whilst there are a few software packages already available for ventilation network simulation, there are not many that are capable of a full thermodynamic analysis and the simultaneous distribution of contaminants such as heat, dust and gases throughout a mine network. Within *VUMA*, user-friendly interfaces allow networks to be quickly constructed and 'what-if' studies to be easily performed.

A third system is *RTP Control*™ by *Honeywell Inc* [8]. This system enables commercial and industrial customers to respond to real-time pricing. It has been used in a case study on the Marriott Marquiss hotel in New York City.

Currently the system focuses on load shedding but it aims to include the optimisation of the scheduling of the charging/discharging of thermal energy storage (TES) systems.

Scientific literature

Most literature in the field of energy cost minimisation by means of optimum scheduling or control, involves commercial buildings. Several researchers have pursued this topic in the 1990s. Kintner-Meyer et al used a theoretical case study to demonstrate the feasibility of optimal control of an HVAC system using cold storage facility and the thermal capacitance of the building [9].

The problem is considered at hourly intervals over a 24-hour horizon. A standard non-linear optimisation package was used to find the optimum control set points. Zaheer-uddin et al conducted a similar study and had similar findings [10]. They computed supervisory control profiles for a theoretical two-zone building with cold storage.

The optimisation problem was defined as a three-stage problem namely unoccupied, start-up and occupied stages. Each stage was divided into an arbitrary number of time intervals. The multistage problem was solved with a gradient search method.

Daryanian et al reported on a complete energy management system for buildings under real-time pricing [11]. They developed a practical system that optimises the scheduling of a thermal storage system in Massachusetts. They demonstrated a 9% cost reduction compared to the existing situation over a six-week measurement period.

The scheduling algorithms were run on an office computer and the resulting charging schedules for the thermal storage system were downloaded via modem. The system automatically retrieved price and weather information, implemented a building demand-forecasting model and calculated an optimal charging schedule.

Bojic et al considered energy cost optimisation of factories with combined heat and power (CHP) systems [12], [13]. The heat and power can be produced inside the factory or be bought from an outside plant. Using mixed integer linear programming a cost diagram was derived.

The diagram aids the energy plant operator in deciding on the optimum energy composition. This allows for the control of complex energy industrial systems without using a computer.

The optimisation of district heating (DH) systems is actively researched in Denmark. Benonysson et al. investigated the optimisation of operational cost for DH networks by selecting the optimum supply temperatures [14]. The dynamics of the DH consumers and the DH distribution network affect the operation of the system heavily.

They used the so-called node method to simulate the temperature and flow in the network. A standard optimisation package calculates the supply temperatures. The method can be applied in an on-line operational planning system that recalculates the optimum supply temperatures hourly.

There are a limited number of articles regarding the simulation, control and energy cost optimisation of mine ventilation and cooling systems. In general it seems as if there is a reluctance to use "high-tech" solutions for the optimisation of energy costs, especially in South Africa.

This view is shared by Glehn, a past president of the Mine Ventilation Society of South Africa [15]. He stated:

"*Typical mining projects can involve ventilation and cooling systems for a single shaft where up to R250-million in investment with annual running costs of about R25-million are required. Surely such expenditure deserves a high technical approach to the active control of these resources? If monitoring and active control of underground ventilation and cooling systems are considered from the point of view of energy alone, control of such systems at a sophisticated level can easily be justified*".

Several publications have reported on ways to design for energy efficient mining cooling and ventilation systems. As an example Baker et al. showed how turbines, pre-cooling towers and storage dams could be used to reduce energy consumption and to shift electrical load to off-peak periods [16].

They showed how *Coolflow* (a mine energy analysis program released in 1991) was used to determine the economic feasibility of these devices at the design stage. In a similar vein Stroh demonstrated how energy could be conserved by including turbines, ice systems and pre-cooling towers in the design of cooling systems [17].

There are also a few references to operational control systems that have the aim of minimising energy costs. De Ruiter et al. described the development of a mine monitoring and control system that had an estimated saving of R400,000 per annum [18], [19].

The savings are primarily a result of intelligent load shedding of the ventilation system. No specific consideration was given to time-of-use tariffs, load shifting or energy cost optimisation.

3.4. MATHEMATICAL SIMULATION MODELS

Thermal storage dam model

A schematic view of a dam is shown in Figure 3-1. This schematic will be used for modelling [20] purposes.

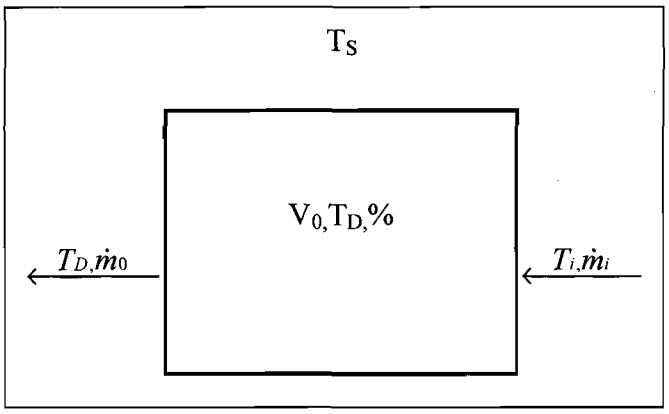


Figure 3-1: Schematic drawing of a thermal storage dam.

It can be assumed that the thermal storage dams react like an electrical capacitor [21].

The temperature within the tank is a function of initial temperature, initial volume, solar air temperature, which includes the emittance and absorption of the air on the dam wall, and the convection coefficient on the wall surface.

The exposed areas, horizontal and vertical, also need to be accounted for. Taking convection, emittance and absorptance into account, the basic equation for dams can be given by:

$$C.\frac{dT}{dt} = \dot{m}_i.c_p.(T_i - T_D) + UA(T_s - T_D) \tag{3.1}$$

Where T_D is the water temperature in the dam. Furthermore, T_s is the solar air temperature given by [22]:

$$T_s = T_A + \alpha\frac{G_t}{h_0} - \frac{\varepsilon\Delta R}{h_0} \tag{3.2}$$

This formula incorporates the atmospheric, dry bulb temperature T_A and the effects of absorption ($\alpha\frac{G_t}{h_0}$) and emittance ($\frac{\varepsilon\Delta R}{h_0}$) heat transfer by the air on the dam wall.

This value will be calculated for every hour, using climate data. Multiplying the terms of Equation 3.1 and separating the variables give the following results:

$$C.\frac{dT}{dt} = -T_D.a + b$$

With

$$a = \dot{m}_i.c_p + UA$$

$$b = \dot{m}_i.c_p T_i + UAT_s$$

$$C = C_0 + (\dot{m}_i - \dot{m}_0)c_p.\Delta t$$

$$C_0 = V_0.c_p$$

Separating the terms and rearranging the results to:

$$\int_{T_{D_0}}^{T_D} \frac{1}{T_D.a - b} dT = \int_0^1 \frac{-1}{C} dt$$

Using exponential rules after integration, the equation becomes:

$$\frac{1}{a}.\ln\left(\frac{T_D.a - b}{T_{D_0}.a - b}\right) = \frac{-\Delta t}{C}$$

$$T_D = \frac{1}{a}\left((T_{D0}.a - b).e^{\frac{-a\Delta t}{C}} + b\right) \tag{3.3}$$

With

$C = \max, when C \geq \max$
$\dot{m}_0 = 0, C = 0 when C \leq 0$

One of the most important parameters of the thermal storage dam model is the volume or level of the dam. Due to variation in flow rates of the inlet and outlet water of the dam, the volume or level of the dam will change over time.

For the simulation model the change in level is dependent on the flows in and out (L/s), and the time interval Δt. The model can be formulated by:

$$V_t = V_{t-1} + \frac{(\dot{m}_i - \dot{m}_o)\Delta t}{1000} \tag{3.4}$$

With

$\dot{m}_o = 0, when V_{t-1} = 0$
$\dot{m}_i = 0, V_t = V_T, when V_{t-1} \geq V_T$

To be able to use the model appropriately, the user needs to provide certain information pertaining to the model. This includes the basic design of the dam, the total volume of the dam and the initial conditions for the volume of the dam (volume fraction between 0 and 1).

Pumping model

A schematic view of a pump is shown in Figure 3-2. This schematic will be used for modelling [23] purposes.

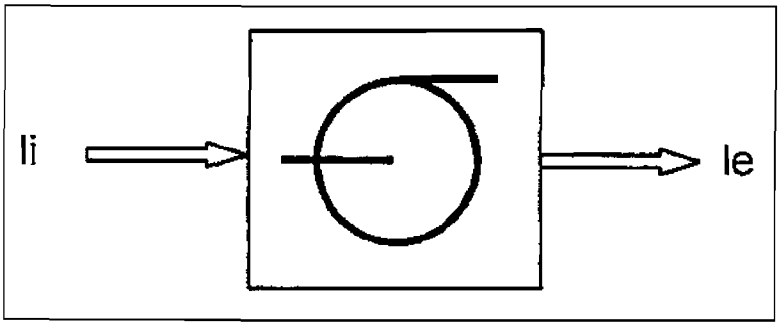


Figure 3-2: Schematic diagram of a pump.

The model is based on the following two non-dimensional variables, which can be derived by employing the Buckingham-Pi theorem [24].

The flow coefficient defined as:

$$K_f = \frac{\dot{m}_l}{\rho_l n D^3} \tag{3.5}$$

Where

$$\dot{m}_l = \frac{\dot{m}_l}{k} \quad \text{(parallel cascade only)} \tag{3.6}$$

With ρ_l the fluid density (1,000kg/m^3), n the rotational speed of the pump and D the rotor diameter.

The pressure head coefficient is defined as:

$$K_h = \frac{dP_l}{\rho n^2 D^3} \tag{3.7}$$

With dP_l defined as the static pressure rise.

Any specific pump is characterised by the relation between these two coefficients. Simple polynomial regressions will be used namely:

$$K_h = a_0 + a_1 K_f + a_2 K_f^2 + ... + a_k K_f^k \tag{3.8}$$

With a_0 to a_k the k+1 correlation coefficients derived from the data sheets. The order of the polynomial equation may vary from model to model and will be determined by the shape of the K_h versus K_f relation.

Also

$$\eta_{pump} = b_0 + b_1 K_f + b_2 K_f^2 + ... + b_k K_f^k \tag{3.9}$$

Where

$$Q_l = \frac{(1-\eta_{pump})\dot{m}_l dP_l}{\rho_l \eta_{pump}} \tag{3.10}$$

And

$$T_{le} = T_{li} + \frac{Q_l}{\dot{m}_l c_{pl}} \tag{3.11}$$

With c_{pl} = 4,187J/kg°C.

The power required is defined by:

$$Pwr = \frac{k\dot{m}_l dP_l}{\rho_l \eta_{pump} \eta_{motor}} \tag{3.12}$$

To be able to use the model appropriately, the user needs to provide certain information pertaining to the model. This includes the amount of stages, efficiency of the pump, static pressure rise and mass flow rate through the pump.

Chiller model

The schematic layout of a water-cooled chiller is shown in Figure 3-3. This schematic was used to derive the models [25], [26].

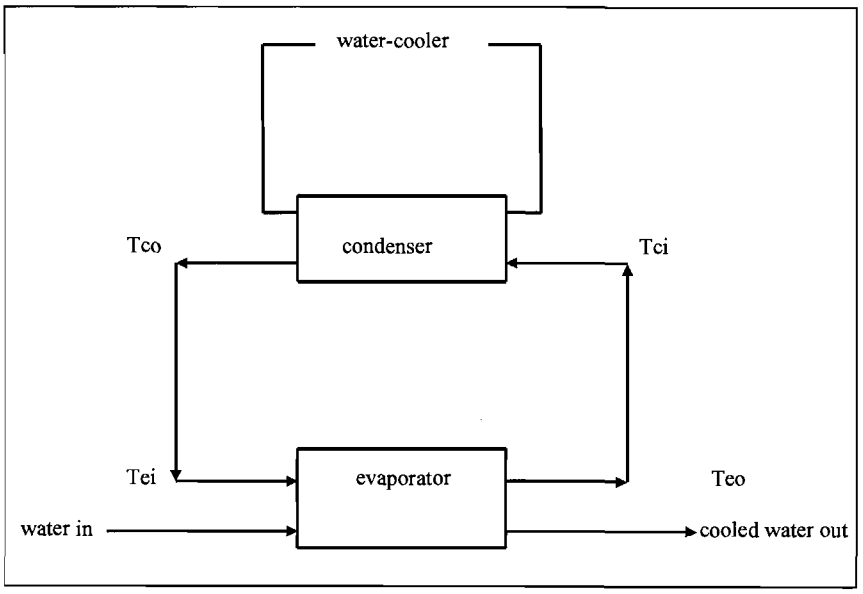


Figure 3-3: Schematic layout of a water-cooled chiller [27].

Explicit equations yield:

$$Q_e = f\left(a_0 + a_1 t_{li(cond)} + a_2 t_{li(evap)}\right) \tag{3.13}$$

With

$$a_2 = 0.0266Cc + 2.8714$$

$$a_1 = -0.01Cc + 0.2289$$

$$a_0 = Cc - (t_{ci}a_1 + t_{ei}a_2)$$

Coefficients a_2 and a_1 were found to be linear over a wide range of chillers with respect to cooling capacity. a_0 is calculated from the one given operating point obtained from the supplier or measurements. This implies that only one operating point is needed to obtain the mathematical model of a specific chiller.

$$Pwr = f(b_0 + b_1 t_{li(cond)} + b_2 t_{li(evap)}) \tag{3.14}$$

With

$$b_2 = 0.007P + 0.3549$$

$$b_1 = 0.0124P + 0.4207$$

$$b_0 = P - (t_{ci}b_1 + t_{ei}b_2)$$

Coefficients b_2 and b_1 were found to be linear over a wide range of chillers with respect to compressor power. b_0 is calculated from the one given operating point from the supplier or measurements. This implies that only one operating point is needed to obtain the mathematical model of a specific chiller.

$$t_{le(cond)} = t_{li(cond)} - \frac{Q_e + Pwr}{m_{l(cond)}c_{pl}} \tag{3.15}$$

$$t_{le(evap)} = t_{li(evap)} - \frac{Q_e}{m_{l(evap)}c_{pl}} \tag{3.16}$$

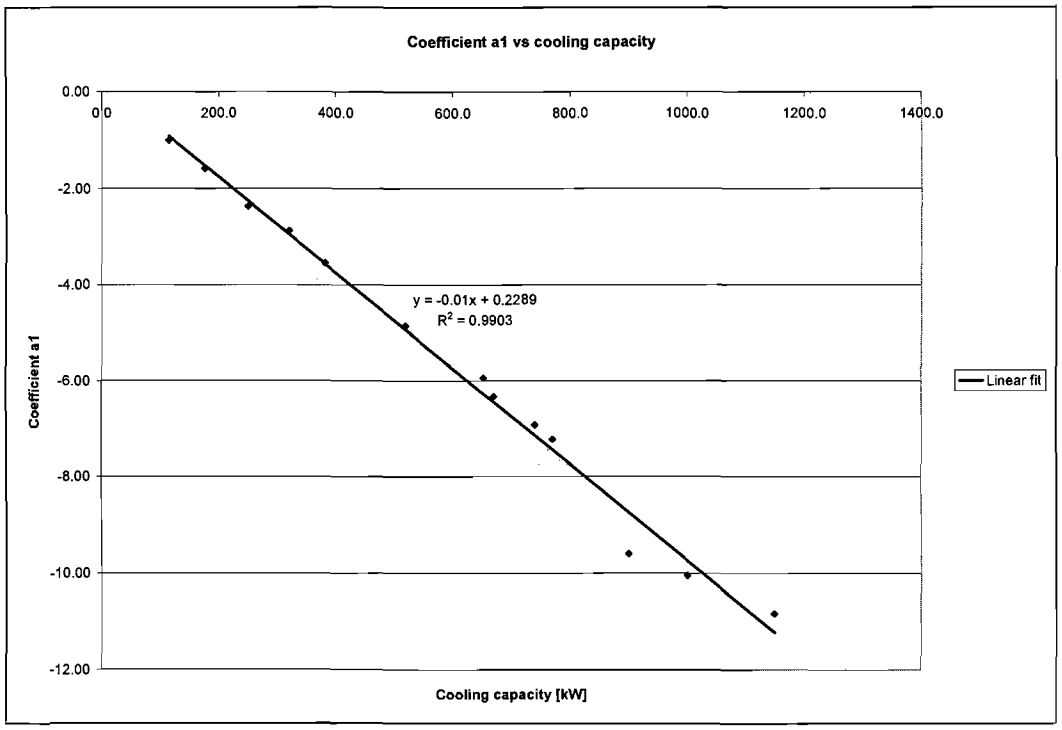


Figure 3-4: Coefficient a1 as a function of cooling capacity.

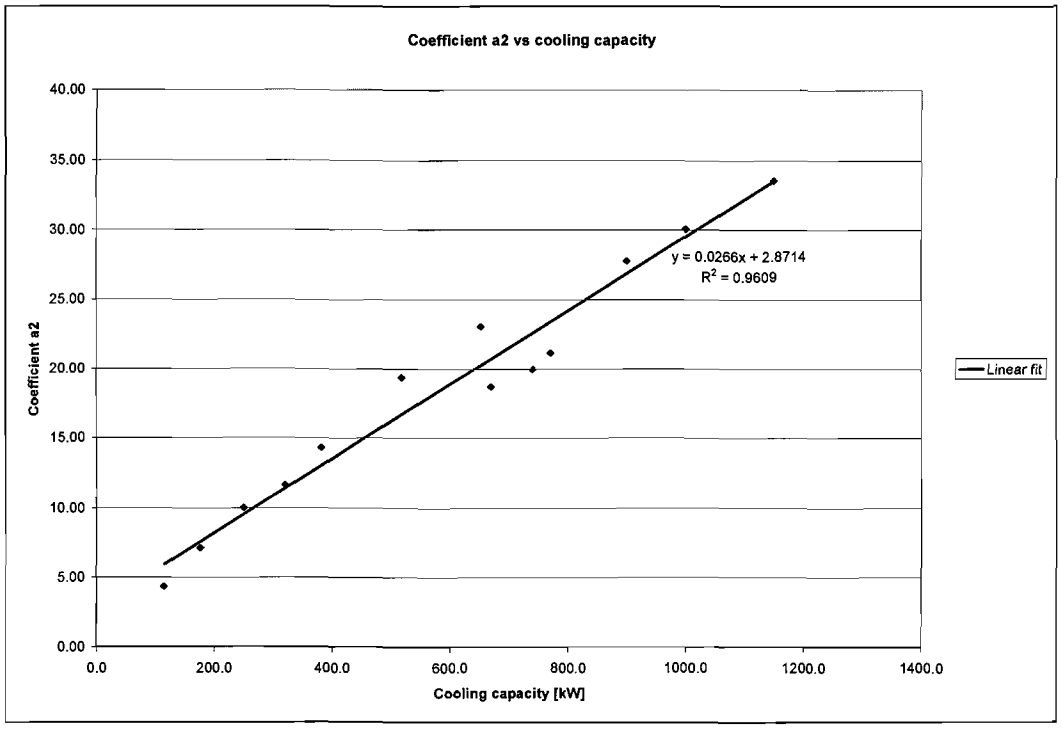


Figure 3-5: Coefficient a2 as a function of cooling capacity.

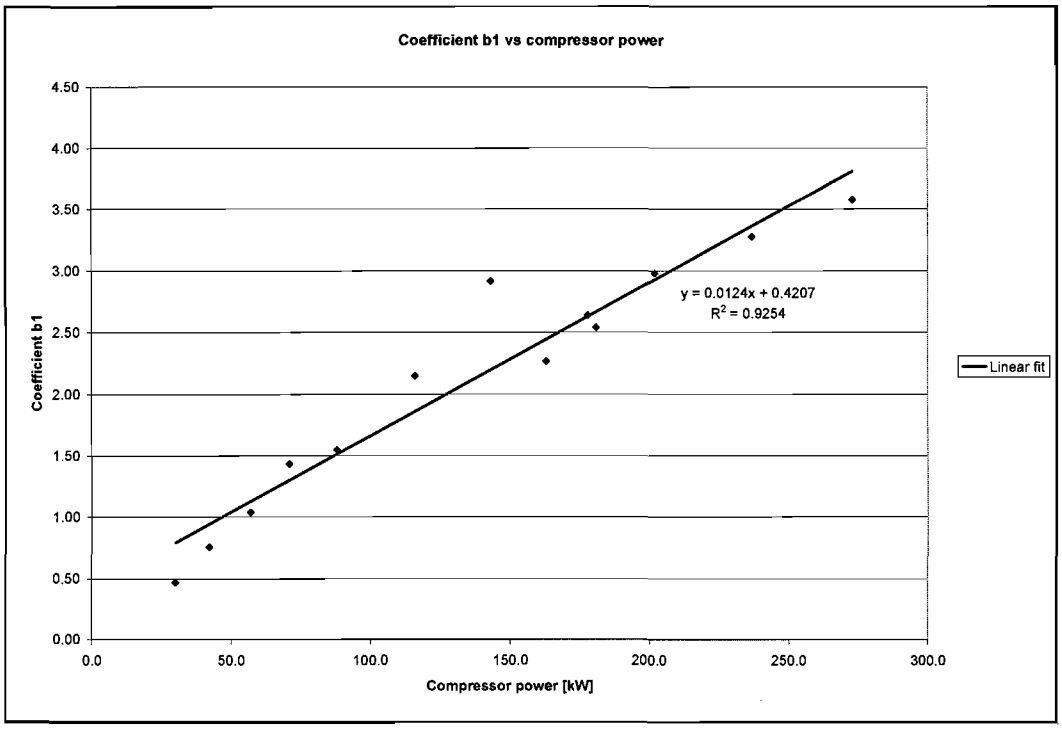


Figure 3-6: Coefficient b1 as a function of compressor power.

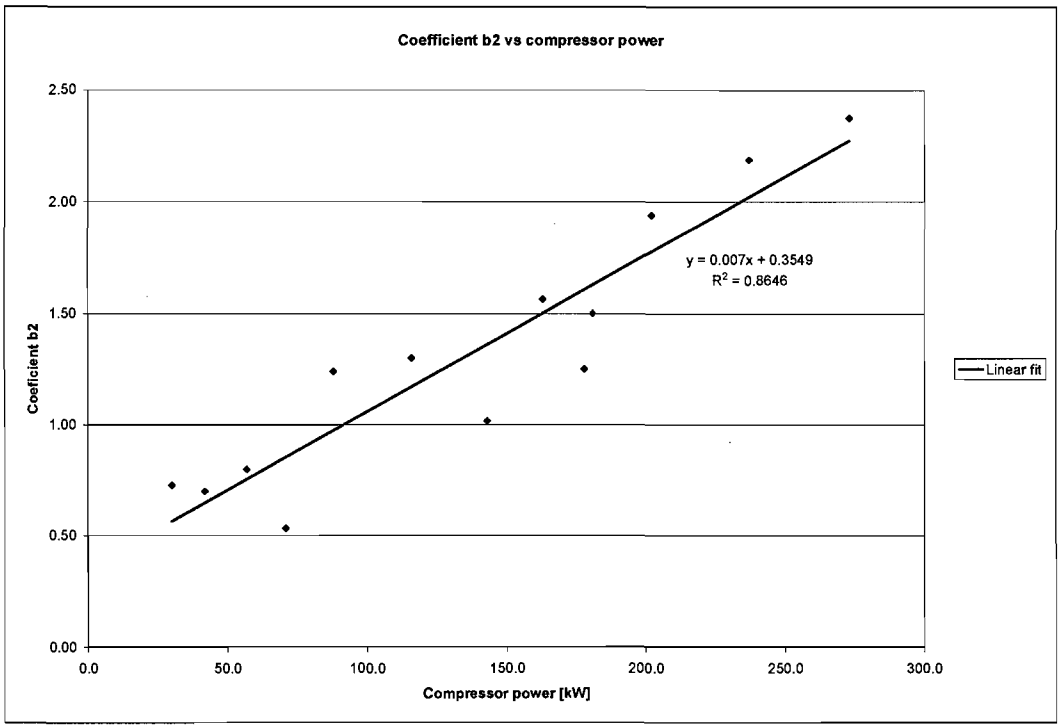


Figure 3-7: Coefficient b2 as a function of compressor power.

Cooling Towers

Many systems make use of cooling towers in various forms. The most common application is on the condensing side of a chiller. It is used to reject heat to the atmosphere by reducing the temperature of water circulated through the condensers or other heat rejecting equipment [22]. This same principle can also be used to cool down hot air with cooled water. It then becomes known as a bulk-air cooler (BAC). Figure 3-8 shows the schematic view of the cooling tower model.

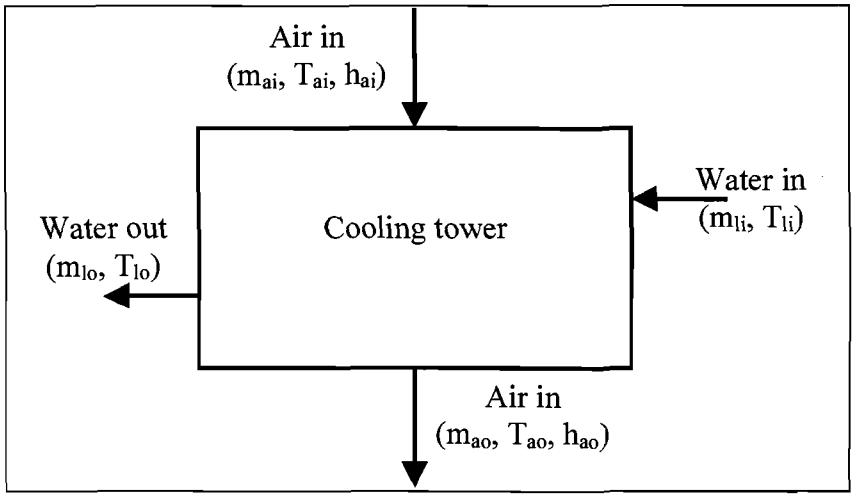


Figure 3-8: Schematic view of a cooling tower.

Data from manufacturing catalogues is used to predict the explicit equation of the cooling capacity, Q_c, for a cooling tower model [28]. The relation between the cooling capacity and the water mass flow can be given by:

$$Q_c = A(T_{wb})m_{li}^B \tag{3.17}$$

with m_{li} the water mass flow (Liquid) through the cooling tower and T_{wb} the wet-bulb temperature of the ambient air. The variable B is constant over a range of various cooling towers.

The constant A is a function of the wet-bulb temperature of the air flowing through the cooling tower as described by Equation 3.18.

$$A = C(T_{li})T_{wb} + D(T_{li}) \tag{3.18}$$

The gradient (C) and the constant (D) are functions of the water inlet temperature, T_{li}, as described in Equations 3.19 and 3.20.

$$C = a_0 T_{li} + a_1 \tag{3.19}$$

$$D = a_2 T_{li} + a_3 \tag{3.20}$$

The coefficients a_0, a_1, a_2, a_3 are empirical curve fit coefficients. By substituting Equation 3.18, 3.19 and 3.20 into Equation 3.17 an empirical equation is derived for the cooling capacity of a cooling tower.

$$Q_c = [(a_0 + a_1 T_{li})T_{wb} + a_2 T_{li} + a_3]m_{li}^B \tag{3.21}$$

With the cooling capacity calculated, the outputs of the model, outlet temperature (T_{le}) and air enthalpy (h_{ae}) can be calculated through:

$$T_{le} = T_{li} - \frac{Q_c}{m_l c_p} \tag{3.22}$$

$$h_{ae} = h_{ai} + \frac{Q_c}{m_a} \tag{3.23}$$

The exit air temperature (T_{ae}) can be calculated using psychometric relations if it is assumed that the air is completely saturated. Once again, some of the inputs are user inputs on a form of interface and the rest is gained from the calculations from the previous component.

3.5. VERIFICATION PROCEDURE

To successfully verify a simulation model a proper verification protocol is compulsory. Verification and validation of analysis tools are generally neglected or only performed as an afterthought [29], [30]. Lack of a well-defined verification protocol or methodology and difficulties in obtaining good data are often stated as reasons for this [31]. Shortage of funds, time and published information also contribute to this problem [32].

It's a fact that one cannot manage what cannot be measured, or as former *GE Co.* CEO Jack Welch said, *"If you're not measuring it, it's just a hobby"* [33].

The United States Department of Energy, in consultation with organisations and experts from over 25 countries, formulated a measurement and verification protocol to assist businesses in using and gaining financial advantages with energy management [34]. The protocol offers the client and specialised consulting company the following advantages:

- Increase energy savings;
- Reduce cost of financing of projects;
- Encourage better project engineering;
- Help demonstrate and capture the value of reduced emissions from energy efficiency and renewable energy investments;
- Increase public understanding of energy management as a public policy tool; and
- Help national and industry organisations promote and achieve resource efficiency and environmental objectives.

This protocol is applicable to a variety of facilities, including residential, commercial, institutional and industrial buildings and processes. It can be used as a measure with which savings can be calculated and can help ensure sustainability of energy management programmes.

Verification is of critical importance. In most, if not all simulation models assumptions are made at some stage. Verification and validation is one of the only methods of testing these assumptions and proving them valid. Verification and validation of simulation tools can be done through three techniques [30]:

- Analytical verification: The model or tool is tested and compared to exact solutions;
- Inter-model comparisons: The predictions of various tools and models are compared to each other; and
- Empirical validation: The tools simulated results are compared to measured data from an actual system.

The last technique is the most exact. It offers tangible results that the user can use and understand. Irving and Bowman [35] et al describe the advantages and disadvantages of all three techniques mentioned above. They also describe the last option as the one with the most potential, but Bowman also warns of difficulties and uncertainties that may occur.

Most of these difficulties can be negated with a proper verification procedure. The following verification procedure was used to verify model predictions (see
Figure *3-9*):

1. The first step in the verification process is to identify a suitable mine for the exercise. It must have a typical ventilation, cooling and pumping system. Non-standard equipment will need additional development of mathematical models. The mine must be large in size to serve as an extreme case. This will establish good verification, acceptable for all other size mines.
2. A detailed schematic description of the mine's ventilation, cooling and pumping (VCP) systems is required. This can also help in determining possible measuring points where the verification measuring equipment can be placed for the needed measurement data. Making sure at an early stage that measuring equipment can be placed in certain areas will ensure the timely completion of the measuring stage.

3. Obtain detailed specifications of the equipment. This can be done in various ways. It is important to get as much information on the system as possible for it will minimise guesswork and assumptions later on. Do a walk-through with the engineer or maintenance technician.
4. Get the original specifications from the mine engineer or manufacturers. Often there exists a maintenance manual with most of the relevant data. This can be used as a source for comparing measured data to see if the system is working properly.
5. With the detailed information of the system and its equipment, build up the integrated simulation model. Using the specifications of the equipment, the individual components in the software can be constructed.
6. From the detailed layout of the system, determine the measuring equipment needed and what is available at the mine. Many mines use their own measuring systems, like the SCADA system, where the mine measures certain temperatures, fluid flows and power consumption for their own control and management systems.
7. Using such systems can greatly cut back on measuring equipment needed and therefore project cost. It is important to still use separate measuring equipment for important measurements to ensure and check the accuracy of the mine's own measuring system.
8. After a period of time the measured data can be retrieved and interpreted. It can be processed into useful formats that can be used later on for verification purposes.
9. With the measured data the simulation system and equipment can be calibrated further to ensure the best possible simulation results.
10. A typical day must be selected from the measured data. The simulation model must be built up to emulate this typical day. Important considerations for this are: scheduling of equipment, control set points, etc.
11. The simulated results can now be compared to the measured data for that day.
12. If the results are acceptable (error between measured and simulated data is small) the model can be used for further studies and the analysis of different control strategies and system configurations.
13. If the results are not sufficiently accurate the simulation system has to be recalibrated and the system adjusted. The simulation has to be run again and compared to the measured data until a satisfactory result is obtained.

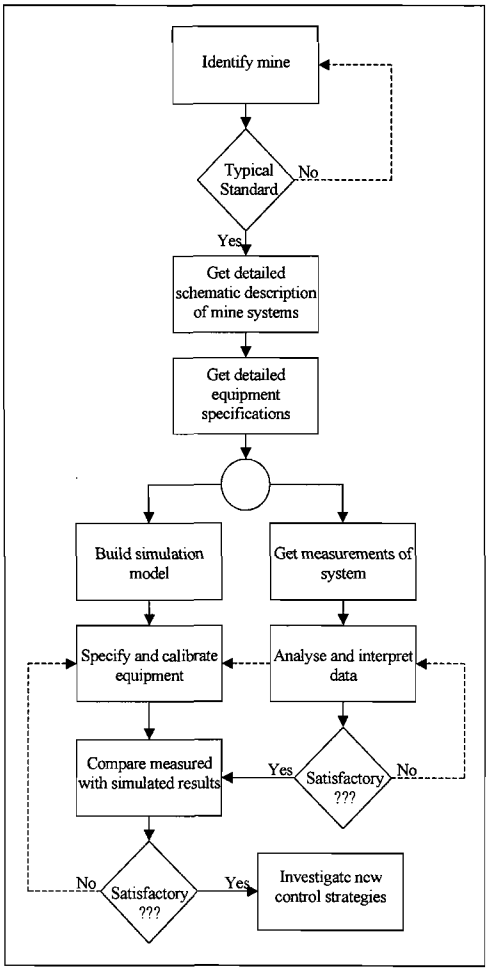


Figure 3-9: Flowchart of verification process.

3.6. MODEL CALIBRATION AND VERIFICATION

VERIFICATION CASE STUDY: KOPANANG GOLD MINE

Software for dynamic, integrated simulations already exists for the same type of DSM investigations in buildings [36], [37], and [38]. The software, named *QUICKControl*, which was developed by *TEMM International*, could be adapted to mining applications because it is entirely component based. The simplified component models were integrated into this existing software.

The surface refrigeration system of Kopanang Gold Mine was modelled and simulated. Actual system measurements over a period of three months (obtained from the system's SCADA) were used to calibrate and verify simulation model predictions. A typical summer day was averaged from the data and used for verification purposes.

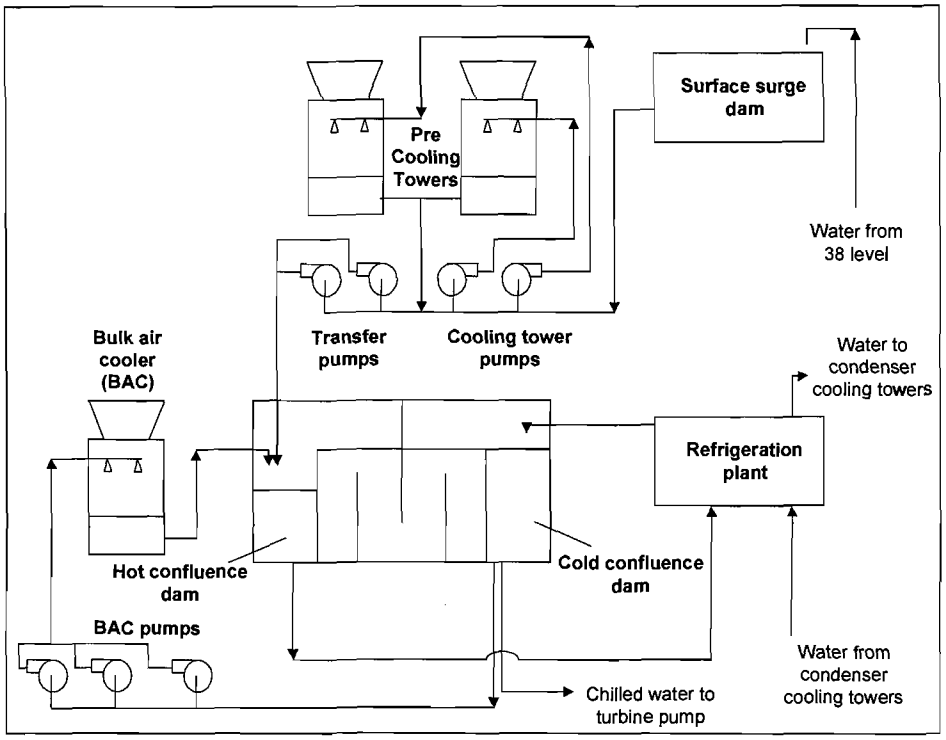


Figure 3-10: Schematic layout of refrigeration system at Kopanang.

The water enters the surge dam at 27°C from the mine. This water is pumped through the two pre-cooling towers. The water leaves the pre-cooling towers at a temperature of ± 15°C. The transfer pumps pump this water to the hot confluence dam. Here the water returning from the BACs and the pre-cooling towers, mix.

This water is now reticulated to the refrigeration plant. The plant consists of six identical chillers with a combined thermal capacity of 33 MW. The coefficient of performance (COP) of the chillers is 5.5. The evaporator pumps pump the hot water through the evaporator where it leaves the evaporator on its way to the cold confluence dam at 3.5°C.

The condenser water is pumped to the condenser cooling towers to be cooled. Each chiller has its own condenser cooling tower. The water at the cold confluence dam is sent to the turbine (250kg/s) and to the bulk air cooler (250kg/s per cell). The bulk air cooler (BAC) consists of three cells in parallel each with its own pump. The BAC is used to cool the entering ventilation air used for cooling. The water leaves the BAC at 8°C.

Temperature verification

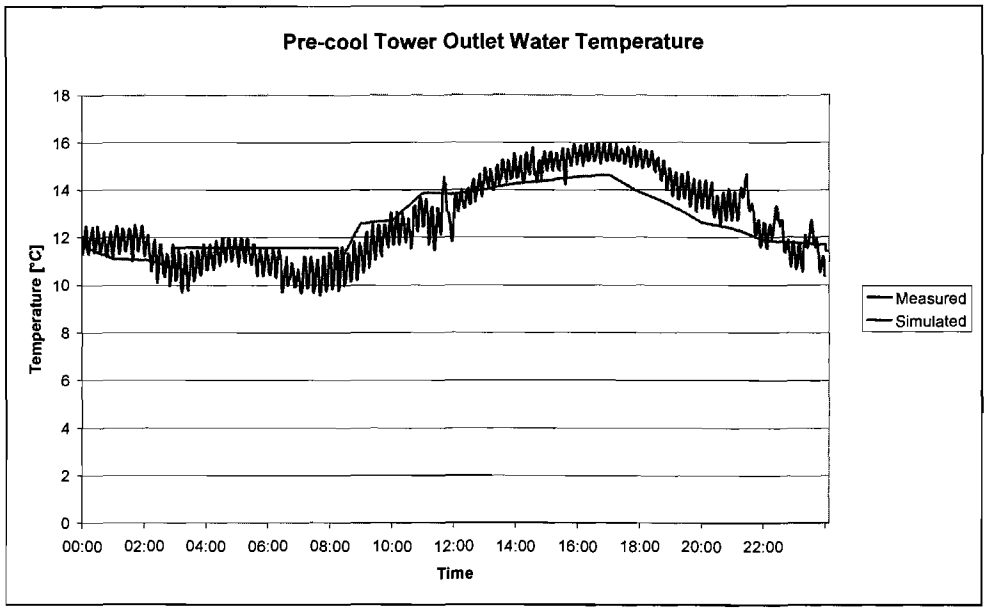


Figure 3-11: Pre-cooling outlet water temperature.

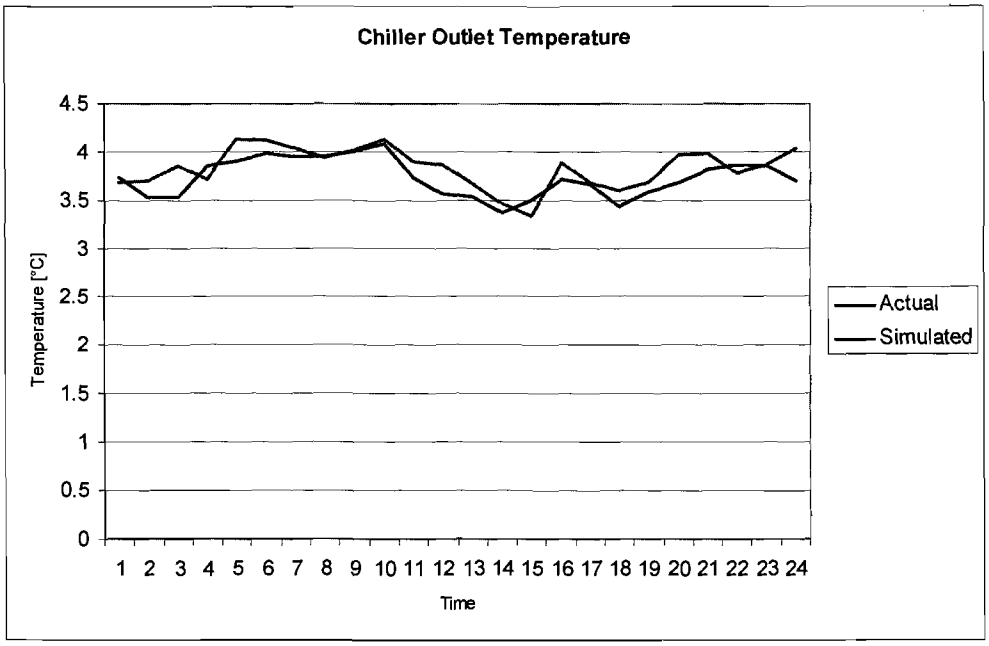


Figure 3-12: Chiller outlet water temperature.

