# AN INTEGRATED APPROACH TOWARDS THE OPTIMIZATION OF VENTILATION, AIR COOLING AND PUMPING REQUIREMENTS FOR HOT MINES

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# ABSTRACT

## AN INTEGRATED APPROACH TOWARDS THE OPTIMIZATION OF VENTILATION, AIR COOLING AND PUMPING REQUIREMENTS FOR HOT MINES


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*This thesis contends that optimization of energy resources through active control and predictive simulation modelling is possible, and that such monitoring leads to large savings in the electricity costs of hot mines (where refrigeration has to be employed). In addition, active monitoring and control can positively affect the establishment of a safe, healthy and productive working environment.*

*In the entire optimization process certain guidelines were set to ensure that the requirements of the Mine Health and Safety Act were met. Varying the quantity of air supplied underground by means of Variable Speed Drives (VSD's) is one of the crucial factors in the interactive approach towards the optimization of ventilation, as is refrigeration and the pumping requirements associated with refrigeration. This research highlights the interaction between the amount of air supplied and the effect it has on refrigeration requirements underground. This thesis also considers the effect that this would have on contaminant control.*

*Various tools are available for ventilation and cooling design for mining. These tools are based on the assumption of steady state conditions and do not take into account instantaneous changes in conditions day to day or hour to hour (such as for temperature and contaminants). They also do not take into account the optimization of energy resources related to the creation of the acceptable underground conditions. With these tools worst-case and best-case scenarios are identified, and strategic decisions are made accordingly.*

*Currently, the amount of the fresh air, the velocity of the air, and its general temperature in the mine are only changed when one production phase changes into another (or when unacceptable conditions occur as a result of poor design or neglect). This means that during a specific production phase (which can last for several months), there can be an oversupply, or undersupply, of energy resources, which will obviously affect the concentration levels of the various contaminants (through under or oversupply of air).*

*Studies done at the Target Mine in the Free State, South Africa, investigated the possibility of optimizing air cooling, air supply, and water pumping. A unique simulation programme was designed for the mine – initially to monitor how the mine normally utilized energy resources in air-supply cooling and water pumping. Once this had been done, an 'optimization schedule' for energy use on the mine was established, using predictive simulation. A potential saving in energy costs of approximately R2,6 million per annum was identified. This study ends with recommendations for the implementation of simulation programmes, as well as with suggestions for future work.*

# SAMEVATTING

# 'N GEINTEGREERDE BENADERING VIR DIE OPTIMISERING VAN VENTILASIE, LUGVERKOELING EN POMP VEREISTES VIR WARM MYNE


## RCW WEBBER-YOUNGMAN

| | |
|---|---|
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*Die hoof gevolgtrekking van hierdie verhandeling is dat die optimisering van energie bronne deur aktiewe beheer en voorspellings simulasie wel moontlik is en dat sulke monitering tot groot besparings in elektrisiteits koste vir warm myne kan lei (waar verkoeling van die lug toegepas moet word). Aktiewe monitering, beheer en optimisering het ook die addisonele voordeel dat dit sal bydrae tot die daar stel van 'n veilige, gesonde en produktiewe werksomgewing.*

*In die hele optimiserings proses is daar sekere riglyne gestel om te verseker dat die vereistes van die Myn Gesondheid en Veiligheid Wet nagekom word. Een van die mees kritieke komponente in die interaktiewe benadering vir die optimisering van lugvoorsiening en lugverkoeling vir 'n warm myn, is die vermoë om die hoeveelheid lug wat ondergrond voorsien word, te kan varieer. Dit kan gedoen word met behulp van 'n variërende spoed motor wat die waaier aandryf. Hierdie navorsing beklemtoon die interaksie tussen die hoeveelheid lug voorsien en die effek wat dit op byvoorbeeld verkoeling en die beheer van kontaminante kan hê.*

*Wanneer dit kom by die ontwerp van lugvoorsiening en verkoeling sisteme vir myne, is daar baie tipes toerusting beskikbaar. Hierdie toerusting is gebaseer op die feit dat gestadigde kondisies sal geld en neem nie kontinue verandering in kondisies ondergrond op 'n dag tot dag of 'n uur tot uur basis in ag nie. Dit neem ook nie die optimisering van energie bronne wat met die daarstel van aanvaarbare kondisies te make het nie, in ag nie. Met hierdie tipe*

*toerusting word die slegste en beste kondisies geidentifiseer en strategiese besluite word dan dienooreenkomstig geneem.*

*Huidiglik word die hoeveelheid lug, die snelheid en die temperatuur daarvan ontwerp, geimplementeer en slegs verander wanneer daar van een produksie fase na 'n ander oorgegaan word (of in geval van nood waar onaanvaarbare toestande ontstaan of indien daar tydens die ontwerp 'n fout met sekere aannames gemaak is). Dit beteken dat gedurende 'n sekere produksie fase (wat vir verskeie maande kan aanhou), dat daar die moontlikheid van oor of ondervoorsiening van beskikbare energie kan wees, wat uiteraard die konsentrasie vlakke van kontaminante kan beinvloed (die oor of onder voorsiening van lughoeveelhede).*

*Studies wat op Target myn gedoen is, het die moontlikheid van optimisering van lugvloei, lugverkoeling en water pomp ondersoek. 'n Unieke simulasie program is vir die myn ontwerp -- aanvanklik om die myn se huidige verbruik van energie bronne te bevestig en nadat dit gedoen is, is 'n optimiserings skedule vir energie besparing opgestel deur van voorspelling simulasie tegnieke gebruik te maak. 'n Potensiële besparing in elektrisiteits koste van nagenoeg R2,6 miljoen per jaar is geidentifiseer. Die verhandeling sluit af met voorstelle vir implementering van die verskillende simulasies sowel as voorstelle vir toekomstige navorsing.*

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5. *Finally, but definitely not least, my gratitude to God, who, through His wisdom, always knew why I had to come back to Pretoria.*

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| °C | Degrees Centigrade |
| ACP | Air-cooling power |
| ACS | Alternating Current Systems |
| ACGIH | American Congress for Group Industrial Hygienists |
| BAC | Bulk air cooling |
| BP | Barometric pressure |
| CANMET | The Canadian Centre of Mineral and Energy Technology |
| CAPEX | Capital expenditure |
| CBL | Customer baseline |
| CCOD | Compensation Commission for Occupational Diseases |
| COMRO | Chamber of Mines Research Organization |
| COP | Coefficient of performance |
| CP | Cooling power |
| DB ($t_{db}$) | Dry-bulb temperature |
| DME | Department of Minerals and Energy |
| DPM | Diesel particulate matter |
| DSM | Demand side management |
| E | Energy |
| EPROM | Erasable Programmable Read Only Memory |
| Eskom | Electricity Supply Commission |
| FC | Fully Closed |
| FV | Face velocity |
| h | Hour |
| HSM | Heat stress management |
| ICRP | International Commission for Radiological Protection |
| IBD | Inlet box dampers |
| IPS | Integrated Predictive Simulation |
| IRR | Internal Rate of Return |
| ISO | International Standards Organization |
| J | Joule |
| kt | Kiloton |
| kPa | Kilopascal |
| kW | Kilowatt |
| kWh | Kilowatt-hour |
| ℓ | Litre |
| M | Mega- |
| m | Metre |
| min | Minute |
| MD | Maximum demand |
| ML | Megalitre |
| MW | Megawatt |
| NPV | Nett Present Value |
| NRR | National Radiation Regulator |
| OD | Outlet damper |
| OEL | Occupational exposure limit |
| OPEX | Operating expenditure |
| OHSA | Occupational Health and Safety Act |
| PLC | Programmable logic controller |
| POD | Point of delivery |
| PV | Present value |

| | |
|---|---|
| R | Rand |
| RCP | Respirable carbon particles |
| REMS | Real-time Energy Management System |
| RH | Relative humidity |
| Rm | Million rand |
| RTP | Real-time pricing |
| s | Second |
| $T_{nwb}$ or $T_w$ | Natural or unventilated wet-bulb temperature |
| $T_{wb}$ | Psychrometric or ventilated wet-bulb temperature |
| TES | Thermal energy storage |
| TJ | Terrajoule |
| TLV | Threshold limit value |
| TWL | Thermal work limit |
| U/G | Underground |
| V or u | Air velocity |
| VCP | Ventilation, cooling, pumping |
| VIV | Variable inlet vanes |
| VRT | Virgin rock temperature |
| VSD | Variable speed drive |
| VUMA | Ventilation of underground mine atmospheres |
| W | Watt |
| WB ($t_{wb}$) | Wet-bulb temperature |
| WBGT | Wet-bulb globe temperature |

# CHAPTER 1

# OVERVIEW AND NEED FOR INVESTIGATION

# 1. OVERVIEW AND NEED FOR INVESTIGATION

## 1.1 Introduction

The Mine Health and Safety Act, 29 of 1996, and the Regulations were promulgated primarily to promote a culture of health and safety, provide for the enforcement of health and safety measures and to provide for effective monitoring systems and inspections, investigations and inquiries to improve health and safety [1].

It is therefore important to have systems in place to identify risks on mines by using historical data and results. Preventative measures can then be taken to eliminate and/or minimise risks and in the same way minimise costs.

In establishing a safe, healthy and productive working environment underground, three physical factors play a significant role. These are the fans, the refrigeration units and the chilled water pumped to the bulk air coolers underground or on surface. Figure 1.1a shows a diagrammatical layout of this equipment in a typical hot mining environment.

The fresh air ventilating a mine enters at the downcast shaft and is drawn through the working place, where it becomes contaminated and is removed from the mine via the up-cast shafts. A typical hot mine has one or more downcast shafts where the fresh air from surface enters the mine; intake airways through which the air flows to the workings; various connections between the workings; and return airways through which the air passes from the workings to the up-cast shaft (or shafts) and out to surface. Fans are used to remove exhaust air through the mine since natural ventilation is normally inadequate and unreliable. To distribute and control the air to the different levels and workings, ventilation appliances such as ventilation doors, walls, regulators, booster fans and auxiliary fans are used [2].

The amount of refrigeration that is needed is dependent on the amount of air supplied. The more air supplied, the less refrigeration required and the less chilled water pumped. These pieces of equipment make out a large portion of the capital, running and maintenance costs of the total budget of a hot underground mine. These are however in balance, and the significance of air supply and refrigeration costs for increased depths will become evident through this investigation.

The amount of air that is supplied also has an important influence in the control of contaminants. The greater the air quantity available, the easier it is to dilute the contaminants. Greater air quantities also have the ability to remove more heat and in this way control the temperature of the working environment. If the air has lost its ability to remove heat (that is when the temperature of the air has increased the required reject temperatures) it is cooled and made available for use again.