Flow verification

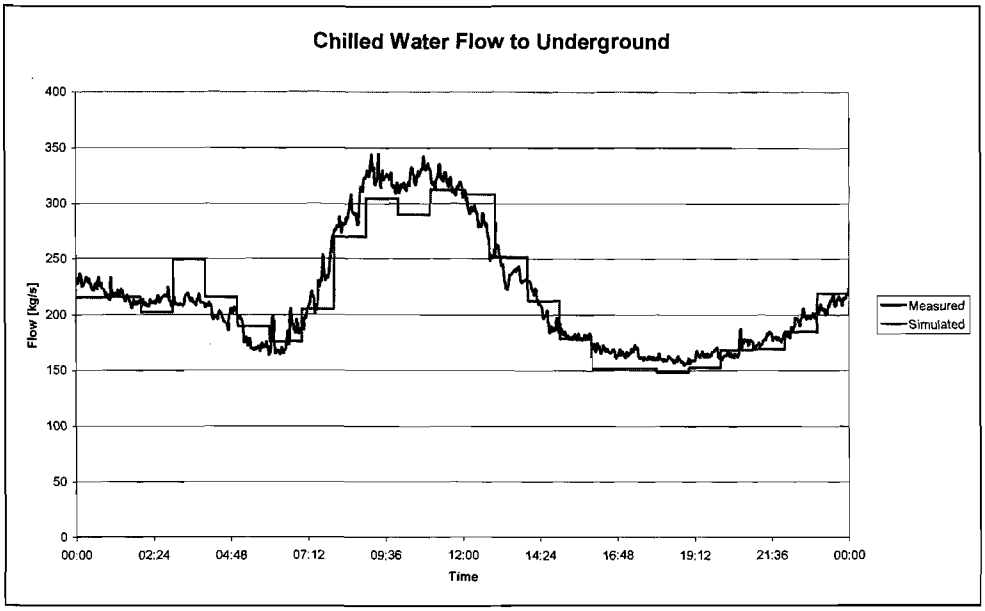


Figure 3-13: Chilled water flow to underground.

Storage level verification

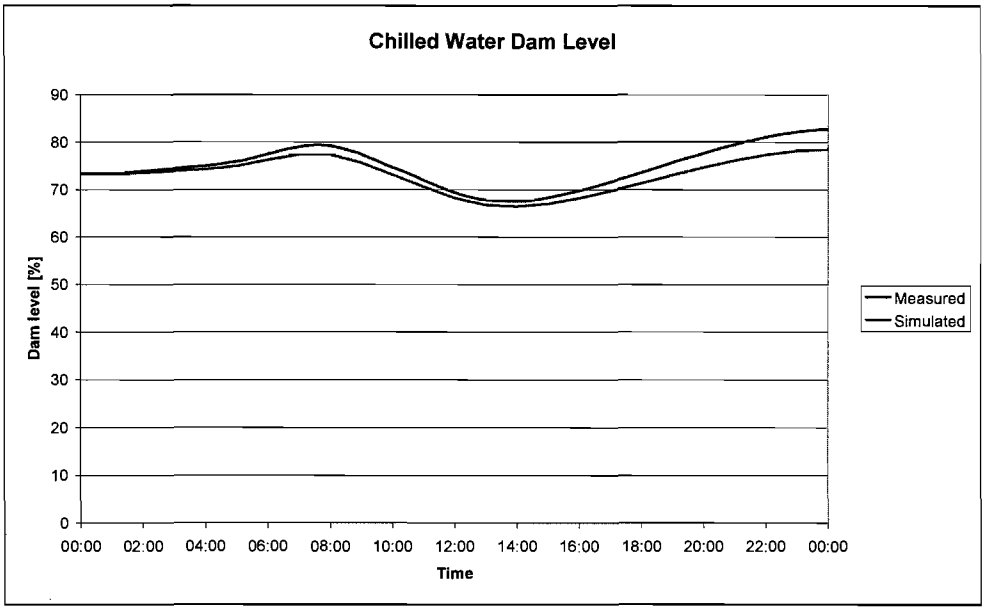


Figure 3-14: Chilled water dam level.

Compressor power verification

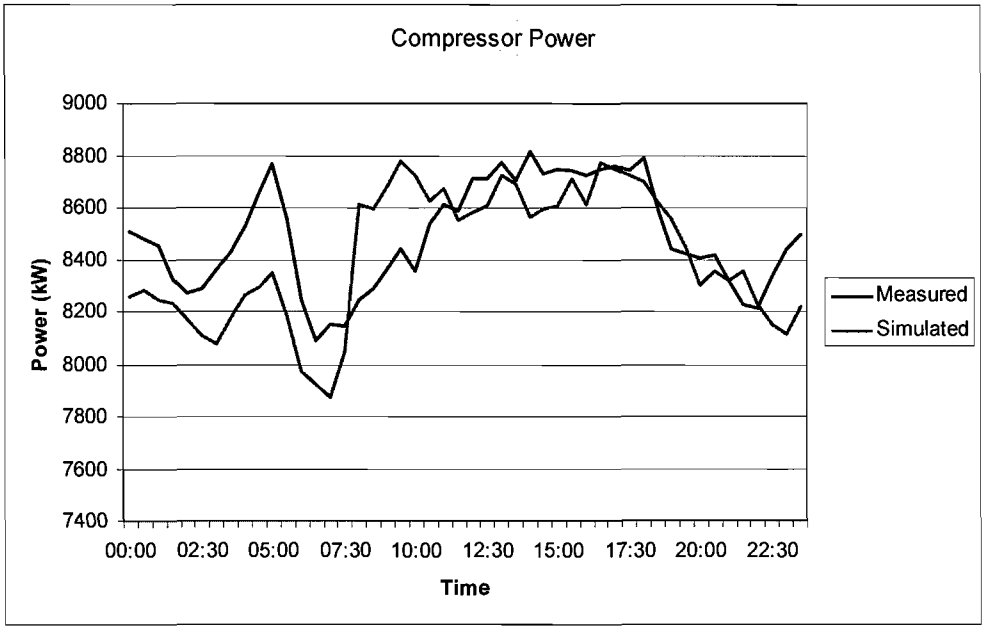


Figure 3-15: Compressor absorbed power.

Average chilled water temperature, chilled water flow, storage dam level and machine absorbed power baselines were calculate from the SCADA data and used for verification purposes. These baselines represent the system operation on a typical summer day.

It was decided that a $\leq 10\%$ difference between predicted and actual results would be sufficient for verification purposes. Verification results proved to be adequate ranging between 90% and 98% accuracy between measured and applicable predicted results.

PARAMETER	AVERAGE ERROR
Chiller outlet temperature	2.68%
Flow to underground	2.08%
Chill dam level	5.71%
Compressor power	8.19%

Table 3-1: Summary of the verification results of important system parameters for an average typical day of system operation.

3.7. DEVELOPING A LOAD SHIFT CONTROL STRATEGY

In Chapter 1 an introduction to the Eskom tariff structure MegaFlex was given. According to this structure the cost of energy during the evening peak period (18:00 – 20:00) is much more expensive than other periods of the day (an expensive peak also exists in the morning from 07:00 to 10:00). Chapter 1 also gave an overview of the challenge Eskom is facing providing sufficient energy during the evening peak period.

If electrical power can be moved from this evening peak period to a cheaper period of the day, the mine will save on electricity cost, and such a project can be registered with Eskom as a DSM project (and as such qualify for capital investment from Eskom DSM – see Chapter 1). Through optimal machine usage and utilisation of chilled water storage capacity, an attempt could be made to shift electrical load from the evening peak period to an off-peak period.

An electrical energy baseline was developed from historical data (3 months – this is an Eskom requirement). This was done to obtain a realistic picture of the power absorbed by the refrigeration system over a typical 24-hour period, and to quantify DSM attempts in terms of electrical energy.

The strategy discussed in Section 2.6 (utilisation of thermal storage capacity) was further developed. The simulation model was used to attempt to move electrical power for 2 hours (18:00 – 20:00) and quantify the response of the rest of the system. Required control algorithms were identified and developed into "controllers". These controllers are:

1. Valve controllers for control of:

    - Evaporator flow;
    - Condenser flow;
    - Back-pass flow;
    - Normal reticulation system flow; and
    - Dam levels.

2. Chiller machine controllers for:

    - Machine shutdown;
    - Machine start-up; and
    - Back-pass capability.

3. Chilled water reticulation controllers (named "T-pipe" controllers in this study) for control of:

    - Divergent flow; and
    - Convergent flow.

4. Dam level controller for control of:

    - Chilled water dam levels;
    - Cold water dam levels;
    - Pre-cool water dam levels; and
    - Hot water dam levels.

5. Dam temperature controllers for control of:

    - Chill dam water temperatures.

6. Overall system preparation controller for:

    - System preparation for load shifting incorporating all above mentioned controllers (this controller has predictive as well as adaptive capabilities).

These control algorithms are discussed in more detail in Chapter 4 and 5.

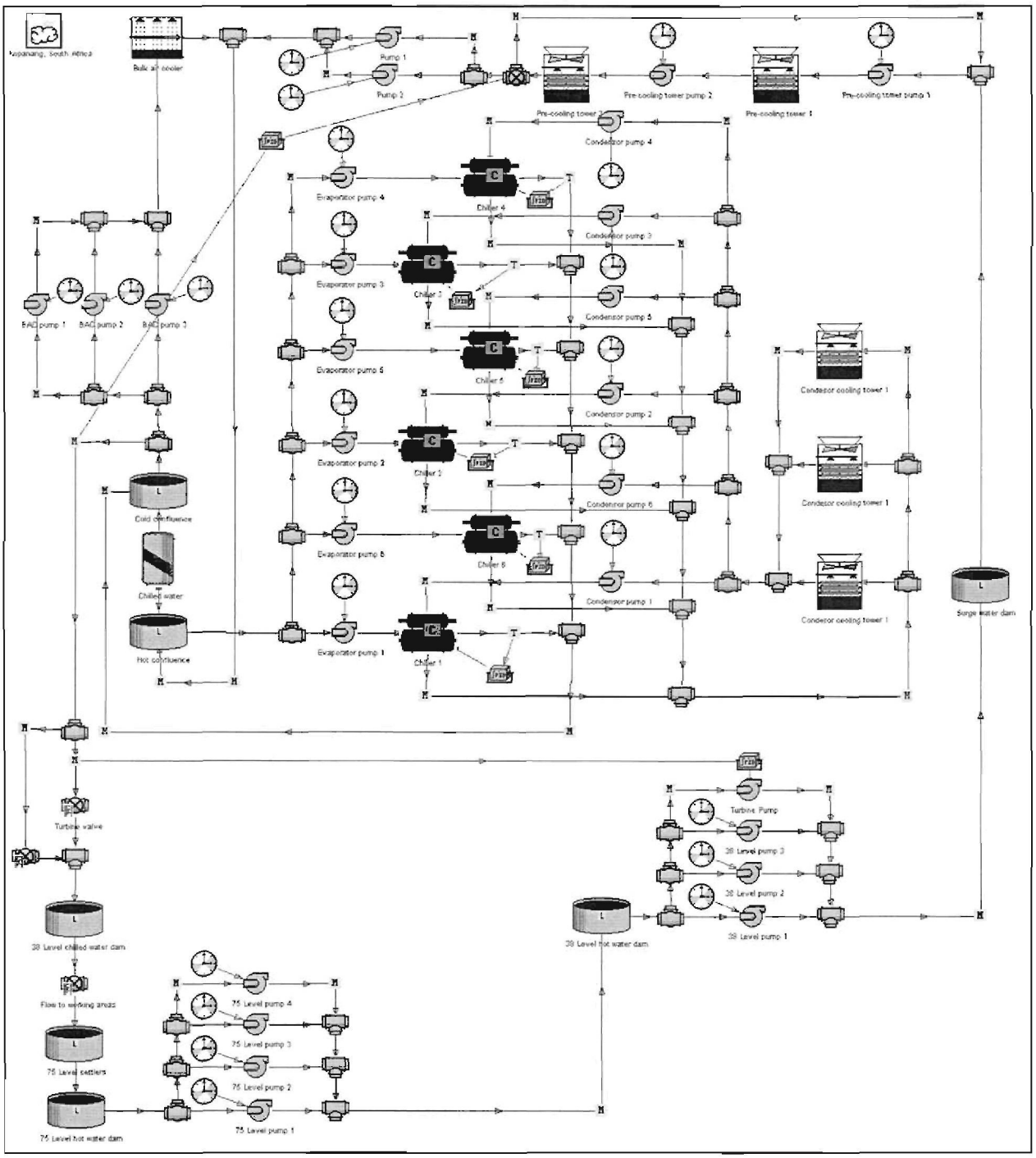


Figure 3-16: QUICKControl simulation model layout.

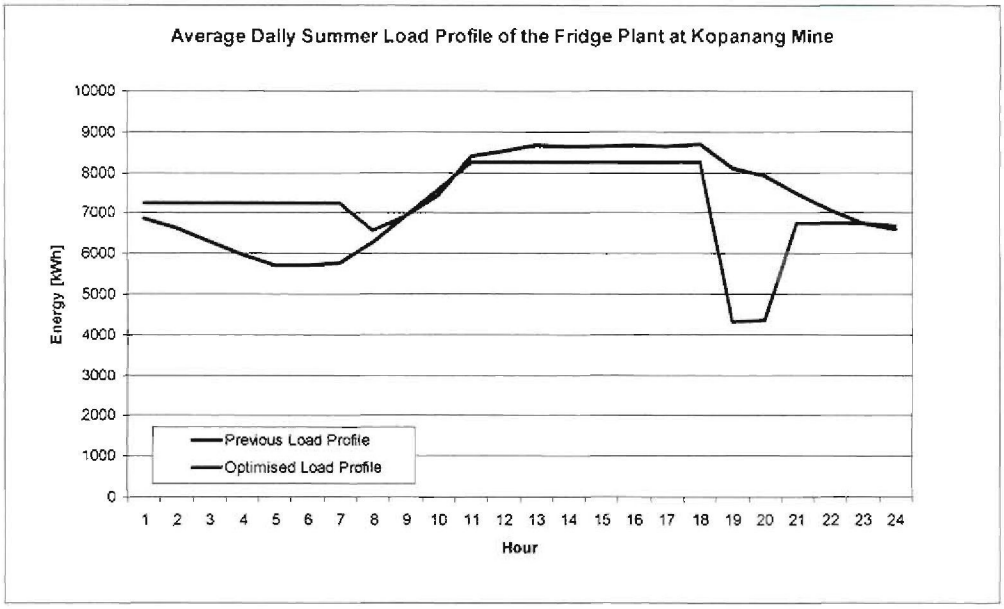


Figure 3-17: Target load shift result (simulated for summer).

The figure above shows the simulated optimised load shift profile. Load could be shifted from the system's operational profile without influencing the supply or temperature of chilled water to the BAC-circuit or underground equipment. Through simulation it was possible to attempt a load shift strategy and investigate the effect on important system parameters.

3.8. CONCLUSION

Traditionally, proposing a load shift strategy in mine refrigeration systems was met with great resistance from mine personnel. This was greatly because of stringent system constraints applicable to the supply of chilled water to mine systems and because the effect on the system due to load shifting could not be predicted.

By using a verified simulation model which can simulate the entire chilled water supply system, the response of this system due to load shifting can be predicted. Through adequate control algorithms the load shift potential (if a potential exists) can be realised, while making sure no constraints are violated. The predictions made by the simulation system developed in this Chapter were verified with accuracy results above 90% compared to actual measurements.

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CHAPTER 4

ESTABLISHING DSM POTENTIAL IN DEEP MINE REFRIGERATION SYSTEMS

4. ESTABLISHING DSM POTENTIAL IN DEEP MINE REFRIGERATION SYSTEMS

4.1. PREAMBLE

New control algorithms were developed to control the refrigeration system of a mine for load shift purposes. These algorithms were combined into a new global control philosophy which can be applied to a refrigeration system to establish a load shift potential. A unique investigation protocol was developed which can be used to investigate any refrigeration system for a load shift potential.

A detailed integrated control strategy is needed to realise a load shift potential in a refrigeration system. To ensure that the process constraints of these systems are adhered to, these control strategies need to be simulated to predict a system's response to load shift strategies. Through application of a generic investigation methodology a load shift potential can quickly and accurately be established in these systems.

A population of South African mines were identified and investigated for DSM purposes. The process parameters of the identified case studies were established and used in the simulation models as boundary constraints. These systems were simulated and the investigation and control methodologies were applied to them.

Simulation results of the four identified case studies showed load shift potentials ranging from 2.5 to 6MW (reduced from the evening peak period of 18:00 – 20:00).

The generic nature of the global control philosophy was proved. The application of the DSM investigation protocol proved to be quick and accurate.

4.2. NEW CONTROL ALGORITHMS

CONTROL LAYOUT

Schematically the control layout of a fridge plant should look as follows (control signals are given to plant PLCs via a SCADA system):

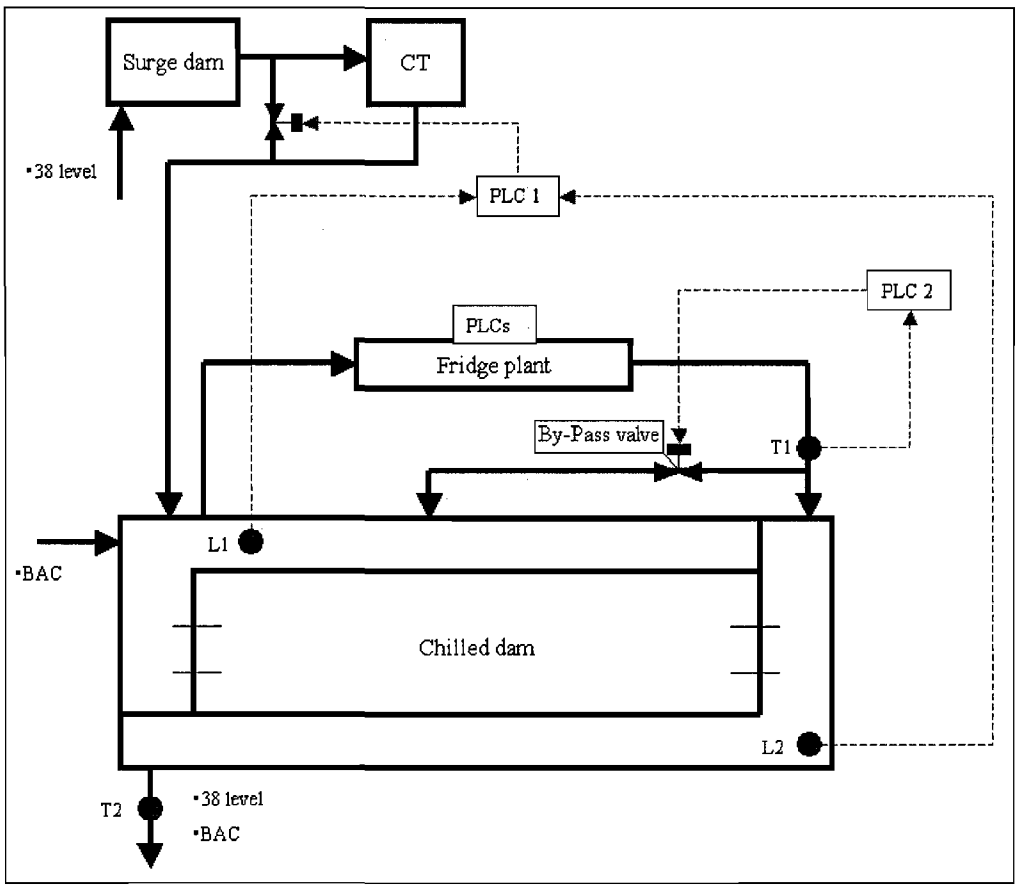


Figure 4-1: Control layout of Kopanang refrigeration system.

VALVE CONTROLLER

System variables

The valve controller must consider various system variables such as:

- Available control valves;
- Inlet temperature constraints (into machines for back-passing, into dams, etc.);
- Dam level limits; and
- System water flow rates.

The main purpose of the valve controller is to enable back-pass functionality in the system (this is done to reduce the inlet temperature to the machines). Two sub-controllers are therefore required:

- Temperature controller; and
- Dam level controller (to check the level of the dam where chilled water is being back-passed from).

Temperature controller

The following abbreviations are applicable:

- T_{open} = Temperature where the valve must be fully open (°C);
- T_{closed} = Temperature where the valve must be totally closed (°C);
- $T_{current}$ = Current temperature of the specific water in the system (°C);
- $V_{opening}$ = Proportional opening of the valve (%);
- T_{wanted} = Target control temperature (°C).

The following algorithms are used to calculate the valve opening to control the chiller machine's inlet water temperature:

$$V_{opening\ i} = \frac{T_{wanted} - T_{closed}}{T_{open} - T_{closed}} \tag{4.1}$$

Then:

$$V_{opening\ i+1} = V_{opening\ i} + \frac{T_{current} - T_{wanted}}{T_{open} - T_{closed}} \tag{4.2}$$

With:

If $V_{opening} > 1$ then $V_{opening} = 1$

If $V_{opening} < 0$ then $V_{opening} = 0$

As a safety precaution a control range and a temperature where the back-pass valve must be totally closed (T_{closed}) is specified. It is clear that the by-pass valve will close as soon as the inlet temperature reaches the T_{closed} temperature constraint. It will open again at the calculated quantity as soon as the control range temperature is reached and higher than the T_{closed} temperature.

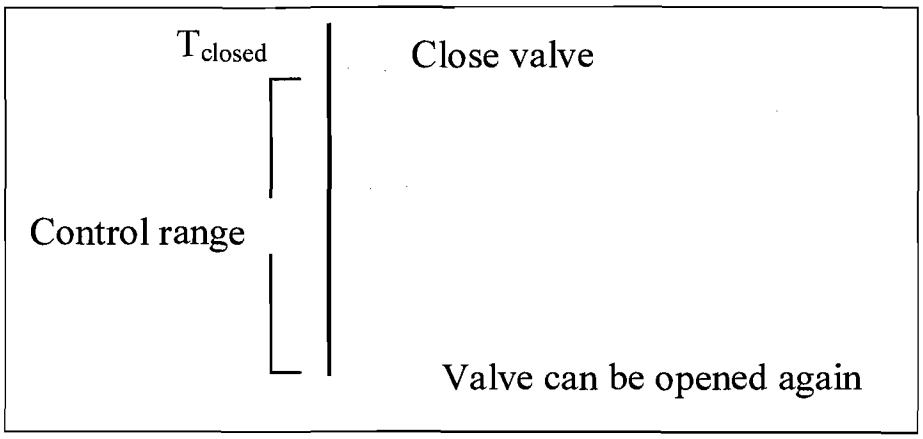


Figure 4-2: Illustration of control range application.

The dam level controller will change the valve opening according to dam level percentage. It is based on the same principle as the temperature controller, but only dependant on dam level and not inlet temperature. Algorithms to control the dam level via valve control are shown below:

$$V_{opening\ i} = \frac{Wanted\ \% - Min\ \%}{Max\ \% - Min\ \%} \tag{4.3}$$

Then:

$$V_{opening\ i+1} = V_{opening\ i} + \frac{Current\ \% - Wanted\ \%}{Max\ \% - Min\ \%} \tag{4.4}$$

With:

If $V_{opening} > 1$ then $V_{opening} = 1$

If $V_{opening} < 0$ then $V_{opening} = 0$

The outputs (%valve opening) of the algorithms explained in this section are conveyed via a SCADA system to the applicable valve control PLC (see Figure 4-1).

Input interfaces

Valve controller

Name	Check Temperature 1	Check Temperature 2	Check Dam levels	Check Water flow
Valve 1	T1		DL 1	M1
Valve 2	T3			
Valve N	T2	T1	DL 3	M3

	Control permission	Opening
Valve 1	T2	0.6
Valve 2	T1	0.2
Valve N	M3	0.N

Figure 4-3: Valve controller constraints input interface (summary).

Valve N

	Temperature: Enabled								Dam level: Enabled						Water flow: Disabled				
	Set at deg C	Control range		Control Privelege (CP)	Activation T deg C	Control range		Control Privilege (CP)	Disable when T >	Min Opened %	Max Closed %	Min outflow dam level %	Set dam level %		Control Privilege (CP)	Lose CP when inlet T >	l/s	Min outflow dam level %	
1	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
2	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
3	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
4	3	2	Enabled	3	5	0.3	Enabled	2	5	50	80	35	65	Enabled	1	5	200	35	Disabled
5	3	2	Enabled	3	5	0.3	Enabled	2	5	50	80	35	65	Enabled	1	5	200	35	Disabled
6	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
7	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
8	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
9	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
10	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
11	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
12	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
13	3	2	Enabled	2	5	0.3	Enabled	1	5	50	80	35	65	Enabled	3	5	200	35	Disabled
14	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
15	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
16	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
17	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
18	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
19	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
20	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
21	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
22	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
23	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled
24	3	2	Enabled	1	5	0.3	Enabled	2	5	50	80	35	65	Enabled	3	5	200	35	Disabled

Closed at 1 deg C
Opened at 6 deg C
Temperature tag

Temperature tag

Level tag | Control range 5 %

Max flow 300 (l/s)
Min flow 0 (l/s)

Flow tag
Temperature tag

Figure 4-4: Valve controller detail input interface.

CHILLER MACHINE CONTROLLER

Machine shutdown controller

The following abbreviations are applicable:

- C = Current available cold water dam capacity (l);
- $C_{C\%}$ = Current cold water dam level (%);
- C_{max} = Maximum cold water capacity (l);
- $C_{min\%}$ = Minimum cold water dam level (%);
- M_{supply} = Total water supply rate through entire refrigeration plant (l/s);
- M_{CH} = Water flow rate per plant (l/s);
- S_{ti} = Shutdown time for a specific plant (seconds);
- M_{mine} = Water flow from mine (l/s);
- ps = Peak period time (seconds);
- N = Number of machines available;
- I = Number of machines active during the peak period;
- Damlevel% = Predicted cold water dam level at end of the peak period; and
- Q = Predicted load shift (kW).

The following algorithms are used to establish chiller machine shutdown control [1], [2]:

$$C = \frac{(C_{C\%} - C_{min\%}) \times C_{max}}{100} \tag{4.5}$$

$$M_{SUPPLY} = (N \times M_{CH}) - ((N - i) \times M_{CH}) \tag{4.6}$$

$$St_i = C + \frac{ps \times M_{SUPPLY}}{M_{mine}} \tag{4.7}$$

$$Damlevel\% = \frac{\left[\left(C_{C\%}/100 \times C_{\max}\right) - \left(M_{\min e} \times ps\right) + \left(M_{SUPPLY} \times ps\right)\right] \times 100}{C_{\max}} \tag{4.8}$$

$$Q = \frac{\left(M_{\min e} - FridgePlant\ water\ \sup ply_{live\ tag}\right) \times C_p \times Typical\ \Delta T}{COP} \tag{4.9}$$

Where the C_p is the specific heat of water = 4.2 [kJ/kg°C]

Input and output interfaces

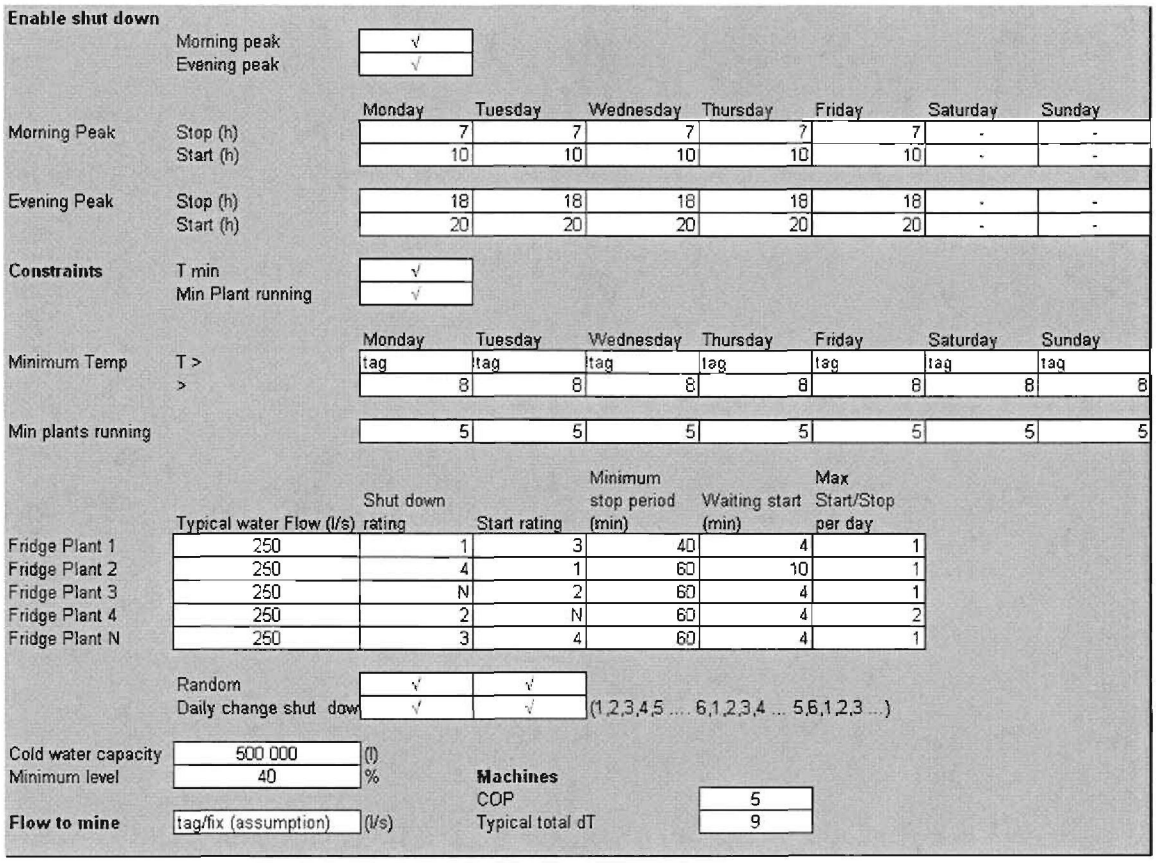


Figure 4-5: Input interface for shutdown controller.

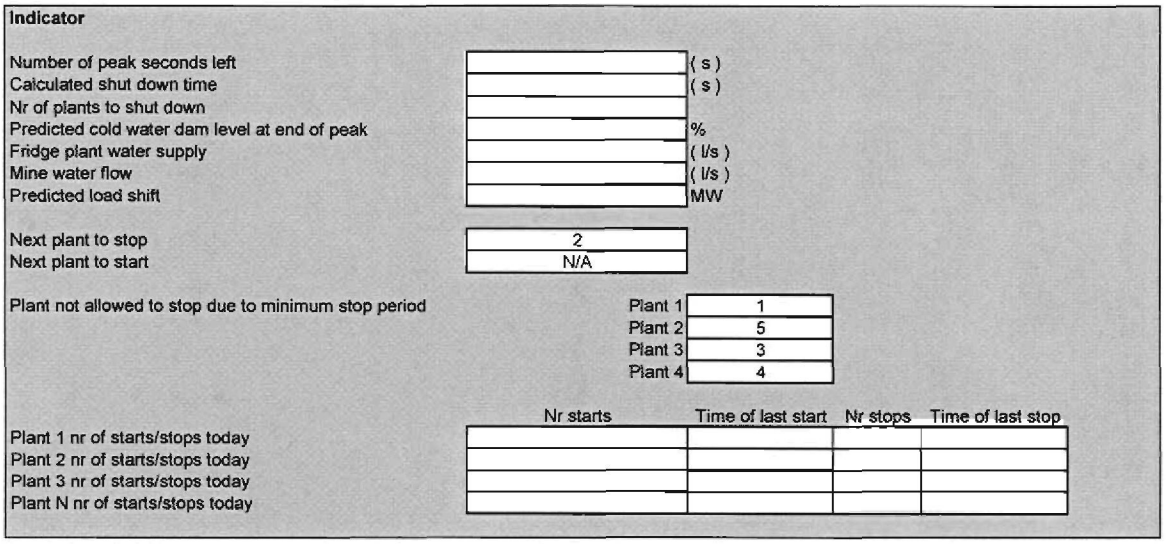


Figure 4-6: Output interface for the shutdown controller.

WATER RETICULATION CONTROLLERS

"T-pipe" controller

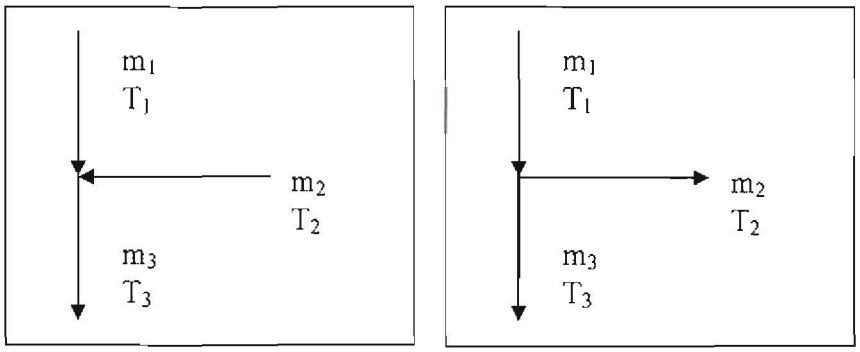


Figure 4-7: Illustration of flow convergence and divergence.

The following abbreviations are applicable:

- $\dot{m}$ = Mass flow (l/s);
- T = Temperature (°C).

Control algorithms used to account for convergent and divergent (in this order) flows are shown below:

Convergence:

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2 \tag{4.8}$$

$$T_3 = \frac{T_1\dot{m}_1 + T_2\dot{m}_2}{m_1 + m_2} \tag{4.9}$$

Divergence:

$$\dot{m}_3 = \dot{m}_1 - \dot{m}_2 \tag{4.10}$$

$$\begin{aligned} T_3 &= T_1 \\ T_2 &= T_1 \end{aligned} \tag{4.11}$$

Input interface

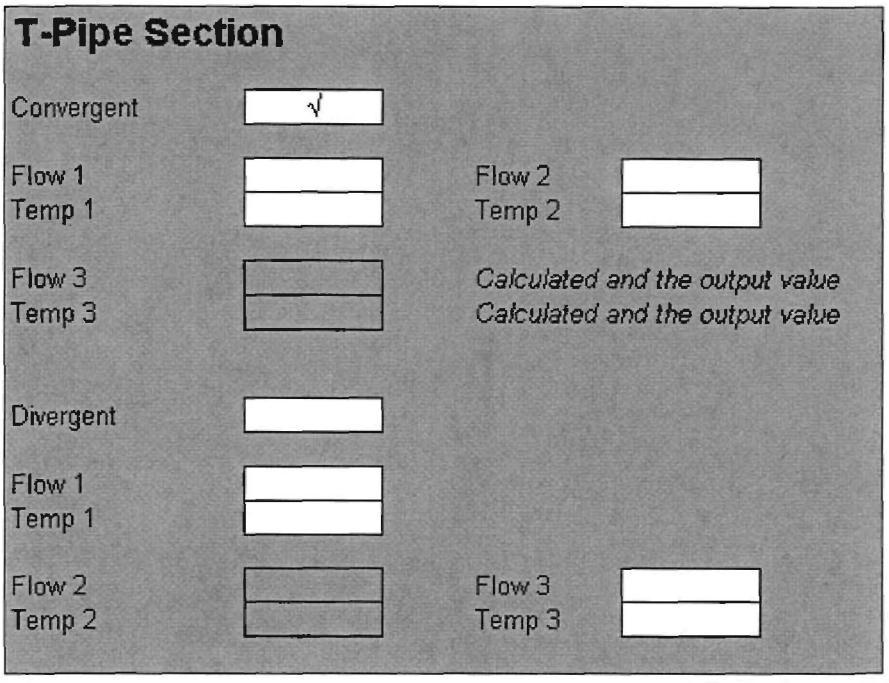


Figure 4-8: Interface for the T-pipe control algorithm.

DAM LEVEL CONTROLLER

Chilled water dam level controller

This controller forms part of the "preparation" controller, which is used to prepare the refrigeration system for load shifting during a certain period. The chilled water dam level controller calculates the required increase or decrease of chiller machine flow rate needed to increase or decrease the chilled water dam level.

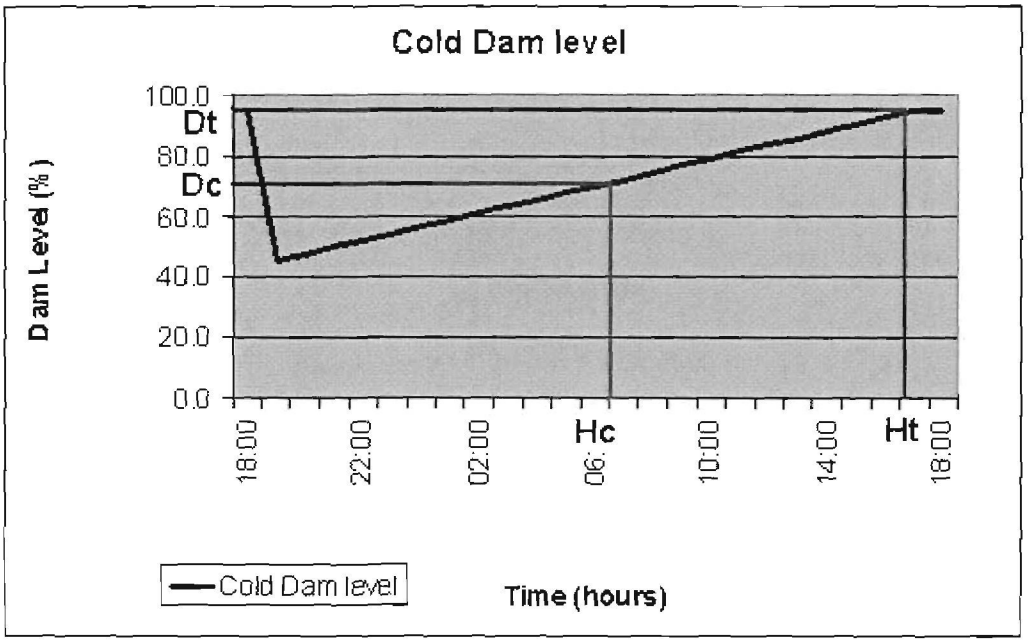


Figure 4-9: Illustration of cold or chilled water dam level control.

The following abbreviations are applicable:

- D_t = Target dam level (%);
- D_C = Current dam level (%);
- H_t = Target hour; this will be hour at which peak time begins;
- H_C = Current hour;
- D_R = Rise in dam level (%/hour);
- D_{tc} = Total dam capacity (m^3);
- F_R = Rise in inflow from refrigeration machines (l/s);

- F_{out} = Outflow from the cold water dam (l/s);
- F_{in} = New inflow from refrigeration machines (l/s);
- F_{max} = Maximum refrigeration plant flow rate (l/s);
- F_{min} = minimum refrigeration plant flow rate (l/s).

$$D_R = \frac{(D_t - D_C)}{H_t - H_C} \tag{4.12}$$

$$F_R = \frac{(D_R \cdot D_{ic})}{360} \tag{4.13}$$

$$F_{in} = F_{out} + F_R \tag{4.14}$$

F_{in} is defined as the "ideal flow rate" necessary to obtain the cold water dam target level before peak time (i.e. the period targeted for load shifting). These calculations must be done hourly, and the controller must adjust the ideal flow rate as necessary. The controller must ensure that F_{in} does not exceed the maximum or minimum flow rate limits as specified in the input interface.

Input interface

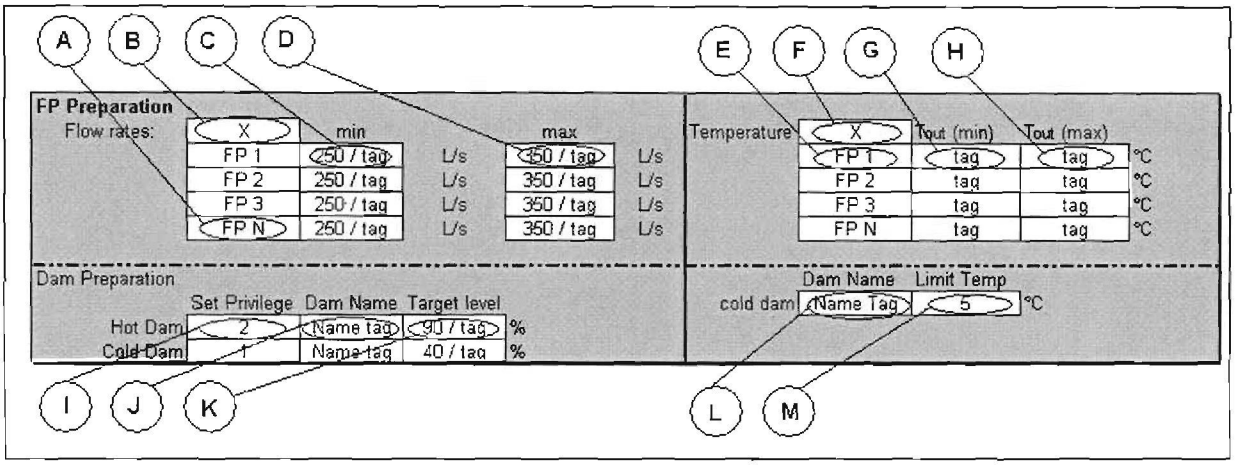


Figure 4-10: Input interface applicable to the chilled water dam level controller.

DAM TEMPERATURE CONTROLLER

Chilled water dam temperature controller

At the beginning of the targeted peak period the controller will initiate a "prediction" calculation using the specified limit and maximum temperatures.

If the controller calculates that the maximum and minimum outlet temperatures of the refrigeration plants are within limits, it will control the dam temperature between set values; otherwise it will control the outlet temperature between the maximum machine temperature and the minimum outlet temperature (refer to Figure 4-9).

The following abbreviations are applicable:

- T_{LD} = Limit dam temperature (°C);
- T_{CD} = Current dam temperature (°C);
- F_C = Current refrigeration plant flow rates (l/s). Note: This will also be F_{in} if the flow controller is active;
- T_{LT} = Limit target temperature (°C);
- T_{max} = Maximum temperature (°C).

The following algorithm is used:

$$T_{LT} = \frac{\frac{D_{ic} \cdot D_C}{100} \cdot (T_{LD} - T_{CD}) + (F_C \cdot T_{LD} \cdot 3.6)}{F_C \cdot 3.6} \qquad (4.15)$$

The software version of all input and output interfaces shown in this section will be presented in Chapter 5. Overall system control will also be discussed in Chapter 5.

4.3. A NEW GLOBAL CONTROL PHILOSOPHY

The same control philosophy is applicable every time a load shift potential is being investigated in a refrigeration system. The controllers discussed in the previous section are applied in a generic way to establish a load shift potential. Constraints applicable to a refrigeration system are generic and therefore the control of such a system should also be.

A global control philosophy was developed which can be applied for the purposes of a DSM investigation in any refrigeration system. This philosophy is not only used for simulation purposes, but also for actual control purposes (this will be proven in Chapter 6).

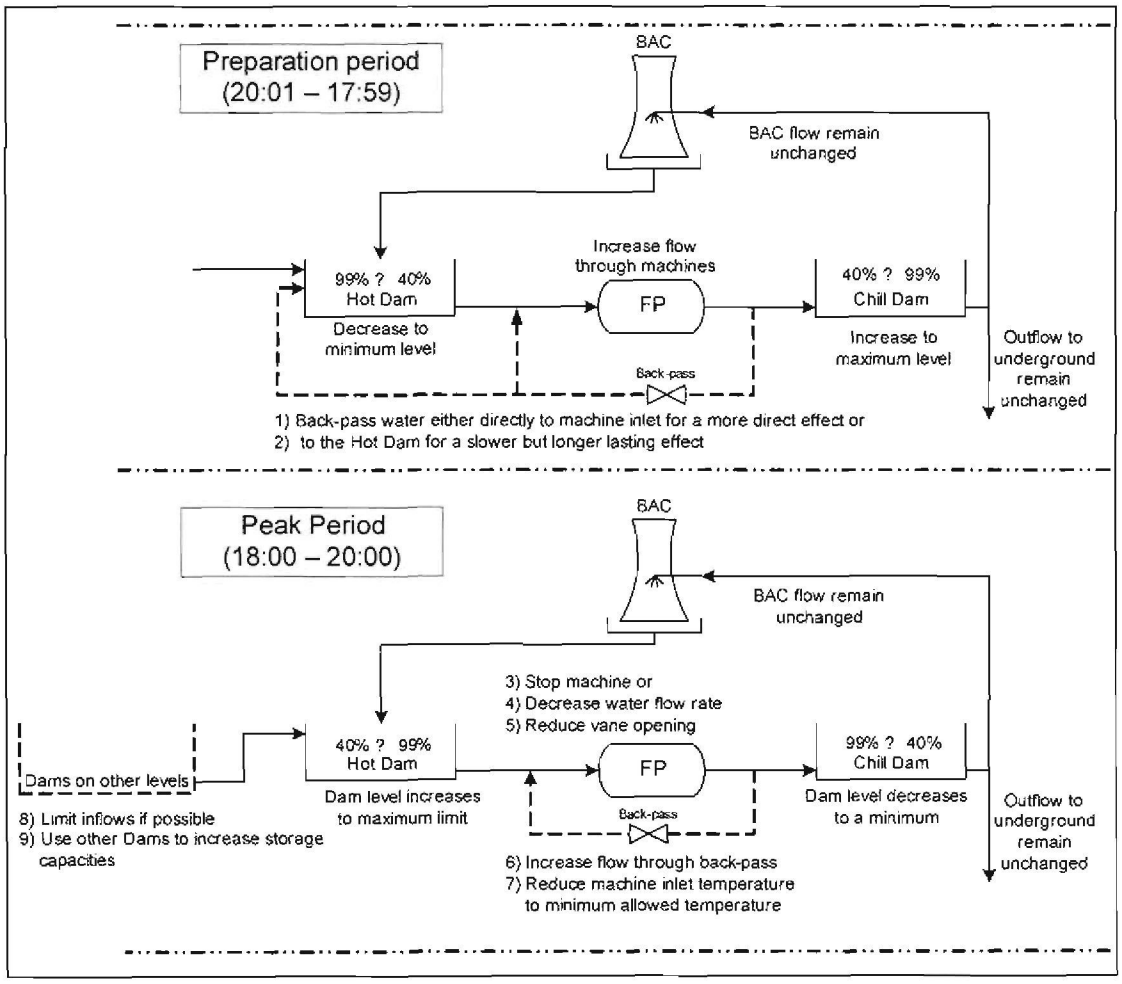


Figure 4-11: Schematic view of the global control strategy.

The control philosophy (inputs and outputs) can be summarised as follows (assuming the target load shift period is 18:00 to 20:00):

1. Preparation period

- Decrease the hot water dam level (to generate capacity for mine water inflow);
- Increase the rate of water flow through the refrigeration machines (to supply increased water usage from hot water dam and supply to the chilled water dam). Effectively, the machines will work "harder" during this period - this is in fact the period where the load is being shifted to;
- Increase the chilled water dam level (to generate a buffer storage capacity which can be utilised during the load shift period); and
- Back-pass chilled water to decrease machine inlet temperatures (this in turn will reduce chiller compressor absorbed power with the compressor effectively "cutting-back"). Water can either be back-passed into the hot dam or directly into the machine inlet manifold.

2. Peak period

- Stop machines according to system constraints (the load has been shifted to the preparation period);
- Increase hot water dam level to maximum limit (limit mine water inflow into hot water dam if possible);
- Decrease chilled water dam level; and
- Back-pass chilled water (if applicable) to decrease machine inlet temperatures (this in turn will reduce chiller compressor absorbed power). Water can either be back-passed into the hot dam or directly into the machine inlet manifold.

Please note that chilled water supply (L/s and °C) to ventilation or mine underground equipment must remain unchanged.

4.4. A UNIQUE DSM INVESTIGATION PROTOCOL

It was shown in the previous section that the end-goal control philosophy to realise a load shift potential in a refrigeration plant is generic in nature.

A new generic investigation method or protocol was therefore developed. This protocol can be used to investigate any refrigeration system to establish a load shift potential.

The protocol is divided into two stages (summarised below):

Stage 1 - Preliminary investigation:

- Identification of systems to investigate;
- Obtain relevant plant and system layouts, data, process and physical constraints, etc.;
- Determine baseline energy profile;
- System modelling; and
- Administration.

Stage 2 – Load shift potential assessment:

- Optimise baseline;
- Update simulations with control strategies;
- Optimisation process;
- Apply control philosophy;
- Establish load shift potential;
- Determine infrastructure requirements; and
- Cost analysis.

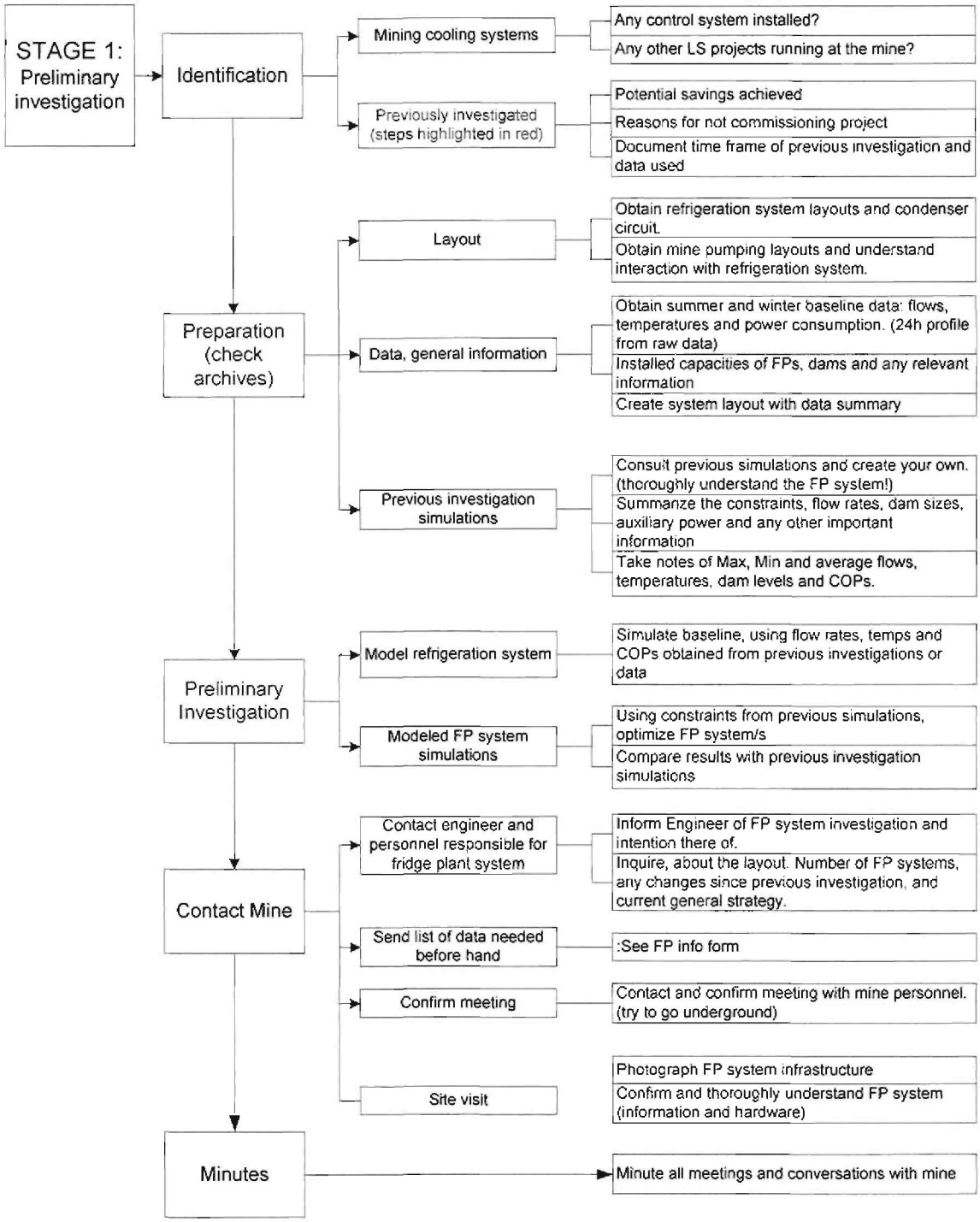


Figure 4-12: Stage 1 guidelines of the investigation protocol.

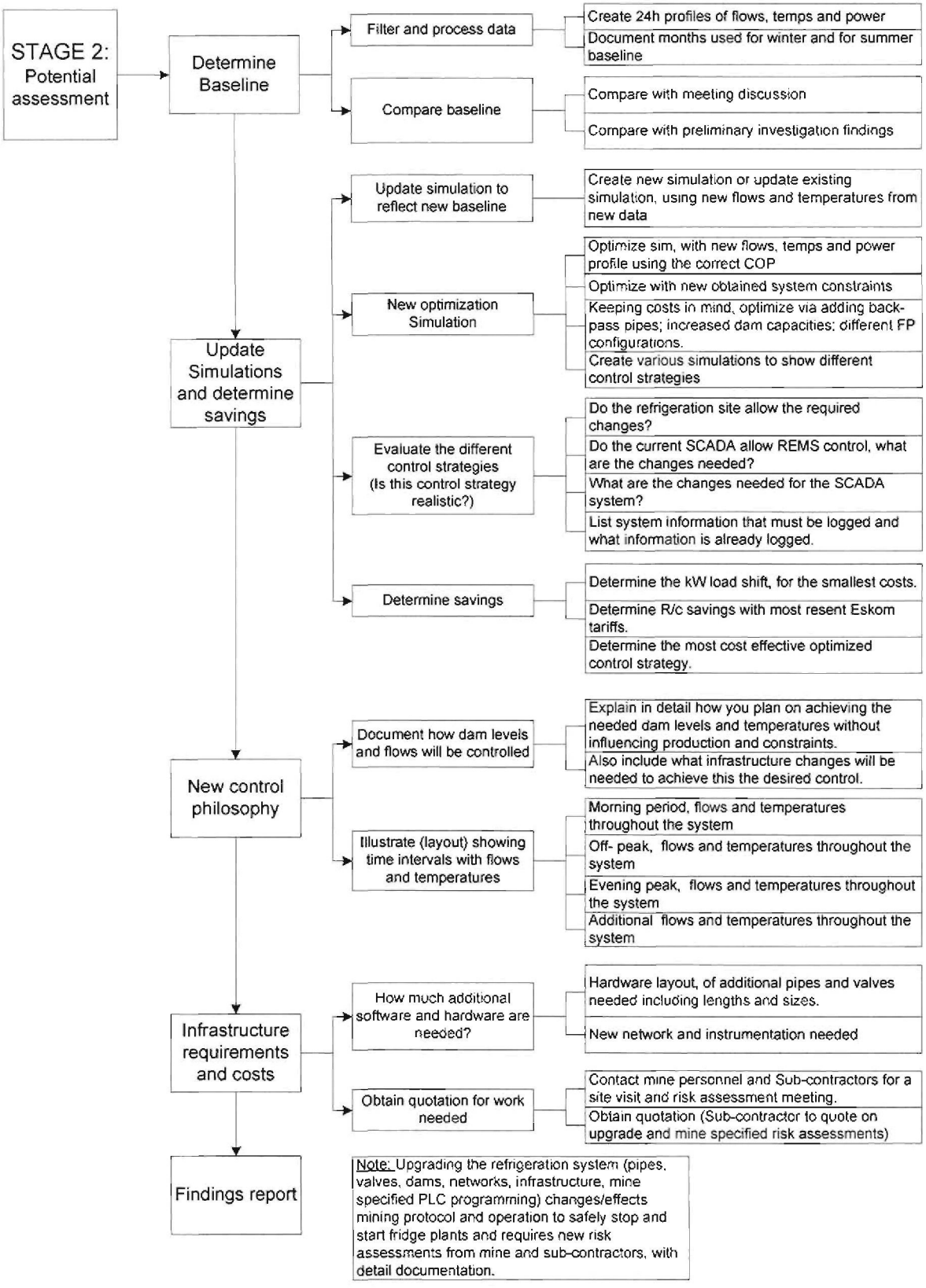


Figure 4-13: Stage 2 guidelines of the investigation protocol.

4.5. IDENTIFYING REFRIGERATION SYSTEMS TO INVESTIGATE

A total of twelve mine refrigeration systems were identified to investigate for load shift potential by using the investigation methodology described in the previous section. Two important parameters were established to make a quick decision if further investigation into a system is warranted.

Chiller machine utilisation:

- As part of the load shift potential assessment a baseline energy usage profile needs to be established. An average 24-hour energy usage profile is created (averaged over a period of 3 months);
- The average electrical load ($Q_{average}$) of this average 24-hour baseline profile is compared against the installed electrical energy value of the plant ($Q_{installed}$);
- $$Utilisation\% = (1 - \frac{Q_{average}}{Q_{installed}}) \times 100 \quad (4.16)$$
- This value actually determines if there is capacity or "potential" to shift the load to;
- It was determined that if this value is greater that 10%, there is capacity in the system to shift load (i.e. there is an opportunity for increased machine utilisation during other periods of the day);
- The closer this value gets to zero, the less "potential" there is in the system's capacity to shift load to; and
- It must be noted that this factor is only applied to a summer base load energy profile as it will give the best case result.

Chilled water dam flow supply capacity:

- It was found that on average 50% of the installed chilled water dam capacity (V_{cd}) in ML is available to use for load shift strategies. The reason for this is mainly due to process and mine constraints;

- The chilled water demand rate (m_{supply}) in l/h is usually known for refrigeration systems and the supply capacity of the chilled water dam (T_{supply}) in hours can therefore be calculated;
- $$T_{sup\,ply} = \frac{V_{cd}}{m_{sup\,ply}} \quad (4.17)$$
- If the supply period of the dam is equal to or above 2 hours there is capacity to shift load;
- It should be noted that a supply period below 2 hours could also be acceptable should the average of the energy shift for this period be worthwhile to pursue.

The following abbreviations are applicable:

- Q_t = Installed thermal energy (kW);
- COP = Coefficient of Performance;
- Q_e = Installed electrical energy (kW);
- $Q_{average}$ = Average electrical load (kW);
- V_{cd} = Chilled water dam capacity (Ml);
- m_{supply} = Required chilled water flow (Ml/h);

The two parameters described above are used to determine if further investigation is needed. The table below shows the population of mine refrigeration systems identified for investigation purposes.

Mine	Shaft	Qt [kW]	COP	Qe [kW]	Qaverage [kW]	Vcd [ML]	msupply [ML/h]
Anglo Gold Ashanti	Kopanang	36980	4	9245	8000	2.75	3.5833
Harmony Gold	Elandsrand	56800	4	14200	11725	11.5	2.1771
Harmony Gold	Tshepong	29150	5.5	5300	4050	5	2.0833
Goldfields	South Deep	25650	5	5130	4500	5.6	1.3333
Harmony Gold	Target	39179	3.86	10150	8000	2	1.15
Harmony Gold	Evander 7	7687.5	5.125	1500	1200	5.2	0.7292
Harmony Gold	Masimong 4	15200	4.75	3200	2800	5.5	1.1875
Harmony Gold	Bambanani	75189	3.53	21300	19800	7	2.9167
Anglo Platinum	Amandelbult 2	22500	5.1	4350	3000	4	1.2958
Anglo Platinum	Frank 2	12000	4.8	2500	2300	0.5	1.1
Anglo Gold Ashanti	Moab Khotsong	61029	5.63	10840	7500	5	2.5917
Goldfields	Beatrix 4	39310	5	7862	6000	4	3.3833

Table 4-1: Mine investigation population.

Applying the parameters discussed in this section yield the information supplied in the following table.

Shaft	Q_e [kW]	$Q_{average}$ [kW]	V_{cd} [ML]	m_{supply} [ML/h]	Utilisation [%]	Available V_{cd} [%]	T_{supply} [h]
Kopanang	9245	8000	2.75	3.583333333	13%	90%	0.69
Elandsrand	14200	11725	11.5	2.177083333	17%	50%	2.64
Tshepong	5300	4050	5	2.083333333	24%	90%	2.16
South Deep	5130	4500	5.6	1.333333333	12%	50%	2.10
Target	10150	8000	2	1.15	21%	50%	0.87
Evander 7	1500	1200	5.2	0.729166667	20%	50%	3.57
Masimong 4	3200	2800	5.5	1.1875	13%	50%	2.32
Bambanani	21300	19800	7	2.916666667	7%	50%	1.20
Amandelbult 2	4350	3000	4	1.295833333	31%	50%	1.54
Frank 2	2500	2300	0.5	1.1	8%	50%	0.23
Moab Khotsong	10840	7500	5	2.591666667	31%	50%	0.96
Beatrix 4	7862	6000	4	3.383333333	24%	50%	0.59

Table 4-2: Mine system investigation elimination process.

An initial four mines were identified for further investigations and will be further discussed as case studies:

- Kopanang (although its chilled water dam supply capacity is small, the nature of the plant enables other cost saving opportunities);
- Elandsrand;
- Tshepong;
- South Deep.

4.6. PROCESS PARAMETERS AND CONSTRAINTS

To accurately determine a load shift potential in refrigeration systems, process parameters must be established. The application of a load shift strategy in a refrigeration system may not compromise these parameters (adherence to these constraints is tested through simulation).

Process parameters include for example:

- Temperatures;
- Minimum and maximum dam percentages;
- Flow rates; and
- Machine operating constraints.

The process parameters for each of the identified case studies will now be discussed. These parameters were set-up with input from mining personnel.

Kopanang

- The hot water coming from the underground mining levels has an average flow of 263l/s with a maximum flow rate of 463l/s and a minimum flow rate of 230l/s during a typical summer weekday;
- The pre-cool towers cool the hot water down to an estimated average temperature of 22°C during an average summer weekday;
- During the summer period a total of 6 chiller machines (situated in a parallel configuration) cool water to an average outlet temperature of 3.2 - 3.6°C. The water flow rate through each chiller machine is 253l/s;
- During the winter periods only 3 of the 6 chiller machines are used, with an average flow rate of 253l/s;
- Cold water sent underground is approximately 230l/s – 263l/s throughout an average weekday;
- The total electrical power used by the surface refrigeration plant is approximately 203,835kWh per average summer day, and 101,574kWh per average winter day; and
- The main Bulk Air Coolers (BACs) situated on surface use approximately 750l/s to cool the air sufficiently.

Elandsrand

Surface and underground refrigeration plants service Elandsrand Gold Mine. The process parameters for Elandsrand are discussed.

For the surface refrigeration plant:

- The hot water coming from the underground mining levels has an average flow of 300l/s with a maximum flow rate of 350l/s and a minimum flow rate of 240l/s during a typical summer weekday;
- The pre-cool tower cools the hot water down to an average temperature of 19°C during an average summer weekday;
- During the summer periods the surface chiller machines (situated in a lead-lag configuration) cool water to an average outlet temperature of 4.5°C. The water flow rate through each fridge plant pair is 310l/s;
- During the winter periods the flow rate through each machine pair decreases to approximately 220l/s throughout an average weekday. Depending on the water consumption and ambient temperatures one pair may be stopped during the winter months;
- Cold water sent underground amounts to approximately 250l/s – 300l/s throughout an average weekday;
- The total electrical power used by the surface refrigeration plant is approximately 158,202kWh per average summer day, and 141,203kWh per average winter day; and
- The main Bulk Air Coolers (BACs), situated on surface, use between 180l/s -- 220l/s of chilled water.

For the underground refrigeration system on 71L (71 Level), the parameters for the functioning of the refrigeration system do not change significantly throughout the year, seeing that the underground ambient temperature remains the same throughout the year. The parameters of this system are:

- Hot water coming from 100L has an average flow rate of 95l/s and an average temperature of 26.5°C during a typical weekday;
- The 71L hot water dam is cooled to approximately 22°C (a small amount of chilled water is being back-passed into the dam);
- Both the 71L hot water dam and 71L chilled water dam are controlled between 78 and 99%. The reason for this being, that these dams have accumulated a large amount of sludge and cannot be cleaned without influencing production;
- The chiller machines 1&2 and 7&8 (situated in a lead-lag configuration) cool water to an average outlet temperature of 8°C. Chiller machines 3&4 cool water to approximately 3.5°C. The water flow rate through each refrigeration plant pair is 120l/s, 120l/s and 220l/s respectively;
- Water cooled on surface is sent directly to 71L chilled water dam, at a temperature of 8°C;
- Cold water sent to the mining levels amount to approximately 395l/s throughout an average weekday;
- The total electrical power used by the 71L refrigeration plant is approximately 118,500kWh per average weekday; and
- Main Bulk Air Coolers (BACs) are situated at 75L and use between 220l/s – 250l/s to cool the air sufficiently.

South Deep

- The hot water coming from the underground mining levels has an average temperature of 22°C and flow of 280l/s – 320l/s during a typical summer weekday;
- The pre-cool towers cool the hot water down to an average temperature of 18°C during an average summer weekday;
- During the summer periods the four York machines (situated in a parallel configuration) cool water with an average temperature difference of 8°C, and an average total flow rate of 460l/s (average flow rate through one York machine is thus 115l/s);

- During the winter periods the flow rates through the four York machines decrease to approximately 360l/s throughout an average weekday. Thus only three machines are usually operated during winter periods, each maintaining an average flow of 120l/s;
- Second stage cooling is done by the Howden machine (ammonia), which cools the water with an average temperature difference of 6.5°C and maintains a flow of 280l/s;
- The temperature of the water going to the underground mining levels, after cooling, is usually maintained at approximately 3.6°C;
- The amount of cold water used by the underground mining levels is approximately 280 – 320l/s throughout an average weekday;
- The total electrical power used by the system is approximately 106,445kWh per average weekday; and
- Bulk Air Coolers (BACs) are situated underground; therefore it is extremely important that the refrigeration plant must be able to provide a constant cold water flow rate throughout the day.

Tshepong

- The hot water coming from the underground mining levels has an average temperature of between 20°C – 22°C and flow of 420l/s – 450l/s during a typical summer weekday and between 320l/s – 350l/s during a typical winter weekday;
- During the summer periods the 4 chiller machines (situated in a parallel configuration) cool water with an average temperature difference of 9°C with a maximum total flow rate of 780l/s. One machine can have a flow of up to305l/s;
- The mine's cold water consumption is 320l/s and the BAC water consumption is 270l/s during an average summer weekday;
- During the winter periods the total flow rate will decrease to 490l/s throughout an average weekday;
- The mine's cold water consumption is up to 510l/s and the BAC water consumption is approximately 343l/s during an average winter weekday;

- The temperature of the water going to the underground mining levels, after cooling, is usually maintained between 3.5 - 5.5°C in the summer and between 3.5 -4.5°C in the winter; and
- The total electrical power used by the plant is approximately 105,809kWh per average summer weekday and approximately 37,217kWh per average winter weekday.

4.7. APPLYING THE DSM INVESTIGATION PROTOCOL

SYSTEM DESCRIPTIONS AND SCHEMATIC LAYOUTS

Kopanang

Water enters the surface surge dam at 27°C from underground. This water is pumped through two pre-cooling towers. The water leaves the pre-cooling towers at a temperature of ± 15°C. The transfer pumps pump this water to the hot confluence dam. Here the water returning from the BACs and the pre-cooling towers mix.

This water is now sent to the refrigeration plant. The plant consists of six identical chillers with a combined capacity of 33 MW. The coefficient of performance (COP) of the chillers is 5.5. The pumps of the evaporator pump the hot water through the evaporator where it leaves the evaporator on its way to the cold confluence dam at 3.5°C.

The condenser water is pumped to the condenser cooling towers to be cooled. Each chiller has its own condenser cooling tower. The water at the cold confluence dam is sent to the turbine (250kg/s) and to the bulk air cooler (250kg/s per cell). The bulk air cooler (BAC) consists of three cells in parallel each with its own pump. The BAC is used to cool the entering ventilation air used for cooling. The water leaves the BAC at 8°C.

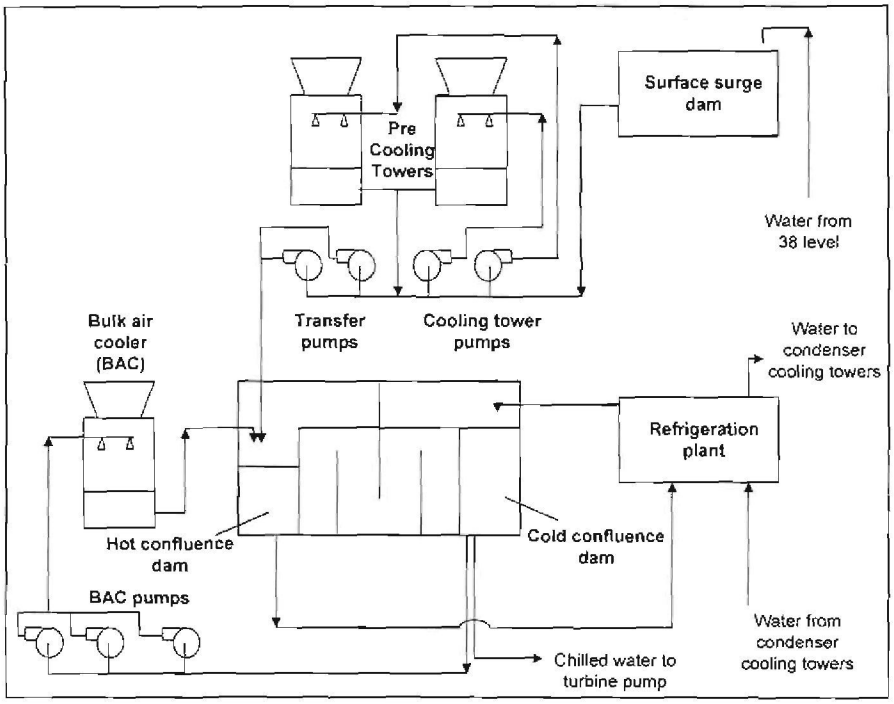


Figure 4-14: Kopanang overall system layout.

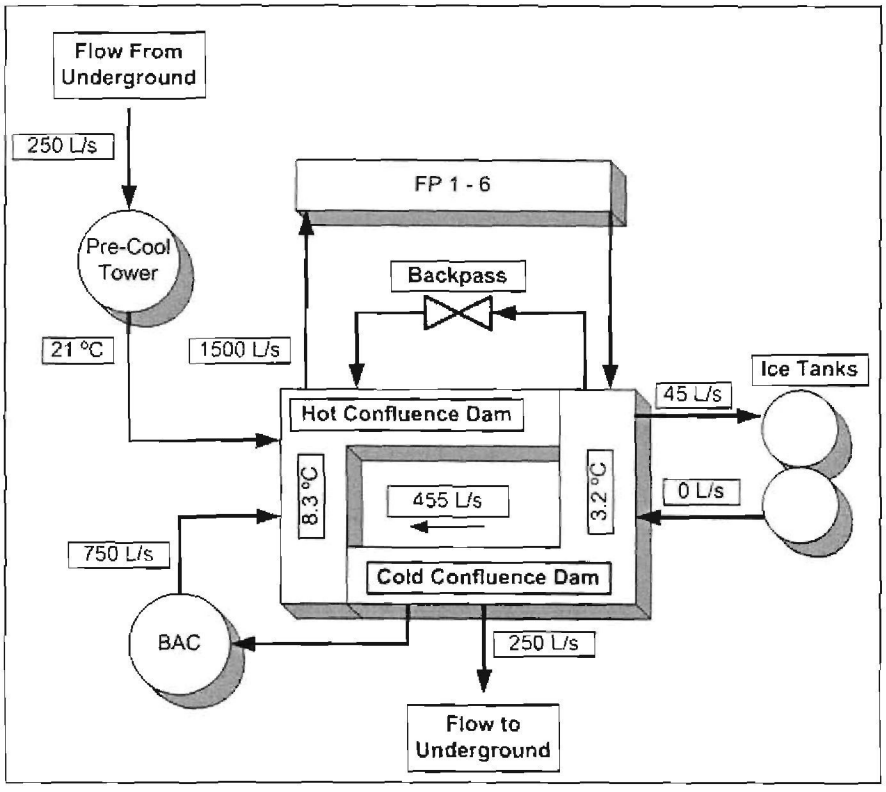


Figure 4-15: Kopanang plant layout.

Elandsrand

Surface refrigeration system:

Hot water enters the hot dam, and is sent through the pre-cool towers, and into the pre-cool dam. The average temperature in the pre-cool dam is 18°C. A total of 25Ml/day is pumped from underground during the average summer day, and a total of 20 Ml/day during the winter months. The pre-cooled water is processed via two pairs of chiller machines situated in lead-lag configuration (four chiller machines in total).

The combined cooling capacity of the surface chiller machines is 42MW. The combined COP of the surface chiller machines is 5.25. Once the water is cooled, approximately 220l/s is sent to the BACs (Bulk Air Coolers) and sent back to the pre-cool tower dam. The remaining water is sent to the surface chill dam; from there the water is sent to 71L chill dam.

71L Refrigeration system:

Hot water is pumped from 100L, to the 71L hot dam. The total amount of water being pumped is 8.2Ml/day. There are three chiller machine pairs. Currently chiller machines 3 and 4 are in a closed loop configuration with the BAC at 75L. The BAC has a designed water flow rate of 290l/s, but the flow is currently only 240l/s.

Water from surface is sent to the 71L chill dam. Chilled water needed at the mining levels is acquired from the 71L chill dam. The total amount of water used at the mining levels is estimated at 34Ml/day. Water from the 71L hot dam is sent through chiller machine 7 and 8, from there a small amount of water is send back to the hot dam (approximately 25l/s), the majority of the water is sent through chiller machines 1 and 2 and into the 71L chill dam.

The combined COP of chiller machines 7 and 8 and machines 1 and 2 is 2.93. The COP of chiller machines 3 and 4 is 4.69. The total installed cooling capacity of the 71L refrigeration system is 28MW.

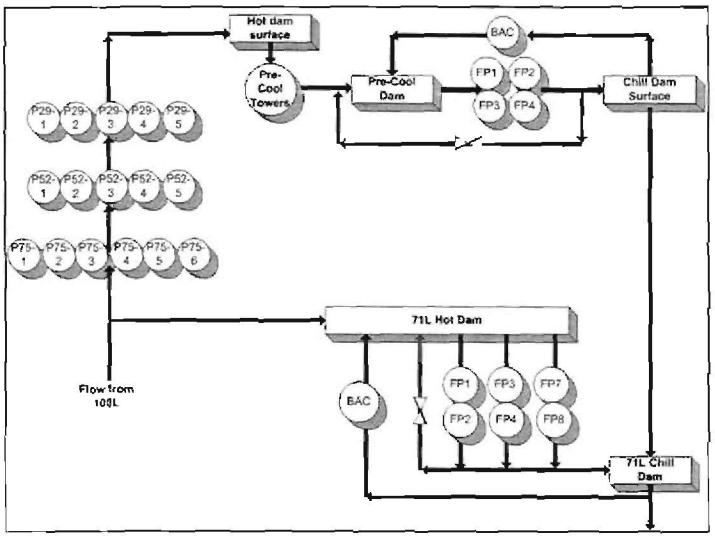


Figure 4-16: Elandsrand surface and underground refrigeration systems.

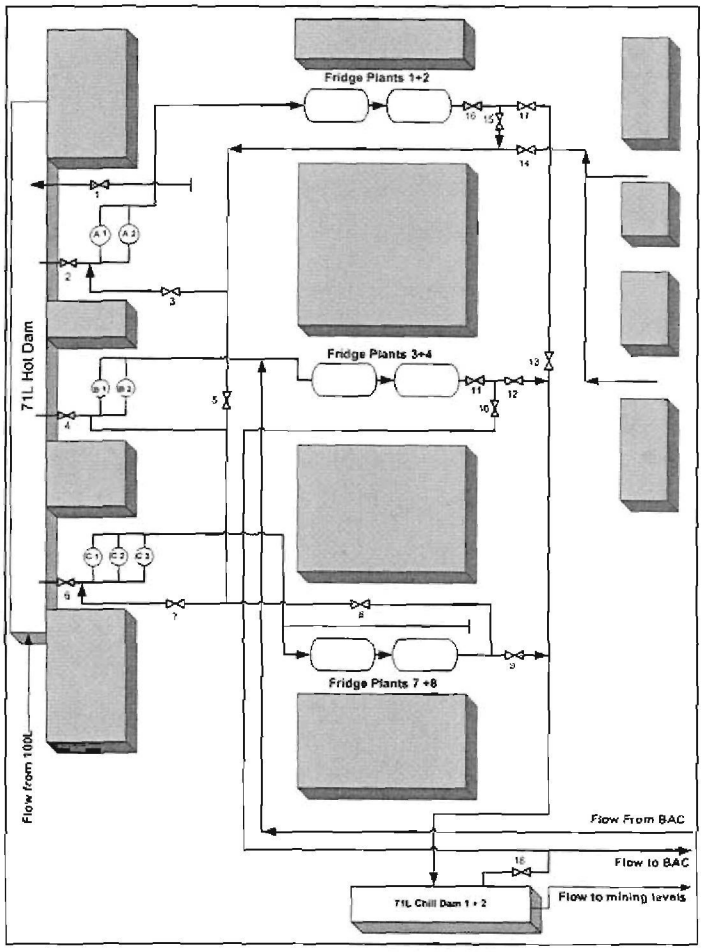


Figure 4-17: Elandsrand underground refrigeration system.

South Deep

Water enters the surface hot dam at a flow rate of 340l/s and at a temperature of 25°C. Water is pumped to a pre-cool tower and then stored in a pre-cool dam. The temperature of the water is between 17°C and 18°C. The water is now sent to four York chiller machines. Water flows through the chiller machines at a rate of 360l/s and an outlet temperature of 9°C. It has a thermal cooling capacity is 17.6 MW. The combined Coefficient of Performance (COP) is 3.96.

The water is stored in the first surface chill dam. The water is now sent to the Howden chiller machine. Water flows through the chiller machines at a rate of 340l/s and an outlet temperature of 3°C. It has a thermal cooling capacity is 18.2 MW. The Coefficient of Performance (COP) is 5.7. The water is stored in the second and third surface chill dams.

The condenser water is pumped to the condenser cooling towers to be cooled. There are four York condenser pumps and they have a flow rate of 280l/s per pump. The Howden condenser pump has a flow rate of 430l/s. The BAC is used to cool the entering ventilation air used for cooling, and is underground. The water consumed by the BAC forms part of the system outflow.

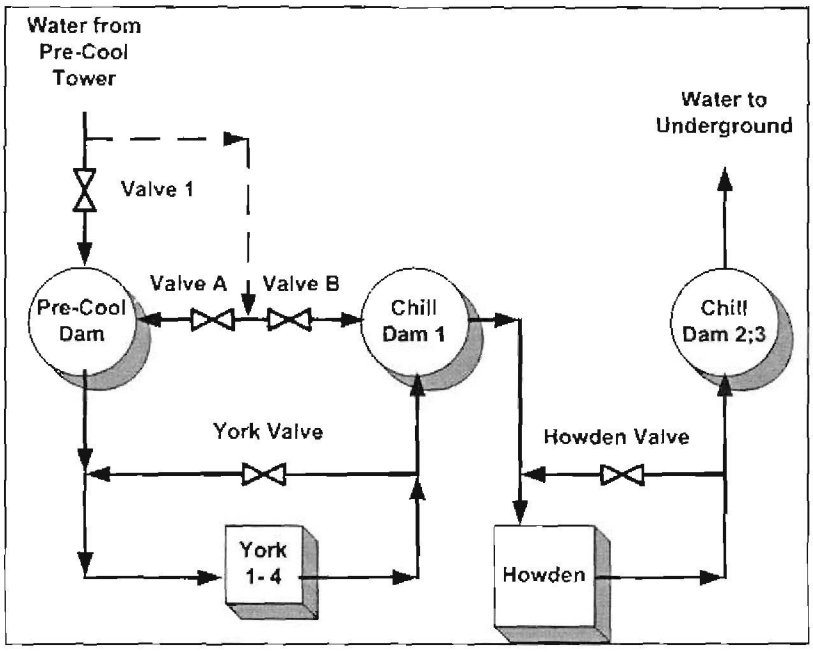


Figure 4-18: South Deep refrigeration system layout.