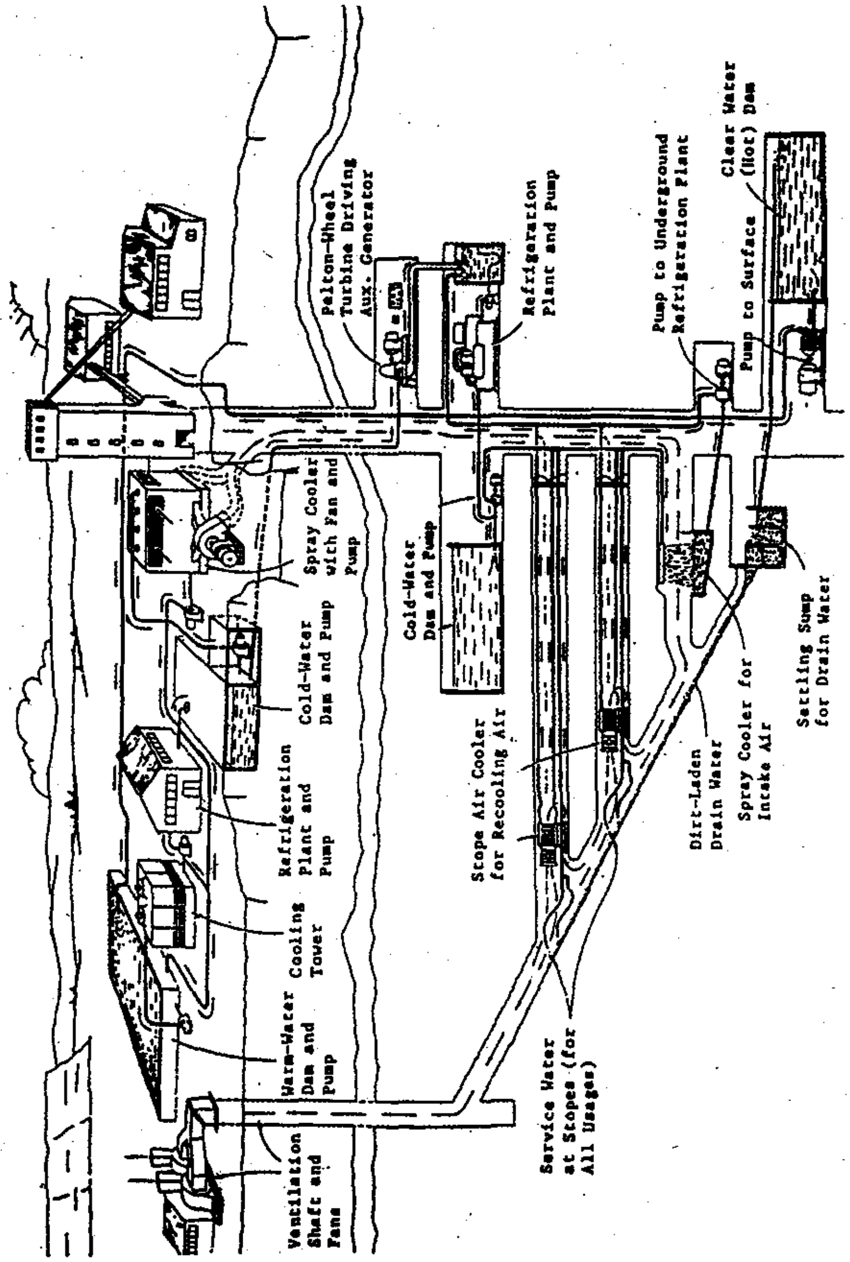



**Figure 1.1a: Graphical presentation of a hot mine layout**

From the statements made it is quite obvious that there is an interaction amongst all these processes and that a change in one of the processes has a direct effect on the others. All these processes take place at the same time and can all be monitored continuously. These results are readily available on mines equipped with adequate monitoring equipment. Typical types of information that are currently available are, the air quantities (through velocity measurements), the temperatures (wet-bulb and dry-bulb), contaminant amounts and concentrations and many more.

In the fridge plant all technical data pertaining to the refrigeration units such as waterflow rates, flow temperatures, co-efficient of performance (COP) values and compressor status are readily available. The information that is available can be processed to establish trend lines for specific types of information gathered. The changing heat loads in a mine can be shown through real-time monitoring of temperatures at strategic places and monitoring the physical condition of the working environment (dust and gas concentration levels). This information (real-time monitoring) can then be used to design optimized airflow quantities and refrigeration requirements.

The challenge is therefore to have a simulation programme in place that would not only optimize the physical requirements in establishing a safe, health and productive environment, but also to optimize the energy resources associated with the relevant equipment. The programme must also be able to adapt to changing inputs, so that the optimization is based on current results, which predict future needs. Through active monitoring, control and predictive simulation the whole process will be optimized with the inclusion of real-time energy costs.

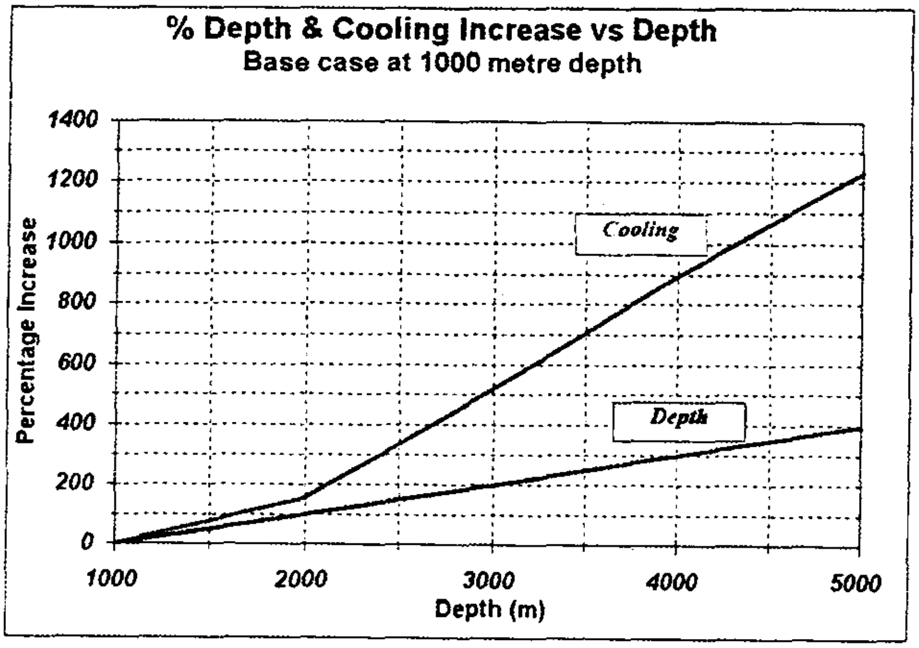
In the past, many suggestions were made, and new technologies implemented to optimize the use of energy resources and to make sure that mining operations were kept profitable by lowering both their electricity-associated running costs, and the costs relating to mine environmental control. It has now become important to have in place an integrated simulation programme to optimize the air supply, cooling and pumping requirements for hot mines.

Over the last few years, a number of authors had definite comments about the cost of energy and energy optimization. Middleton stated that deep-level mining in South Africa is dependent on the development and implementation of innovative technologies to ensure that the exploitation of deeper ore reserves remains economic. This statement seems applicable not only to deep mines, but to *any* that uses a lot of electricity in its air supply and cooling strategies. Middleton highlights the obvious fact that running costs would become increasingly critical as the need for electricity supply grows. Moreover, working costs need to be kept in check without jeopardizing the worker's safety and health [3].

Marx states that the heat load in deep hot mines is directly dependent on working depth, and that the high capital and running costs of air supply and cooling installations will have a dramatic effect on the profitability of mining at such depths. Marx also states that in order to mine profitably and yet maintain safe, healthy and productive working environments, new and innovative technologies have to be implemented [4].

Figure 1.1b shows the dramatic increase in cooling-related costs associated with increased depth. Marx notes that the supply of air becomes critical to reduce heat at depth, which inevitably has an effect on the COP of the refrigeration units, and thus impacts on the electricity cost associated with the air supply. He points out, too, that the use of diesel driven mechanised equipment will further increase the heat load.

Larger pieces of equipment need larger airways, which reduces the velocity of the air for a specific air quantity supplied. Marx indicates that the air velocity and the quantity of air cooled are critical in establishing a safe and healthy working environment, and that the costs of supplying and cooling the air are huge, let alone the cost of pumping chilled water to the bulk air coolers (BAC) on surface or underground.




**<u>Figure 1.1b:</u> Percentage increase in cooling versus depth (Marx [2])**

As long ago as 1990 Ramsden pointed out that mine refrigeration costs -- the running costs, as apposed to capital costs of setting up cooling plants -- would increase in future. In 1984 the production costs on South Africa's gold mines were among the lowest in the world, but by the 1990s costs were among the highest. This adverse change led to various new strategies and new technologies being implemented. As implied by the present study, the process continues.

Ramsden also noted that the cooling principle employed (the same principle as currently employed) is that the work environment is cooled to the design temperatures or below. That is done by means of cold water sent to bulk air coolers or closed-circuit cooling units. The cooling of the water requires refrigeration compressor motors. There is potential here for various cost savings, as the pumping costs in large cooling installations using compressor motor power can be huge: money can be saved here by optimizing pumping and compressor schedules [5].

Bluhm et al. note that the planning and design of ventilation control systems for future mines will require extensive optimization and that it will be necessary to evaluate a number of options and scenarios, not only for the ventilation system, but also for the overall design of the mine. They also maintain that the mine layout should be conceptualised first, before the ventilation system is designed, so that the latter will be appropriate for the mine layout. When it comes to this planning, the Ventilation of Underground Mine Atmospheres (VUMA) simulation tool plays a crucial role [6].

When designing the ventilation and air cooling of a mine, many different factors must be considered. The planning and implementation of a specific mine ventilation and air cooling design have many different aspects to consider. To maintain the status quo with the optimization of the daily/monthly/yearly ventilation, cooling and pumping requirements, remains a challenge, even today. The rest of this chapter will highlight the various issues pertaining to optimized planning and the actual stages of implementation of the plan. The mine, through its life, will go through various production stages and it is during these changes in production that ventilation, cooling and pumping should be optimized.

## 1.2 From planning to implementation of mine ventilation and cooling

In order to create a safe healthy working environment on any mine, it is important to estimate, based on previous experience and simulations, the possible conditions that can be expected in any "new" working environment. These estimations (or assumptions) must be made in the early planning stages, so as to ensure that the ventilation requirements (including cooling) are not under- or overestimated. The over- or under-design of the ventilation requirements of any mine can and will have a long-term impact, but there are excellent simulation tools (such as VUMA) allowing the actual requirements to be incorporated into the design and planning quite accurately. A flexible, though systematic, approach is therefore necessary. According to Bluhm et al., the process can be summarized as shown in Figure 1.2 [7].