Tshepong

Water enters the surface pre-cool dam at a temperature of between 17°C - 18°C from the pre-cool towers. This dam receives water from the pre-cool towers, as well as return water from the bulk air coolers (BACs). This water is now sent to the refrigeration plant. The plant consists of four chiller machines with a combined cooling capacity of 29MW.

The combined coefficient of performance (COP) of the chillers is 5.5. The evaporator pumps pump the hot water through the evaporator to the chill dam at a temperature of between 3.5-5.5°C. The condenser water is pumped to the condenser cooling towers to be cooled. There are three condenser cooling towers. Each has a flow rate of between 500l/s and 570l/s.

The BAC consists of three cells each in parallel with its own pumps and fans. It has an average flow rate of 330l/s. The BAC is used to cool the entering ventilation air. The water leaves the BAC at 8°C.

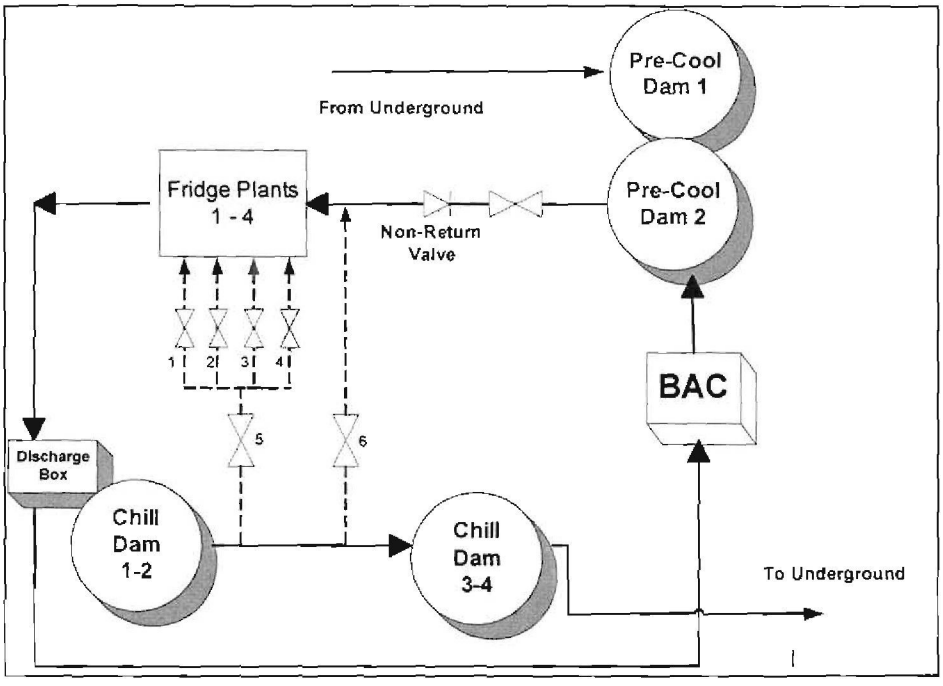


Figure 4-19: Tshepong refrigeration system layout.

SYSTEM SIMULATION LAYOUTS

Kopanang

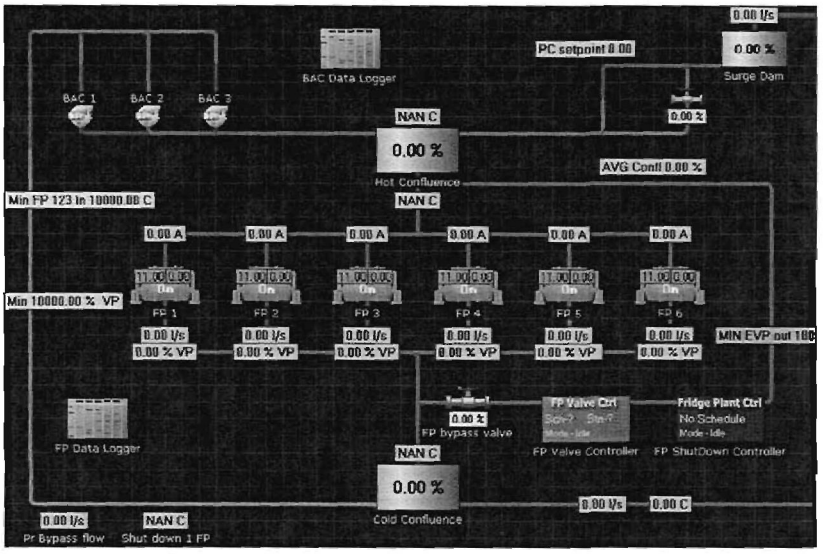


Figure 4-20: Kopanang simulation layout.

Elandsrand

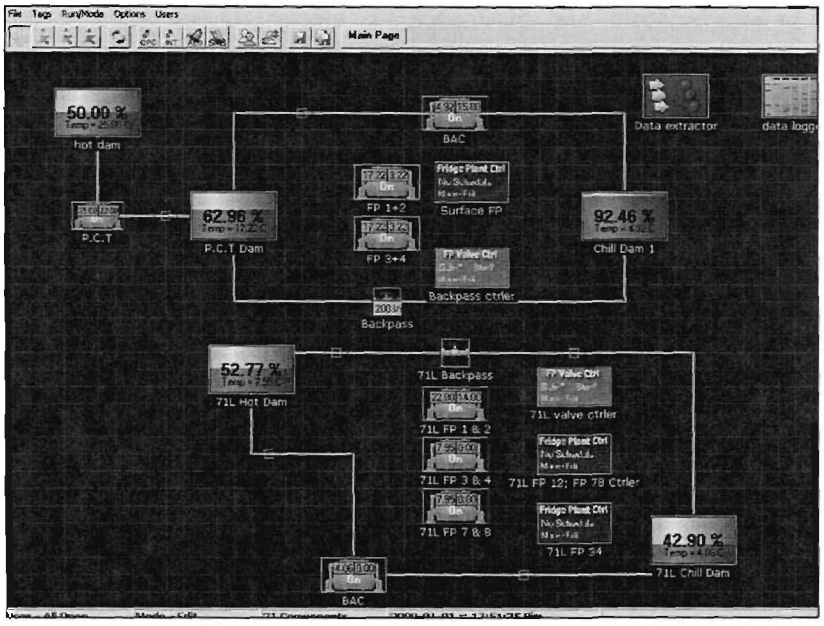


Figure 4-21: Elandsrand simulation layout.

South Deep

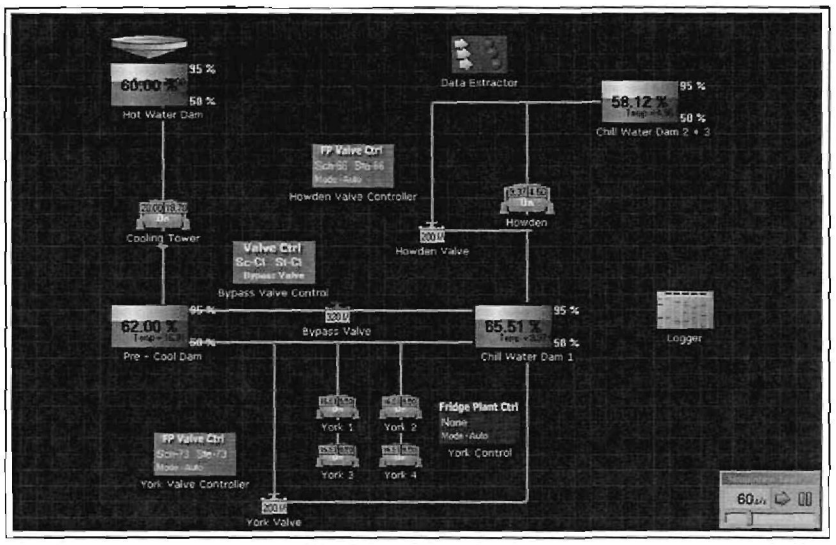


Figure 4-22: South Deep simulation layout.

Tshepong

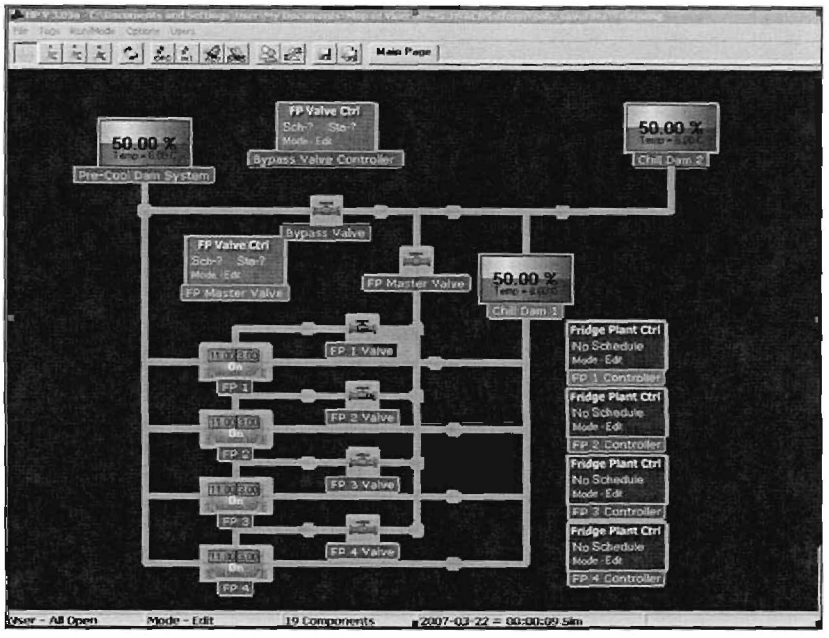


Figure 4-23: Tshepong simulation layout.

SIMULATION RESULTS: LOAD SHIFT POTENTIAL

Simulation models were created for the four identified systems. Through application of the discussed DSM control strategies, the DSM potential for each of the systems could be quantified, while ensuring no violation of critical process constraints. These results were used to compile business case proposals to Eskom DSM (see Chapter 5).

Kopanang

The absorbed power of the refrigeration system could be reduced by approximately 3.5MW during the evening peak period (18:00 – 20:00) in summer months.

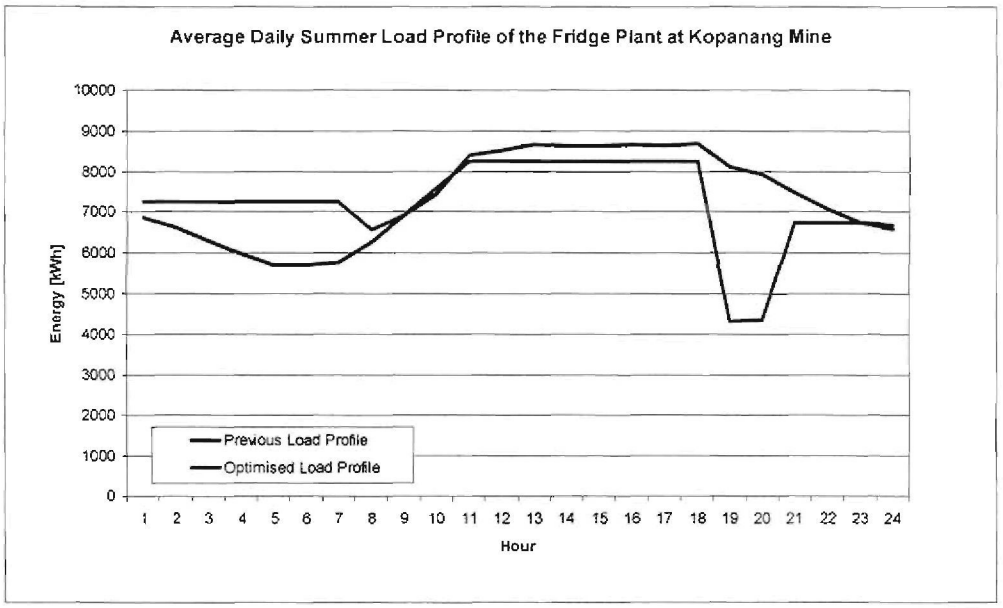


Figure 4-24: Kopanang load shift result (simulated).

Elandsrand

The absorbed power of the refrigeration system could be reduced by approximately 6.0MW during the evening peak period (18:00 – 20:00).

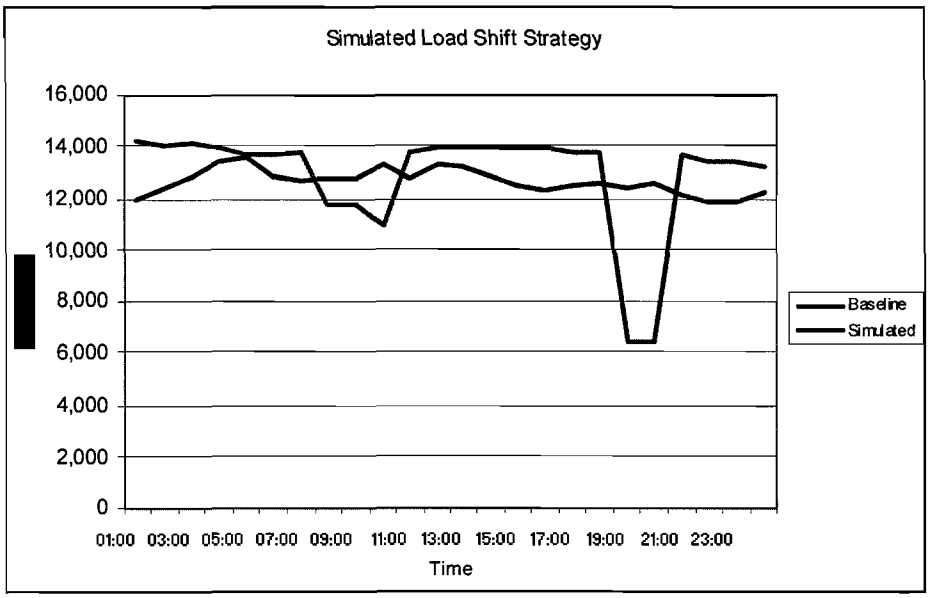


Figure 4-25: Elandsrand load shift result (simulated).

South Deep

The absorbed power of the refrigeration system could be reduced by approximately 4.2MW during the evening peak period (18:00 – 20:00).

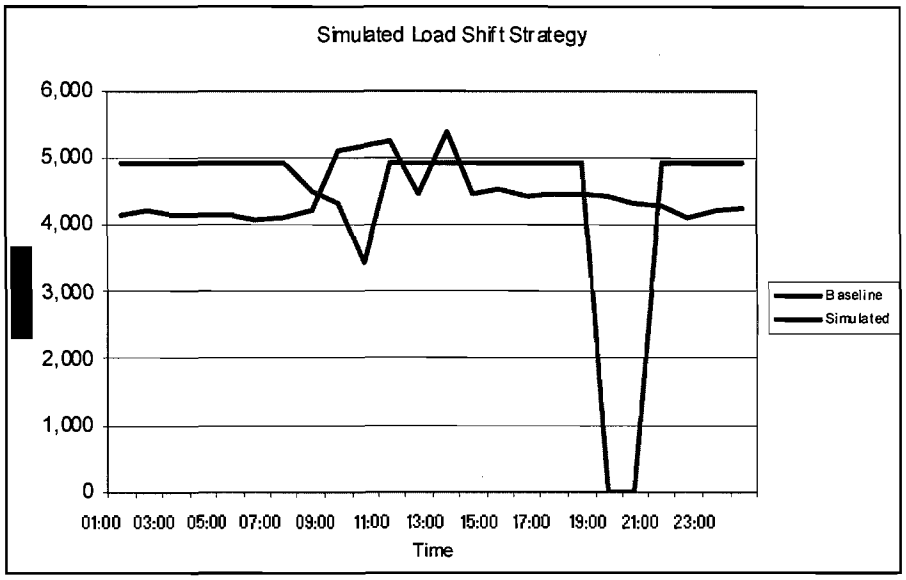


Figure 4-26: South Deep load shift result (simulated).

Tshepong

The absorbed power of the refrigeration system could be reduced by approximately 3.7MW during the evening peak period (18:00 – 20:00).

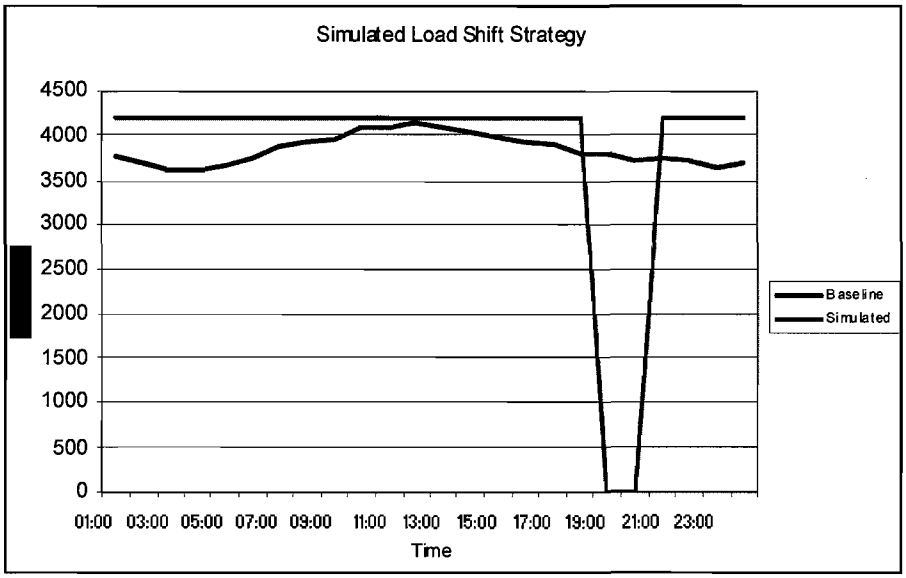


Figure 4-27: Tshepong load shift result (simulated).

4.8. CONCLUSION

The application of the investigation protocol and global control philosophy proved successful in identifying and establishing a load shift potential in mine refrigeration systems – it was proven on four case study mines. A combined load shift potential of 16.4MW could be established by applying the methodologies described in this chapter to these systems whilst adhering to all process constraints.

4.9. REFERENCES

[1] Mills, A.F, "Heat Transfer handbook", IRWIN Boston, 1992.

[2] McQuiston, F.C., Parker, J.D., "Heating, Ventilating, and air conditioning: Analysis and Design", Fourth Edition, John Wiley and Sons, Inc., 1994.

CHAPTER 5

A NEW ENERGY MANAGEMENT CONTROL SYSTEM FOR MINE REFRIGERATION SYSTEMS

5. A NEW ENERGY MANAGEMENT CONTROL SYSTEM FOR MINE REFRIGERATION SYSTEMS

5.1. PREAMBLE

The only way to realise a DSM potential in refrigeration systems, via optimised control, is through the implementation of an automated Energy Management System (EMS).

To ensure sustainability, the EMS must be a fully automatic control solution. It needs to communicate with system equipment (SCADA, PLCs, etc.) in order to realise the identified DSM potential. The required control infrastructure to enable the EMS to optimally control the refrigeration system is mostly generic for each refrigeration system.

The EMS resembled in this study was developed into a software solution. Technical control specifications were created and were used to identify required control infrastructure. The cost of the required infrastructure was established through formal sub-contractor quotations. Through a cost analysis the total project cost per load shift MW was calculated. These costs were used to develop business cases for submission to Eskom DSM.

The combined load shift potential for the four case studies identified, amounts to 16.9MW. The control infrastructure required, amounts to almost R15-million. The generation cost of the "virtual" peaking power station created through realisation of the load shift potential, therefore equates to approximately R2-million per MW (ESCo and EMS expenses included).

This is much lower than the approximate R16-million per MW generation cost involved with the building of new power stations. Sustainable DSM projects therefore make business sense to Eskom DSM due to its much lower power "generation" costs.

5.2. ENGINEERING A NEW ENERGY MANAGEMENT CONTROL SYSTEM

TECHNICAL CONTROL SPECIFICATIONS

There are technical constraint control specifications applicable to the operation of every refrigeration plant. These control specifications ensure that plant process, maintenance and safety constraints are adhered to. Most of these specifications were supplied by the mine.

Kopanang

- The hot confluence dam level must not be lower than 55%;
- The cold confluence dam level must not be lower than 49%;
- The inlet temperature of all the chiller machines must be controlled between 4°C and 9.9°C; and
- The outlet temperatures of the chiller machines must remain within 1°C - 6°C.

Elandsrand

- The surface dam levels must be controlled between 55% and 95%;
- The 71L dam levels must be controlled between 78% and 95%; and
- The inlet temperature of all the chiller machines may not be lower than 14°C.

South Deep

- All dam levels must be controlled between 50% and 95%;
- The inlet temperature of the York machines may not be lower than 14°C;
- The York Valves and Howden Valve have a maximum flow rate of 200l/s;
- The additional pipes and valves must have a flow rate of 320l/s.

- The Howden inlet temperature may not be lower than 5°C; and
- During the evening peak times, chill dams 2 and 3 must be able to provide the underground with an average flow of 280l/s.

Tshepong

- All dam levels must be controlled between 50% and 95%;
- The machine inlet temperatures may not be lower than 12°C; and
- During the evening peak times, chill dams 1 and 2 must be able to provide the underground with an average flow of 280l/s.

PROPOSED CONTROL SOLUTIONS

Kopanang

In summary, the following additional equipment needed to be installed in the Kopanang refrigeration system:

- PLC machine automation;
- Integration into the existing SCADA system; and
- Actuator for the back-pass control valve (between the cold confluence dam and hot confluence dam).

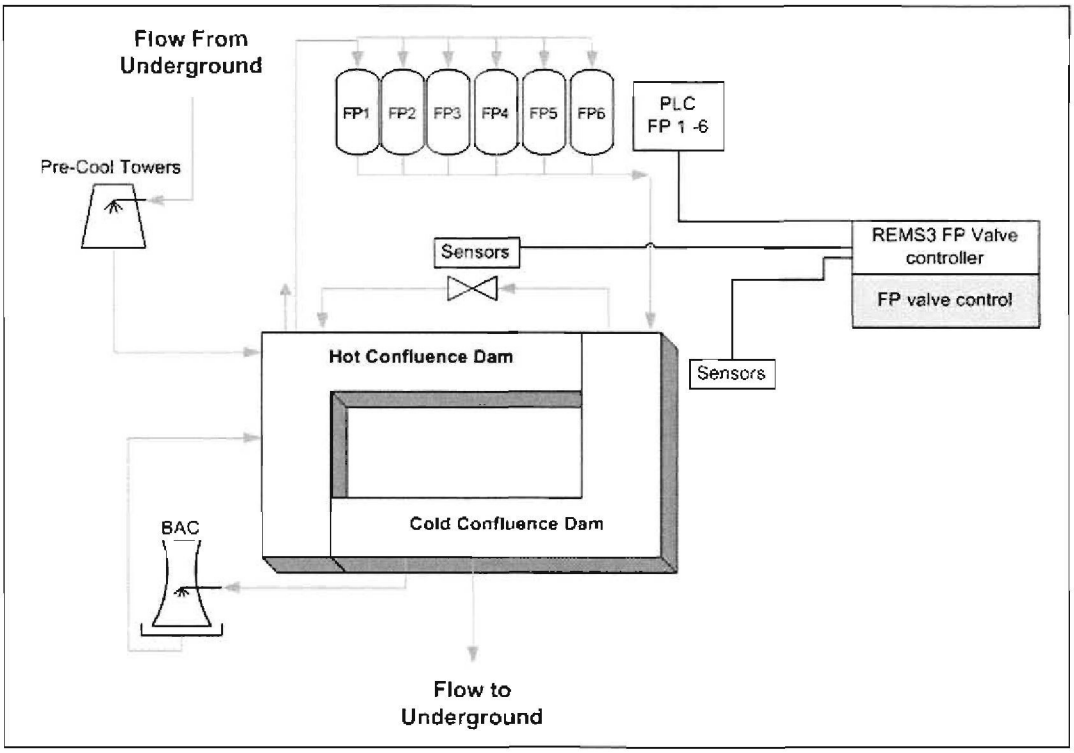


Figure 5-1: Layout of the Kopanang proposed solution.

Some of the control flowcharts for the Kopanang system can be seen in the following figures.

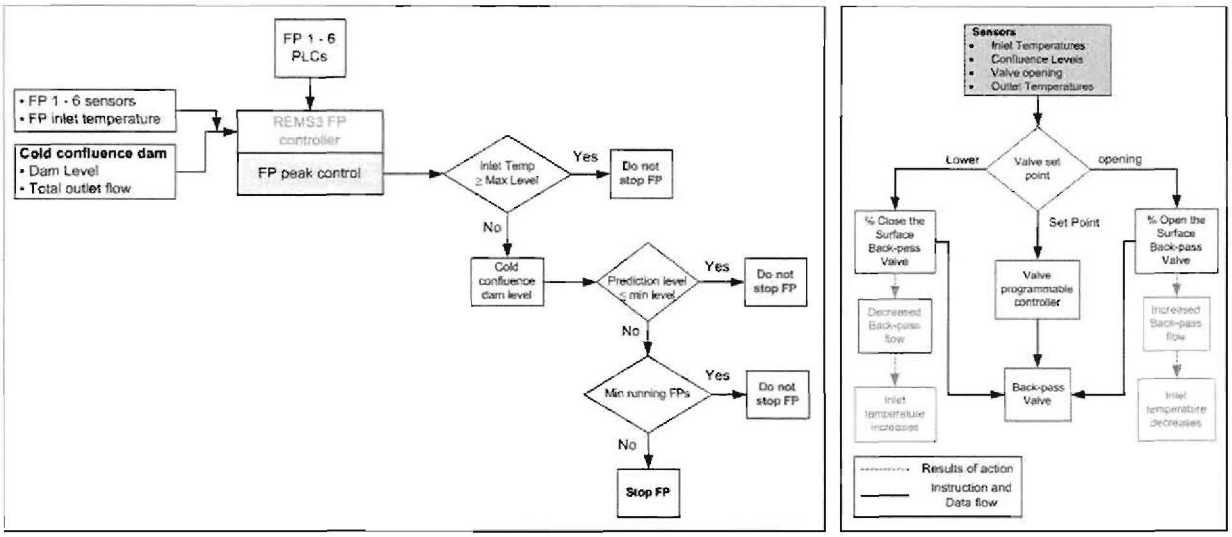


Figure 5-2: Chiller machine and back-pass valve control diagrams.

The previous pages show flow diagrams of the refrigeration machine emergency checklist and back-pass control strategy. Dam levels and temperatures need to be within acceptable parameters before control capability over machines and/or valves can be enabled.

Elandsrand

In summary, the following additional equipment needed to be installed in the Elandsrand surface refrigeration system:

- PLC machine automation;
- Integration into the existing SCADA system;
- Back-pass pipe and control valve (connecting the chiller machine outlet manifold with the surface pre-cool dam); and
- Machine control valves (evaporator and condenser).

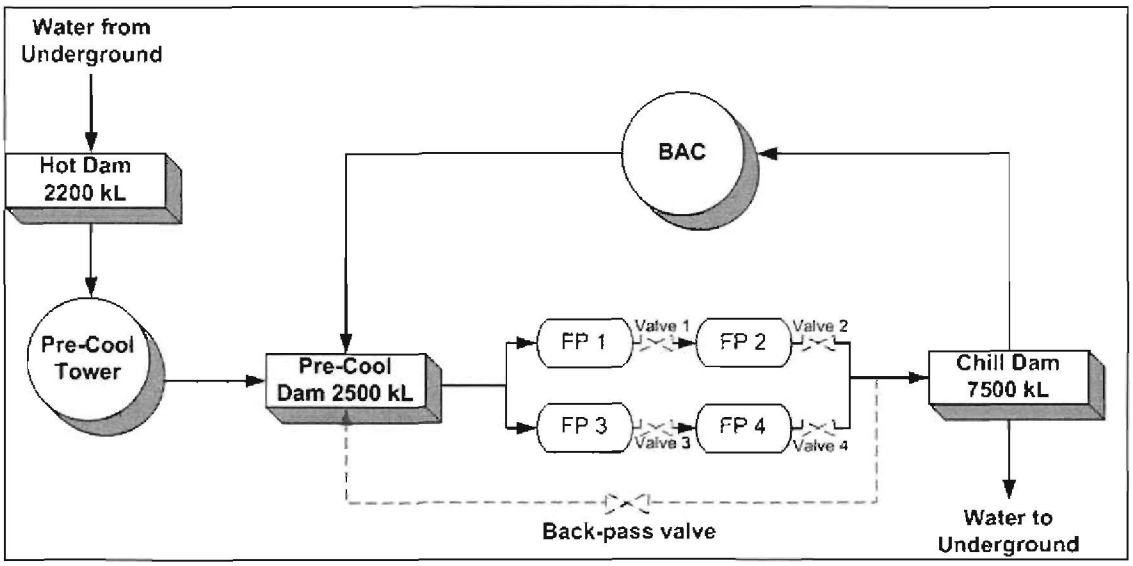


Figure 5-3: Layout of the Elandsrand surface plant proposed solution.

In summary, the following additional equipment needed to be installed in the Elandsrand underground (71L) refrigeration system:

- PLC machine automation;

- Integration into the existing SCADA system;
- Additional control valves and piping to establish back-pass capabilities; and
- Additional piping to enable 75L BAC return water to be reticulate directly into the hot water.

In Figure 5-4 the layout of the underground refrigeration system (71 Level) is shown. Additional equipment (indicated in red) can also be seen. Most of the additional equipment required for the 71Level system is used to enable flow monitoring and specific reticulation control.

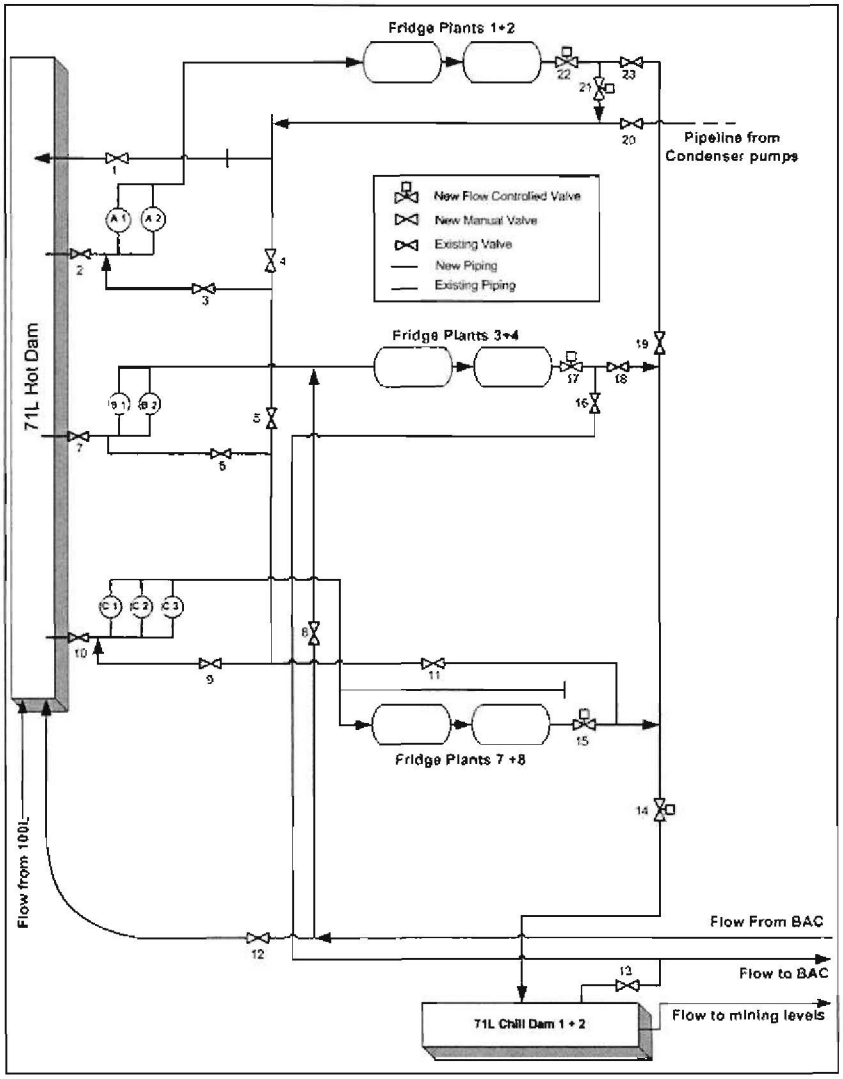


Figure 5-4: Layout of the Elandsrand 71L plant proposed solution.

Figure 5-5 and Figure 5-6 show the surface plant machine control flowchart and the machine emergency checklist. All system parameters must be adhered to before the machine controller is enabled.

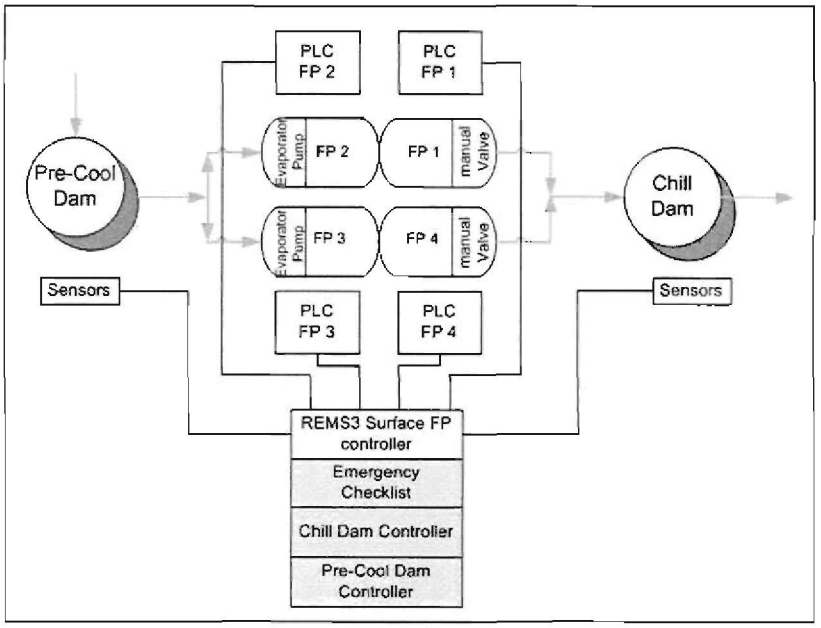


Figure 5-5: Surface machine controller.

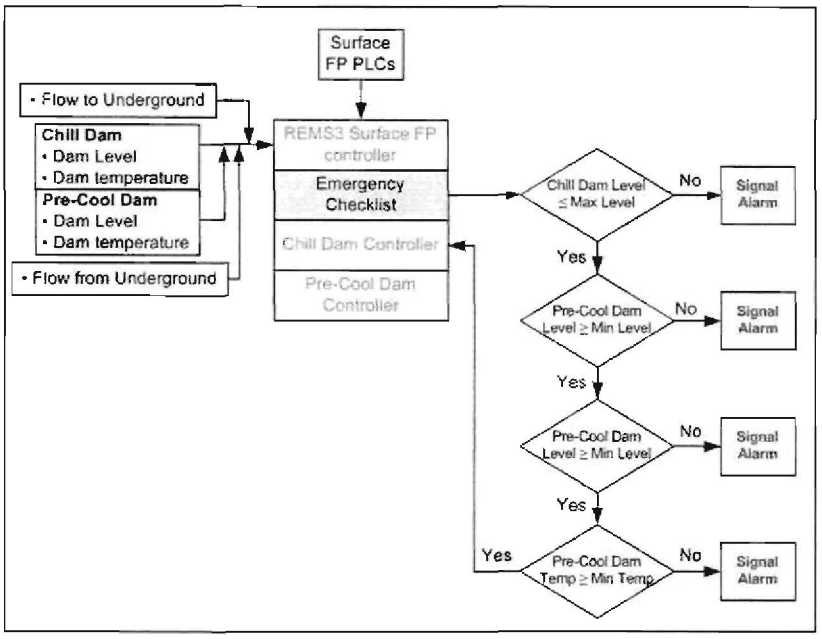


Figure 5-6: Chiller machine emergency checklist.

On surface the chilled water dam needs to be prepared sufficiently before any machines can be stopped. Machine water flow is controlled to establish correct preparation. The temperature of the storage dam is also controlled to ensure that enough chilled water at the correct temperature has been stored before the Eskom evening peak period.

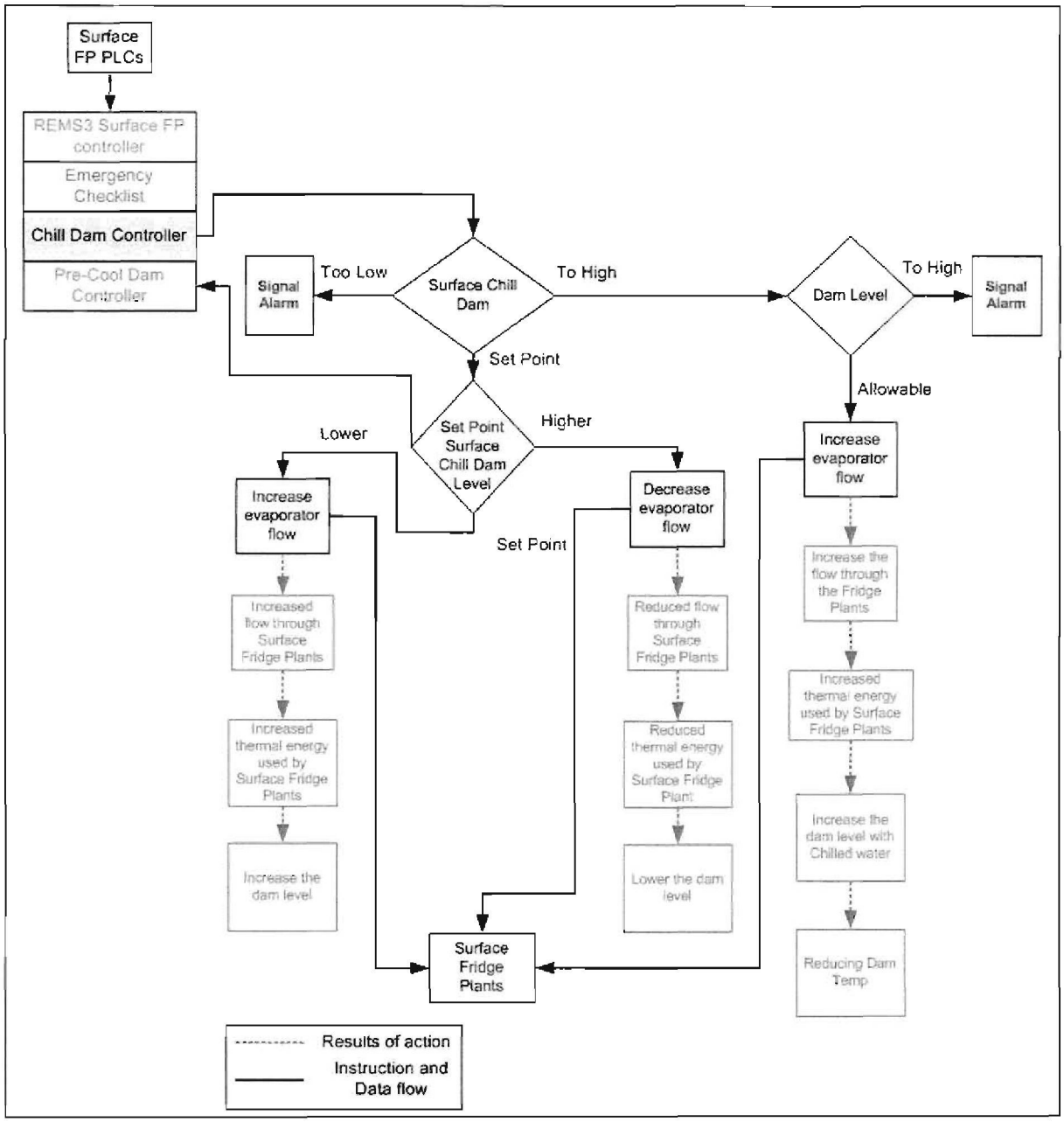


Figure 5-7: Surface fridge plant chilled water dam controller.