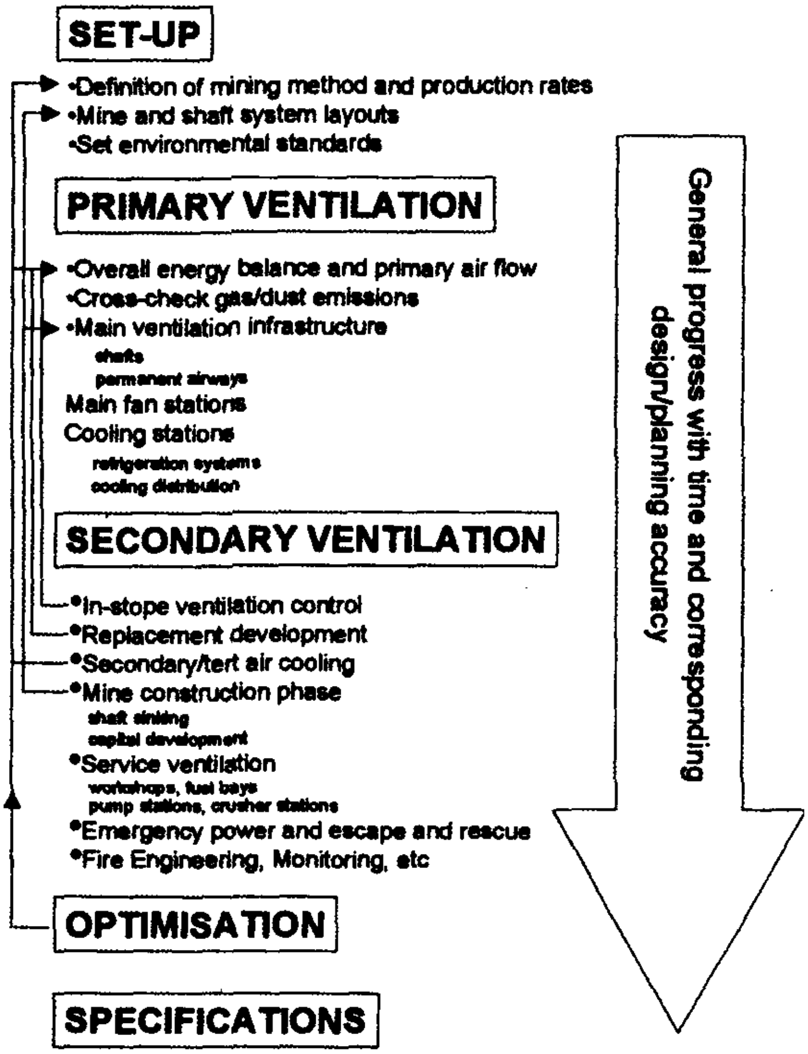



**Figure 1.2:** **The planning optimization process (Bluhm et al. [7])**

Bluhm et al., differentiate between primary and secondary ventilation systems [8]. Primary ventilation refers to the main ventilation and cooling infrastructure. It includes the main surface fan, main booster fans, up-cast and downcast shafts, ventilation raises, main airways, bulk air coolers, central refrigeration systems, etc. The objective of the primary system is to provide airflow to the sections and service zones in sufficient quantities and at appropriate temperatures and quality. Secondary ventilation refers to the control of the ventilation systems in the actual sections and service zones.

Long-term planning of ventilation and cooling normally focuses on the primary requirements because these define the large single capex (capital expenditure) items, but the secondary systems, with their multiplicity of auxiliary fans, ducts and so forth, can also require surprisingly high electrical power inputs and related costs.

### 1.2.1 Planning with simulations

Planning of ventilation and cooling requirements is done with the help of computer software, which enables the user to do various "what-if" runs once a basic layout has been established, making it invaluable in determining the optimized design. What makes the simulation tool so invaluable is that long-term strategies, such as increased fan requirements and the cooling needed, can be identified timeously and be included in the design. Such matters have a major impact on the capital and working cost expenditures, and subsequently on the actual cash flow of the mine. In the case of deep mines, the actual scheduling of the requirements will be critical to the feasibility of a mining project.

As already stated, the cost of providing a specific thermal and healthy (gas and dust control) environment is governed by both the capital and operating costs of the required cooling and ventilation systems. The design and performance specifications for ventilation and cooling systems are, in turn, determined mainly by the total cooling and the airflow volume required to achieve a specific wet-bulb temperature and air velocity to satisfy human requirements and dilute harmful substances such as dust, gases, fumes, radiative substances to acceptable levels.

Bluhm et al. highlight the following phases in overall mine project planning,: a concept phase, an optimization phase and a formal feasibility phase before implementation. These are followed by various stages in the life of the mine and can be described as follows [9]:

- The **mine construction stage** is characterised by shaft sinking, capital development, opening initial stope lines and generally establishing the operation up to the stage where production begins. This stage accounts for most of the capital allocations and has a definite duration for both tax purposes and managerial control. This stage is generally characterized by the use of temporary ventilation systems. While most mine infrastructure is established during the mine-construction phase, the main ventilation and cooling systems are often brought into service only later, during production build-up.

- The **build-up and full production stage** is characterised by the main ventilation and cooling equipment coming on to load, and the full establishment of the primary ventilation networks and secondary ventilation systems for follow-on development. During the full production stage, mining generally moves out on strike and gets deeper. In particular, the cooling systems are phased in to operate at their full capacity. The build-up and full production stage is followed by production depletion, which is not really relevant in early planning, except in this sense: consideration might be given to rehabilitation-related issues, and whether large pieces of equipment may be moved to other mining operations.

### 1.2.2 Planning for the dynamic nature of mining operations

Bluhm et al. point out, quite rightly, that the single most fundamental issue to be appreciated in mine planning is that mining is a continuously evolving, dynamic and flexible process, and that the ability of systems to adapt to new changes is critical in the design process. It is therefore important that ventilation and cooling designs and planning incorporate a high degree of flexibility. The thinking needs to be *modular* in the sense that cooling systems should be capable of being gradually phased in, added to or removed.

In addition, the possibility of increasing or decreasing ventilation and cooling resources should be given high priority throughout the planning and implementation process. Some of the design flexibility required to make this possible can be incorporated when drawing up the engineering hardware specifications. Indeed, this versatility must be a major part of these specifications. A powerful approach during the strategic planning is to carry out "what-if?" sensitivity studies. These analyses can effectively be carried out using computer simulation programmes by simply varying part of the network evaluation [10]. The design of the optimized plan is therefore based on steady-state conditions.

In the past, the idea was that ventilation and cooling could be stepped up in phases, as shown in Figure 1.2.2a. Equipment bought, such as fans and refrigeration units, had the appropriate design features to cater for greater future loads. However, during these between-phase stages, it was critical to monitor and control the actual running cost of the system (fans, pumping and refrigeration units). It is one of objectives of this investigation to show that, currently, there is little control over predicting future requirements, and matching these with current exigencies.

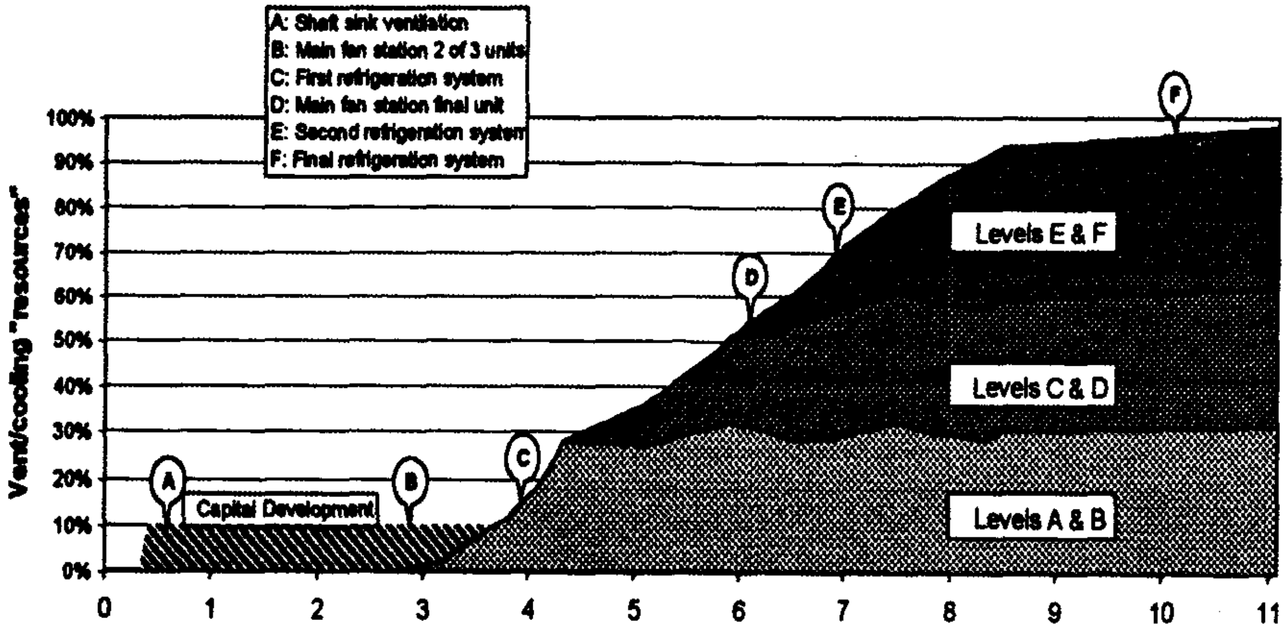



**Figure 1.2.2a: Example of ventilation and cooling phase-in profile (Bluhm et al.[10])**

Bluhm et al. also performed life-cycle analyses, including capital and running costs for refrigeration units, main and recirculation fans, pumps turbines and so forth. The results showed the capital cost and running (electrical power) cost versus the total downcast air with a portion of recirculated air. Figure 1.2.2b below shows the results of this investigation [10].

These findings support the argument that the running cost component of the life-cycle costs is critical and will become more so in future and that design tools should be put in place not just to monitor electricity consumption, but also to optimize electrical power costs. Currently, cost savings resulting from a reduced supply of air or cooling underground are only achievable where management arrange for extra fans or cooling plants to be switched off over weekends and/or public holidays, or where a mine applies peak demand energy management strategies.

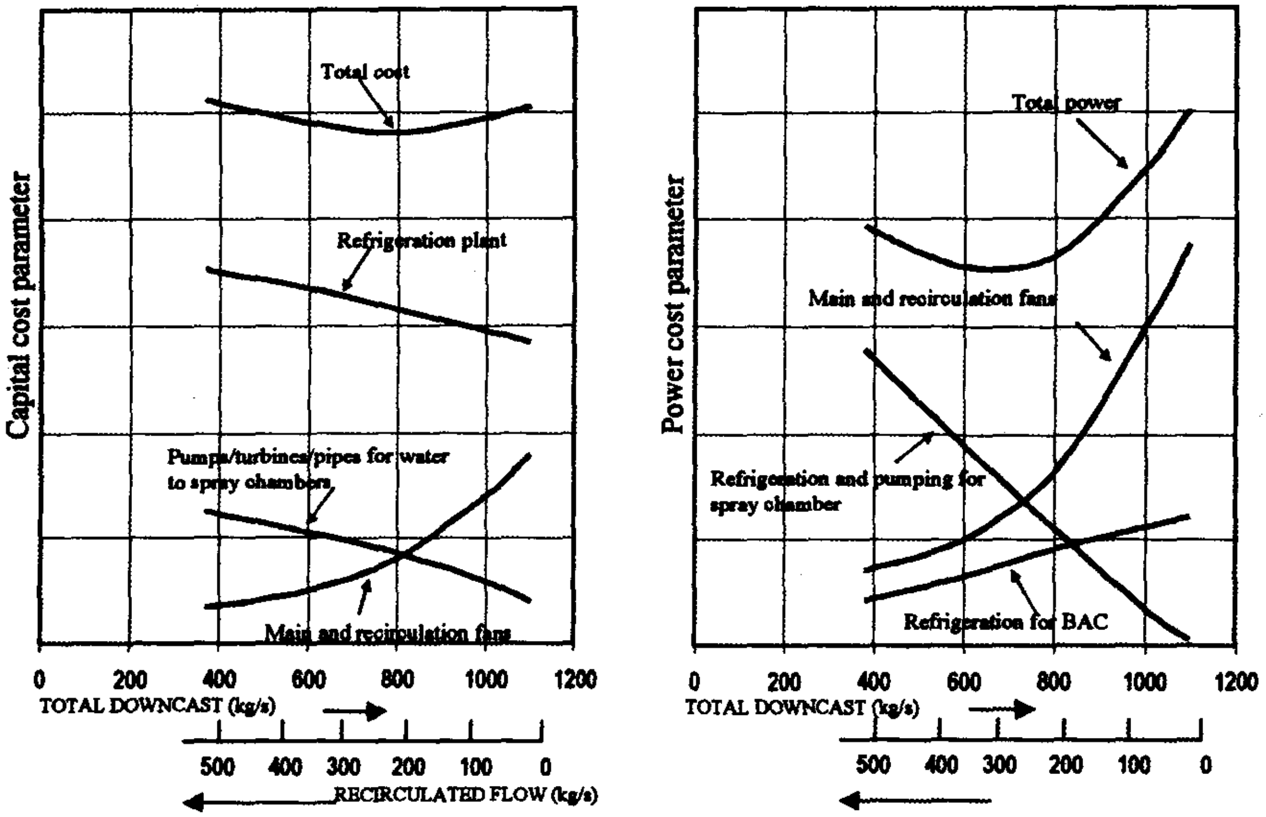



**Figure 1.2.2b: Example of results from design optimization study (Bluhm et al.[10])**

## 1.3 Establishing a safe and healthy working environment underground

Through the whole planning and implementation process there is one invariable: the supply of fresh air, and having systems to ensure that the air provided meets certain requirements. Mine ventilation is therefore the continuous supply of air of adequate quality to all parts of a mine, where people are required to travel or work. This continuous supply of air is required to:

- Supply oxygen for breathing and must be above 19% by volume
- Remove heat and provide comfortable working conditions and hence improve productivity

- To dilute and remove noxious and flammable gases that may be encountered during mining operations
- To dilute and remove hazardous airborne pollutants created by various mining operations (i.e. dust, fumes, aerosols, vapours, radioative contaminants etc.)

This is to create and maintain a working environment that is conducive to the productivity, health and safety. However it must be borne in mind that the most important matter to be considered in a hot mine, is the removal of heat. Heat is integral to any deep mine and aspects thereof will be dealt with in the following section.

As ventilating air circulates through a mine, the principal sources of heat affecting it are auto-compression and heat flow from the rock. Heat can be transferred through various processes. The main cause of heat transfer is the difference in temperature between two substances or bodies. The three major components in the heat transfer process are conduction, convection and radiation [11].

### 1.3.1 Distribution and control of air

A mine is usually divided into sections or ventilation districts and the total volume of air down-casting must be distributed between these various ventilation districts or sections. As air will always take the shortest route or path of least resistance, different ventilation appliances are used to ensure that a sufficient quantity of air reaches each ventilation district. Effective installation and maintenance of such ventilation appliances is also important to prevent air wastage and hence maintain adequate air volumes to all districts. In this, active monitoring can play an important role in highlighting wastages and dangerous conditions (such as high gas or dust concentrations). It is important how the information obtained from the monitoring is used and how fast this information is reacted to.

Adequate air volumes may enter a stoping- or development end section, but not all this air will reach the working faces where it is required. Production needs in different areas in a mine vary continuously; a mine is therefore subdivided into different ventilation districts. It is therefore important that mechanisms are in place to ensure that the optimized amount of air (in both financial and safety/health terms) is available at all times [11].

## 1.4 Energy consumption and planning parameters

From the above it can be seen that all these planning parameters and schedules will eventually be introduced in practice, and that control measures are needed to ensure optimum implementation of the said systems. The optimization of resources plays a significant role in the planning/design stages, and the real-time optimization of resources during the actual life-of-mine should be an even more critical part of the total project management cycle and the profitability of the operation.

### 1.4.1 Energy consumers (electrical) in mine environmental engineering

The main operations that consume electricity are the air supply (fans) and the cooling of the air (which includes the refrigeration units, and the pumping of chilled water). Optimal air supply should be ascertained: what actual quantity (and temperature) of air is needed, and through this to establish the optimized energy cost for cooling and pumping associated with it.

In providing the ideal working environment (available quantity of air, contaminant control and design temperatures), it must be remembered that these parameters are interrelated with regard to costs. It is of no use to increase the *velocity* of the air, and in that way increase the fan input power cost (and over supply of air to control contaminants when it is not needed), when it could have been cheaper simply to reduce the *temperature* of the air. At great depths, the pressure losses associated with the necessary fan motor input power could be huge.

The temperature of the air is normally reduced by means of additional cooling through bulk air coolers or spot coolers, which includes the pumping of water and an additional workload on the compressors. The opposite of the above mentioned is also true. It is therefore necessary to establish a way of optimizing the required air velocity and temperature dynamically (in effect, optimizing the whole air supply and contaminant concentration control and cooling process).

### 1.4.2 Electricity consumption on South African mines (present and future)

In the past electricity was available in abundance in South Africa and was also relatively cheap. This has changed and several companies now have demand side management (DSM) systems for electricity, but other companies still need to address this problem. In a report by Statistics South Africa, 2001, it was pointed out that although the electricity supply industry only contributes 2,8% of the country's Gross Domestic Product (GDP), all other industries use it to deliver their products [12].

The National Electricity Regulator also stated in 1999 that the electricity sales from the national transmission system in South Africa could be divided into the following groups shown in Table 1.4.2a (highest to lowest use) [13].

**Table 1.4.2a: Electricity sales breakdown for South Africa**

| Sector | Percentage electricity sales (1999) |
|---|---|
| Manufacturing | 43,8 % |
| Mining | 18,4 % |
| Domestic | 18,0 % |
| Commercial | 9,4 % |
| General | 4,6 % |
| Agricultural | 3,3 % |
| Transport | 2,6 % |

Statistics South Africa noted in 2001 that the mining, manufacturing and commercial sectors constitute almost 72% of South Africa's total electricity sales. The mining industry contributed 7,2% of the country's GDP or more than R59 billion (US$7,4 billion) for the year 2000 [12]. In a report by Gcabashe in 2001, it was also noted that the mining industry had purchased more than R4,2 billion (US$0,53 billion) of electricity in 2001 [14].

All hot mines in South Africa make use of ventilation systems, which consist of air supply, refrigeration plants and pumping systems. Els highlighted interesting facts pertaining to energy supply in South Africa. He noted that the ventilation system of a typical deep mine can consume up to 40% of the mine's total electricity bill [15]. Lane noted in 1996 that for a typical gold mine, a more typical and conservative contribution figure to the electricity bill would be ±25% (average) for ventilation (air supply), cooling and pumping [16].

Furthermore, the product prices of the minerals mined vary with time in response to global business cycles. These prices influence the profit margin of the mines. The University of Cape Town (UCT) released a report in 2000, which indicated that mining, and its associated activities is largely an export industry, contributing about 50% to South Africa's exports [17].

With the varying economy and mineral prices, the need for retrieving the maximum amount of ore in the most energy efficient way has become apparent. Unfortunately, the ore reserves (with specific reference to gold mining in South Africa) have become more difficult to extract, as the ore reserves for gold are now only to be found deeper and deeper, with current research contemplating depths of up to 5 km and beyond. This causes increased intensity of electricity usage per ton of ore mined.

In a report by the Energy Research Institute in 2001, it was stated that this had caused an increase in electricity consumption from 40 TJ/ton in the late 1960s to 150 TJ/ton in the late 1990s [18]. Ryan stated in 1999 that for platinum mines mining at depths in excess of 1 400 m, operations alter radically because of the higher geothermal gradient associated with the Bushveld Igneous rocks. There is a need for much more refrigeration and for changes to the support systems, compared with operations at the same depths on other types of deep mines [19]. For a gold mine, this crucial level is typically 2 000 m and more below the surface. Shone noted in 1988 that at these depths and beyond, the virgin rock temperature rises above acceptable human endurance levels and special ventilation and cooling is needed [20].

This presents a difficult and potentially dangerous situation for mine workers. Viljoen noted in 1990 that satisfactory ventilation would be needed, as well as a means to investigate the impact on the ventilation cycle of heat loads from machines breaking or performing less efficiently [21]. *Active monitoring combined with predictive controlled simulation of the ventilation, cooling and chilled water pumping, can improve health, decrease risk and still offer financial rewards for the mine and other interested parties.* In this statement lies the challenge for the dynamic control of ventilation, cooling and pumping (as an integrated approach). The challenge will be to provide real-time monitoring and predictive active control of conditions, and real-time optimization of the resources available. Lane also identified the main consumers of electricity in the mining environment. These are shown in Table 1.4.2b [16]:

**Table 1.4.2b: The main consumers of electricity on a mine**

| Consumer | Percentage of total use Maximum Demand (MD) | Percentage of total use Electricity (E) |
|---|---|---|
| Compressors for compressed air equipment | 29,1 % | 21,3 %* |
| Underground mining systems and activities | 23,0 % | 18,9 %* |
| Smelting plant/mineral processing/crushers | 13,3 % | 13,7 % |
| The mine winding systems | 10,1 % | 14,2 % |
| Underground pumping stations | 9,9 % | 17,7 % |
| Ventilation and cooling | 9,3 % | 7,9 % |
| Office buildings, hostels, essential services | 5,3 % | 6,3 % |

* Highest consumers of electricity in the mining environment.

Figure 1.4.2 shows the expected increase in the demand for electricity in South Africa for the next few years. It is a real indication of the expected dramatic increase in the cost of electricity in South Africa, which has the potential to affect the mining industry seriously and which adds to the need to have a system to cater for any future increase in the cost of electricity. In *Die Beeld* newspaper the opinion was expressed that South Africa may experience a serious shortage of electricity if role-players in the power supply and distribution industry do not build a new power-generating plant soon [22].

It was also stated that the national peak-time consumption is growing at 4,5% per annum, which is much higher than the expected 2,5% per annum. This means that in 2008, South Africa will use more electricity than it currently produces and that the total maximum demand power consumption will exceed the current supply in 2010. Furthermore, South African electricity prices are too low to ensure any return on investment. Many options are being investigated to cater for the expected shortage, especially the managing of electricity consumption, so as to optimize current resources.

A control system that can do real-time monitoring is needed. Also a simulation programme should be in place in place that could "make suggestions" to optimize electricity use. This should be available for all the major pieces of equipment, so that an integrated approach towards optimization of these resources can be pursued. The system must therefore be able to use historical data of electricity use and apply it in the optimization process. In this way the future consumption can be predicted and control systems can be adapted accordingly, through automatic intervention.

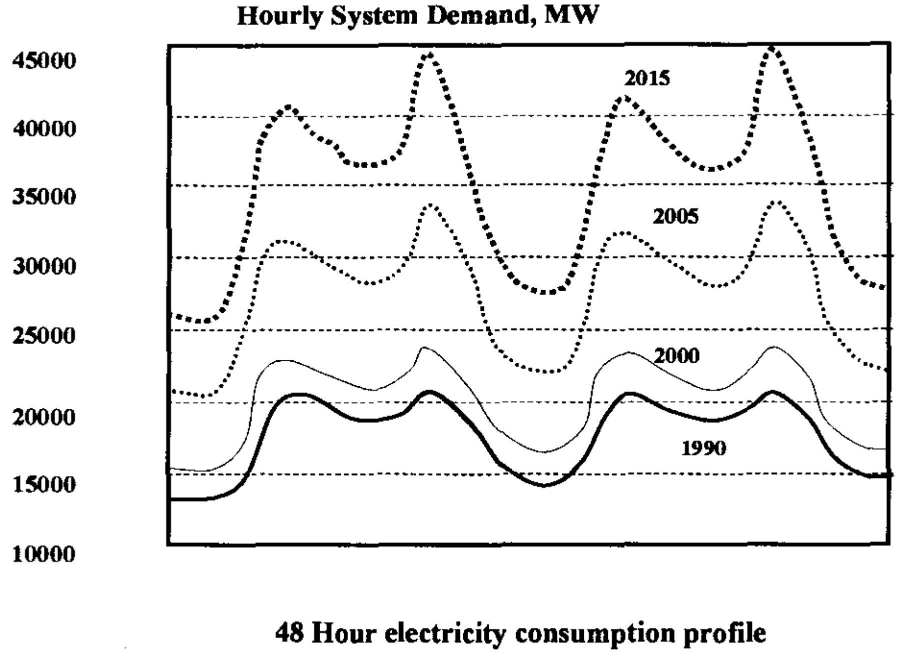



**Figure 1.4.2: Expected increase demand for electricity in South Africa (48 hours)**

## 1.5 Mine monitoring

More and more, conditions in mines are being monitored with the help of computerised technologies. It is now possible to monitor conditions in workplaces, such as air temperatures, velocities, pollutant concentrations and waterflow rates at any time of day. This is done with the aid of temperature sensors, velocity measurements, pollutant-measuring equipment and sensitive waterflow measurement equipment.

These measured results are conveyed to a central data-gathering system and are normally acted upon reactively, meaning that problem areas are identified, but that corrective measures are only put in place much later. This is not an efficient use of the measured data. The ideal would be to use these measured, real-time results to optimize the current resources available (with reference to the energy costs related to them) in an hour-to-hour prediction process. It would be possible to perform continuous workplace monitoring and without undue reliance on specialized equipment or personnel. Hardcastle et al. highlighted the requirements of a comprehensive air-management system as follows [23]:

- A ventilation model/simulator

- Fan control
- Door/regulator control
- Ambient pollutant monitoring
- Airflow monitoring
- Diesel equipment monitoring
- Diesel equipment pollutant monitoring
- Monitoring and control communications

It is vital that the ventilation simulation tool used incorporate all of the above control communications and features in order to ensure that the system will be optimized on the basis of certain limits and constraints set, including the cooling requirements necessary for deep mines. It is possible to monitor real-time conditions and to use the results to establish a proactive approach towards optimizing the resources available and also to optimize the energy consumption of a mine.

The VUMA tool, according to its specifications, will be suitable for designing a specific ventilation layout for a mine, but could also help in the identification of problem areas (with regard to ventilation and cooling). The question now arises: "What systems are in place that could react instantaneously to actual real-time monitoring results?" A dynamic simulation tool that could act on real-time monitoring results, and "suggest" real-time optimized solutions for the total mine environment, should be developed and implemented.

The Canadian Centre of Mineral and Energy Technology (CANMET), has devised such a system for the Canadian mines, but it has been basically designed for airflow simulations only and does not take into consideration the effect of an increased heat flow where refrigeration must be part of the total system. It does, however, cover all the major parameters applicable to an air-management system, such as fan control, ambient pollutant monitoring, airflow monitoring and diesel equipment pollutant monitoring [23].

As mentioned before, in the optimization of energy requirements safety and health obligations must always be kept in mind. Ventilation engineers are constantly reminded of the high capital and running costs of mine ventilation and cooling systems and of the need to reduce these as much as possible, but it was noted by von Glehn that decisions affecting the efficient running of a system are often based on incomplete and imprecise information. Von

Glehn gave an analogous example of the ongoing simulation, monitoring and control of a general chemical process, which included active control and predictive simulation tools that oversaw the process, and suggested that the same approach could and should be applied in mine ventilation systems.

Von Glehn stated that since a mine ventilation system is an expensive process, it is necessary to maintain a hands-on approach throughout the process and to be able to enhance the operation by predictive control. His opinion was that it was time to apply to such systems the high level of technical tools available. He also noted that advanced programmable logic controllers (PLC's) and control technology are being introduced on some new mine refrigeration systems, but that it was fair to say that little equivalent effort is being made for ventilation systems.

"*We need to know what is happening underground by monitoring, we need to be able to predict what will be happening when something changes in the system by simulation and we need to be able to change ventilation systems to ensure acceptable conditions by controlling, for example, fans, doors and movement of equipment*". To this list must be added the ability to predict future conditions and the optimized corrective response to them (including the optimization of energy resources).

Von Glehn states that planned networks are not always compared with existing systems, because not enough information on existing systems is always available. He also indicates that there have been few major advances linking simulation software to monitoring and active control systems. He notes that in examining the ventilation software available for predictive planning, he found that simulators are generally adequate with regard to airflow simulations, but *inadequate with regard to the simulation of integrated cooling systems*. Where active or live control of ventilation and cooling systems is concerned, the situation is also not satisfactory. With regard to monitoring and control, von Glehn also states that there is *some monitoring, but little active control*.

Most of the monitoring systems are used for manual intervention and for reporting. They have no means of automatic control and should therefore rather be regarded as examples of management systems. Von Glehn states that the current status of monitoring, simulation and active control in mine ventilation systems is disappointing and that there has *been little or no routine implementation of active control*. The concept of *feeding monitored information* *directly into simulators has fared even worse*. Here lies the uniqueness of this investigation as this aspect is also dealt with here. Von Glehn notes that it is wasteful to provide ventilation and cooling where and when it is not necessary and that this leads to unnecessary costs.

An *active predictive simulation* and control system will have great benefits in identifying varying heat loads, minimising operating costs for cooling and ventilation, and also minimising investment costs in ventilation and cooling equipment. Areas that can be targeted in this integrated optimization will be specific work areas that need more cooling, primary and secondary fans, refrigeration equipment, air coolers, storage dams and specific cyclic needs in particular zones. In this way, the heat profile, refrigeration and pumping and fan supply energy can be minimised.

In his concluding remarks, von Glehn states that the use of mine monitoring, simulation and control systems was not satisfactory in 1999 and that there is still room for change and improvement. He also states that in future the operators on a mine should be able to interact with a live network, that parameters should be monitored continuously, that predictive and calibrating simulations should carried out regularly, and that an active control system should continuously regulate flows (of both air and water) to ensure a safe and healthy working environment, while at the same time minimising energy requirements [24]. The main objective of this study was to prove that this was in fact possible.

## 1.6 Shortcomings of the current system

In the South African mining industry the amount of air supplied during various phases of the production stage remains fairly constant -- except for a major increase (or decrease) in the amount of air needed when a new production phase is entered into. This means that in times when production is actually depleting, fans still run at the higher production rate requirement, leading to substantial amounts of wastage in energy.

The opposite scenario also creates a problem. If higher volumes of air are needed to establish better working conditions (either because of higher contaminant levels or increased heat), the situation cannot be rectified immediately. Additional booster or auxiliary fans must be installed, or the duty of the main fans on surface must be increased manually. This obviously takes time, which means that workers must be removed until the situation is rectified.

Unfortunately workers are not always removed and can therefore exposed to unsafe and unhealthy conditions. The above mentioned therefore highlights that a need for changing the air quantities does indeed exist. In summary the increase in air quantities has some of the following possible advantages:

- Possible shorter re-entry periods after blasting
- Higher additional volumes of air when needed
- Quicker gas dilution because of high volumes of air available
- Much quicker removal of heat and a reduction in chilled water circulation

A decrease in air quantities on the other hand, has the possibility of lower costs and less maintenance of fans. Through this investigation the possible advantages mentioned above will be substantiated and quantified. The technology for monitoring of conditions in mining has improved dramatically over the last 5 years. There is almost no parameter that cannot be measured, i.e. air velocities, temperatures, contaminant levels, gas concentrations and radioactivity levels. An explosion of information is available to the mining environmental engineer and occupational hygienist.

All this information is now available, but it is not always known what to do with it. This is the real shortcoming of the current scenario. Information pertaining to substandard air quantities and contaminant concentrations is used reactively. For example when a substandard area is identified, measures are then put in place manually to rectify the situation, but this can unnecessarily expose workers to risk.

If, for instance, the temperature in a specific workplace is unnecessarily high over a period of time and also has high dust concentration levels, the electronic monitoring system that is currently available will identify the problem area. Current mining practices would deal with the situation as follows:

1. The high temperature of the area must be rectified and the only way to do this is either to increase the quantity of air that flows through the workplace (which will increase the heat removal capacity of the air) or to decrease the temperature of the air. To do this instantaneously in the current mining scenario is not possible. The situation can only be changed over a period of time by changing the air quantity to a specific

workplace, either through regulators installed in other areas or the installation of booster and or auxiliary fans for that area. Cooler air can also be re-routed from other work areas.

There is a definite relationship between the quantity of air supplied and the amount of chilled water that will cool the air. An increase in waterflow rate to the bulk air coolers will mean less air necessary to remove heat from the air in the work areas. If the amount of air is not adjusted to be in "energy balance" with water supplied, it will lead to huge wastage. The opposite argument also holds true.

There is therefore a need for a system that can "balance" the energy consumption of the total system, associated with the air supply and the cooling of the air instantaneously. This "balancing" does not have to be done and considered on micro scale. Balancing for every ventilation district would be ideal, but is not always possible. On a macro scale such balancing might be easier to implement (main fans and cooling units), provided it was catered for in the planning and design stages.

It is however important to note that if the air quantities are to be changed instantaneously, variable speed drive (VSD) motors for the fans are a pre-requisite. The major flaw (changing of required air quantities) in the current system is that the quantity of air cannot be changed depending on need (for instance more air for higher heat load removals). This can only be done through manual intervention (reactively) and this takes time.

2. Higher volumes of air are needed to dilute high dust concentrations (provided that the higher volumes do not create more dust). The higher air quantities, which are needed for this dust dilution, can only be provided instantaneously if a VSD fan is available. The same applies to the dilution of other contaminant levels. In times of "perfect" conditions, it is possible that unnecessarily high air quantities are supplied to areas not needing them, and low air temperatures where they are not needed (over supply of energy resources).

Every workplace has a history of temperature and contaminant levels over a period of time and all this information is available. This information can be used to establish trends and introduce methods to deal with the situation. This information can form part of a predictive simulation programme, that reacts pro-actively to dangerous situations (high temperatures, high gas concentrations etc.), but also do it in the most economical way possible. In this way the physical and economical optimization can be achieved. The current shortcomings can therefore be summarized as follows:

- Varying of air quantities on a "when needed" basis does not exist
- Active *monitoring* does exist, *but little or no active control*
- A lack of real-time optimization of resources
- Lack of automated intervention in the control of resources such as fan, and compressors to make integrated optimization possible. There is no simulated Integrated Predictive Simulation (IPS) approach in optimizing the air supply, air cooling and chilled water pumping, in establishing a safe and healthy working environment, and optimizing the electricity cost associated with it.

From the above it is clear that an investigation into an integrated approach towards the optimization of the ventilation, cooling and pumping requirements for hot mines, is needed

## 1.7 Problem statement

To establish an integrated approach towards the optimization of ventilation, air cooling and cooling related pumping requirements for hot mines, incorporating the optimization of energy resources and the optimization of contaminant levels in an integrated simulated optimization programme.