The following figure shows the layout of the underground refrigeration system with the additional control instrumentation. This equipment includes PLC, flow control valves and field instrumentation (sensors).

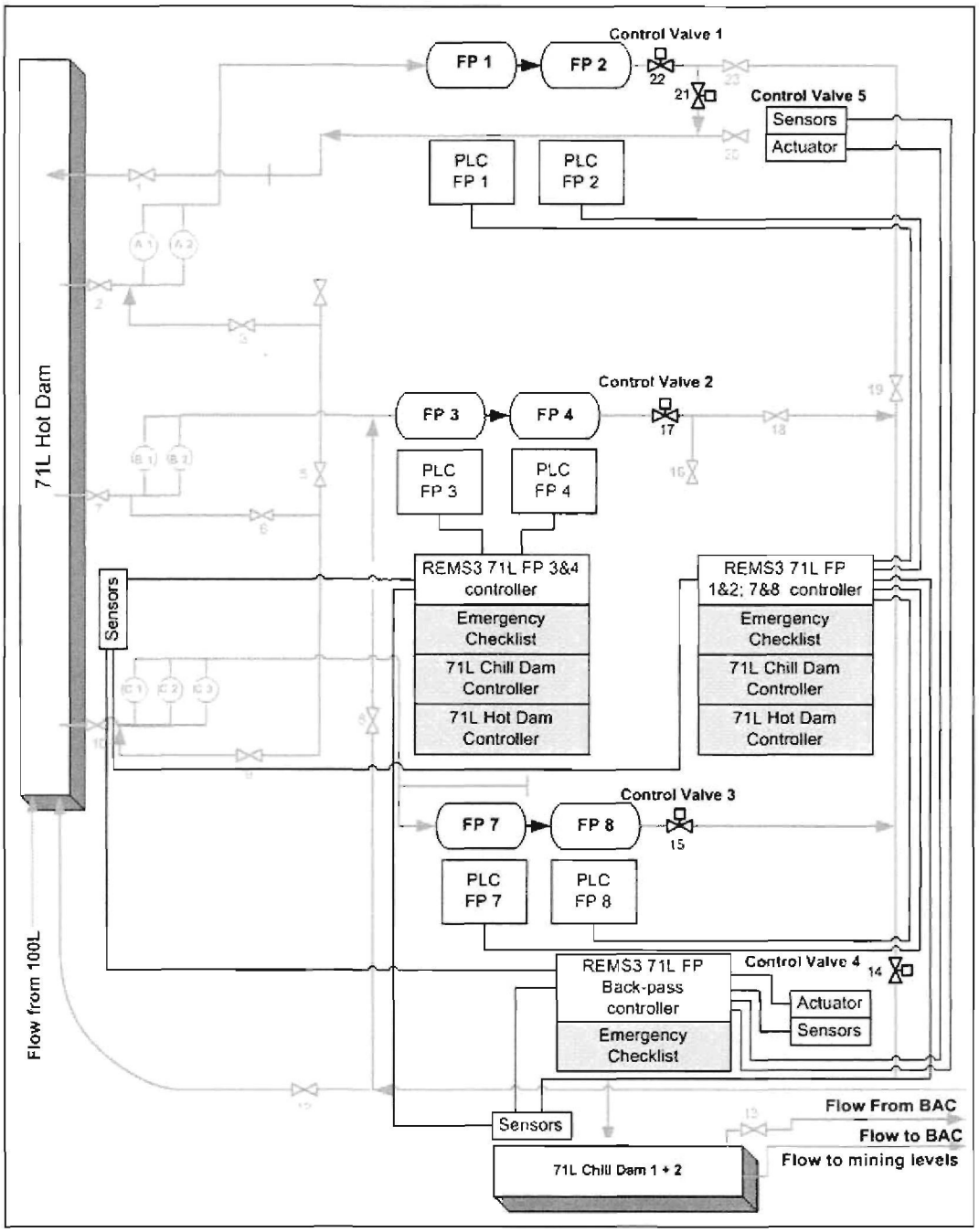


Figure 5-8: 71L machine controller.

South Deep

In summary, the following additional equipment needed to be installed in the South Deep refrigeration system:

- PLC machine automation;
- Integration into a SCADA system;
- Back-pass control valves (connecting the chiller machine outlet manifold with its inlet manifold);
- Machine control valves (evaporator and condenser); and
- Pre-cool dam bypass pipe and valve system.

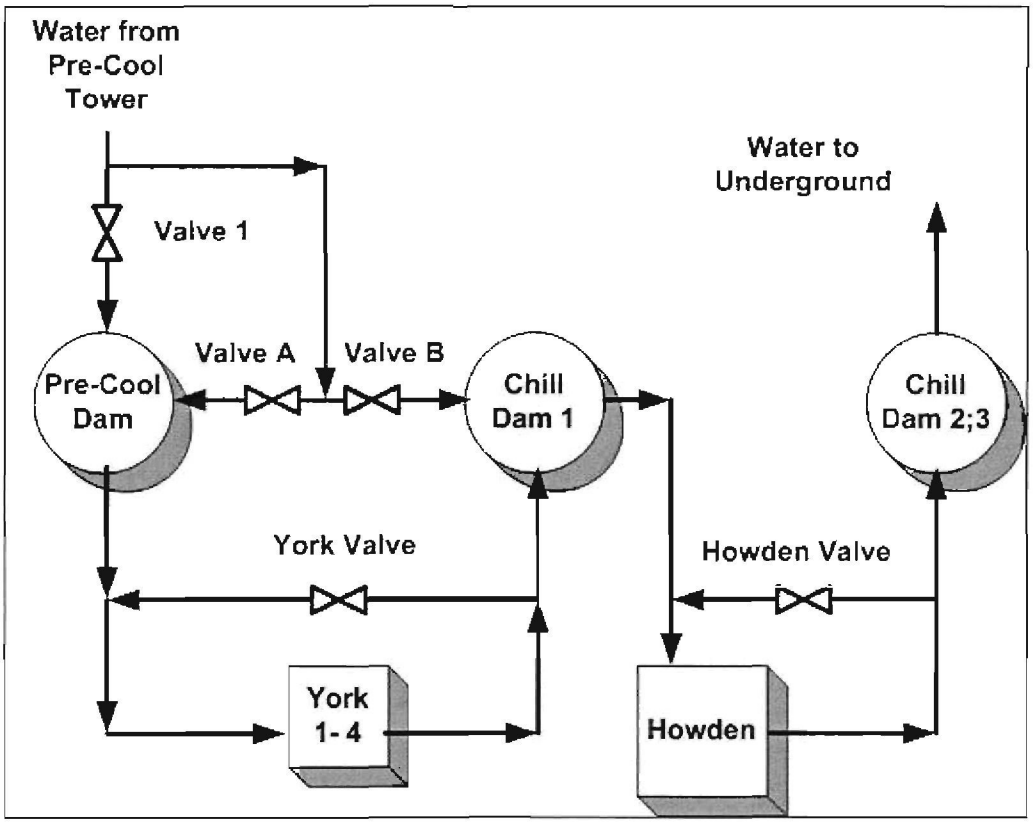


Figure 5-9: Layout of the South Deep plant proposed solution.

The control strategy for the preparation of the South Deep system's chilled water storage dams can be seen in the figure below. If the chilled water storage level is not reached at the correct temperature, the chiller machines cannot be stopped because their controller will be disabled.

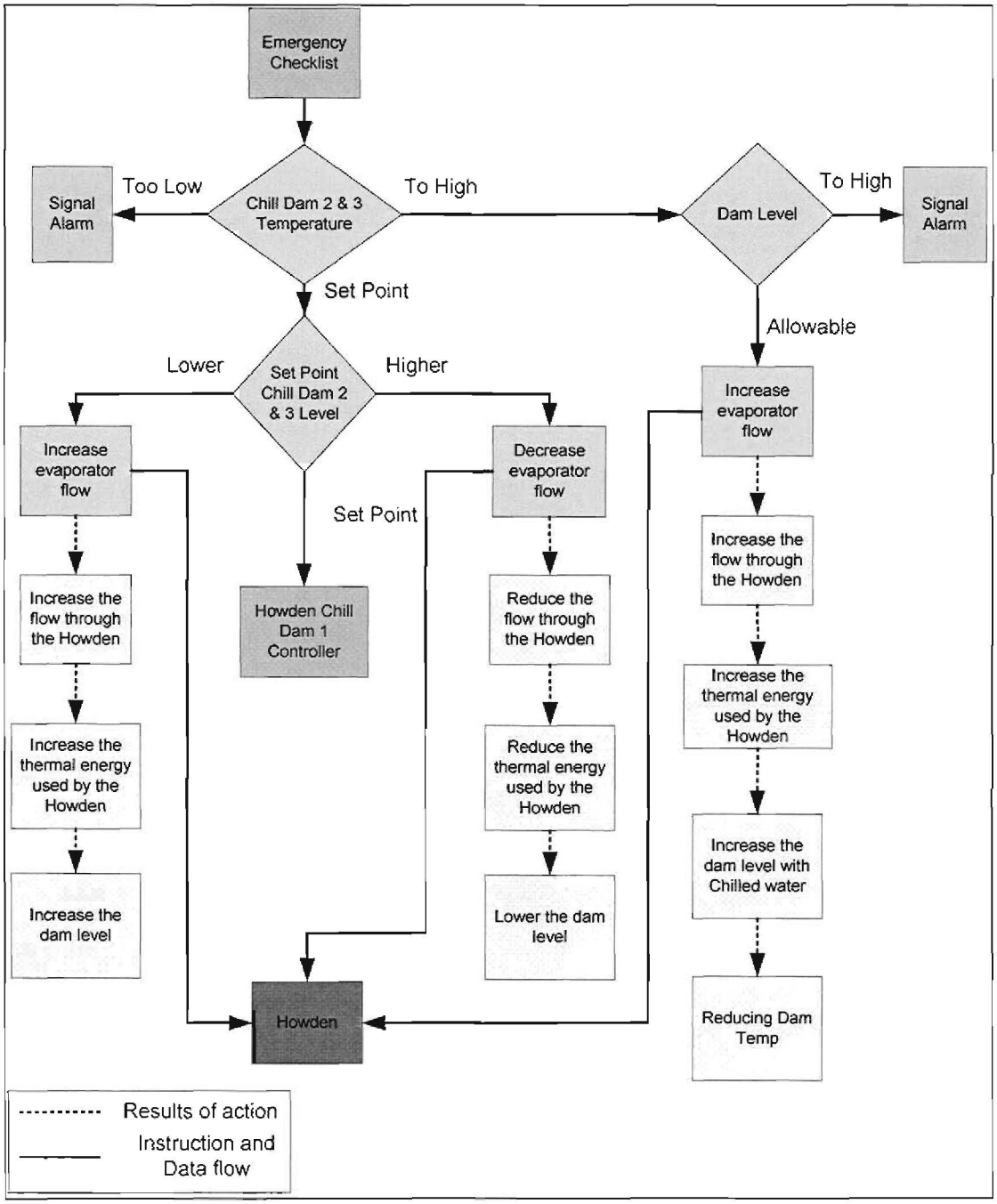


Figure 5-10: Chill dam 2 & 3 level and temperature controller.

To reduce the inlet temperature to the machines (and constitute an energy saving via compressor cut-back), very specific back-pass valve control is needed. The basic flowchart for this control can be seen below.

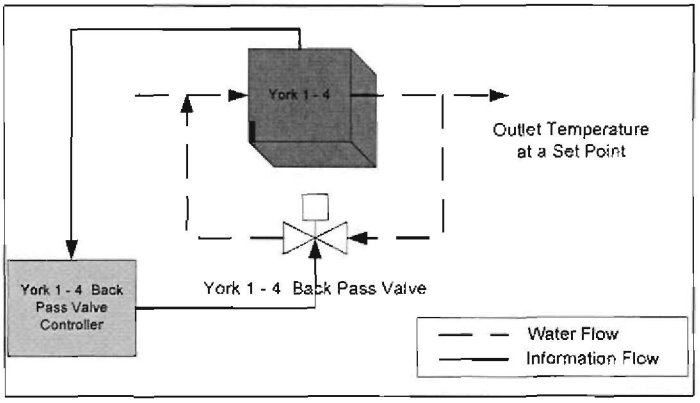


Figure 5-11: York back-pass controller schematic.

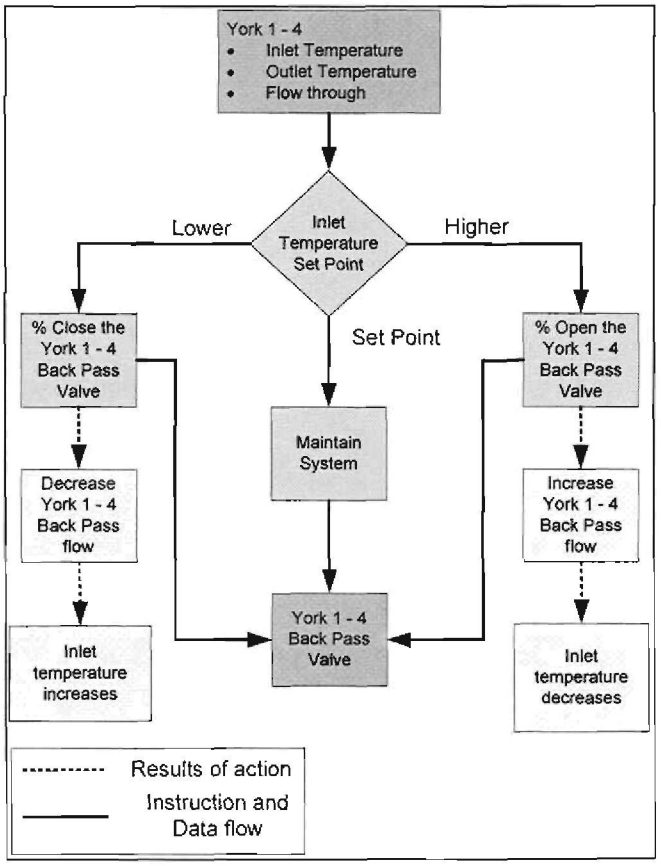


Figure 5-12: Back-pass controller flowchart.

Tshepong

In summary, the following additional equipment needed to be installed in the Tshepong refrigeration system:

- Integration into a SCADA system;
- Back-pass pipes and control valves (connecting the chilled water dam with the inlet manifold of the chiller machines); and
- Actuated and non-return valves (to control pre-cool water flow to the chiller machines).

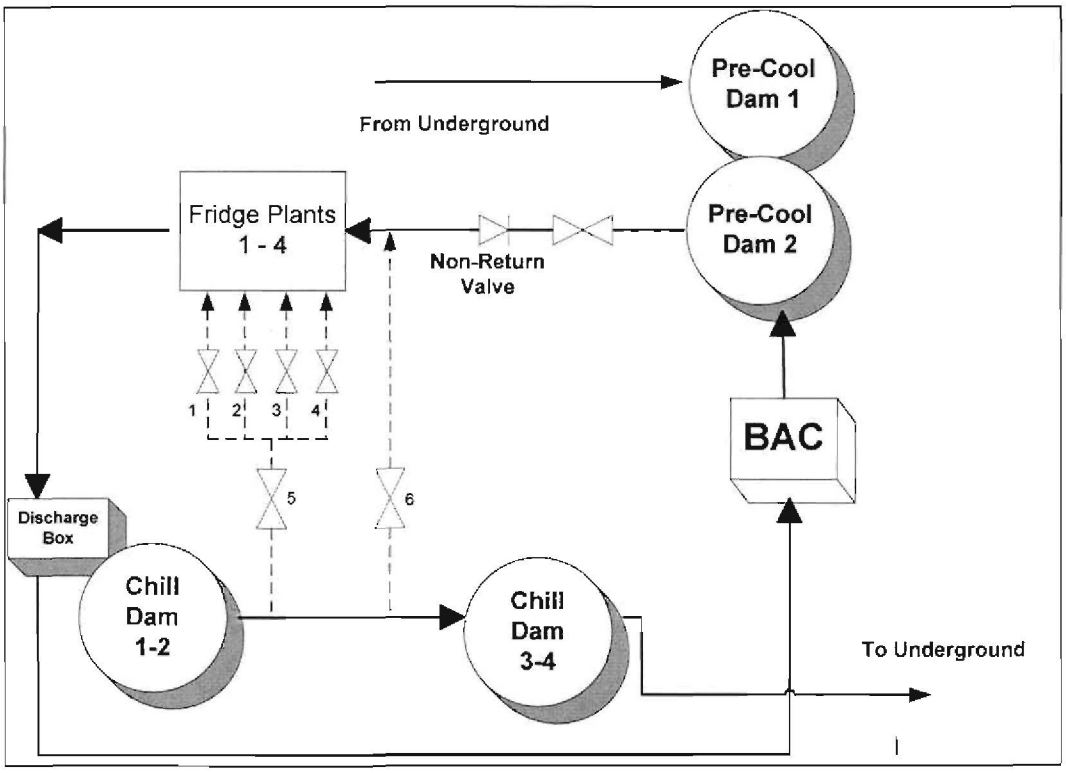


Figure 5-13: Layout of the Tshepong plant proposed solution.

The following figures show the required chilled water reticulation control during the normal operating period and Eskom evening peak period.

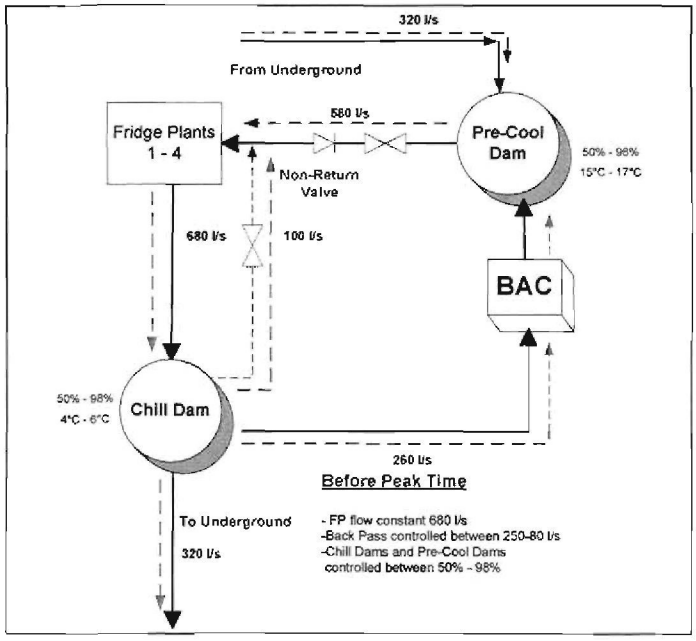


Figure 5-14: Proposed water balance during off-peak period.

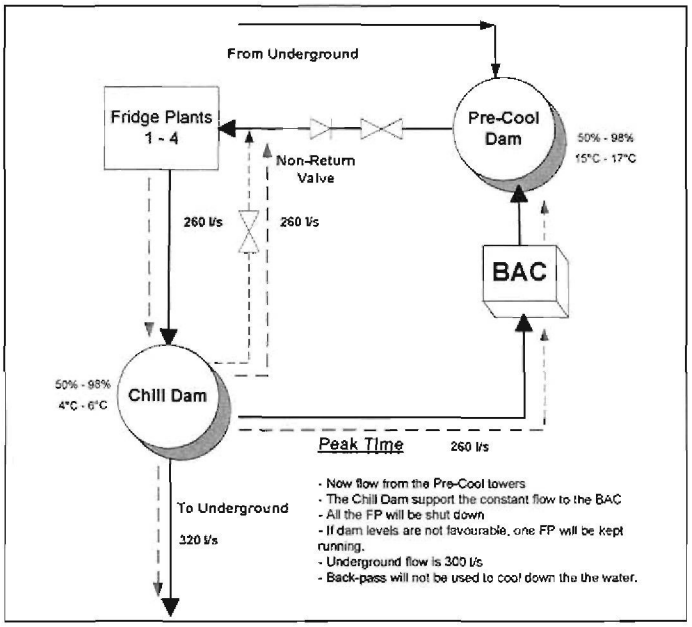


Figure 5-15: Proposed water balance during peak period.

At Tshepong mine, during the evening Eskom peak period, the pre-cool dams are isolated from the machines. On top of the chilled water dams, a distribution box is situated where to the BAC is supplied with chilled water. The distribution box needs to be filled at all times – to ensure that this happens; new piping, valves and sequential control strategies were required.

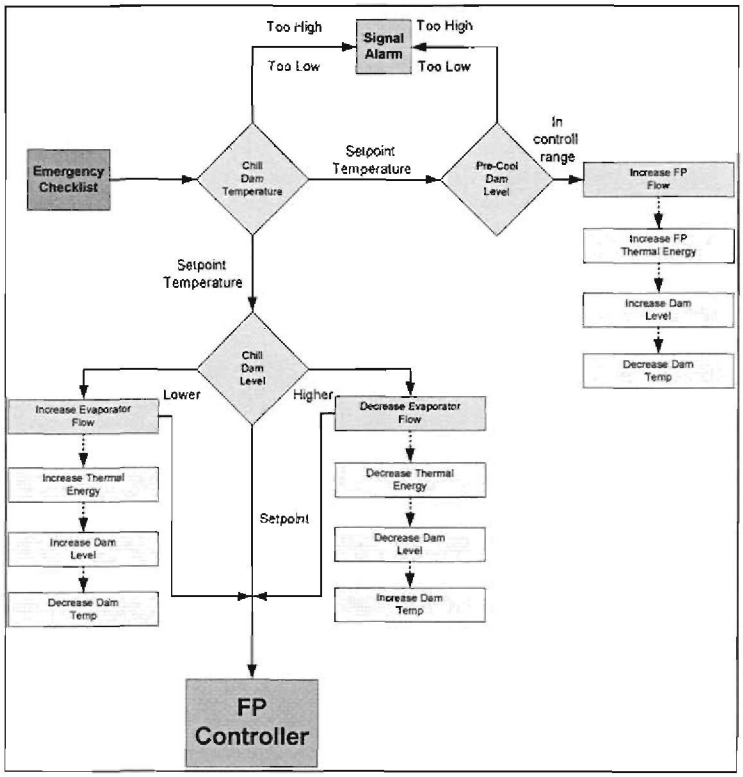


Figure 5-16: Chill Dam 1-4 controller schematic.

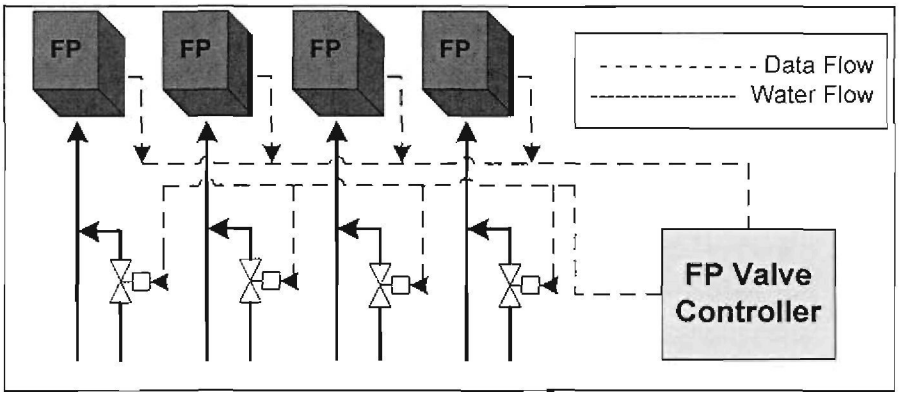


Figure 5-17: Refrigeration plant flow control.

5.3. INFRASTRUCTURE REQUIREMENTS

BACK-PASS FUNCTIONALITY

Kopanang

- Multi-turn electrical actuator for the back-pass valve;
- Valve position sensor; and
- Fibre communication to PLC.

Elandsrand

- Multi-turn flow control electrical actuators;
- Flow control valves;
- Vane control actuators;
- Valve position sensor;
- Electromagnetic flow meters;
- Fibre communication to PLC; and
- Piping.

South Deep

- Multi-turn flow control electrical actuators;
- Flow control valves;
- Valve position sensor;
- Electromagnetic flow meters;
- Fibre communication to PLC; and
- Piping.

Tshepong

- Flow control valves;
- Non-return valve;
- Valve position sensor; and
- Fibre communication to PLC.

PLANT CONTROL FUNCTIONALITY

Kopanang

- PLC equipment;
- HMI equipment (Human Machine Interface);
- PLC panels;
- Fibre communication;
- Network equipment;
- Field instrumentation (temperature probes and transmitters, pressure transmitters, pressure switches, pressure gauges, vibration transmitters);
- Condenser electromagnetic flow meters;
- Evaporator electromagnetic flow meters;
- Interfacing with existing SCADA; and
- Backup power supply.

The following figures show the necessary control instrumentation layout for Kopanang. The REMS system communicates with the SCADA system and controls plant equipment by monitoring and manipulating the values of equipment tags. Some of these tags can be seen below.

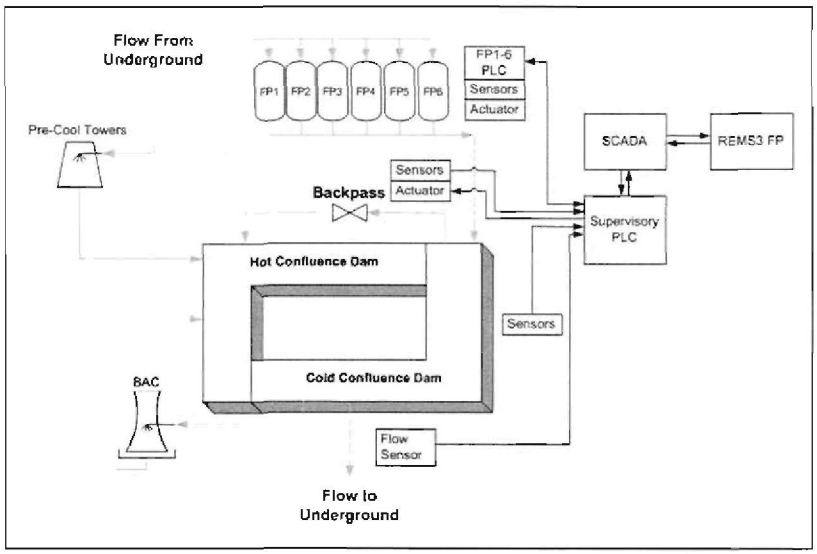


Figure 5-18: Control overview of the Kopanang system.

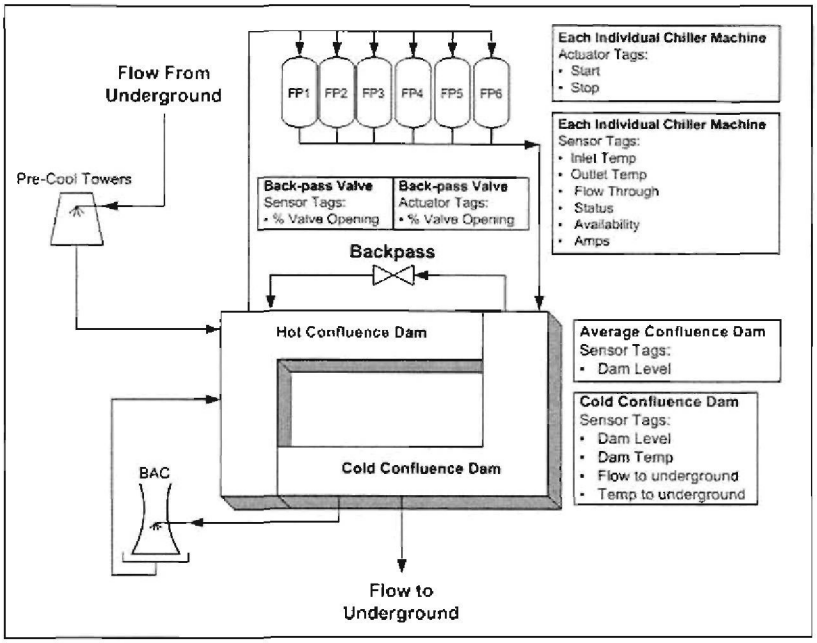


Figure 5-19: Kopanang SCADA sensor and actuator tags.

Elandsrand

- Surface PLC equipment;
- Surface HMI equipment;
- Surface PLC panels;
- Surface field instrumentation (temperature probes and transmitters, pressure transmitters, pressure switches, pressure gauges, vibration transmitters);
- Surface fibre communication;
- Surface network equipment;
- Surface electromagnetic flow meters;
- 71L PLC equipment;
- 71L HMI equipment;
- 71L PLC panels;
- 71L field instrumentation (temperature probes and transmitters, pressure transmitters, pressure switches, pressure gauges, vibration transmitters);
- 71L fibre communication;
- 71L network equipment;
- 71L electromagnetic flow meters;
- 75L BAC automation;
- Interfacing with existing SCADA; and
- Backup power supply.

The following figures show the control network for the Elandsrand refrigeration system (surface and underground).

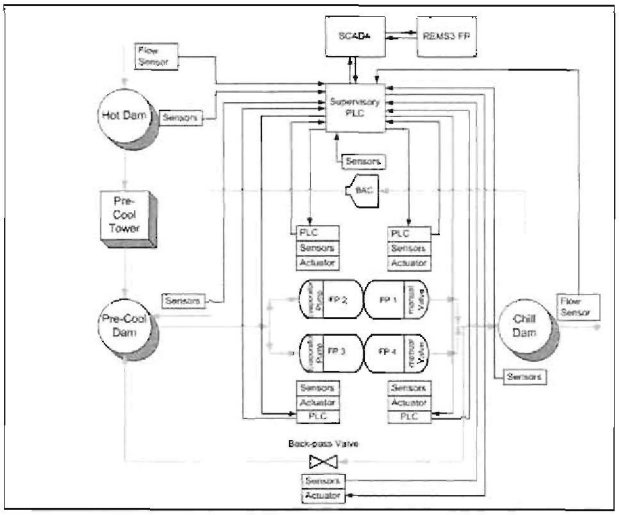


Figure 5-20: Control overview of the Elandsrand surface system.

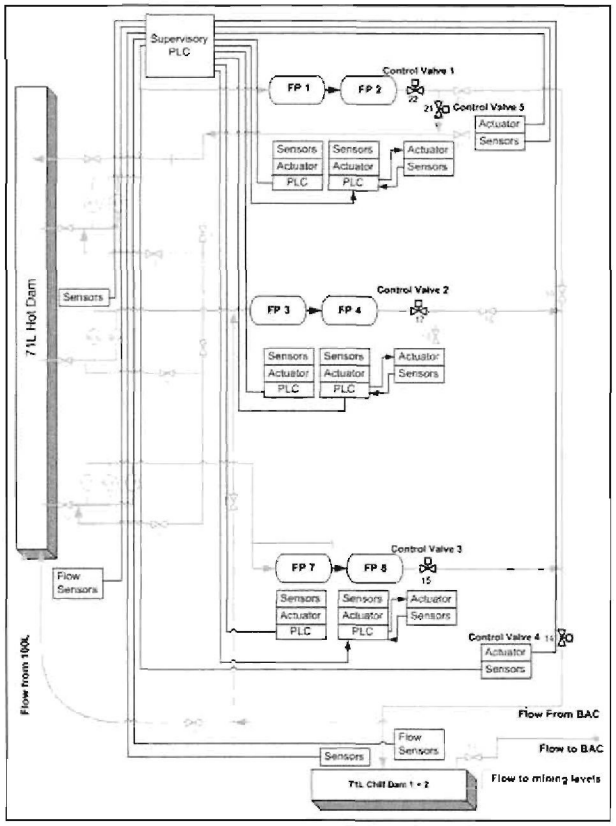


Figure 5-21: Control overview of the Elandsrand 71L system.

Various equipment tags need to be accessed via the SCADA system. The specific required tags for the REMS system to operate are shown in the following figures.

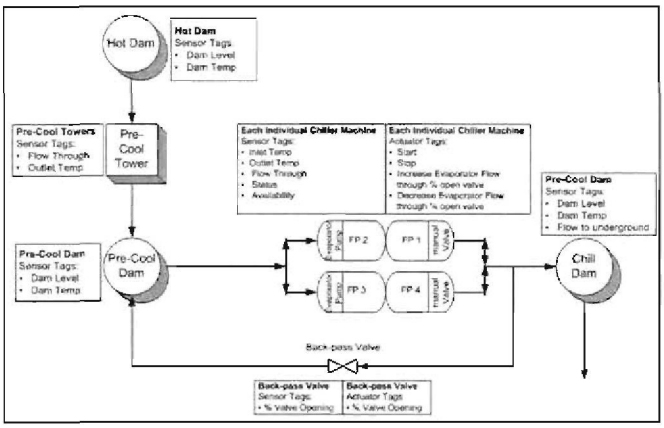


Figure 5-22: Elandsrand surface SCADA sensor and actuator tags.

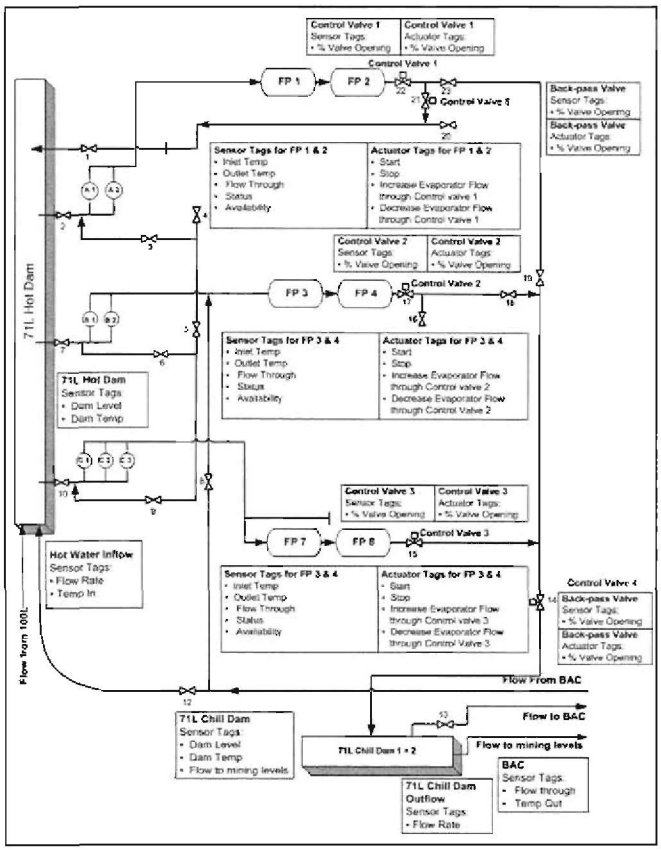


Figure 5-23: Elandsrand 71L SCADA sensor and actuator tags.

South Deep

- York machines PLC equipment;
- Howden machine PLC CPU upgrade;
- York machines HMI equipment;
- Howden machine HMI upgrade;
- York machines PLC panels;
- York machines field instrumentation (temperature probes and transmitters, pressure transmitters, pressure switches, pressure gauges, vibration transmitters);
- Surface fibre communication;
- Surface network equipment;
- New SCADA system;
- Flow control valves (condenser and evaporator);
- Electromagnetic flow meters; and
- Backup power supply.

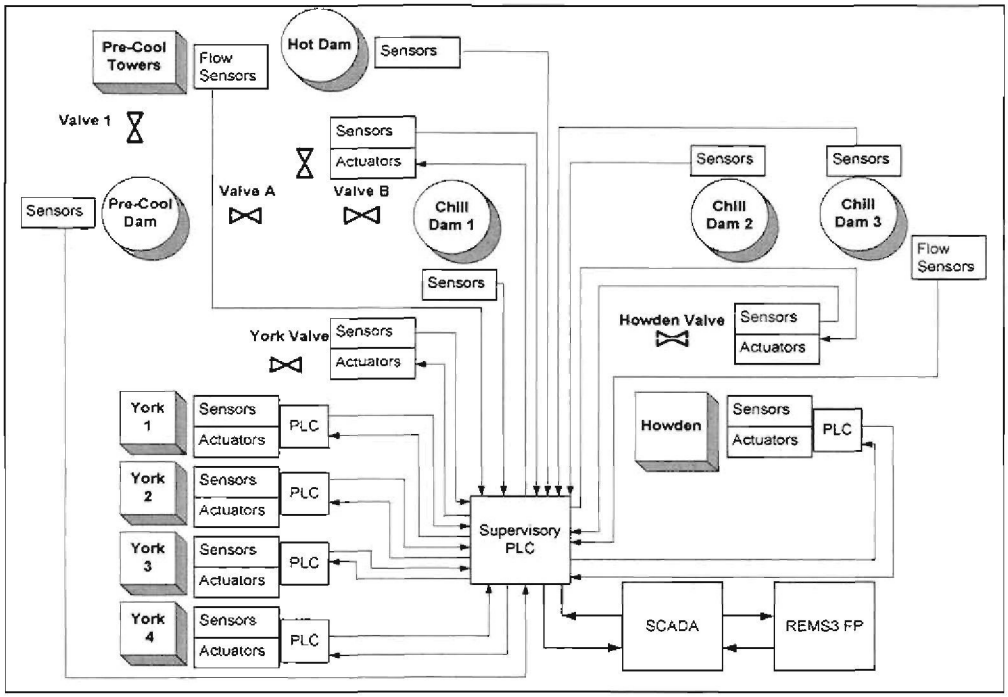


Figure 5-24: Control overview of the South Deep system.

Figure 5-24 shows the control infrastructure layout for South Deep. All PLC, sensor and other control equipment are interfaced into a SCADA system. The REMS system will access the SCADA system and manipulate control tags for control purposes (see figure below).

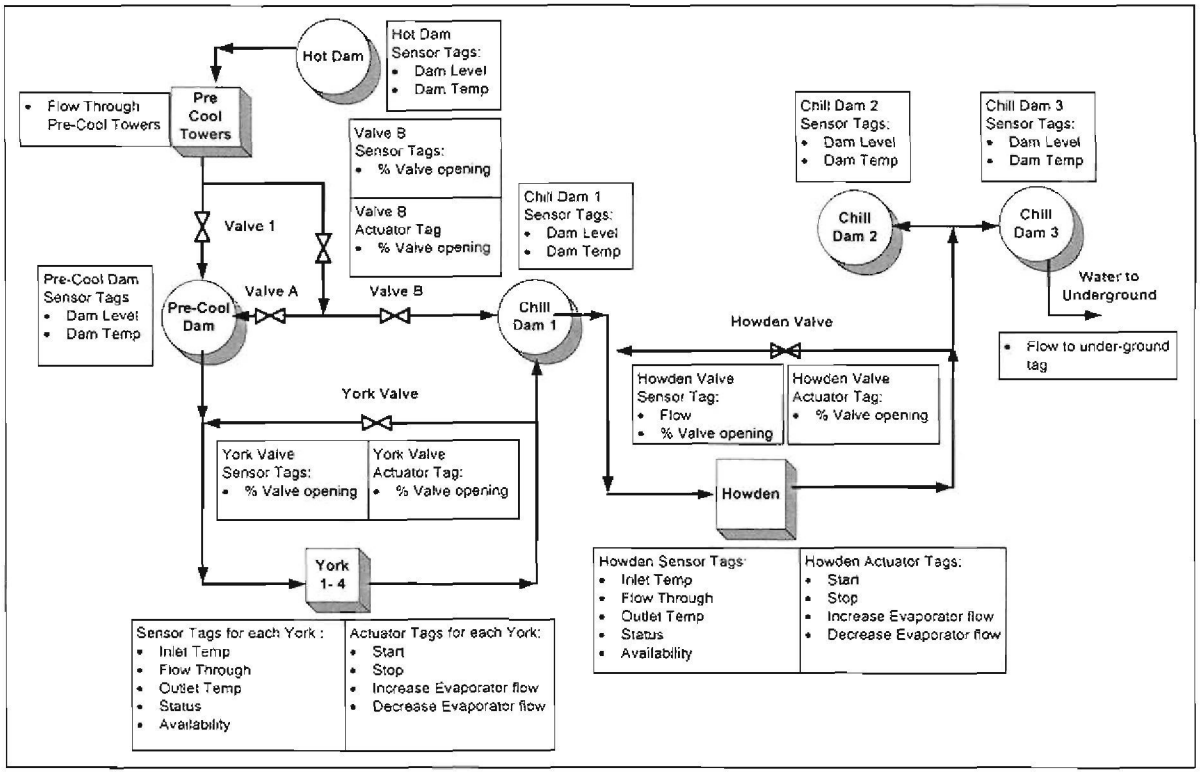


Figure 5-25: South Deep SCADA sensor and actuator tags.