## 1.8 Objectives of this investigation

Several objectives were set for this investigation and will be discussed in the sections that follow below.

### 1.8.1 Literature study

A detailed study was done to establish the following:

- All aspects pertaining to fan airflow monitoring and control, basic airflow control measures, power saving associated with airflow control measures and a comparison of power saving potential of various airflow control measures

- All aspects pertaining to variable speed drives, including costs, reasons for non use in South African mining, as well as costs associated with variable speed drive motors (including payback calculation) and the identification of advantages and disadvantages related to variable speed drive motors
- The identification of the most important contaminants in the working environment, such as dust, gases and radioative contaminants. The literature study also includes the various aspects pertaining to these contaminants such as properties, dangers and prevention or control methods associated with these contaminants
- The role of recirculation of air on the saving of energy and the effect on the total amount of air required when re-circulation of air is employed
- Heat transfer in mining, also including the main sources of heat as well as the effect of heat on productivity
- Air temperature control methods currently employed on South African mines
- The various aspects pertaining to heat transfer processes underground
- Identifying any other indicators that highlight the need for an integrated approach to optimization, such as Air-Cooling Power (ACP, applicable to hot mines) and Thermal Work Limit (TWL)
- Identifying work done in the field of optimization and predictive simulation in mining, and the shortcomings of current energy management systems, including an investigation into Real-time Energy Management Systems (REMS) and the development of REMS
- To identify the most critical parameter in the optimization of the air supply, air cooling and cooling related pumping if an integrated approach was to be followed in the optimization process

### 1.8.2 Quantifying the importance of air quantity changes

It was important to show the effect of air quantity changes on contaminant control and the amount of refrigeration required. This was done by physically showing the effect of air quantity changes on:

- the dilution of contaminants such as gas and dust and the direct impact on the Air Quality Index (AQI) related to dust concentrations to satisfy the requirements of the Mine Health and Safety Act for different Occupational Exposure Levels (OEL's) for these contaminants

- the amount of refrigeration required, as well as the cooling related pumping by using the ventilation for underground mine atmospheres (VUMA) simulation package

### 1.8.3 Critical parameters associated with variable speed drives (VSD's)

It was necessary to establish the critical parameters associated with variable speed drive motors such as capital costs, maintenance costs and running costs. It was also necessary to do a sensitivity analysis on the effects of air quantity changes on the Net Present Value (NPV), Internal Rate of Return (IRR), as well as the cost saving potential for specific air quantity distributions. It was also necessary to establish the sensitivity of the rand/euro exchange rate on the viability of the inclusion of VSD's.

### 1.8.4 Actual case study and investigation work

The whole investigation was dependent on the availability of a mine where the different theories for this research project could be applied and evaluated. The objectives for this part of the investigation, were as follows:

- Identify a mine for a case study
- Set up a model to simulate real-time conditions
- Calibrate the simulation model
- Optimize the actual simulation and investigate possibility of predictive simulation
- Evaluate the actual potential cost savings to be gained through optimized simulation
- Identify the importance of varying air quantity changes in the optimization process
- Evaluate the results
- Investigate the feasibility of implementing air control and fridge plant compressor control
- The thesis is concluded with a summary of the major findings, recommendations and suggestions for further work

## 1.9 Methodology

The real need for the investigation is shown in the background section of this chapter. The purpose of the literature study is to highlight and quantify issues relating to the investigation as mentioned in the objectives above. It also has the objective of relating to other similar investigations elsewhere in the world (if any) and of identifying shortcomings and preventing repetition (re-invention of the wheel).

The objectives were met as follows:

- A literature search, which included worldwide gathering of related articles through Internet search and library collaboration. Through this effort various types of information were obtained such as worldwide trends with regard to other related research, such as simulation packages employed for optimization of resources

- All aspects pertaining to fan airflow monitoring and control, basic airflow control measures, power saving associated with airflow control measures and a comparison of power saving potential of various airflow control measures were stipulated and evaluated

- Heat sources and their effect on production as well as the mechanisms for heat transfer were obtained through the literature search. The importance of heat in the South African hot mining environment was highlighted

- Through personal communications with various companies, such as ABB Engineering, Howden Safanco, Anglo Vaal and Harmony mines, valuable information pertaining to electricity consumption on mines, variable speed drives, fan related information and costs associated with all these parameters was obtained

- One of the objectives of this investigation was to establish the integrated relationship between the air quantity and refrigeration required. The most important contaminants in the mining environment have been identified, and through physical calculation showed the sensitivity of contaminant concentration to an increase/decrease in the air quantity

- A financial analysis was conducted on Excel spreadsheet of the various parameters associated with variable speed drives such as the capital cost, running and maintenance cost. Parameters such as NPV, IRR and distribution of air quantities over the life of the project were compared

- Aspects relating to the recirculation of air (which formed an integral part of the Masters dissertation of Webber) were also included to highlight the importance of re-circulation of air on the quantity of air required, as well as the possibility of reduction in fan related pressures when re-circulation of air is employed.

- Identifying any other indicators of the need for an integrated approach to optimization, such as Air-Cooling Power (ACP, applicable to hot mines) and Thermal Work Limit (TWL) challenging (ACP) as heat stress index through work done by Webber.

- A case study for REMS done on Kopanang mine in the Free State was used as an important real-time reference for the current integrated approach to optimization of resources related to air supply, air cooling and cooling related pumping, underground and on surface

- The VUMA simulation package was used to show the effect of reduction/increase in air supply on the refrigeration requirements of a platinum mine

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# CHAPTER 2

# LITERATURE STUDY

# 2. LITERATURE STUDY

## 2.1 Introduction

Chapter 1 describes the need for the investigation and various factors that will enhance an integrated approach towards the optimization of air supply, cooling and chilled water pumping have been identified. They are:

- Active monitoring and control
- Active real-time and predictive simulation
- Active real-time optimization of resources
- Automated intervention in controlling resources

In the establishment of the above, and the establishment of a safe, healthy and productive environment, certain physical components and processes play an important role. The purpose of the literature study is to identify the role of each of these components and processes and determine how it will influence the optimization process. It was also found that varying the quantity of air instantaneously would play a significant role in the integrated optimization simulation process -- if it is possible. Fans, with specific reference to VSD motors for fans, form an integral part of this investigation.

If it is indeed possible to vary the air quantity, this will have an effect on contaminant control and heat removal (including amount of refrigeration). In this literature study the most important contaminants found underground, and matters pertaining to heat and heat removal will be dealt with (including air temperature control). Another important aspect to be dealt with is the recirculation of air as a method to optimize air supply costs. Indicators that prove the need for an integrated approach to optimization are also part of the literature study. The literature study is concluded by an investigation into energy management systems.

## 2.2 Fans and air supply

Chapter 1 highlights the fact that air supply plays a key role in the integrated optimization process. Issues pertaining to air supply covered in this literature study include:

- Airflow monitoring and control currently employed on South African and other mines

- Establishing the current airflow control measures employed on mines (with specific reference to fans)
- Power saving associated with airflow control measures
- Comparison of power saving potential
- Variable speed drives

Fans supply air to the workings and are assisted by the placement of booster and auxiliary fans in strategic places. Fans are large consumers of electricity, but through correct planning and implementation these costs can be minimised. The purpose of this section is to highlight the various parameters associated with air supply. It must also be assessed to what extent air supply has been monitored and controlled in the South African mining industry. It must also be determined how airflow quantities can be controlled and the cost-saving implications.

In an article by Eadie and Marples in 1985, the authors asked some interesting questions. "*Will future development in mining change radically the type of fan offered for major installations on surface or underground? Will the type of drive and control equipment for air quantity regulation change because of the future demands of mining or advancing of technology?*" The answer to all these questions is a definite "Yes". Technology has changed significantly with regard to design and control tools available, and it is possible to introduce several of these new technologies in the mining environment.

The authors also say that ever deeper, ever hotter mines – South African mines are among the deepest in the world – must require continued improvements in fan technology, with the concomitant need for higher fan pressures and air quantities, while maintaining reliability and negligible downtime [1]

South African mines need to optimize resources, with specific reference to the quantity of air supplied. With depth, the fan pressure required becomes greater, as does the quantity of air needed for cooling, dilution and breathing. The electric energy needed for these large fan installations has now become a major expense in South African deep mines and therefore needs to be monitored and controlled. In an article by Hardcastle et al., the following comments are made [2]:

- *"Today the ventilation practitioner has the opportunity to optimize a mine's ventilation system to the point where air is supplied only on an as-required basis both by volume and location.*
- *The above-mentioned can reduce electricity cost associated with ventilation, as this can make out up to 40% of a mine's electricity usage.*
- *Mine operators have the opportunity of improving the work environment by supplying more air for shorter periods of time with potentially lower costs than currently incurred.*
- *Historically (and currently), mines tended to supply a fixed volume of air based on peak demand; this is very wasteful if a mine is only working at full demand for a small portion of its active life.*
- *Today it is fairly easy to remotely control surface, booster and auxiliary fans through variable pitch blades, variable inlet vane control or variable-speed motors and simply turning them on or off.*
- *For mines to be their most cost efficient, they must embrace existing and emerging technologies to optimize the use of their air; namely, maximising its work in diluting and removing pollutants, limiting leakages and avoiding the unnecessary loss of costly fan pressure."*

When we consider the statements made by these authors, it must be noted that in South African mines there is currently little or no fan air quantity control (instantaneously changing the quantity of air when needed). Quantity and volume control per se, is practised on South African mines (at different stages of production), but there is no control of the day-to-day, hour-by-hour, needs. With the changing technology in fan design, it is important that the advantages of having remote and optimized fan control be made clear.

The running cost of air supply (of the fans) has been and in future will be a noticeable expense. It is therefore necessary that action plans be put in place to monitor and optimize the electricity cost associated with it. It is also important to highlight the real advantages for changing the air quantities required, using a more scientific approach (active monitoring and predictive simulation).

### 2.2.1 Airflow monitoring and control

The output of a fan can be controlled by various means, including outlet dampers, inlet-box dampers, variable inlet vanes, variable pitch, variable speed, or even varying the number of fans in operation. Each of these techniques affects the flow rate, specific output, stability, turndown ratio, start-up, and power savings. It is therefore necessary to establish what current methods there are for controlling the quantity of air delivered by fans and to what extent these control measures will influence the electricity input power requirements for fans.

To determine the amounts of energy that can be saved, it is necessary to monitor the pressure and quantities delivered by these fans, and here some problems have been identified. Krzystanek and Wasilewski highlight some of these problems [3]. Monitoring problems are caused by extremely unfavourable conditions in the up-cast fan channel, which means that all measuring instruments have to be robust, and special data-processing methods must be used. Nevertheless, without knowledge of the current operating points of main fans, any discussion about energy-saving control of ventilation would be useless.

The problem as highlighted by Krzystanek and Wasilewski is not unique.. Monitoring the airflow quantities through main fans is still a general problem and here innovative technology is needed to ensure that the real-time measurement of fan pressures and quantities can be done on a continuous basis. This will give the ventilation engineer the necessary information for establishing real-time air supply needs and pressures, and the results can be used to establish an optimized predictive simulation solution.

Von Glehn notes that for predictive simulation and producing a fully live network by on-line monitoring to function properly, a number of sensors in the mine would be needed to update and calibrate the network simulator continuously. This would also ensure that potential problems in the circuit could be identified or "what-if?" analyses be carried out with confidence [4].

#### *2.2.1.1 Basic airflow control measures*

In "An Engineer's Handbook on Fans and their Applications"[5], Jorgensen highlights various issues pertaining to airflow control measures. It is noted that the location of the actual operating point or duty (pressure at specific air quantity supplied) will depend on the setting of the control device, as well as on the system characteristic. This is an important point to remember as different control measures will have different characteristics (for fan efficiency, power use, etc.) [5].

#### *2.2.1.2 Power saving as a result of airflow control measures*

Ventilation processes in deep mines operate with relatively low efficiency due to the following:

- Application of fan-throttling devices and passive control of air distribution in the ventilation network
- Application of the principle to supply the ventilation network with a constant quantity of air, regardless of current demand.

Krzystanek and Wasilewski also note some solutions to the wastage through oversupply of air. They suggest that passive control measures be replaced with active measures, such as auxiliary fans and the implementation of main fans performance control. This will enable the air quantity to be matched to the actual need. Energy losses could therefore be lower if effective monitoring and remote control of the fan operating point were implemented. Krzystanek and Wasilewski also mention that in Polish mines, over US$40 million can be saved per annum, if the whole ventilation air supply process were to be monitored and optimized through simulation software [6].

#### *2.2.1.3 Comparison of power saving potential*

In the comparison of various airflow control methods, it is noted that saving electricity is indeed possible. The savings resulting from an outlet damper may be substantial, but even greater savings are usually possible with inlet box dampers (IBD's) and variable inlet vanes (VIV's). The impressive savings that can be achieved with variable pitch and variable speed are comparable, especially when slip losses are included in the variable-speed application.

The literature showed that the major advantage of a controllable pitch fan in motion is that it is possible to achieve accurate airflow control, while maintaining high efficiency. Stachulak notes that the biggest downfall of a controllable pitch fan in mining is the required maintenance and the possibility of linkage freeze-up. Controllable blade fans work well on true variable volume systems, because the blades are constantly moving a small quantity of air. In mining, it was also observed that adjustment is not done frequently and that the use of a controllable blade fan can be a problem, as the exhaust air is usually saturated and may be slightly acidic.

There are currently not many variable-speed axial-fan installations in the world. One of the reasons mentioned by Stachulak is that variable-speed drives have only become affordable and sufficiently reliable to install on critical fans in the last few years. The advantage of variable speed drive fans is that it is possible to keep the fan operating at its maximum efficiency for all duties falling on the same mine resistance curve [7]. This means that if the mine's resistance changes for whatever reason, the air quantity can be adjusted without jeopardising the efficiency of the fan.

In personal communications with Mr Herman Weder, fan engineer for Howden Safanco, a South African fan manufacturing company, it was pointed out that there are several methods to control the amount of airflow delivered by a fan [8]. There are basically two types of fans used on South African mines, namely axial and centrifugal. The purpose here is not to discuss the differences between axial and centrifugal fans, but to highlight the most common and most applicable air-control methods associated with each.

For centrifugal fans only two types of air-control methods are advised for South African mines, namely through variable-speed drives and through variable inlet vane control. For axial flow fans the most applicable types of airflow-control methods were through inlet vane control, speed control and blade pitch variation. For these two types of vans the most applicable airflow control measures are therefore variable inlet van control and variable speed drives.

Howden also noted that the technology with regard to electronically driven airflow-control-initiating systems is more sophisticated. This means that through computer control it will be possible to increase or decrease the flow of air delivered by a fan. The airflow schedule could therefore be programmed into the computer and controlled through electronic devices, sending Stop/Start and Reduce/Increase airflow signals to the fan, something that in the past seemed unlikely. In the past the airflow was changed only when there was an increase or decrease in production requirements, because of the easy access to and relatively low cost of electricity in South Africa.

Fans, and in particular fan motors, are very high consumers of electricity, so much so, that a small decrease in the quantity of air supplied can have large effects on the amount of electricity consumed. Hardcastle et al. note that the air power needed to ventilate a specific area is governed by the product of the pressure drop and the quantity of air supplied. The electrical input power to the fan motor is dependent on the efficiency of the fan and the fan motor [9]. The input power to the fan motor can be expressed as follows:

$$\text{fan motorinput power} = \frac{pQ}{\eta_{fan}\ \eta_{motor}} = \frac{RQ^2 x\, Q}{\eta_{fan}\ \eta_{motor}} = \frac{RQ^3}{\eta_{fan}\ \eta_{motor}}$$

Where: p = pressure drop in Pa

Q = Air quantity in $m^3/s$

R = Resistance of the airway in $N/s^2/m^8$

$\eta$ = % Efficiency of fan or motor

This shows that for the same fan efficiency and airway resistance, the amount of power needed for the fan motor is dependent on the quantity of air supplied (quantity to the power 3).

### 2.2.2 Variable speed drives

Variable speed drives are a natural extension of experience gained in operating two speed motor systems. With the variable speed drive, the speed of the alternating current (AC) motor is adjusted by changing the frequency of the AC power feeding the motor. This saves energy by maintaining the precise speed at a specific required duty. The "brains" (the control system) determine the proper frequency by interpreting an electric signal from a transducer or other device installed in the process equipment such as the piping or ductwork.

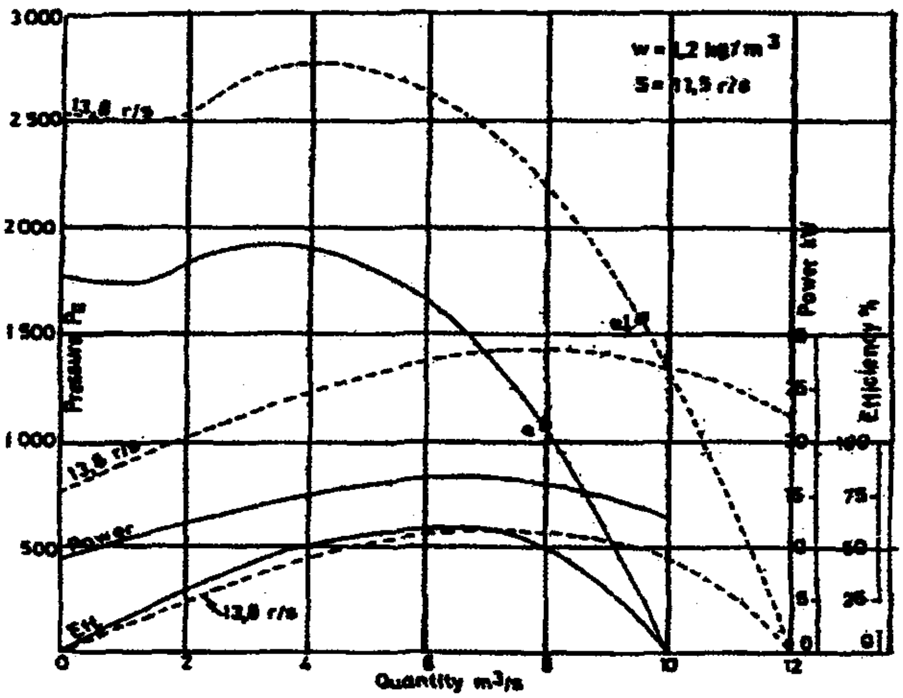
Variable speed drives are used in many applications such as the speed of fans, compressors, pumps, blowers, etc.[10]. For the purpose of this investigation the emphasis will be on the control of the speed of fan, which in effect will influence the air quantity supplied. It was noted above that the use of the variable speed drive with centrifugal fans had the added effect that the fan is always operating at maximum efficiency for all duties falling on the mine resistance curve.

Each fan has a characteristic curve associated with it. An increase or decrease in the speed of the fan the fan curve is adjusted accordingly. The same applies to the air density at which the fan will eventually operate. Figure 2.2.2a shows the effect on the fan curve when the actual speed of the fan is increased and is based on simple fan law formulas. Also shown in this graph is the relationship to the efficiency of the fan. Some of the fan laws to calculate the pressure at a new speed, as well as the input power into the fan motor, are as follows (the fan efficiency remains unchanged, no matter what the speed) [11]:

$$P_2 = P_1 \times \left(\frac{S_2}{S_1}\right)^2 \times \left(\frac{\rho_2}{\rho_1}\right)$$

$$Power_2 = Power_1 \times \left(\frac{S_2}{S_1}\right)^3 \times \left(\frac{\rho_2}{\rho_1}\right)$$

Where: fan efficiency$_1$ = fan efficiency$_2$
Q = volume flow rate in $m^3/s$
P = Fan static pressure kPa
Power = Power in kW
S = fan speed in revolutions per second
$\rho$ = air density at fan inlet for conditions 1 and 2




**<u>Figure 2.2.2a:</u> Typical fan curve with increase speed of fan (Intermediate [11])**

In personal communications with Mr Arthur Tucker, managing director of ABB Engineering in Alberton, and from the catalogue for various speed drives, some aspects pertaining to variable speed drives were noted [12]. Figure 2.2.2b is an illustration of the basic drive system configuration, which consists of the supply side, the converter and the motor. In this personal communication it was also highlighted that there were real advantages and disadvantages to using variable speed drive motors for fans. These are:

**Advantages**

- The potential of large savings in energy related costs, as the motor can run according to the actual need
- It is possible to keep the fan operating at its maximum efficiency for all duties falling on the mine resistance curve
- The possibility of better pollutant control by having higher quantities of air available when required
- The flexibility to reduce air quantities in non-production times
- Very reliable. Major maintenance required every 7 years and minor maintenance required annually
- ACS 1000 drive availability 99,98%
- The mean time between failures is 20 years (a significant number)
- Delivery dates of the complete variable speed drive motor system within 18 weeks from date of order (readily available)
- Current squirrel cage motors can be converted to include variable speed drives
- Maintenance programmes and backup services 24 hours available

**Disadvantages**

- High initial capital cost
- Less reliable in the sense that they require controlled conditions for operation, i.e. moisture and dust control
- Extra maintenance cost every 7 years for capacitor replacement
- Not suitable for robust mining environments (unless the drive mechanism is sealed off in an enclosed environment). Needs to be operated at ambient temperatures and dust control according to 60721 specifications
- Capital equipment is rand/euro sensitive (a strong rand will be beneficial to the import of a variable speed drive)

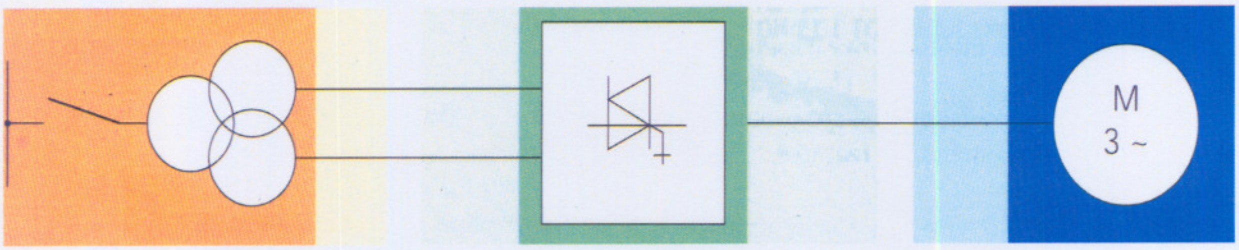



Figure 2.2.2b: The basic drive system configuration

### 2.2.3 The significance of the available information

Following is a summary of the significance of the information supplied under points 2.1.1 to 2.1.5, and to what extent it can add value to the investigation. The significance of all matters pertaining to air supply and control that needs further investigation is noted.