Tshepong

- Network equipment;
- Electromagnetic flow meters;
- Flow control valves (evaporator and condenser); and
- Interfacing with existing SCADA.

As for the Kopanang, South Deep and Elandsrand refrigeration systems, the Tshepong system required control infrastructure to enable the efficient operation of the REMS system. Details can be seen in the figures below.

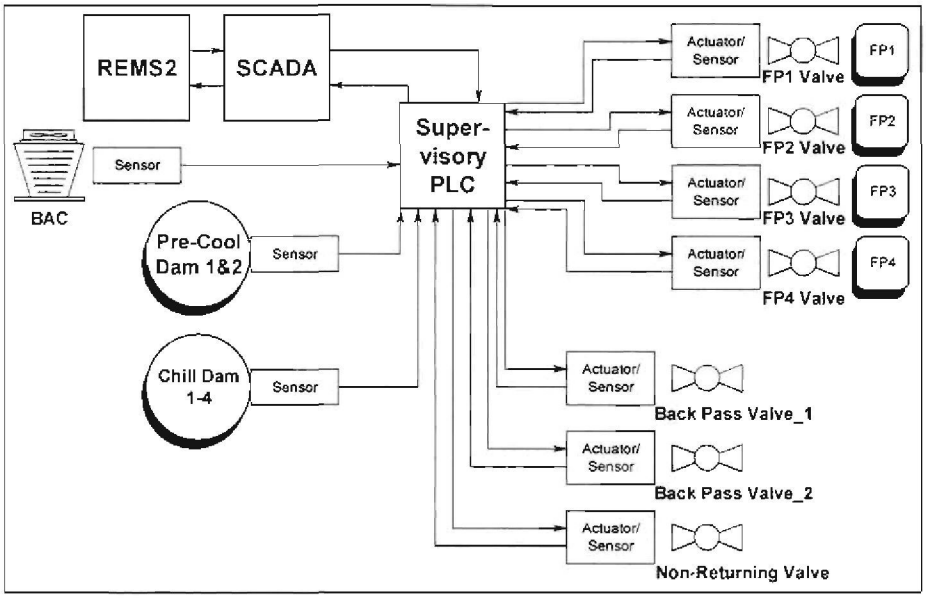


Figure 5-26: Control overview of the Tshepong system.

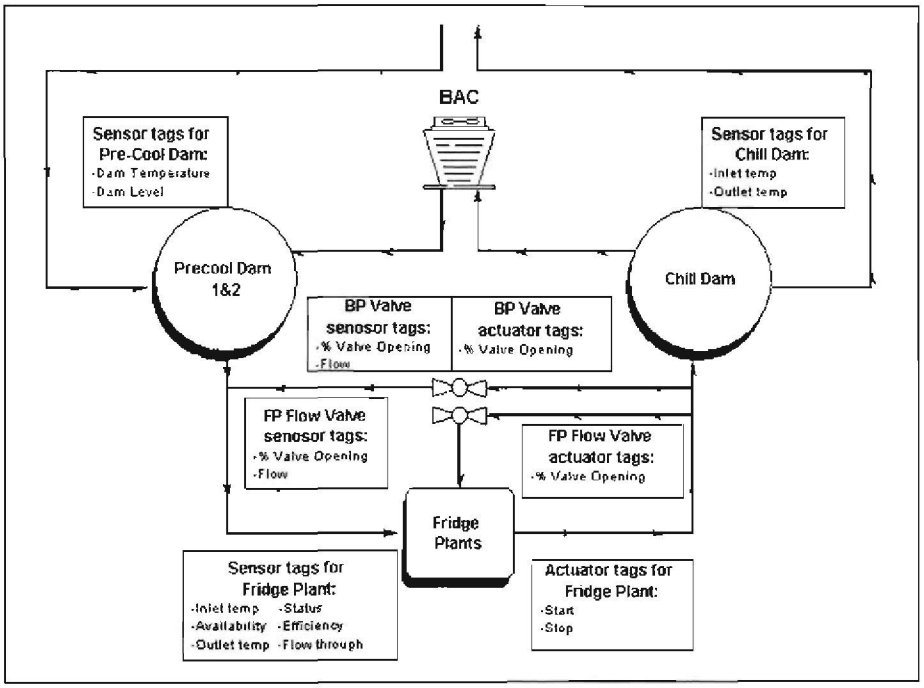


Figure 5-27: Tshepong SCADA sensor and actuator tags.

5.4. AN INTEGRATED SOFTWARE CONTROL SOLUTION

The new control algorithms and global control philosophy were integrated into a software solution and called REMS (Real-time Energy Management System). This system is an energy management system and its goal is to minimise the electricity cost of a refrigeration plant by moving electrical load from expensive tariff periods to less expensive periods.

The REMS system communicates with the mine SCADA system via an OPC (OLE for Process Control) connection. It obtains plant information in tag-format and can write new values to control tags. The REMS system is a control system and controls the operation of the plant in a safe and efficient manner. The REMS system also consists of added functionalities, i.e. reporting, database, alarms, etc.

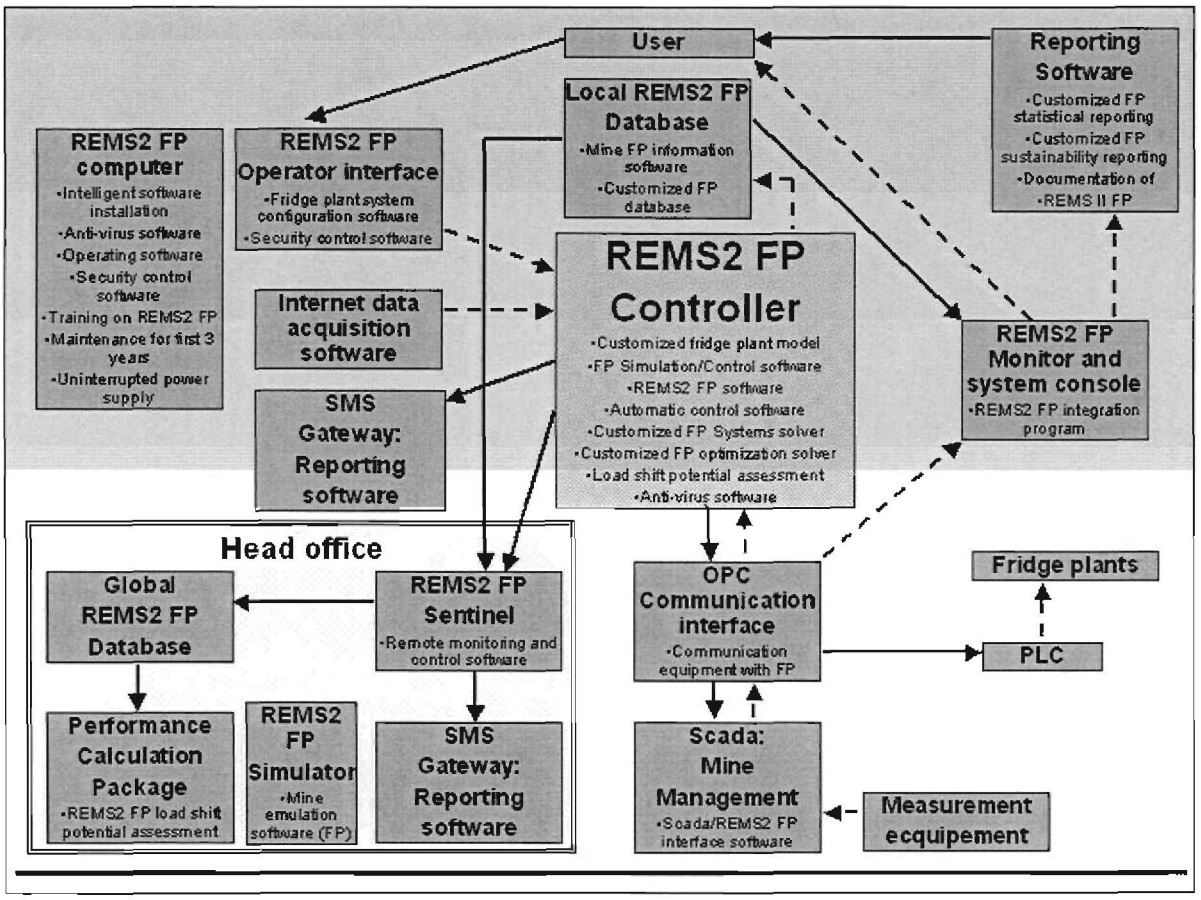


Figure 5-28: REMS system information flow.

Some of the software interfaces can be seen in the following figures. The Dam Editor interface allows the user to enter dam capacities, minimum and maximum levels, etc. The Fridge Plant Controller Editor is used to enter numerous details surrounding the control of the machines, e.g. shutdown times, constraints, shutdown selection, etc.



Figure 5-29: Dam information editor.

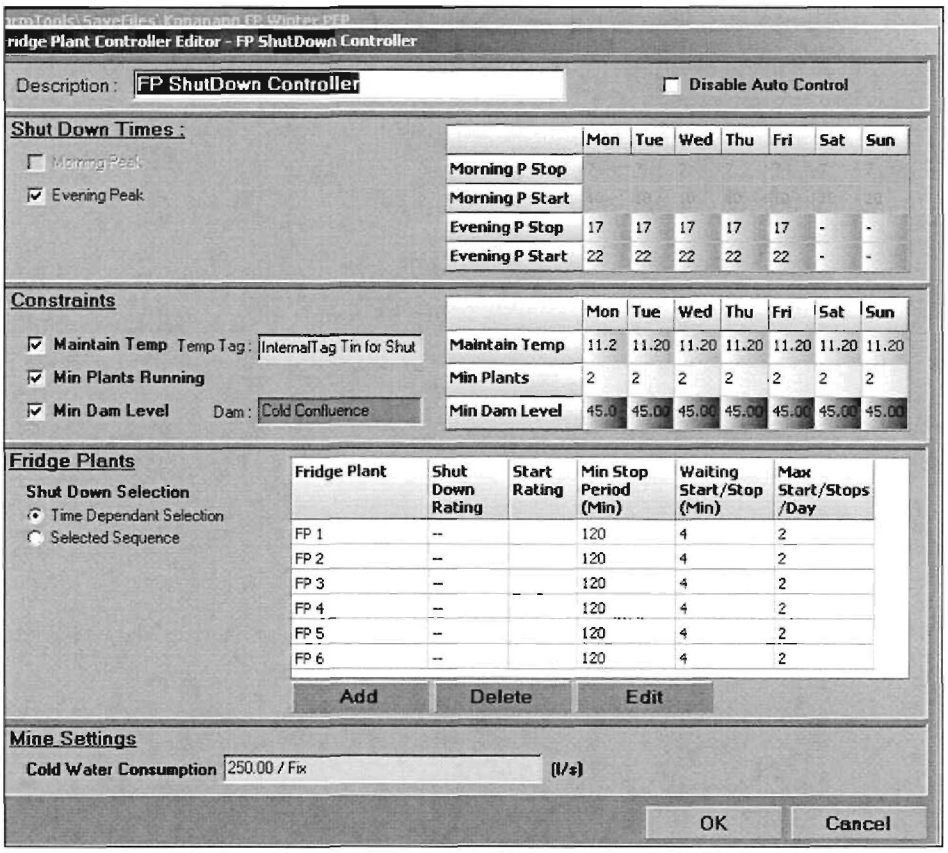


Figure 5-30: Machine controller interface.

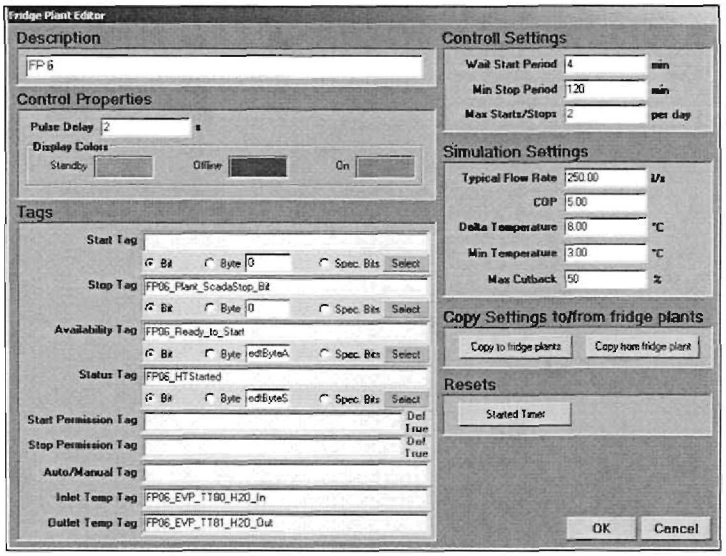


Figure 5-31: Machine information editor.

The Machine Information Editor allows the user to edit machine details. A Function Editor helps the user to display tag information on the system interface.

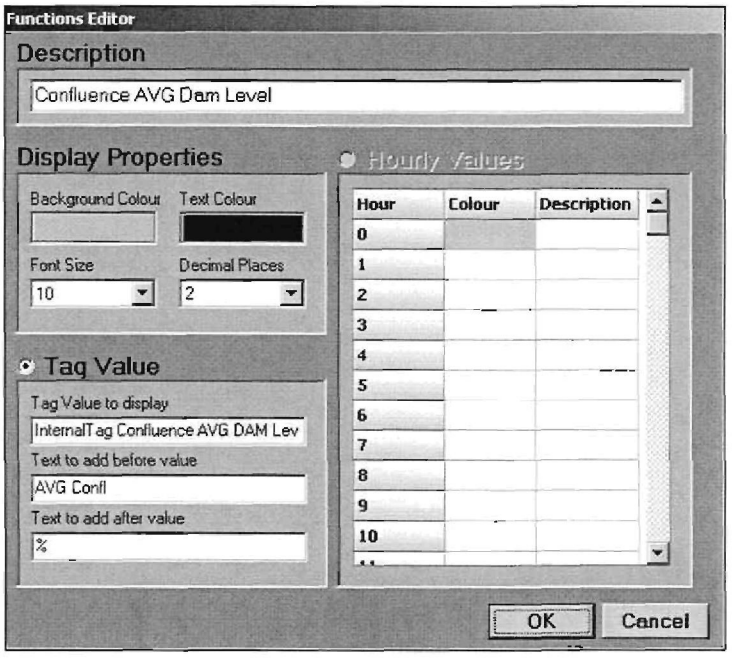


Figure 5-32: Dam, valve, temperature input interface.

A Generic Data Logger interface can be used to input specific tags for which the user would like to log data (e.g. for analysis purposes).

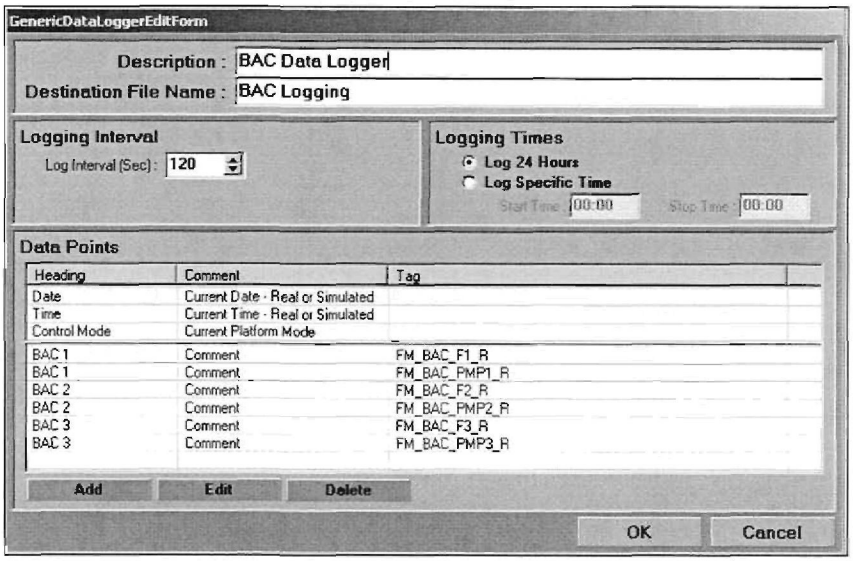


Figure 5-33: Data logger interface.

The Internal Tag Manager is used to manage user-created tags used for calculation and control purposes.



Figure 5-34: Internal tag manager.

A Programmable Tag Editor interface was created which helps the user to program internal tags for specific display or control purposes.

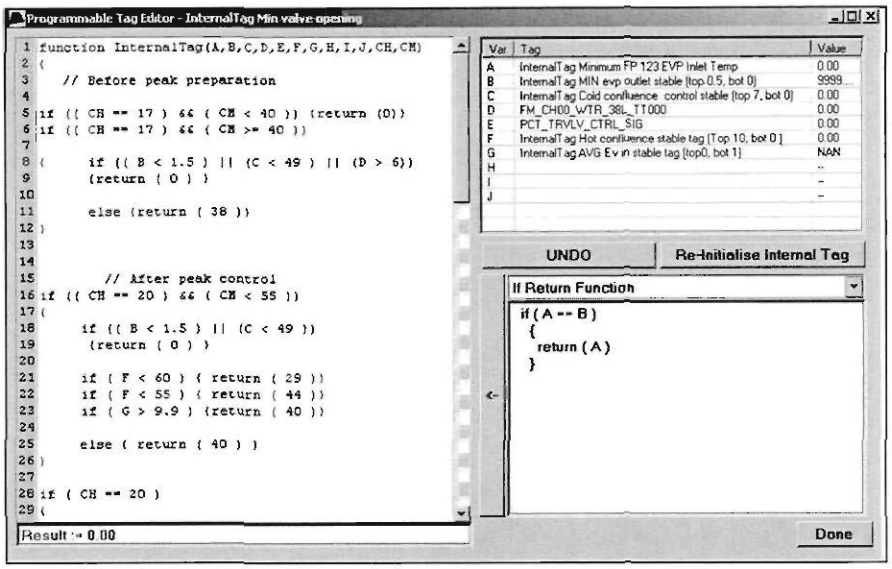


Figure 5-35: Programmable tag interface.

The Valve Controller Editor allows the user to input specific valve information and control parameters (this can be for the back-pass valves or other controllable valves).

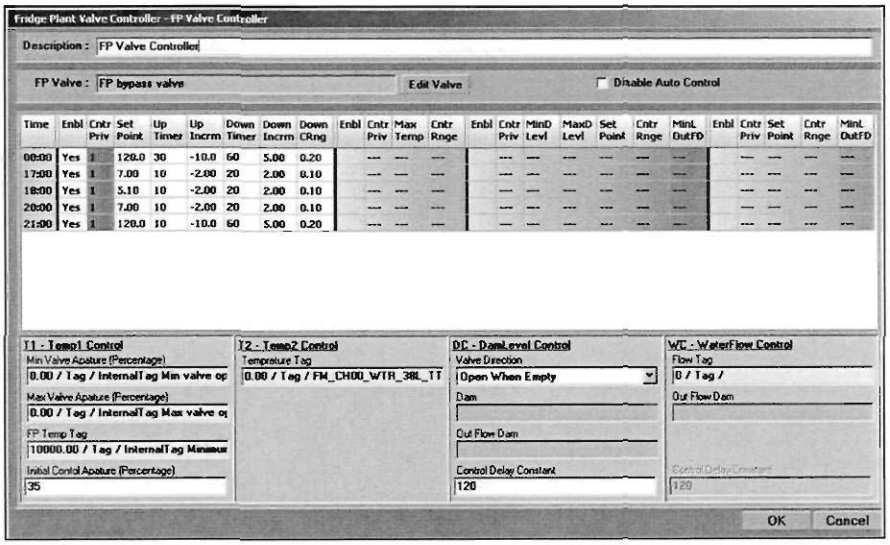


Figure 5-36: Valve controller interface.

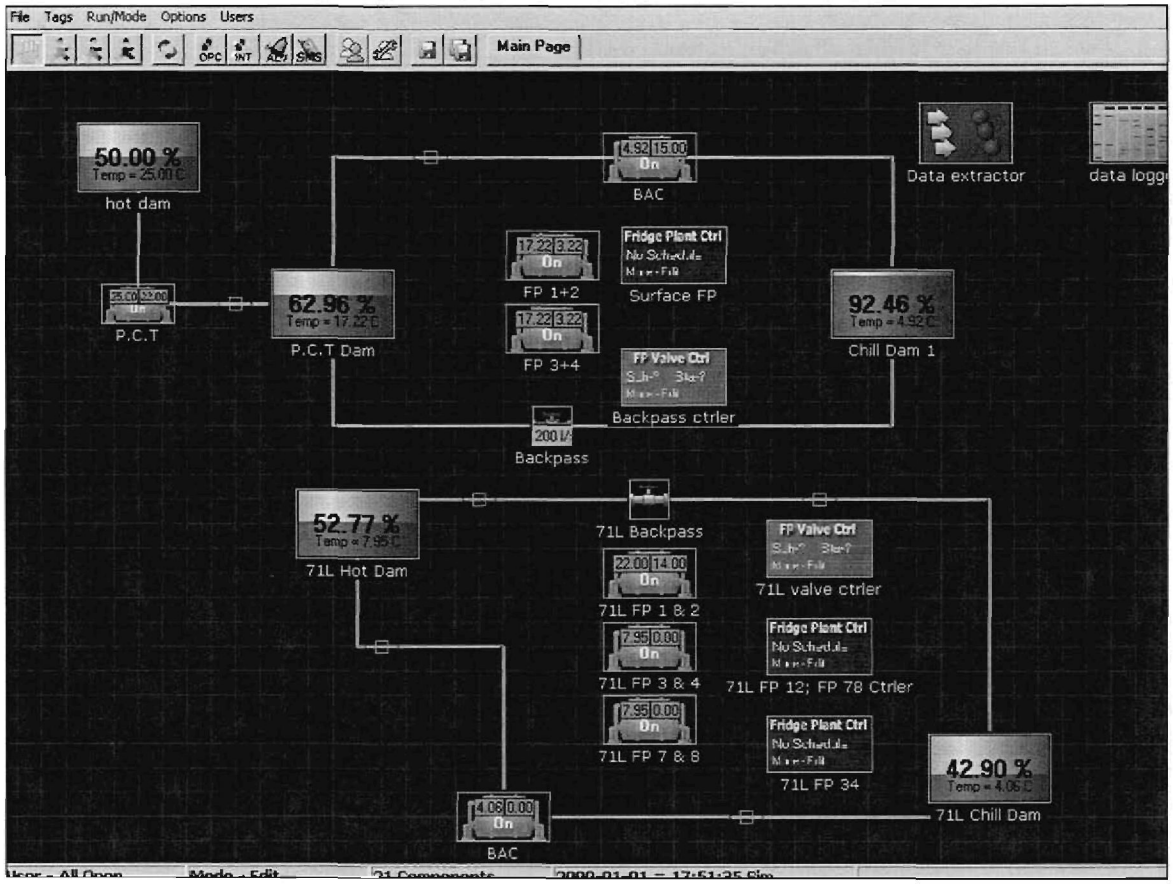


Figure 5-37: Control screen layout.

5.5. QUANTIFYING DSM POTENTIAL FOR IDENTIFIED PROJECTS

Because the utilisation of the refrigeration plants in summer differs from their operation in winter, the load shift potential was established for a typical summer day and a typical winter day. A weighted average was then calculated (using 9 summer months and 3 winter months). These weighted averages were used to quantify the DSM potential to Eskom.

Project	DSM Potential [MW]
Kopanang	3.2
Elandsrand	6.3
South Deep	4.2
Tshepong	3.2
Total	**16.9**

Table 5-1: Weighted average load shift potential.

5.6. COST ANALYSIS

Detail sub-contractor quotations for the hardware infrastructure identified were obtained [1], [2], [3] and [4].

Detail quotations for these four projects can be found in Appendix A.

A summary of the infrastructure costs are shown below.

Project	Infrastructure Cost [R-million]
Kopanang	3,080
Elandsrand	6,343
South Deep	4,157
Tshepong	1,165
Total	**14,745**

Table 5-2: Summarised infrastructure costs.

5.7. CREATING BUSINESS CASES FOR ESKOM DSM

In accordance to Eskom's latest planning, building a new peaking power station (which normally supplies in the range of 1,000MW of power) can take up to 7 years to build [5] at a cost of R16-billion [6], and three years for the return of mothballed and gas-fired plants. These peaking power stations are typically used during Eskom's evening peak period.

A large (called "six-pack") base load power station can generate up to 4,255MW of power. To build such a station could cost as much as R70-billion [7]. The cost of building new power stations therefore equates to approximately R16-million per MW of generation capacity.

The Eskom DSM program aims at building a "virtual" peak power station. The infrastructure costs involved with the projects discussed in this study, amount to approximately R15-million. This equates to a capacity "generating" cost of approximately R900-thousand per MW from an infrastructure point of view.

The ESCo who submits the proposal to Eskom DSM might also add to the cost depending on what arrangements it has with its clients. For the case studies identified in this study, the ESCo also supplies a software control system and other services, increasing the cost of these projects to approximately R2-million per MW.

The MWs delivered through the DSM program are very attractive from a cost point of view to Eskom, hence its strong pursuit for DSM MWs in South Africa. Even though the availability of Eskom DSM's virtual power station might be lower than that of a base load or peaking power station, it is still a viable and attractive route for Eskom to pursue.

5.8. CONCLUSION

The DSM solutions proposed in this study are system control solutions. The identified DSM potentials can only be realised through real-time optimised automatic control. An Energy Management System (EMS) was developed for this purpose. It is a software solution and optimally controls plant equipment through a SCADA system whilst adhering to all plant constraints.

To "prepare" a refrigeration system for shifting electrical load from a specific period of time, the system must be retrofitted with control infrastructure, e.g. flow control valves, dam level sensors, temperature sensors, flow meters, PLC-equipment, SCADA, fibre communication network, etc. Automation infrastructure for refrigeration systems is generic and some systems have them installed already.

When electrical load is shifted from Eskom's evening peak period (18:00 – 20:00) a virtual peaking power station is created. In this study it is proposed that a total of 16.9MW be shifted from the peak period. The infrastructure cost to sustainably realise this load shift potential, is approximately R15-million. This then relates to a power generation cost of below R1-million per MW, which is much lower than the R16-million per MW required for building a new power station.

The MW "supplied" by Eskom DSM virtual power station therefore comes at a much lower cost, which makes it a viable solution to pursue.

5.9. REFERENCES

[1] Welkom Industrial Controls, Project Quotation, Ref. 401H (Rev. 2), 21 October 2004.

[2] Prime Instrumentation, Project Quotation, Elandsrand Fridge Plant Quotation, PI-1108 (Rev. 5), 15 May 2007.

[3] Prime Instrumentation, Project Quotation, Elandsrand Fridge Plant Quotation, PI PI-1102/2, 16 April 2007.

[4] Welkom Industrial Controls, Project Quotation, Ref. 2936, 23 April 2007.

[5] Eskom, "Demand Side Management's information guide for Energy Services Companies", Online, www.Eskom.co.za, Eskom, Postal address: PO Box 1091, Johannesburg, 2000, 2002.

[6] Kok, S., "The impact of domestic solar water heaters on South Africa", TEMM International (Pty) Ltd, Postal address: PO Box 55577, Arcadia, 0007, p.44, 1994.

[7] Creamer Media, Engineering News, Electrical Power Generation and Transmission, "Eskom now budgeting some R70bn capex for Lephalale project ", 6 Feb 2007.

CHAPTER 6

VERIFYING THE NEW ENERGY MANAGEMENT CONTROL SYSTEM

6. VERIFYING THE NEW ENERGY MANAGEMENT CONTROL SYSTEM

6.1. PREAMBLE

The REMS system was installed on the refrigeration systems of the Kopanang and Tshepong Gold Mines. The purpose of the REMS systems was to automatically shift electrical load from the Eskom evening peak period (18:00 – 20:00) to low demand periods without violating any equipment, process, maintenance or plant and mine safety constraints.

By shifting load from the Eskom evening peak period a "virtual" peaking power station is generated for Eskom, helping them with their current peak supply problems. The added benefits of these projects include plant automation infrastructure and electricity cost savings. To accurately determine the load shift results of the two projects discussed in this chapter, measurement and verification (M&V) methods needed to be established and clarified.

For the Kopanang system, a specific M&V methodology needed to be developed to account for the energy efficiency component of the project. The M&V approach for the Tshepong project, being a load shift project, had to ensure that the electrical energy profiles were energy neutral. Both projects were measured and verified by the North West University acting as an independent M&V operation for Eskom DSM.

The Kopanang DSM project produced an average 3.6MW DSM result, while the Tshepong project produced a 4.0MW DSM result during the Eskom evening peak period. Both these projects over-performed against their proposed DSM targets.

The successful operation of the REMS system is evident in the DSM results for the Kopanang and Tshepong projects. The REMS system on Kopanang has been consistently operating for more than 20 months, realising over R2-million in electricity cost saving for the mine for this period. The Tshepong project will realise cost savings in the order of R500,000 per annum for the mine.

6.2. MEASUREMENT AND VERIFICATION: KOPANANG GOLD MINE

The baseline load profile for Kopanang was determined by using actual measured electrical feeder data (from January 2004 to December 2004). From this data an average summer load profile (9 months) and winter profile (3 months) were established. These baseline power profiles were then submitted to Eskom DSM (with the proposed DSM potential based on them).

During the DSM infrastructure implementation on the refrigeration system of Kopanang Gold Mine, the mine used the downtime opportunity to also replace the R-12 refrigerant with R-134a, as well as conduct yearly maintenance practices on the machines [1]. The plant COP was actually improved through combination of all the work conducted on the system. This rendered energy efficiency (EE) in the operation of the system [1].

Also of note is the fact that during the winter of 2004, the bulk air-coolers (BACs) of the mine were actually operated. This practice was discontinued from June 2005 onward.

Power measurements during the winter of 2006 not only showed a COP improvement but also a 2MW reduction in power when compared to the baseline profile submitted to Eskom DSM. This combination of energy efficiency and load reduction in the Eskom evening peak period (18:00 – 20:00) makes the verification process even more difficult [1].

Therefore a new procedure to confirm the actual results with the predicted results had to be developed. The method consists of an equation related to the pre-implementation conditions of the refrigeration system, by comparing the ratio between the thermal energy and the electrical power consumption respectively.

This figure therefore represents the amount of energy used to generate the thermal energy needed to cool down the water down in the pre-implementation period.

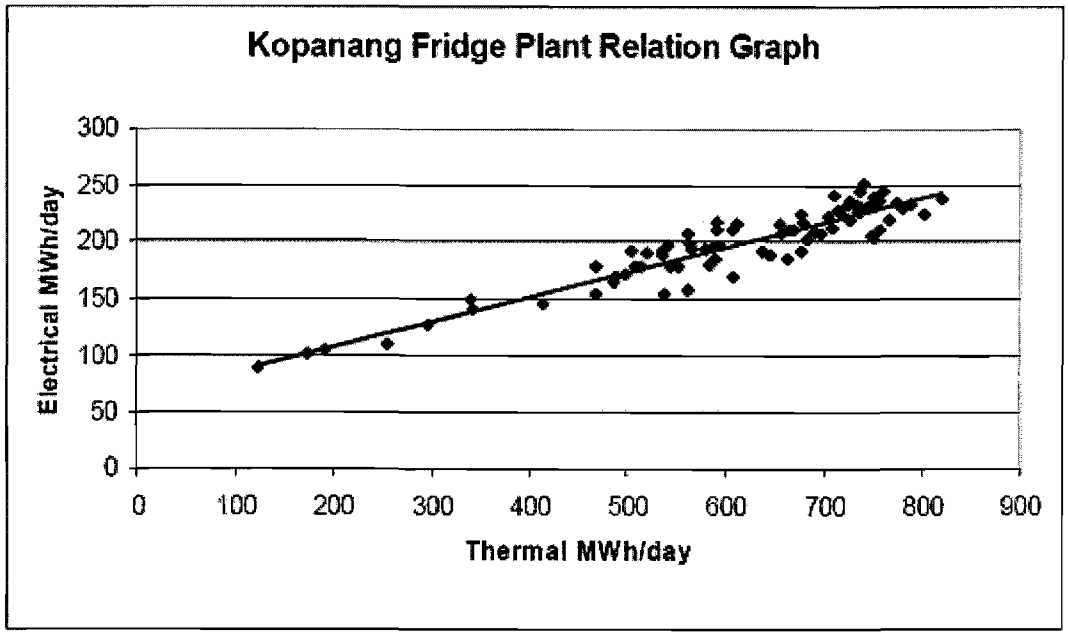


Figure 6-1: Kopanang refrigeration relation graph [1].

The baseline is scaled by using the thermal energy (per day) in the post-implementation period in the equation:

$$y = 0.2184x + 64.657 \tag{6.1}$$

This equation is used to determine what the electricity usage would be before implementation of the DSM project. The resulting electrical energy usage (MWh/day) calculated in the equation is then used to scale the baseline to determine the load reduction outcome for the specific day.

The effect of the new scaled baseline can then be seen in the figure below, where X is the result of the EE and the load reduction during the peak time. The 'feeder data' is the actual kW usage during the day.

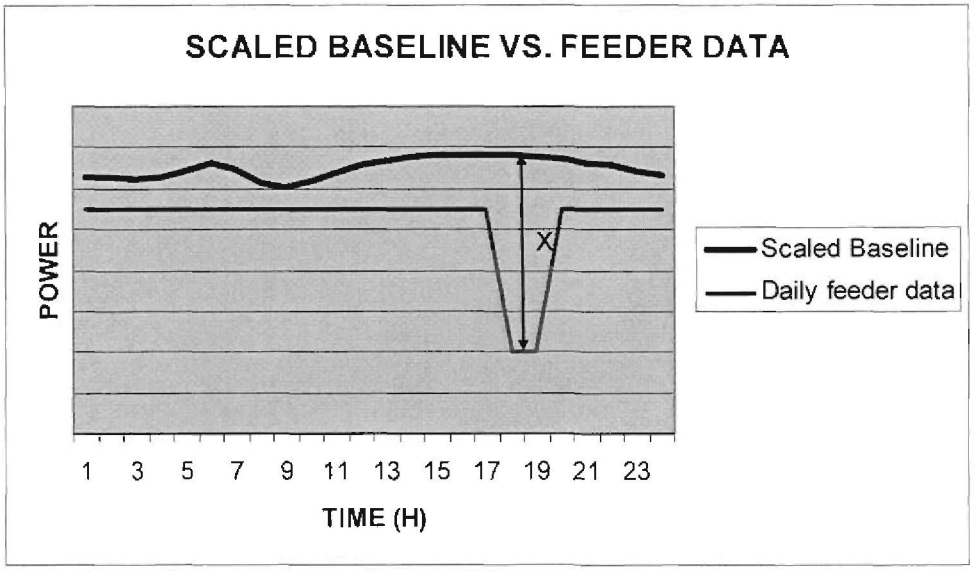


Figure 6-2: Scaled baseline vs. feeder data.

6.3. DSM RESULTS: KOPANANG GOLD MINE

The predicted average (weighted) annual load shift from the Eskom evening peak for the refrigeration system of Kopanang was 2.9MW. This was calculated by weighing the summer load shift potential (3.5MW for 9 months) and winter load shift potential (1.9MW for 3 months) over a 12-month period.

The result of the DSM initiative however showed that one machine could be stopped in the evening peak period, without actually putting its energy back into the system during another period (mainly caused by the overall COP improvement of the plant – less electrical energy is absorbed for the same thermal energy supply). Hence no load shifting actually took place, but rather a load reduction in the Eskom evening peak period [1].

In Eskom DSM terms, the phenomenon explained above is called Load Reduction (LR). Because the purpose of LR remains the reduction of power usage in Eskom's evening peak period, the DSM department still funds these types of projects with 100% of the capital required for planned infrastructure.

When a DSM project is implemented (REMS system is fully operational), the project's performance is assessed over a 3-month period. This assessment will determine if the proposed DSM targets are attained. The following figures represent the optimised load profile for the cooling system of Kopanang mine during the performance assessment period.

The figures show the achieved load reduction profile, scaled baseline and the intended load profile. The improved efficiency of the plant can also be seen.

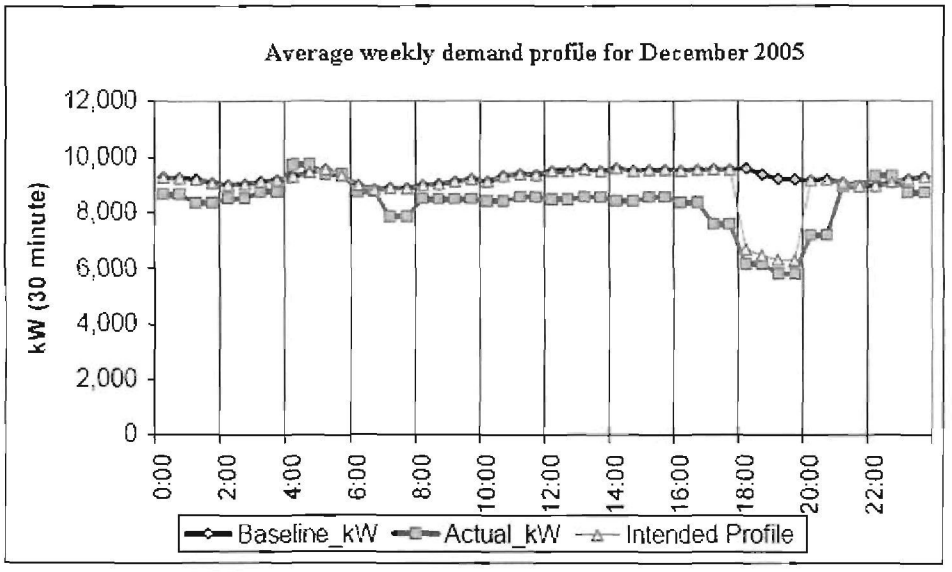


Figure 6-3: December 2005 optimised load profile vs. scaled baseline [3].

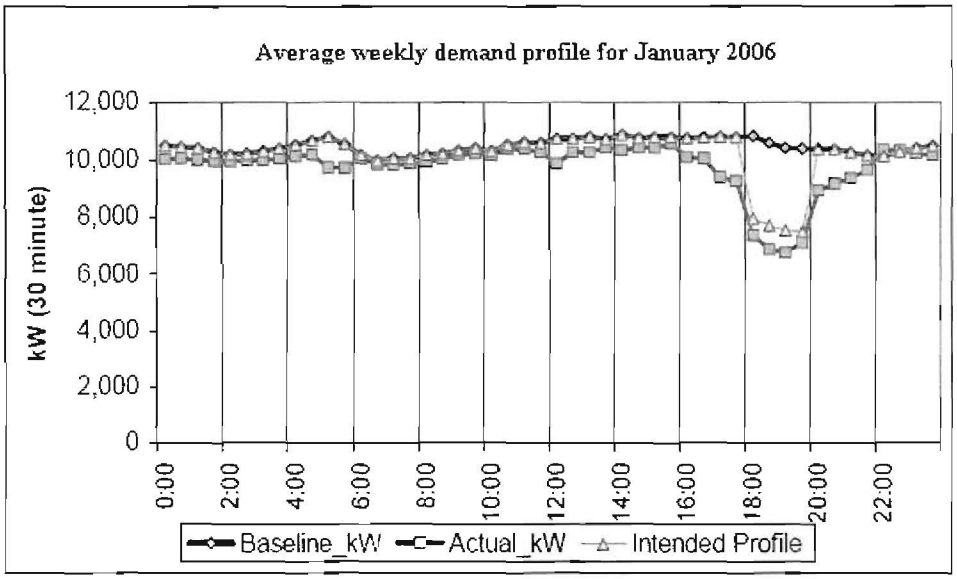


Figure 6-4: January 2006 optimised load profile vs. scaled baseline [4].

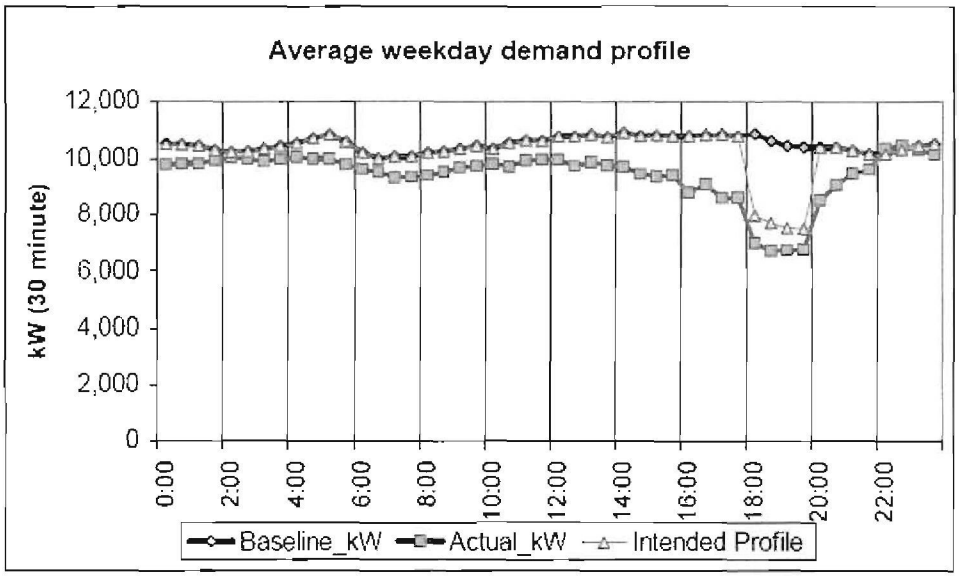


Figure 6-5: February 2006 optimised load profile vs. scaled baseline [5].

The following figure shows the winter DSM results of the project. The power contribution that the BACs made to the original baseline can clearly be seen (approximate 2MW difference between the actual profile and the baseline profile).

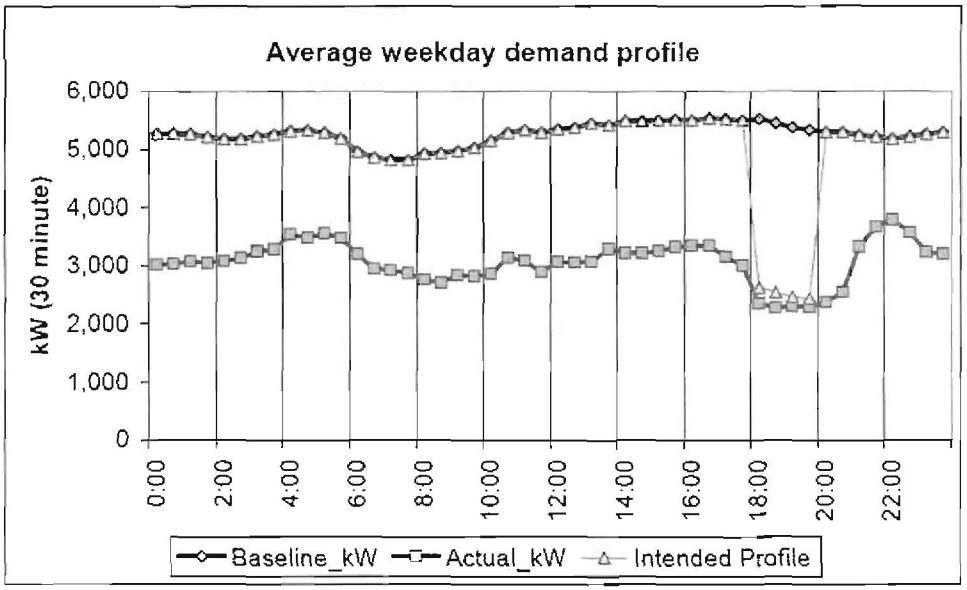


Figure 6-6: July 2006 optimised load profile vs. scaled baseline [6].

The table below shows the DSM results during the performance assessment period. The results show the success of the DSM project.

Period	Proposed DSM Saving [MW]	Achieved DSM Saving [MW]
Dec-05	3.5	3.4
Jan-06	3.5	3.6
Feb-06	3.5	3.8

Table 6-1: Kopanang performance assessment results (against the summer target).

6.4. MEASUREMENT AND VERIFICATION: TSHEPONG GOLD MINE

The Tshepong project is a load shift project. This means that the baseline energy profile and the actual energy usage of the system (after load shifting has taken place), must be energy neutral.

To ensure energy neutrality, the total kWh of the actual daily electrical energy profile is divided into the total kWh of the baseline electrical energy profile. The result is a scaling factor which is then used to scale the baseline electrical energy profile.

The following abbreviations are applicable:

- $E_{baseline}$ = Total baseline electrical energy (kWh)
- E_{daily} = Total daily and actual electrical energy (kWh)
- $SF_{neutral}$ = Scaling factor to establish energy neutrality

The scaling factor is calculated as follows:

$$SF_{neutral} = \frac{E_{daily}}{E_{baseline}} \tag{6.2}$$

6.5. DSM RESULTS: TSHEPONG GOLD MINE

The performance assessment of the Tshepong DSM project started on 1 October 2007. The table below displays a sample size of 4 days worth of actual performance data. The project is currently operating in full automatic control mode and electrical load is being shifted from the system's operation every weekday from 18:00 to 20:00.

The summer load shift target for Tshepong is 3.7MW while the winter target is 1.6MW. These targets are combined into a yearly weighted average target of 3.2MW.

Time	Original Baseline	Day 1 Actual	Day 1 Scaled Baseline	Day 2 Actual	Day 2 Scaled Baseline	Day 3 Actual	Day 3 Scaled Baseline	Day 4 Actual	Day 4 Scaled Baseline
[h]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
00:00	5235	2994	4079	4540	4210	4855	4202	4744	4002
01:00	5387	4697	4197	4529	4332	4857	4325	4752	4118
02:00	5390	4688	4199	4541	4335	4854	4327	4754	4120
03:00	5246	4700	4087	4538	4219	4845	4211	4750	4010
04:00	5230	4694	4075	4565	4206	4862	4199	4753	3998
05:00	5021	4687	3912	4698	4038	4858	4031	4688	3838
06:00	4935	4691	3845	4699	3969	4840	3961	4193	3772
07:00	5031	3874	3919	4557	4046	4636	4038	4230	3846
08:00	4951	4016	3857	4296	3982	4467	3975	4072	3785
09:00	4886	3704	3807	4538	3930	4642	3923	4313	3735
10:00	5006	4531	3900	4296	4026	4702	4019	4550	3827
11:00	5051	4329	3935	4698	4062	4693	4055	4101	3861
12:00	5170	4841	4028	4538	4158	4699	4151	4427	3952
13:00	4855	3880	3782	4296	3904	4703	3897	4748	3711
14:00	5125	3276	3993	4529	4122	3770	4114	4791	3918
15:00	5109	4696	3980	4698	4109	3919	4101	4640	3906
16:00	5116	4759	3986	4540	4115	4497	4107	2131	3911
17:00	5111	4218	3982	3485	4111	4104	4103	1696	3907
18:00	5036	0	3924	0	4050	0	4043	0	3850
19:00	5098	0	3972	0	4100	0	4093	0	3898
20:00	5261	4228	4099	4495	4231	2542	4224	3868	4022
21:00	5370	4853	4183	4696	4318	4540	4311	4622	4105
22:00	5434	4851	4234	4695	4370	4544	4363	4652	4154
23:00	5239	4853	4082	4690	4213	4546	4206	4781	4005
Total Energy [kWh]	123296	96059	96059	99156	99156	98977	98977	94254	94254
SF		0.78		0.80		0.80		0.76	

Table 6-2: Load shift results of the Tshepong DSM project.

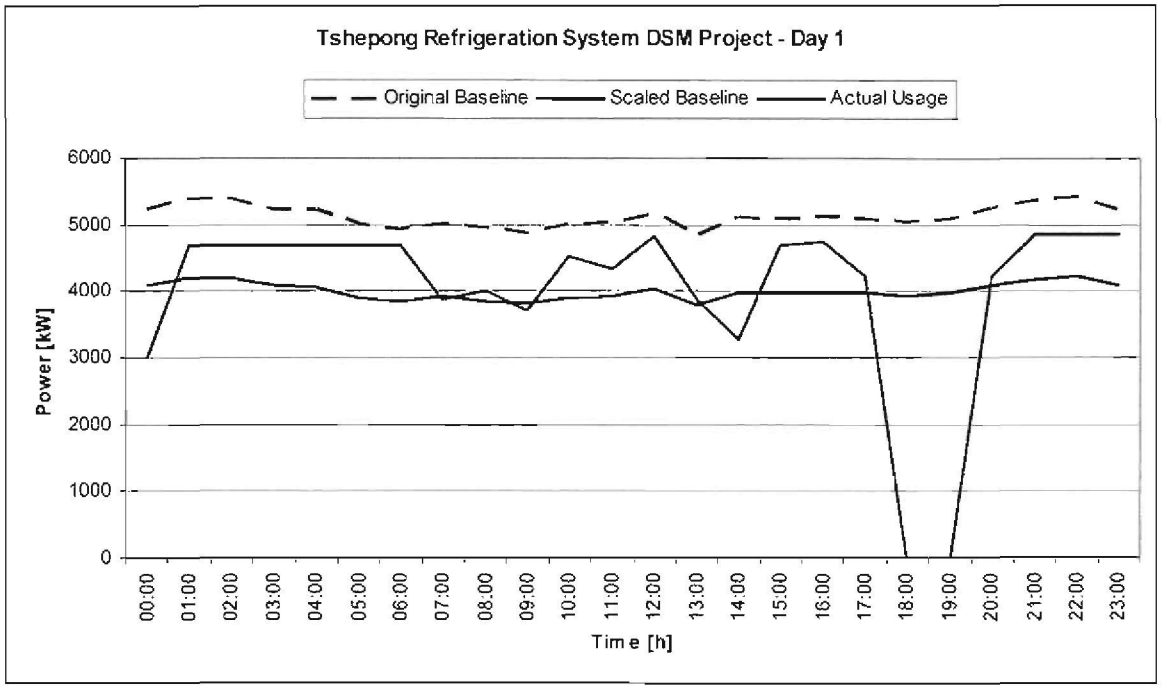


Figure 6-7: Tshepong Day 1 load shift performance.

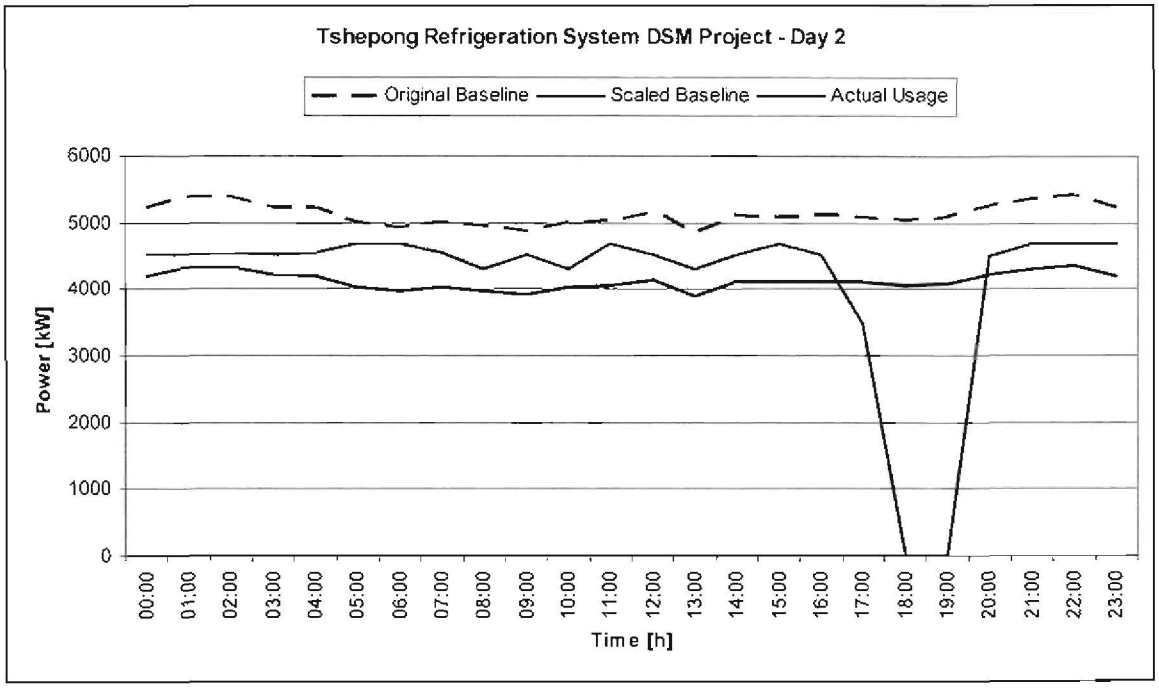


Figure 6-8: Tshepong Day 2 load shift performance.

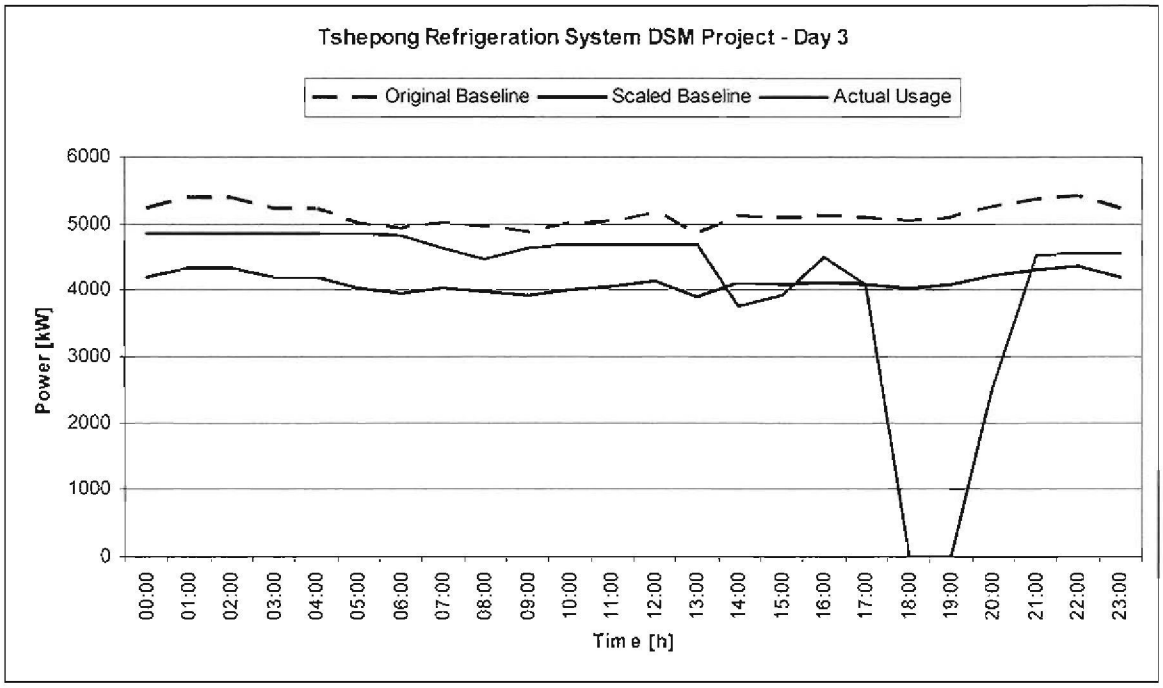


Figure 6-9: Tshepong Day 3 load shift performance.

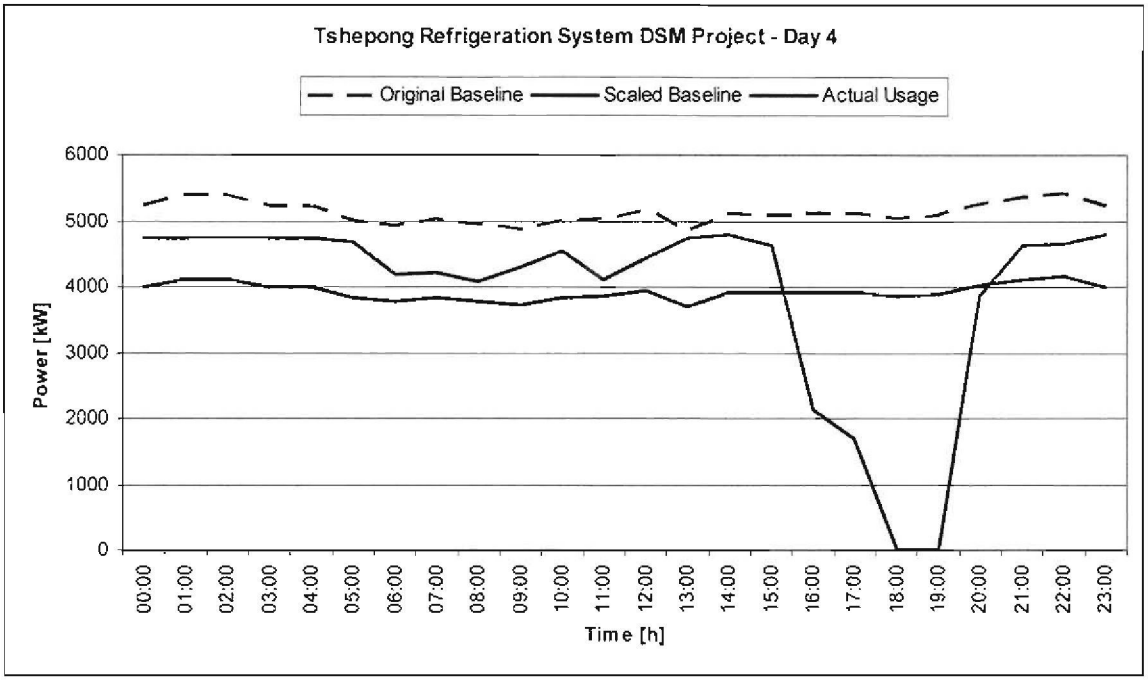


Figure 6-10: Tshepong Day 4 load shift performance.

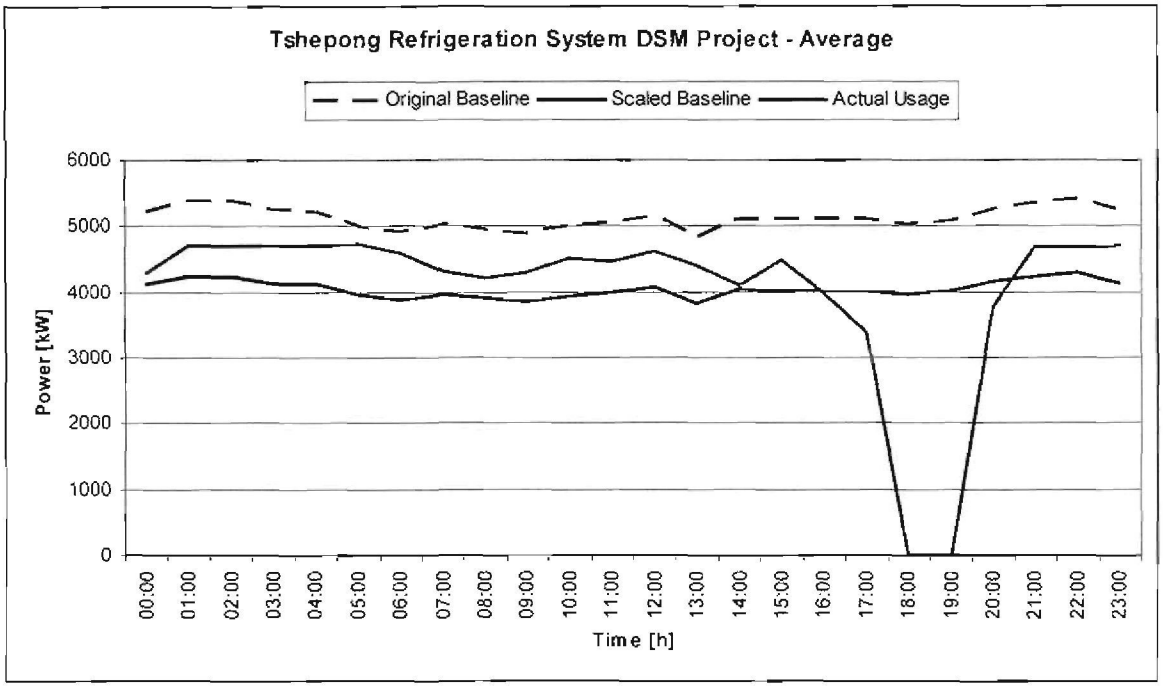


Figure 6-11: Tshepong average load shift performance.

The table below shows the load shift results.

Period	Proposed DSM Saving [MW]	Achieved DSM Saving [MW]
01-Oct-07	3.2	3.9
02-Oct-07	3.2	4.1
03-Oct-07	3.2	4.1
04-Oct-07	3.2	3.9
Average	3.2	4.0

Table 6-3: Tshepong load shift results (against the weighted yearly average).

The load shift results are well above the yearly weighted average load shift target, as well as the summer target of 3.7MW.

6.6. ELECTRICITY COST SAVING ANALYSIS

On Kopanang Gold Mine, the REMS system has been operational for more than twenty months [6]. To date, the REMS system has saved Kopanang Gold Mine almost R2-million in electricity costs.

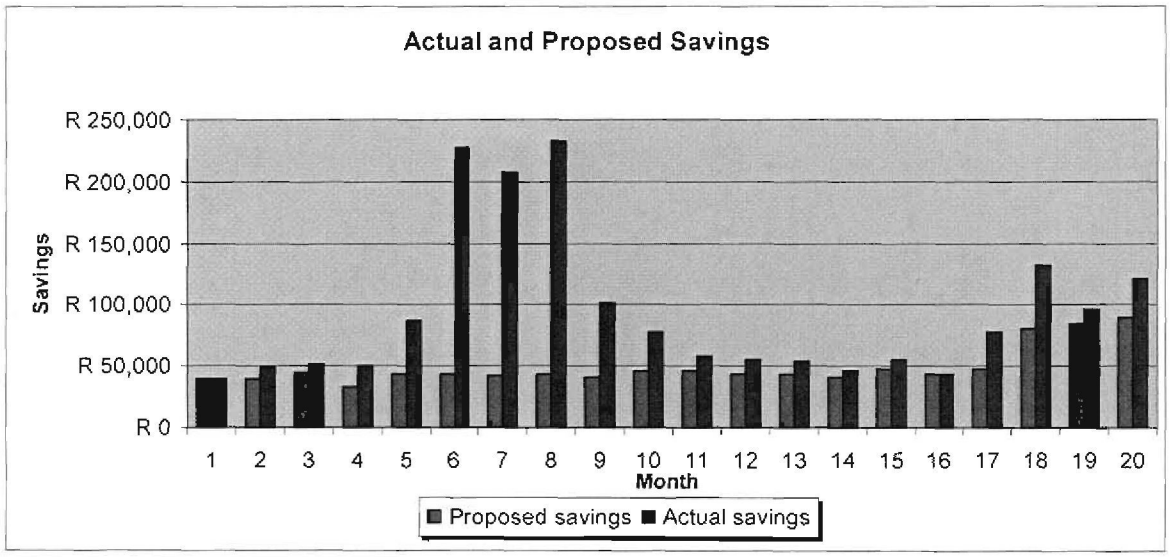


Figure 6-12: Actual and proposed savings for the duration of the project.

Month	Proposed Daily Savings	Actual Savings	Unrealised Potential/ Over Performance	Accumulated Proposed Savings	Accumulated Actual Savings
Jan-06	R 39,480	R 40,204	R 724	R 78,960	R 89,348
Feb-06	R 39,480	R 49,144	R 9,664	R 118,440	R 138,492
Mar-06	R 45,402	R 51,477	R 6,075	R 163,842	R 189,969
Apr-06	R 33,558	R 50,740	R 17,182	R 197,400	R 240,709
May-06	R 43,428	R 86,784	R 43,356	R 240,828	R 327,493
Jun-06	R 43,656	R 227,772	R 184,116	R 284,484	R 555,265
Jul-06	R 41,672	R 207,612	R 165,940	R 326,156	R 762,877
Aug-06	R 43,656	R 232,395	R 188,739	R 369,812	R 995,272
Sep-06	R 41,496	R 102,402	R 60,906	R 411,308	R 1,097,674
Oct-06	R 45,646	R 77,412	R 31,766	R 456,954	R 1,175,086
Nov-06	R 45,646	R 57,830	R 12,184	R 502,600	R 1,232,916
Dec-06	R 43,571	R 55,178	R 11,607	R 546,171	R 1,288,094
Jan-07	R 43,570	R 53,968	R 10,398	R 589,741	R 1,342,062
Feb-07	R 40,917	R 45,646	R 4,729	R 630,658	R 1,387,708
Mar-07	R 47,720	R 55,426	R 7,706	R 678,378	R 1,443,134
Apr-07	R 43,572	R 43,748	R 176	R 721,950	R 1,486,882
May-07	R 47,720	R 77,435	R 29,715	R 769,670	R 1,564,317
Jun-07	R 81,291	R 131,703	R 50,412	R 850,961	R 1,696,020
Jul-07	R 85,162	R 96,869	R 11,707	R 936,123	R 1,792,889
Aug-07	R 89,767	R 121,997	R 32,230	R 1,025,890	R 1,914,886

Table 6-4: Actual electricity cost savings for Kopanang Gold Mine.

The electricity cost savings analysis follows for Tshepong.

Day	Proposed Daily Savings	Actual Savings	Unrealised Potential/ Over Performance	Accumulated Proposed Savings	Accumulated Actual Savings
01-Oct-07	R 304	R 430	R 126	R 304	R 430
02-Oct-07	R 304	R 400	R 96	R 608	R 830
03-Oct-07	R 304	R 410	R 106	R 912	R 1,240
04-Oct-07	R 304	R 413	R 109	R 1,216	R 1,653

Table 6-5: Daily electricity cost savings for Tshepong Mine (based upon summer tariffs).

Extrapolating the expected consistent results of the Tshepong DSM project to include summer and winter cost savings, yields an expected annual electricity cost saving of approximately R500,000 per annum.

6.7. EXPANDING THIS RESEARCH TO OTHER MINES

The control philosophies and strategies developed in this study can be applied to any mine refrigeration system (surface and underground). Apart from the Kopanang and Tshepong systems, Eskom DSM has already approved the Elandsrand and South Deep proposed DSM projects (see Chapter 4).

These projects are currently in infrastructure installation phases. The South Deep project will be completed by December 2007, while the Elandsrand project will be completed by February 2008. Another 10 refrigeration systems have already been targeted for investigation using the principles developed in this study.

The great advantage of the methodologies developed in this study is that fast and accurate results can be generated, which in turn will help to generate more proposals to Eskom DSM. Preliminary investigations show that a potential 65MW worth of DSM projects exist in mine refrigeration systems.

6.8. CONCLUSION

The success of the REMS systems on Kopanang and Tshepong is evident in this chapter. The REMS system has been automatically realising a DSM results of 3.6MW in the Eskom evening peak period for more than 20 months. The REMS system has realised an electricity cost saving of more than R2-million for Kopanang Gold Mine for this period.

Results for the Tshepong project show an average of 4MW of load shifted consistently from the peak period to cheaper tariff periods of the day. It is expected that the REMS system will save Tshepong Gold Mine approximately R500,000 per annum.

Vast opportunities exist for the REMS system developed in this study if it is to be implemented on other mine refrigeration systems. Preliminary investigations show an untapped 65MW worth of DSM potential in these systems. The methodologies, strategies and systems developed in this study can realise DSM potential in mine refrigeration systems which will be efficient, sustainable and cost effective solutions for Eskom's DSM effort.

6.9. REFERENCES

[1] Calitz, J.J., "Research and implementation of a load reduction system for a mine refrigeration system", Dissertation presented in partial fulfillment of the requirements for the degree of MASTER of ENGINEERING in the faculty of mechanical and materials engineering, North West University, Potchefstroom, 2006.

[2] Britt, I., Measurement and Verification, Anglo Gold - Kopanang Fridge Plant system, Baseline Draft, Corporate Division, Corporate Technical Audit Department, Report number 0509 V1R0, North-West University, p11, September 2005.

[3] Britt I, Measurement and Verification, ESKOM, Corporate Division, Corporate Technical Audit Department, Anglo Gold - Kopanang Fridge Plant system, Project number 2004011, 1st Performance Assessment, North-West University, p7, January 2006.

[4] Britt, I., Measurement and Verification, ESKOM, Corporate Division, Corporate Technical Audit Department, Anglo Gold - Kopanang Fridge Plant system, Project number 2004011, 2nd Performance Assessment, North-West University, p7, February 2006.

[5] Britt, I., Measurement and Verification, ESKOM, Corporate Division, Corporate Technical Audit Department, Anglo Gold - Kopanang Fridge Plant system, Project number 2004011, 3rd Performance Assessment, North-West University, p7, March 2006.

[6] Britt, I., Measurement and Verification, ESKOM, Corporate Division, Corporate Technical Audit Department, Anglo Gold - Kopanang Fridge Plant system, Project number 2004011, NWU-Savings Report 2004011 Kopanang FP July06 200605 v5r2, North-West University, p10, 26 August 2006.

CHAPTER 7

CONCLUSION

7. CONCLUSION

7.1. CONCLUSIONS

Eskom produces more than 95% of South Africa's electricity requirements. On the supply side of electricity it has launched various electricity supply projects, e.g. in the form of base load coal fired power stations, nuclear power stations, refurbishment of decommissioned power stations, etc. On the demand side of electricity it has launched a Demand Side Management (DSM) program.

In South Africa, Eskom's DSM strategy comprises a dual approach: to reduce electricity demand at peak periods (07:00-10:00 and 18:00-20:00) by shifting load to off-peak periods and by overall electricity consumption reduction (24-hour reduction) by installing energy efficient equipment and optimising industrial processes.

Eskom has increased the DSM program's target to 3000MW by 2012. This target implies that Eskom is serious about its DSM program, and that it sees it as a sustainable solution to South Africa's energy challenge. Energy Service Companies (ESCos) are private companies that help realise DSM goals.

Normally ESCos operate in a three way partnership between themselves, the electricity supplier (Eskom) or regulatory body (NERSA) responsible for DSM and the electricity consumer. They make use of DSM programs, technologies and optimisation packages to determine and realise DSM results at the electricity consumer. ESCos have their work cut out for them if they are to help Eskom realise its 3000MW target by 2012.

The primary source of mine cooling is by normal ventilation air. Temperatures have, however, increased due to the geothermal gradient, which increases with depth, as well as the auto-compression heat added per vertical meter of depth. This has resulted in underground cooling strategies.

Chilled water from the refrigeration plants are reticulated through surface bulk air coolers, underground station bulk air coolers, crosscut coolers and in-stope coolers. Chilled water is also utilised as service water. Currently the only cost saving strategies employed in mine refrigeration systems are ice systems (although the main purpose of these systems in the mining industry is to add thermal energy to existing systems).

When refrigeration systems are located on surface the warm water has to be pumped back from underground, at great cost. One of the advantages of using ice sent down from surface to absorb the heat load is that the quantity of water to be pumped back out of the mine can be reduced to about a quarter of that for an all-water cooling system, thus giving cost savings. But these systems are very expensive to install and to maintain.

Extensive research into commercially available simulation software was conducted. Findings showed that none of the available simulation models focuses on the simulation of refrigeration plant equipment and water reticulation systems (i.e. supply of chilled water). To investigate load shift (through an optimised control solution) potential in refrigeration systems, it is necessary to simulate the response of the system to make sure constraints are adhered to.

Mathematical models of refrigeration equipment were simplified and integrated into simulation software. The surface refrigeration plant of Kopanang Gold Mine was simulated and simulation predictions compared against actual plant measurements (the mine has an extensive SCADA system in place). The simulation model was calibrated and the potential to shift load from the system's operation was investigated.

Verification results showed above 90% accuracy for predictions made. System constraints were identified and the primary constraints were found to be the minimum and maximum dam levels of the chilled water storage dam, the temperature of the chilled water in this dam, the chilled water flow rate to the BACs and the chilled water flow rate underground. The simulation proved its accuracy and could be used to predict system response to load shift strategies.

A detailed integrated control strategy is needed to realise a load shift potential in a refrigeration system. To ensure that the process constraints of these systems are adhered to, these control strategies need to be simulated to predict systems' response to load shift strategies. Through application of a generic investigation methodology a load shift potential can quickly and accurately be established in these systems.

A population of South African mines was identified and investigated for DSM purposes. Four case studies were identified. The process parameters of the identified case studies were established and were used in the simulation models as boundary constraints. These systems were simulated and the investigation and control methodologies mentioned above were applied to them.

Simulation results of the four identified case studies showed load shift potentials ranging from 2.5 to 6MW (reduced from the evening peak period of 18:00 – 20:00). The generic nature of the global control philosophy was proven. The application of the DSM investigation protocol proved to be quick and accurate.

The only way to realise a DSM potential in refrigeration systems, via optimised control, is through the implementation of an automated Energy Management System (EMS). To ensure sustainability, the EMS must be a fully automatic control solution. It needs to communicate with system equipment (SCADA, PLCs, etc.) in order to realise the identified DSM potential.

The required control infrastructure to enable the EMS to optimally control the refrigeration system is generic for each refrigeration system. The EMS resembled in this study was developed into a software solution – REMS (Real-Time Energy Management System). Technical control specifications were created and were used to identify required control infrastructure.

The cost of the required infrastructure was established through formal sub-contractor quotations. Through a cost analysis the total project cost per load shift MW was calculated. These costs were used to develop business cases for submission to Eskom DSM.

The combined load shift potential for the four case studies identified amounts to 16.9MW per weekday Eskom evening peak period. The control infrastructure required amounts up to almost R15-million. The generation cost of the "virtual" peaking power station created through realisation of the load shift potential between 18:00 and 20:00, therefore equates to approximately R2-million per MW (ESCo and EMS expenses included).

This is much lower than the approximate R16-million per MW generation cost involved with the building of new power stations. Sustainable DSM projects therefore make business sense to Eskom DSM due to its much lower power "generation" costs.

The REMS system was installed on the refrigeration systems of the Kopanang and Tshepong Gold Mines. The purpose of the REMS systems was to automatically shift electrical load from the Eskom evening peak period (18:00 – 20:00) to low demand periods without violating any equipment, process, maintenance or plant and mine safety constraints.

By shifting load from the Eskom evening peak period a "virtual" peaking power station is generated for Eskom helping them with their current peak supply problems. The added benefits of these projects include plant automation infrastructure and electricity cost savings for the mines. To accurately determine the load shift results of the two projects discussed in this study, measurement and verification (M&V) methods needed to be established and clarified.

For the Kopanang system, a specific M&V methodology needed to be developed to account for the energy efficiency component of the project. The M&V approach for the Tshepong project, being a load shift project, had to ensure that the electrical energy profiles were energy neutral. Both projects were measured and verified by the North West University, acting as an independent M&V organisation for Eskom DSM.

The Kopanang DSM project produced an average 3.6MW DSM result, while the Tshepong project produced a 4.0MW DSM result during the Eskom evening peak period. Both these projects over-performed against their proposed DSM targets.

The successful operation of the REMS system is evident in the DSM results for the Kopanang and Tshepong projects. The REMS system on Kopanang has been consistently operating for more than 20 months, realising over R2-million in electricity cost saving for the mine for this period. The projected savings for the Tshepong project are in the order of R500,000 per annum.

Vast opportunities exist for the REMS system developed in this study if it is to be implemented on other mine refrigeration systems. Preliminary investigations show an untapped 65MW worth of DSM potential in these systems. The methodologies, strategies and systems developed in this study can realise the DSM potential in mine refrigeration systems and are efficient, sustainable and cost effective solutions for Eskom's DSM effort.

7.2. RECOMMENDATIONS FOR FURTHER WORK

New DSM concept

- The new DSM concept of shifting load from a mine refrigeration system through optimised control needs to be implemented and tested on other systems (specifically underground systems) to confirm its applicability to all systems.

Simplified integrated simulation model

- The predictions of the new simplified model need to be verified (or tested) on more case studies to confirm its applicability to all types of refrigeration systems subjected to load shift strategies.

Control algorithms and a global control philosophy

- The generic nature of the developed strategies and philosophies needs to be confirmed by application to more refrigeration systems.

DSM investigation methodology

- Applicability of the DSM investigation method needs to be confirmed by applying it to more systems; and
- Further development might be necessary to ensure that the method can truly be used by any person.

Automated software control solution

- It was found that continuous additions need to be made to the REMS system. This is mainly due to specific custom aspects of each refrigeration system or requirements from mine personnel.

Added benefits of the new control solution

- The success of the methods and systems developed can only really be confirmed by the number of business cases that can be generated and submitted to Eskom DSM; and
- Actual energy cost savings (and other savings e.g. preventative maintenance opportunities) need to be confirmed over time.

Sensitivity analysis

- The process constraints for each refrigeration system are unique, and largely established by plant personnel (most of the time no technical explanation can be given for the stringent constraints);
- Optimisation of the control strategies (to maximise cost savings) can be done through a proper sensitivity analysis of the control models, i.e. upper and lower process limits (flows, temperatures, etc.) should be tested to pursue the "actual" process limits.

APPENDICES

APPENDIX A

INFRASTRUCTURE QUOTATIONS

QUOTATION

WELKOM
INDUSTRIAL CONTROLS

Co. Reg. No.: 2000/001057/07

✉461 Welkom 9460 No:20, 11th Street ☎(057)396-5907 Fax(057)396-5519 email: olivia@wic.co.za

The Manager

Reference No 401H
Anglogold

(revision 2)
Kopenang Mine
Vaal Reefs
2621

21 October 2004

Attention: Mr. Ludwich Pretorius

ITEM	QTY	DESCRIPTION	UNIT	TOTAL
		HVAC Fridge Plant (Per Plant)		
A	6	**PLC - Main**		
A1	1	Simatic S7-300, load power supplies 307, 120/230V ac, 24V dc, 5A Part no.: 6ES73071EA000AA0		
A2	1	Simatic Net, CP 343-1 communications Processor for connection of Simatic S7-300 w.ind Ethernet using ISO, TCP/Ip and udp, S7, comm., fetch/write. Part no.: 6GK73431EX110XE0		
A3	1	Simatic S7-300, CPU 315-2DPCPU with MPI interface integrated 24V dc power Supply 128Kbyte working memory , Interface DP-master/slave Part no.: 6ES73152AG100AB0		
A4	1	Simatic S7, Micro memory card, S7-300/C7/ET 200S IM151 CPU, 3.3V Nflash, 128Kbytes Part no.: 6ES79538LG110AA0		
A5	2	Simatic S7-300 rail = 530mm Part no.: 6ES73901AF300AA0		
A6	3	Simatic S7-300, Digital input sm 321, Optically isolated 32DI, 24V dc (1 x 32DI), 40 Pin Part no.: 6ES73211BL000A00		
A7	1	Simatic S7-300, Digital output SM 322, Optically isolated, 32DO, 24V dc, 0.5A,		

2.

QUOTATION

WELKOM INDUSTRIAL CONTROLS

Co. Reg. No.: 2000/001057/07

✉461 Welkom 9460 No:20, 11th Street ☎(057)396-5907 Fax(057)396-5519 email: olivia@wic.co.za

ITEM	QTY	DESCRIPTION	UNIT	TOTAL
A8	6	Simatic S7-300, Analog input SM 331, Optically isolated, U/I/Thermocouple/ Resistance interrupt, diagnostics Resolution 9/12/14 bits, 8AI Part no.: 6ES73317KF020AB0		
A9	7	Simatic S7-300, front connector for signal Module switch with screw contacts, 20 pin Part no.: 6ES73921AJ000A00		
A10	4	Simatic S7-300, front connector 392 with Screw contacts, 40-pin40-polig Part no.: 6ES73921AM000AA0		
A11	1	Simatic IM360 Part no.: 6ES73603AA010AA0		
A12	1	Simatic IM361 Part no.: 6ES73613CA010AA0		
A13	1	Simatic S7-300 Analog output 4AO 20 pin Part no.: 6ES73325HD010AB0		
A14	1	Simatic 1m connecting cable Part no.: 6ES3683BB010AA0		
		Total for x 6 PLC's		
		HMI:		
A15	1	Simatic multipanel MP37012" color TFT Display, touch/windows CE3.0 configurable With pro tool from Version V5.2+SP3 Part no.: 6AV65450DA100AXO		

QUOTATION

WELKOM
INDUSTRIAL CONTROLS
Co. Reg. No.. 2000/001057/07
461 Welkom 9460 No:20, 11th Street (057)396-5907 Fax(057)396-5519 email: olivia@wic.co.za

ITEM		QTY	DESCRIPTION	UNIT	TOTAL
	A16	1	Hirschmann Industrial Line Switch 2 Port 10/100 Base-TX, RJ45 connection, 2 Port 100Base-FX Multimode 2 x 24V dc Power input. SC Connections, support hipering, RSTP,RMON, Port security, port mirroring, auto negotiation, Auto polarity, auto crossing, VLAN's prioritisation, Fault control relay Part no.: RS2-4R 2MM SC		
			Total for 6:		
			HVAC Fridge Plant (Per Plant)		
B		6	**PLC - Panel**		
	B1	1	Panel complete with 100mm plinth, power supply, circuit breakers, relays, Terminals, sirens, start and stop buttons, Panel lights, trunking, earth terminals, slotted DIN rail, end stops, panel drawings etc.		
			Total for 6:		
			HVAC Fridge Plant (Per Plant)		
C		6	**Field Instruments and cable**		
	C1	300	Metres 8 fibre 50/125 6 element 2LT (PBT) 2.20mmm GRP Gel filled aramid PE Heavy duty duct (HDD)		
	C2	1	3M Splice boxes, trunking, pigtails, entry Glands, midcouplers etc		
	C3	300	1 Pair 1.0mm PCW PE Instrument AL/Mylar PVC SWA LSZH cable		
	C4	200	2 Pair 1.0mm PCW PE Instrument I/OA Mylar PVC SWA LSZH cable		

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QUOTATION

WELKOM
INDUSTRIAL CONTROLS
Co. Reg. No.: 2000/001057/07
461 Welkom 9460 No:20, 11th Street (057)396-5907 Fax(057)396-5519 email: olivia@wic.co.za

ITEM	QTY	DESCRIPTION	UNIT	TOTAL
C5	500	8 Pair 1.5mm PCW PE Instrument I/OA /Mylar PVC SWA LSZH cable		
C6	1	Flow condensor – PROMAG 10W DN 500 20" Electromagnetic flowmeter Part no.: 10W5H-UD0A1AA0A4AA		
C7	1	Flow evaporator – PROMAG 10W DN 400 16" Electromagnetic flowmeter Part no.: 10W4H-UD0A1AA0A4AA		
C8	2	Delta bar S PMD235 (DP) c/w Oliver 5 way Manifold Part no.: PMD235-LU4P2EH3C		
C9	4	Cerabar M PMP41 Part no.: PMP41-GE13S2J11MA		
C10	1	Auma Multi-turn actuator Part no.: SA07.5-B3-22RPM		
		Total for 6:		
D		**HVAC Fridge Plant**		
		Installation and Commissioning:		
D1	6	PLC Engineering		
D2	6	HMI Engineering		
D3	6	Scada Engineering		
D4	6	Panel drawings		

PTO Page 5

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QUOTATION

WELKOM INDUSTRIAL CONTROLS

Co. Reg. No.: 2000/001057/07

✉461 Welkom 9460 No:20, 11th Street ☎(057)396-5907 Fax(057)396-5519 email: olivia@wic.co.za

ITEM	QTY		DESCRIPTION	UNIT	TOTAL
	D5	6	Field Drawings		
	D6	6	PLC Panel installation		
	D7	6	Installation and modification of field Instruments		
	D8	6	Cabling and wiring of field instruments to Junction boxes and PLC Panel		
	D9	6	Cabling and wiring of Remote I/O Base to MCC Panels		
	D10	6	Commissioning of Plant		
			Total for 6 Plants:		
E		1	**Site establishment and de-establishment**		
			Includes security screening, induction, Medical entry and exit clearance		
			GRAND TOTAL:		

Prices quoted exclude VAT
This quote is valid for 30 days, and is subject to any drastic change in the rates of exchange, without prior notice or validity period.
Delivery: ± 12 – 14 Weeks
Signature: Norman Ehlers

prime instrumentation
measured performance

15 May 2007

THE GENERAL MANAGER
HVAC INTERNATIONAL

ATTENTION: J. VAN DER BIJL
ATTENTION: A. FOURIE

OUR REF: PI-1108/ Rev. 5

SUPPLY AND INSTALLATION OF ELECTRICAL AND INSTRUMENTATION
ELANDSRAND MINE FRIDGE PLANT UPGRADE

We thank you for your enquiry and have pleasure in submitting our quotation no: **PI-1108/3**

We are pleased to inform that we are a Black Economic Empowerment company. Prime Instrumentation is committed to equity of employment principles through the maintenance of a philosophy and climate which will enable all people at all levels regardless of gender, race, colour or creed, to have the opportunity to develop and advance within their own capabilities.

These policies emphasize opportunity for all and seek to identify, develop and reward each employee who demonstrates the qualities of initiative, enterprise, hard work and loyalty in their job.

Management effort in seeking to ensure that this policy is applied will be necessary until the diversity of our populations are so evident at all levels in the Company, that any concern with racial and gender profiles will be unneccary.

Prime Instrumentation is a ISO9002 accredited company.
We are very proud for achieving the International Quality & Environmental Management Certification.

☎ (018) 462 7560/1/2 🖷 (018) 462 8762 ✉ prime@lantic.net
🌐 www.primeinstr.co.za ✉ PO Box 10168, Klerksdorp, 2570
Prime House, 6 Industria St., Klerksdorp
Members: D. Hanekom, C.W. Brown, K.G. Modise

TERMS AND CONDITIONS

TOTAL QUOTATION PRICE:
R 6,343,237.00

PAYMENT
Within 30 days after production of our invoices.

V.A.T.
The prices quoted exclude value added tax.

DELIVERY/ COMPLETION PERIOD
8 Months after receipt of an official order

VALIDITY
This quotation is valid for a period of 30 days.

NOTE
TACHI to remove gas from machine for installation.

We thrust this offer meets your requirements and would welcome the opportunity to discuss any queries which you may have.

YOURS FAITHFULLY

NICO WILMANS

ITEM	DESCRIPTION	UNIT	Qty	RATE	AMOUNT	TOTAL
1	PRELIMINARY AND GENERAL	LOT	1			
1.1	**Site establishment costs**	LOT	1			
	Medical & Teba	PERSON	10			
	Induction ,Health and Safety Costs	PERSON	10			
	Labour rate for crew (3days medical 4 days induction)	CREW	1			
	Traveling	CREW	1			
1.2	**Time Related continuing and variable costs**	MONTH	5			
	Project management/meetings	MONTH	6			
	Equipment	MONTH	5			
	Transport costs	MONTH	6			
	Vehicle costs	MONTH	6			
2	FIELD INSTRUMENTATION SURFACE					
	Pressure Transmitters (Oil & Freon) EJX530A-DBS4N-019EF	EACH	15			
	Pressure Transmitters (Oil & Freon) EJX110A-DH4G9-19EB	EACH	4			
	Pressure Transmitters IFM PA 3024 C/W adaptor and cable	EACH	16			
	Mechanical Pressure Switches IFM PK 6524 (0 - 10Bar)	EACH	8			
	Mechanical Pressure Switches IFM PK 6522 (0 - 100Bar)	EACH	4			
	Mechanical Differential Press Switch Fima - DCMV3	EACH	8			
	Flow Transmitters Krohne DN 300 - Remote Mount Integrator	EACH	1			
	Temperature probe c/w Transmitter IFM TA 3231c/w cable	EACH	7			
	Barksdale Temperature Switches THR-H 4S-10R (DPST)	EACH	2			
	Vibration Transmitters Metrix ST 5484E-121-014-00	EACH	4			
	Vane Actuators; EMG Drehmo DSM	EACH	4			
	Flow Control Actuators; EMG Drehmo DSM with Profibus	EACH	3			
	Current Transducers 300-5 Amp to 4-20mA Isolated 2-Wire output.	EACH	4			
	IPACK L RTD converters	EACH	96			
	Temperature Probes Epoxy Sealed	EACH	72			
	Thermowell Length 100mm 1/2" NPT Male Thread	EACH	40			
	Thermowell Length 200mm 3/4" NPT Male Thread	EACH	32			
3	GENERAL EQUIPMENT SURFACE					
	Process Sockets Material 316 SS 3/4" Female BSP Thread;	EACH	24			
	Process Isolators-Water 1/2" F BSP Thread at both ends.	EACH	55			
	Process Isolators	EACH	10			
	Process Fittings	EACH	82			
	Process Piping	EACH	240			
	Sinetech UPS 2 KVA	EACH	1			
	Relays and Bases 24VDC 11Pin;	EACH	84			
	Relays and Bases 220VAC 11Pin;	EACH	4			
	Relays and Bases 110VAC 11Pin	EACH	4			
	E/Stop + Lockout Push Button Station	EACH	20			
	Warning Light + Alarm unit	EACH	4			

4	PANELS SURFACE					
	Field junction boxes	EACH	12			
	Field remote box	EACH	1			
	PLC panels	EACH	5			
	IDB c/w breakers	EACH	1			
5	FIELD INSTRUMENTATION 71 LEVEL					
	Pressure Transmitters (Oil & Freon) EJX530A-DBS4N-019EF	EACH	8			
	Pressure Transmitters (Oil & Freon) EJX110A-DH4G9-19EB	EACH	2			
	Pressure Transmitters IFM PA 3024 C/W adaptor and cable	EACH	8			
	Mechanical Pressure Switches iFM PK 6524 (0 - 10Bar)	EACH	4			
	Mechanical Pressure Switches iFM PK 6522 (0 - 100Bar)	EACH	2			
	Mechanical Differential Press Switch Fima - DCMV3	EACH	2			
	Flow Transmitters Krohne DN 350 - Remote Mount Integrator	EACH	1			
	Temperature probe c/w Transmitter IFM TA 3231c/w cable	EACH	4			
	Barksdale Temperature Switches THR-H 4S-10R (DPST)	EACH	1			
	Vibration Transmitters Metrix ST 5484E-121-014-00 with the	EACH	2			
	Vane Actuators; EMG Drehmo DSM	EACH	6			
	Flow Control Actuators, EMG Drehmo DSM with Profibus	EACH	5			
	Current Transducers 300-5 Amp to 4-20mA Isolated 2-Wire output.	EACH	2			
	iPACK L RTD converters	EACH	38			
	Temperature Probes Epoxy Sealed	EACH	36			
	Thermowell Length 100mm 1/2" NPT Male Thread	EACH	20			
	Thermowell Length 200mm 3/4" NPT Male Thread	EACH	16			
6	GENERAL EQUIPMENT 71 LEVEL					
	Process Sockets Material 316 SS 3/4" Female BSP Thread;	EACH	16			
	Process Isolators-Water 1/2" F BSP Thread at both ends.	EACH	35			
	Process Isolators	EACH	5			
	Process Fittings	EACH	48			
	Process Piping	EACH	120			
	Sinetech UPS 2 KVA	EACH	3			
	Relays and Bases 24VDC 11Pin;	EACH	32			
	Relays and Bases 220VAC 11Pin;	EACH	4			
	E/Stop + Lockout Push Button Station	EACH	10			
	Warning Light + Alarm unit	EACH	2			
7	PANELS 71 LEVEL					
	Field junction boxes	EACH	8			
	PLC panels	EACH	2			
	75L plc	EACH	1			
	Pipe raise JB	EACH	1			
	IDB c/w breakers	EACH	3			

8	SURFACE PLC EQUIPMENT					
8.1	**Surface RefPlant C/Room**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	EACH	1			
	SIMATIC S7-300,LOAD POWER SUPP. PS 307 6ES73071EA000AA0	EACH	1			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	1			
	SIMATIC S7-300, DIGITAL INPUT SM 321, 6ES73211BH020AA0	EACH	1			
	SIMATIC S7-300, FRONT CONNECTOR 20 pin 6ES73921AJ000AA0	EACH	1			
	BUS CONNECTOR FOR PROFIBUS	EACH	1			
	PC477 15" TOUCH, WITH XP EMBEDDED, 6AV78430BF100LB0	EACH	1			
	WINCC FLEXIBLE /SM@RTSERVICE FOR WINCC FLEXIBLE 6AV66187BD011AB0	EACH	1			
	WINCC FLEXIBLE /ARCHIVES FOR WINCC FLEXIBLE 6AV66187ED011AB0	EACH	1			
8.2	**Surface RefPlant MACHINE 1&2**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	EACH	2			
	SIMATIC S7-300,LOAD POWER SUPP PS 307 6ES73071EA000AA0	EACH	2			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	2			
	SIMATIC S7-300, DIGITAL INPUT SM 321, 6ES73211BH020AA0	EACH	2			
	SIMATIC S7-300, DIGITAL OUTPUT SM 322 HIGH SPEED, 6ES73221BH100AA0	EACH	2			
	U/I/RESISTANCE/PT100, NI100, NI1000, LG-NI1000, 6ES73311KF010AB0	EACH	11			
	SIMATIC S7-300, FRONT CONNECTOR 20 pin 6ES73921AJ000AA0	EACH	4			
	SIMATIC S7-300,FRONT CONNECTOR 40-Pin 6ES73921AM000AA0	EACH	10			
	BUS CONNECTOR FOR PROFIBUS	EACH	13			
	SIMATIC DP,RS485 REPEATER For CONNECTION OF PROFIBUS/M 6ES79720AA010XA0	EACH	1			
8.3	**Surface RefPlant MACHINE 3&4**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	EACH	2			
	SIMATIC S7-300,LOAD POWER SUPP. PS 307 6ES73071EA000AA0	EACH	2			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	3			
	SIMATIC S7-300, DIGITAL INPUT SM 321, 6ES73211BH020AA0	EACH	2			
	SIMATIC S7-300, DIGITAL OUTPUT SM 322 HIGH SPEED, 6ES73221BH100AA0	EACH	2			

	U/I/RESISTANCE/PT100, NI100, NI1000, LG-NI1000, 6ES73311KF010AB0	EACH	11			
	SIMATIC S7-300, FRONT CONNECTOR 20 pin 6ES73921AJ000AA0	EACH	4			
	SIMATIC S7-300,FRONT CONNECTOR 40-Pin 6ES73921AM000AA0	EACH	10			
	BUS CONNECTOR FOR PROFIBUS	EACH	13			
	SIMATIC DP,RS485 REPEATER For CONNECTION OF PROFIBUS/M 6ES79720AA010XA0	EACH	1			
8.4	**Surface HMI equipmnet**					
	PC477 15" TOUCH, WITH XP EMBEDDED, 6AV78430BF100LB0	EACH	2			
	WINCC FLEXIBLE /SM@RTSERVICE FOR WINCC FLEXIBLE 6AV66187BD011AB0	EACH	2			
	WINCC FLEXIBLE /ARCHIVES FOR WINCC FLEXIBLE 6AV66187ED011AB0	EACH	2			
8.5	**Surface RefPlant JB box**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	EACH	1			
	SIMATIC S7-300,LOAD POWER SUPP. PS 307 6ES73071EA000AA0	EACH	1			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	1			
	SIMATIC S7-300, ANALOG INPUT SM 331 6ES73317KF020AB0	EACH	2			
	SIMATIC S7-300,FRONT CONNECTOR 40-Pin 6ES73921AM000AA0	EACH	2			
	BUS CONNECTOR FOR PROFIBUS	EACH	2			
9	**PLC EQUIPMET 71 LEVEL**					
9.1	**71 Level Control Room**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	EACH	1			
	SIMATIC S7-300,LOAD POWER SUPP. PS 307 6ES73071EA000AA0	EACH	1			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	1			
	U/I/RESISTANCE/PT100, NI100, NI1000, LG-NI1000, 6ES73311KF010AB0	EACH	1			
	SIMATIC S7-300, FRONT CONNECTOR 20 pin 6ES73921AJ000AA0	EACH	4			
	SIMATIC S7-300,FRONT CONNECTOR 40-Pin 6ES73921AM000AA0	EACH	10			
	BUS CONNECTOR FOR PROFIBUS	EACH	9			
	PC477 15" TOUCH, WITH XP EMBEDDED, 6AV78430BF100LB0	EACH	1			
	WINCC FLEXIBLE /SM@RTSERVICE FOR WINCC FLEXIBLE 6AV66187BD011AB0	EACH	1			
	WINCC FLEXIBLE /ARCHIVES FOR WINCC FLEXIBLE 6AV66187ED011AB0	EACH	1			

9.2	**71 Level RefPlant MACHINE 3&4**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	EACH	2			
	SIMATIC S7-300,LOAD POWER SUPP. PS 307 6ES73071EA000AA0	EACH	2			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	2			
	SIMATIC S7-300, DIGITAL INPUT SM 321, 6ES73211BH020AA0	EACH	2			
	SIMATIC S7-300, DIGITAL OUTPUT SM 322 HIGH SPEED, 6ES73221BH100AA0	EACH	2			
	U/I/RESISTANCE/PT100, NI100, NI1000, LG-NI1000, 6ES73311KF010AB0	EACH	10			
	BUS CONNECTOR FOR PROFIBUS	EACH	13			
	SIMATIC DP,RS485 REPEATER For CONNECTION OF PROFIBUS/M 6ES79720AA010XA0	EACH	1			
9.3	**71 Level HMI equipmnet**					
	PC477 15" TOUCH, WITH XP EMBEDDED, 6AV78430BF100LB0	EACH	1			
	WINCC FLEXIBLE /SM@RTSERVICE FOR WINCC FLEXIBLE 6AV66187BD011AB0	EACH	1			
	WINCC FLEXIBLE /ARCHIVES FOR WINCC FLEXIBLE 6AV66187ED011AB0	EACH	1			
9.4	**71 Level pipe raise JB**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	Each	1			
	SIMATIC S7-300,LOAD POWER SUPP. PS 307 6ES73071EA000AA0	EACH	1			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	1			
	U/I/RESISTANCE/PT100, NI100, NI1000, LG-NI1000, 6ES73311KF010AB0	EACH	1			
	SIMATIC S7-300,FRONT CONNECTOR 40-Pin 6ES73921AM000AA0	EACH	1			
9.5	**71 Level machine 1&2 and 7&8 upgrade**					
	CP343-1 lean(ethernet)	EACH	1			
	CP443-1(ethernet)	EACH	1			
9.6	**75 Level BAC PLC**					
	SIMATIC S7-300, RAIL L=530MM 6ES73901AF300AA0	EACH	1			
	SIMATIC S7-300,LOAD POWER SUPP. PS 307 6ES73071EA000AA0	EACH	1			
	SIMATIC DP, INTERFACE IM 153-1, FOR ET 200M 6ES71531AA030XB0	EACH	1			
	SIMATIC S7-300, DIGITAL INPUT SM 321, 6ES79538LG110AA0	EACH	1			
	U/I/RESISTANCE/PT100, NI100, NI1000, LG-NI1000, 6ES73311KF010AB0	EACH	3			
	SIMATIC S7-300, DIGITAL OUTPUT SM 322 HIGH SPEED, 6ES73221BH100AA0	EACH	1			

	SIMATIC S7-300, FRONT CONNECTOR 20 pin 6ES73921AJ000AA0	EACH	1			
	SIMATIC S7-300,FRONT CONNECTOR 40-Pin 6ES73921AM000AA0	EACH	3			
	BUS CONNECTOR FOR PROFIBUS 6ES73921AJ000AA0	EACH	2			
	SIMATIC S7-300,FRONT CONNECTOR 40-Pin 6ES73921AM000AA0	EACH	3			
10	**NETWORK EQUIPMENT**					
	Moxa EDS408 switch	EACH	9			
	19" Splice Tray	EACH	8			
	Multi mode patch leads (1meter)	EACH	60			
	Midcouplers ST/850	EACH	128			
	Pigtails ST/850	EACH	128			
	Splicing	EACH	128			
11	**CABLES**					
	1.5mm² 3Core cable SWA	P/ M	1500			
	1mm² 1 Pair cable SWA	P/ M	1500			
	1mm² 16 Pair cable SWA	P/ M	500			
	Profibus cable SWA	P/ M	1500			
	Ethernet cable	P/ M	300			
	8 Fibre cable SWA	P/ M	1000			
12	**TERMINATIONS**					
	Terminations	EACH	650			
13	**INSTALLATION AND COMMISSIONING**					
13.1	**Surface installation.**					
	1* Technician	HRS	540			
	1*Boilermaker	HRS	540			
	4*helpers	HRS	2160			
13.2	**71 Level installation**					
	1* Technician	HRS	445			
	1*Boilermaker	HRS	445			
	4*helpers	HRS	1780			
14	**PLC AND SCADA DEVELOPMENT**					
	PLC development	LOT	1			
	Scada development	LOT	1			
	Commissioning	LOT	1			
	Drawings and commissioning	LOT	1			

15	**VALVES**					
	DN250 Okumura 612X Butterfly valve	EACH	1			
	DN350 Okumura 615X Butterfly valve	EACH	4			
	DN400 Okumura 615X Butterfly valve	EACH	2			
	DN450 Okumura 615X Butterfly valve	EACH	2			
16	**TACHI MODIFICATIONS**					
	Induction	EACH	1			
	Surface cooling towers including material	EACH	1			
	71 Level chamber 1	EACH	1			
	71 Level chamber 2	EACH	1			
	71 Level chamber 3	EACH	1			
	71 Level behind fan	EACH	1			
	73 Level	EACH	1			
	Transport	EACH	1			

PRICE SCHEDULE

1	PRELIMINARY AND GENERAL
2	FIELD INSTRUMENTATION SURFACE
3	GENERAL EQUIPMENT SURFACE
4	PANELS SURFACE
5	FIELD INSTRUMENTATION 71 LEVEL
6	GENERAL EQUIPMENT 71 LEVEL
7	PANELS 71 LEVEL
8	SURFACE PLC EQUIPMENT
9	PLC EQUIPMENT 71 LEVEL
10	NETWORK EQUIPMENT
11	CABLES
12	TERMINATIONS
13	INSTALLATION AND COMMISSIONING
14	PLC AND SCADA DEVELOPMENT
15	VALVES
16	TACHI MODIFICATIONS

TOTAL

prime instrumentation
measured performance

THE GENERAL MANAGER
HVAC INTERNATIONAL

16-Apr-07

ATTENTION: J VAN DER BIJL

OUR REF: PI-1102/2

RE: SUPPLY AND INSTALLATION OF ELECTRICAL AND INSTRUMENTATION FOR SOUTH DEEP MINE FRIDGE PLANT UPGRADE

We thank you for your enquiry and have pleasure in submitting our quotation no: **PI-1102/2**

We are pleased to inform that we are a Black Economic Empowerment company. Prime Instrumentation is committed to equity of employment principles through the maintenance of a philosophy and climate which will enable all people at all levels regardless of gender, race, colour or creed, to have the opportunity to develop and advance within their own capabilities.

These policies emphasize opportunity for all and seek to identify, develop and reward each employee who demonstrates the qualities of initiative, enterprise, hard work and loyalty in their job.

Management effort in seeking to ensure that this policy is applied will be necessary until the diversity of our populations are so evident at all levels in the Company, that any concern with racial and gender profiles will be unnecessary

Prime Instrumentation is in the final stages of ISO9002 accreditation and should have everything finalized within the first quarter of this year.

☎ (018) 462 7560/1/2 (018) 462 8762 prime@lantic.net
www.primeinstr.co.za PO Box 10168, Klerksdorp, 2570
Prime House, 6 Industria St., Klerksdorp
Members: D. Hanekom, C.W. Brown, K.G. Modise

TERMS AND CONDITIONS

TOTAL QUOTATION PRICE:
R 4,157,242.00

PAYMENT
Within 30 days after production of our invoices.

V.A.T.
The prices quoted exclude value added tax.

DELIVERY/ COMPLETION PERIOD
6 Months after receipt of an official order

VALIDITY
This quotation is valid for a period of 30 days.

NOTE
South Deep Mine to remove gas from machine for installation.

We trust this offer meets your requirements and would welcome the opportunity to discuss any queries which you may have.

YOURS FAITHFULLY

NICO WILMANS

SOUTH DEEP FRIDGE PLANT AUTOMATION

ITEM	DESCRIPTION	UNIT	Qty	RATE	AMOUNT	TOTAL
1	PRELIMINARY AND GENERAL	Lot	1			
1.1	**Site establishment costs**	Lot	1			
	Medical & Teba	Persons	10			
	Induction ,Health and Safety Costs	Persons	10			
	Labour rate for crew (3days medical 4 days induction)	Crew	1			
	Traveling	Crew	1			
1.2	**Time Related continuing and variable costs**	Month	4			
	Project management/meetings	Month	4			
	Equipment	Month	4			
	Transport costs	Month	4			
	Vehicle costs	Month	4			
2	FIELD INSTRUMENTATION					
2.1	**York Fridge Plants**	/Machine	4			
2.1.1	**Temperature Probes and Transmitters**	/Machine	4			
	Compressor Discharge Temp Tx - Pt100 Probe	Each	1			
	Compressor Suction Temp Tx - Pt100 Probe	Each	1			
	Compressor Thrust Oil Temp Tx - Pt100 Probe	Each	1			
	Drive Motor Bearing Temp Tx(DE) - Pt100 Probe	Each	1			
	Drive Motor Bearing Temp Tx(NDE) - Pt100 Probe	Each	1			
	Gearbox Bearing Temp Tx(LSDE) - Pt100 Probe	Each	1			
	Gearbox Bearing Temp Tx(LSNDE) - Pt100 Probe	Each	1			
	Gearbox Bearing Temp Tx(HSDE) - Pt100 Probe	Each	1			
	Gearbox Bearing Temp Tx(HSNDE) - Pt100 Probe	Each	1			
	Compressor Oil Heater Thermostat Temp Tx - Pt100 Probe	Each	1			
	Econ 1st Stage Liquid Temp Tx - Pt100 Probe	Each	1			
	Econ 2nd Stage Liquid Temp Tx - Pt100 Probe	Each	1			
	Gearbox Oil Temp Tx - Pt100 Probe	Each	1			
	Chilled Water IN Temp Tx - Pt100 Probe	Each	1			
	Chilled Water OUT Temp Tx - Pt100 Probe	Each	1			
	Evap Liquid Temp Tx - Pt100 Probe	Each	1			
	Comp Oil Sump Temp Tx - Pt100 Probe	Each	1			
	Cond Water in Temp Tx - Pt100 Probe	Each	1			
	Cond Water out Temp Tx - Pt100 Probe	Each	1			
	Motor Winding Temp Tx	Each	3			
2.1.2	**Pressure transmitters**	/Machine	4			
	Evaporator Pressure Tx-Yokogawa EJX530A	Each	1			
	Condenser Pressure Tx-Yokogawa EJX530A	Each	1			
	Evaporator Water Diff. Pressure Tx and orifice plate -Rosemount	Each	1			
	Condenser Water Diff. Pressure Tx and orifice plate -Rosemount	Each	1			
	Comp Aux Oil Pressure Tx-Yokogawa EJX530A	Each	1			
	Comp Main Oil Pressure Tx-Yokogawa EJX530A	Each	1			
	Gearbox Pressure Tx-Yokogawa EJX530A	Each	1			
	Economizer Pressure Tx-Yokogawa EJX530A	Each	1			

2.1.3	**Pressure switches**	/Machine	4			
	Gearbox Aux. Pump Pressure Swtich-YokogawaDITM80SS-P2	Each	1			
	Gearbox Oil Pressure Switch low-YokogawaDITM80SS-P2	Each	1			
	Compressor Main Oil Pressure Swtich-YokogawaDITM80SS-P2	Each	1			
	Evaporator Pressure Swtich-YokogawaDITM80SS-P2	Each	1			
	Condenser Pressure Swtich-YokogawaDITM80SS-P2	Each	1			
	Temperature switches	Each	2			
2.1.4	**Pressure gauges**	/Machine	4			
	ST/Steel pipes and fittings	Lot	1			
	ST/Steel panel mount gauges	Each	3			
	ST/Steel ball valves	Each	20			
2.1.5	**Vibration Transmitters**	/Machine	4			
	Drive Motor Vibration	Each	2			
	Gearbox Vibration	Each	2			
	Compressor Vibration	Each	2			
3	**CABLES**	Lot				
	1mm² Single Pair SWA	/Meter	1500			
	1mm² Triad SWA	/Meter	500			
	1mm² 7 Core SWA	/Meter	600			
	1.5 mm² 3 Core SWA	/Meter	1000			
	Ethernet Cable	/Meter	300			
	16 Pair Cable	/Meter	300			
	4 Fibre 50/125 MM SWA PE Black	/Meter	1000			
4	**NETWORK EQUIPMENT**	Lot				
	Mice 2000 managed switch c/w 4 Ethernet ports	Each	3			
	Fibre to Ethernet switch	Each	5			
	16 Port hub	Each	1			
	19" Network panel	Each	2			
	19" Network panel (floorstanding)	Each	1			
	19" Splice Tray	Each	8			
	Multi mode patch leads (1meter)	Each	20			
	Midcouplers ST/850	Each	60			
	Pigtails ST/850	Each	60			
	Splicing	Each	60			
5	**PIPE MODIFICATION AND VALVES**	Lot				
5.1	**Valves**					
	600mm Butterfly valve c/w actuator and positioner	Each	1			
	400mm Butterfly valves c/w actuator	Each	1			
	Control valve c/w actuator and positioner for hot gas bypass	Each	4			
	Control valve c/w actuator and positioner for economizer	Each	4			
	Condenser flow control valve	Each	4			

	Evaporator flow control valve	Each	4
5.2	**Pipe work**		
	Supply, make up and install 15mm gal airlines	Lot	1
	Installation of valves	Lot	1
6	**PLC PANELS**	/Machine	4
	Panel	Each	1
	Circuit Breakers single pole	Each	10
	Circuit Breakers double pole	Each	1
	Terminals, wire, numbers and accessories	Each	1
	2P 230V 25kA 10/350 Class 1 Surge arrester	Each	1
	Electronic E/L relay	Each	2
	E/L CT 350mm ID	Each	2
	Transducer	Each	3
	Hardware design and layout	Each	1
	Manufacture	Each	1
	Integration testing	Each	1
	Field junction boxes	Each	2
7	**SCADA SYSTEM**	Lot	
	RSView Se Server 100 W/RSLINX ENTERPRISE 9701-VWSS100LENE	Each	1
	RSView Se Client 9701-VWSCWAENE	Each	1
	Dell Power edge 840,dual core intel P4,2G DDR2 SDRAM,80GB SATA HD ,48*4G CDRW/DVD ROM	Each	2
	Operating system XP Pro	Each	2
	ell E197FP 19"mainstream LCD Flat panel monitor.	Each	2
8	**UPS POWER SUPPLY**		
	Meissner 220-220, 5 Kva with 25min standby at full load	Each	1
	DB Boards	Each	2
9	**INSTALLATION AND COMMISSIONING**	Lot	1
9.1	**York Fridge Plant no. 1(Instrumentation)**		
	1* Technician	Hrs	108
	1*Boilermaker	Hrs	108
	4*helpers	Hrs	108
9.2	**York Fridge Plant no. 2(Instrumentation)**		
	1* Technician	Hrs	108
	1*Boilermaker	Hrs	108
	4*helpers	Hrs	108
9.3	**York Fridge Plant no. 3(Instrumentation)**		
	1* Technician	Hrs	108
	1*Boilermaker	Hrs	108
	4*helpers	Hrs	108
9.4	**York Fridge Plant no. 4(Instrumentation)**		
	1* Technician	Hrs	108
	1*Boilermaker	Hrs	108

	4*helpers	Hrs	108			
9.5	**LT panels**					
	1*Electrician	Hrs	135			
	1*Helper	Hrs	135			
	Relays and wiring	Lot	1			
10	**SCADA AND PLC DEVELOPMENT AND INSTALLATION**	Lot	1			
	Mobilisation,clarification and verification	Each	1			
	Design specifications	Each	1			
	SW Engineering/scada/pc/network/reporting	Each	1			
	SW Engineering Plc	Each	1			
11	**COMMISSIONING**	Lot	1			
	Cold commissioning	/Machine	4			
	Hot commissioning ,loop checks and performance test	/Machine	4			
12	**DOCUMENTATION**	Lot	1			
	Operator and maintenance manuals	Each	1			
	As built back-up	Each	1			
	Final sat. handover	Each	1			
13	**PLC EQUIPMENT**	Lot	1			
13.1	**Siemens PLC for York machine's**	/Machine	4			
	Simatic S7-300 rail 6ES73901AF300AA0	Each	2			
	Simatic S7-300 PS307 120/230VAC-24VDC5A 6ES73071EA000AA0	Each	1			
	Simatic S7-300 CPU 315-2DP with MPI interface 128 Kbytes working memory2. 6ES73152AG100AB0	Each	1			
	Simatic S7-300 micro memory card. 6ES79538LG110AA0	Each	1			
	Simatic S7-300 Analog input SM 331 8AI 6ES73317KF020AB0	Each	5			
	Simatic S7-300 Analog output SM332 4AO 6ES73325HD010AB0	Each	1			
	Simatic S7-300 Digital input SM 321 32DI 6ES73211BL000AA0	Each	1			
	Simatic S7-300 Digital output SM322 16DO 6ES73221BH100AA0	Each	1			
	Simatic S7-300 Front connector 20pin 6ES73921AJ1000AA0	Each	12			
	Simatic S7-300 Front connector 40pin 6ES73921AM000AA0	Each	1			
	Simatic touch panel with Ethernet interface6AV66420BA0011AX0	Each	1			
	Simatic Net,CP343-1 lean comm.'s processor for connection of S7-300 with industrial Ethernet using TCP/IP and UDP 6GK73431CX000XE0	Each	1			
	Simatic DP interface , IM 153-1 6ES71531AA030XB0		1			
	Simatic net, PB FC standard ,Bus cable 6XV18300EN20		1			
	Simatic DP ,Bus connector 6ES79720BA500XA0		3			
	Sitop modular stabilized power supply 220vac-24vdc/10A		1			
13.2	**Convert modbus comm's to ethernet(Sandfilters)**	Lot	1			
	Simatic Net,CP243-1comm's processor for connection of simatic	Each	9			

	S7-22X to industrial Ethernet. 6GK72431EX000XE0					
	Simatic Net,CP343-1 lean comm.'s processor for connection of S7-300 with industrial Ethernet using TCP/IP and UDP 6GK73431CX000XE0	Each	1			
	Simatic S7-300 CPU 315-2DP with MPI interface 128 Kbytes working memory2. 6ES73152AG100AB0	Each	1			
	Simatic S7-300 micro memory card. 6ES79538LG110AA0	Each	1			
	Starter package ,WINCC flexible 2005, 6AV65512EA011AA0	Each	1			
13.3	**Siemens PLC for Howden machine**	Lot	1			
	Simatic S7-300 rail 6ES73901AF300AA0	Each	2			
	Simatic S7-300 PS307 120/230VAC-24VDC5A 6ES73071EA000AA0	Each	1			
	Simatic S7-300 CPU 315-2DP with MPI interface 128 Kbytes working memory2. 6ES73152AG100AB0	Each	1			
	Simatic S7-300 micro memory card. 6ES79538LG110AA0	Each	1			
	Simatic S7-300 Analog input SM 331 8AI 6ES73317KF020AB0	Each	6			
	Simatic S7-300 Analog output SM332 4AO 6ES73325HD010AB0	Each	1			
	Simatic S7-300 Digital input SM 321 32DI 6ES73211BL000AA0	Each	3			
	Simatic S7-300 Digital output SM322 16DO 6ES73221BH100AA0	Each	2			
	Simatic S7-300 Front connector 20pin 6ES73921AJ1000AA0	Each	2			
	Simatic S7-300 Front connector 40pin 6ES73921AM000AA0	Each	9			
	Simatic touch panel with Ethernet interface6AV66420BA0011AX0	Each	1			
	Simatic Net,CP343-1 lean comm.'s processor for connection of S7-300 with industrial Ethernet using TCP/IP and UDP 6GK73431CX000XE0	Each	1			
	Simatic DP interface , IM 153-1 6ES71531AA030XB0		1			
	Simatic net, PB FC standard ,Bus cable 6XV18300EN20		1			
	Simatic DP ,Bus connector 6ES79720BA500XA0		3			
	Sitop modular stabilized power supply 220vac-24vdc/10A		1			
	Installation and commissioning					
	PRICE SUMMARY					
1	PRELIMINARY AND GENERAL					
2	FIELD INSTRUMENTATION					
3	CABLES					
4	NETWORK EQUIPMENT					
5	PIPE MODIFICATION AND VALVES					
6	PLC PANELS					
7	SCADA SYSTEM					
8	UPS POWER SUPPLY					
9	INSTALLATION AND COMMISSIONING					
10	SCADA AND PLC DEVELOPMENT AND INSTALLATION					
11	COMMISSIONING					
12	DOCUMENTATION					
13	PLC EQUIPMENT					
	TOTAL PRICE:					

QUOTATION

WELKOM INDUSTRIAL CONTROLS

(Pty) Ltd 2000/003135/07

461 Welkom 9460 No.6 1st Street (057)357-5724 Fax(057)352-2155 norman@wic.co.za

The Manager
HVAC International
PO Box 2158
Faerie Glen

Reference : **2936**

Date Create : 2007-04-23 14:56:58
Date Modify : 2007-04-23 15:00:05

Attention : Marius Kleingeld

We thank you for your enquiry and take pleasure in quoting below. This offer is made in accordance with our general terms and conditions of sale. (Available on request)

QTY		DESCRIPTION
		PLC Equipment
3		4 Slot rack controllogix chassis
3		85-265 VAC Power supply (5V @ 10AMP)
3		CLX Ethernet/IP 10/100 Bridge Module - Twisted PR
3		DH+RIO Bridge/Scanner Module
		Sub Total :
		Ethernet Switches
3		Hirschmann Managed Switches MS30 1600 SAAE
9		Hirschmann Managed Switches MM2 - 4TX1
3		Hirschmann Managed Switches MM2 - 4FXM2
6		Hirschmann Managed Switches 943 015 - 001
3		Hirschmann Managed Switches MM4-2TX/SFP
		Sub Total :
		Enclosures
3		Enclosures with 3M Patch Box and PSU for Ethernet fibre cable route 800(H) x 585(W) x 300(D) Installed @ 1x Vent Fans 1x Compresssors 1x Fridge Plants
		Sub Total :
		Valves
1		800mm Varix butterfly valve wafer pattern 10 Bar WP fitted with Rork IQ 18 Electric Actuator : 525V On-Off
1		600mm Varix butterfly valve wafer pattern 10 Bar WP, fitted with Rotork Model IQ 10 Electric Actuator: 525V On-Off
1		800mm Varix Non return valves, wafer pattern, Double Door, 16 Bar WP Stainless Steel Disc
1		800mm Armflex metallic compensator 10 Bar WP flanged both ends Face to Face = 450mm
1		600mm Armflex metallic compensator 10 Bar WP flanged both ends Face to Face = 450mm
2		400mm Varix butterfly valves wafer pattern 16 Bar WP gearbox operated
4		250mm Varix butterfly valves wafer pattern 16 Bar WP fitted c/w Rotork IQ500, 525V Electric actuator, Including CPT & Folomatic 4 - 20 MA
		Sub Total :
1		**Pipework & Cable Racks**
1	0.5	Supply, make up and install all pipes, flanges and gaskets, install supplied valves as measured at Tsepong for 800NB pipeline
1	0.5	Supply, make up and install flanges and gaskets inside fridge plant for chill water pumps inside building Make up delivery pipes on pump no 4
1	0.5	Supply, make up and install all pipes, flanges and gaskets as

		measured.
1	0.5	Supply, make up and install all pipes, flanges and gaskets, install supplied valves as measured at Tsepong for 800NB pipeline
1	0.5	Supply, make up and install flanges and gaskets inside fridge plant for chill water pumps inside building Make up delivery pipes on pump no 4
1	0.5	Supply, make up and install all pipes, flanges and gaskets as measured.
1		Cable Rack for 800mm Valve @ Pre-Cooler
		Sub Total :
1		**Cables**
500		8 Pair 1.00MM SQR (14/0.3MM) XLPE ins ind & oa/mylar LH PVC SWA LH PVC cable
500		Power Cable
		Sub Total :
1		**Programming**
1		Modify of Existing PLCs programs for Valves and Pump Control 3-Pipe, 45L Pumps, 4x Fridge Plant Programs and BAC.
1		Modify and add tags on existing Intouch Scada System
		Sub Total :
1		**Installation & Commissioning**
1		Installation per meter of Instrument & Power cable (Dual)
1		Installation of Cables & Racks
3		Installation of Fibre Enclosures with Ethernet Switches 1x Vent Fan 1x Compressor 1x Fridge Plants
1		Wiring of PLC I/O and open/close and control valves.
1		Commissioning
		Sub Total :
		Grand Total :

APPENDICES

APPENDIX B