**Airflow control measures**

There have been some attempts to introduce continuous control measures in South African mines, but these were abandoned due to high costs associated with VSD's, as well as the need for robust measuring equipment, which was not readily available at that time. The quantity of air needed for a mine is determined by the amount of pollutants that are or will be generated, as well as by the quantity of air needed for cooling or heat rejection. It is well-known that the quantity of air needed changes as production needs change. Depending on circumstances, the amount delivered should be controllable through available technology. Reducing the quantity of air supplied does not necessarily mean that the working environment becomes more dangerous – it all depends on the actual production and the pollutant-levels at that time. During blasting, the fans could also run faster, if capable of doing so. This will allow a quicker removal of blasting fumes and dust from the work areas. In times of low production or less contamination and lower heat loads, it should also be possible to vary the quantity of air supplied.

In this investigation, not one mine in South Africa could be identified that ***currently*** applies effective, or for that matter, any, continuous airflow-control measures (for the main fans or booster fans). The philosophy is that the air is available and that it should be used. This investigation did not aim to establish the optimum quantity of air needed for a specific operation, nor to prove what airflow-control measure was the best for a specific mine. The main objective is to highlight the need for air quantity control and also to optimize the energy cost associated with it.

It is therefore necessary to emphasize the high cost of air supply and identify ways of reducing airflow costs. This can be done by means of proper airflow-control measures and/or by introducing more auxiliary fans or booster fans (provided that enough air was available in the first place) in areas identified. In this way the high-pressure losses associated with surface fans can also be reduced. An added advantage is lower airflow rates through the surface fans at times of low need.

As mentioned before, the whole argument about supplying more or less air is dependent on meeting all the requirements (such as air velocities, OEL levels, temperatures, etc.) With the technology now available, these requirements can be built into any simulation or optimized simulation programme. It is one of the objectives of this investigation to prove that the application of such simulation package in real-time will lead to a reduction in the energy costs and overall improvement of underground working conditions.

**Power saving as a result of airflow control measures**

Energy losses as a result of the lack of fan-control measures are quite substantial. In South African mines there is no instantaneous control of the air quantities delivered by main fan. This should be addressed. It is commonly agreed that the increased demand for electricity in South Africa will put resources under pressure and that innovations are needed to ensure that the air quantity is optimally planned, generated and supplied.

Excessive power consumption by a fan can be due to an unrefined design, careless selection or incorrect installation. However, focusing only on the fan pressure and quantity when selecting a fan is not enough – the fan efficiency will play a significant role in the total power consumption over the life of the mine [13].

There are various fan-selection software packages available today, and if the design of the airflow requirements is done properly (incorporating the various stages of mine design), then the incorrect choice of fan should not be possible. However, in South Africa, the ability of the fan to cater for a change in air supply on a day-to-day, week-to-week or even shift-to-shift basis has never been fully utilised. The reason for this is the high capital cost associated with, for instance, variable speed drives

**Comparison of power saving potential**

In South African mines centrifugal fans and axial flow fans are used in supplying bulk amounts of air well as for auxiliary fan applications. The advice from Howden Safanco is that the best airflow control measures are variable-speed drives and variable inlet vane control for centrifugal fans and inlet vane control, speed control and blade pitch variation for axial flow fans. This is useful information for future use.

Electronically manipulated airflow-control-initiating systems are also a reality and must be pursued, as they play a significant role in the total integrated approach of supplying air that is envisaged in this investigation. The compressibility of the air is not reflected in the fan motor electrical input power formula mentioned before. The purpose of showing the formula is to highlight the significance of the quantity of air in calculating motor input power requirement. The inclusion of the compressibility of air will in fact strengthen the argument (more power will be required if the compressibility of air is included).

**Variable speed drives**

From the literature search and personal communications it became evident that the availability of the variable speed drive is in fact quite high. Furthermore, it was introduced successfully on mines in Canada and Chile. The current economic climate in which the mining industry in South Africa finds itself (especially hard rock (gold) mining), makes the prospect of using variable speed drive motors for fan applications unattractive. This is due to the large initial capital layout. However, when considering the requirements of the Mine Health and Safety Act in establishing a safe, productive and healthy working environment, the possibilities look more promising (increasing the quantity of air instantaneously for example for improved dilution purposes or heat removal).

In Chapter 4 of this document the factors pertaining to the capital, running and maintenance cost for variable speed drive motors will be evaluated. With the expected rise in electricity costs in South Africa, a sensitivity analysis of the electricity price will be done. The effect of inflation and the rand/euro exchange rate will also be considered. Another aspect to be considered is the effect on the NPV, IRR and payback for different air quantities (as well as for different statistical air distribution patterns). These are important to consider, as they will eventually determine the feasibility of introducing variable speed drive motors for fans. The work done in Chapter 4 will quantify this.

## 2.3 Contaminants in the underground working environment

For this part of the literature study only the most important contaminants will be dealt with. The purpose is to show the significance of these contaminants and their effect on the health of workers.

### 2.3.1 Gases in the underground mining environment

The most common dangerous gases can be divided into two groups, namely, toxic or noxious gases, and explosive or flammable gases. Toxic gases are those that if breathed in sufficient concentrations for long enough will have detrimental effects to health and eventually kill a person. Toxic gases can further be sub-divided into asphyxiant gases, irritant gases and protoplasmic gases. The most common gases and their Occupational Exposure Limits (OEL's) are summarized in Table 2.3.1 (ppm = parts per million) [14].

**Table 2.3.1: Most common gases**

| GAS (symbol) | Sources | Allowable concentration (OEL) (**ppm) | SG Relative to air |
|---|---|---|---|
| Carbon dioxide ($CO_2$) | Breathing, fires, diesel fumes, blasting work (inert gas) | 5000 | 1,5 |
| Carbon monoxide (CO) | Diesel fumes, fires, blasting work | 25 | 0,97 |
| Nitrous fumes ($NO_x$) | Diesel fumes, blasting work | 3 | 1,04 |
| Hydrogen sulphide ($H_2S$) | Stagnant water | 10 | 1,2 |
| Chlorine gas ($CL_2$) | Water treatment | 1 | 2,5 |
| Hydrogen cyanide (HCN) | Sand filling | 10 | 0,94 |
| Ammonia ($NH_3$) | Blasting work, fridge plants | 25 | 0,6 |
| Methane ($CH_4$) | Fissures, coal seams | 14 000(or 1,4%) | 0,55 |
| Freon 11 $CCl_3F$ | Fridge plants | | 4,8 |
| Freon 12 $CCl_2F_2$ | Fridge plants | | 4,2 |
| Nitrogen (N) | Normal air (inert gas) | | 0,97 |
| Hydrogen ($H_2$) | Battery charging | | 0,07 |
| Oxygen ($O_2$) | Normal air | | 1,1 |

**Parts per million

#### 2.3.1.1 Prevention of gas accumulations (including flammable gas)

Unacceptably high concentrations of gases can be dealt with removing the gas at the source (ventilation ducts and hoods) and diluting gas concentration by additional quantities of fresh air. It is not always possible to remove the contaminated air from the work environment. Dilution can then be used. Adequate ventilation is one of the primary defences against any gas or flammable gas accumulation. Once a gas has mixed with the air, it is diluted to a safe or acceptable concentration when an adequate air supply is maintained and this can be achieved by:

- Proper distribution and control of available air to all workings through unrestricted airways
- Minimising air leakages and wastage of air into worked out or abandoned workings
- Installing and maintaining effective "in stope" ventilation controls as per mine standards to ensure maximum air velocities on the faces
- Correct installation and maintenance of development ventilation appliances according to approved ventilation layouts and mine standards
- Continuous monitoring (personal or electronic equipment) of the condition and operation of ventilation appliances/systems that can effect the airflow through the working place, followed by *immediate remedial action* in the case of substandard conditions

#### 2.3.1.2 The significance of the available information

Lowering the risk associated with unacceptably high gas concentrations can be achieved through continuous monitoring (currently done by electronic gas detection devices) to identify the source of or exposure to danger (hazard identification). What is lacking however is the immediate response to these unacceptable conditions (*"immediate remedial action"* referred to above).

It was highlighted in Chapter 1 that the usual response to high gas concentrations would be to increase the air quantity through secondary measures, such as the installation of an auxiliary fan in the area where high gas concentrations normally occur. It can also help to build air-tight walls to reduce air leakages, and increase the air quantity available for problem areas. In this sense the response is reactive, and not instantaneous.

The advantage of active monitoring and responding to the information immediately can be utilised in simulation programme that would be able to calculate the amount of fresh air needed for dilution purposes. This information can be sent to a central information point where it can be linked to the frequency control mechanism of a fan in that area, which will either let the fan start or run faster depending on the need. In this way acceptable working conditions can be restored much quicker and the fan can also be switched off or back to normal speed once the situation has returned to normal. In this way there will be a saving in energy and maintenance costs (fans not operating continuously when not needed). Most important though, acceptable conditions for the workers will be established through real-time monitoring, optimization and active response. Currently this is not possible. It is therefore important to have systems that would respond to monitoring results in an active way (instantaneously).

### 2.3.2 Dust and other contaminants and associated dangers

One of the most hazardous substances in mines is dust, the main contributor in health related claims over the last few years. Figures obtained from the Compensation Commission for Occupational Diseases (CCOD) in South Africa, are shown in Table 2.3.2. From the table it is obvious that there is a significant increase in the amount paid for compensation for dust related diseases for almost all the types of minerals mines. The total amount paid out in 2001 was almost R20 million more than the previous year [15].

**Table 2.3.2: Compensation figures (Rm) for airborne dust related claims**

| Mineral | Jan-Sept 1999 | Oct 1999-Sept 2000 | Oct 2000-Sept 2001 | 3 year average |
|---|---|---|---|---|
| **Gold** | 49.1 | 82.7 | 103.2 | **78.3** |
| **Platinum** | 0.8 | 2.7 | 2.5 | **2.0** |
| **Coal** | 1.6 | 1.9 | 3.2 | **2.2** |
| **Asbestos** | 9.9 | 25.5 | 24.1 | **19.8** |
| **Diamond** | * | * | 1.6 | **1.6** |
| **Other mines** | 3.8 | 9.1 | 6.5 | **6.5** |
| **Totals** | **65.2** | **121.9** | **141.1** | **109.4** |

*not available

The actual expenditure by one mining group in South Africa (name not available due to the sensitive nature of the information) for lung diseases, noise-induced hearing loss and loss time injuries totaled almost R162 million for one year. The percentage split was 72% for health related claims (which included a high percentage of dust related diseases) and “only” 18% for fatalities and loss time injuries [15]. This relates to the 80/20 principle and the question to answer is whether the efforts by the mining industry to reduce health related risks are 80% of the total effort.

One of the most basic causes of high dust concentration is that dust dilution does not always take place. The reason for this is that air quantities cannot be increased instantaneously when needed. The high compensation figure is also an indication that serious dust control problems do exist and are still a problem. Air quantities are dependent on the size of the airway and the velocity of the air in the airway. Certain guidelines for the velocity of air in certain work areas exist and these should be incorporated as boundaries or constraints in the optimization model.

#### *2.3.2.1 Properties and control of dust*

In determining whether an environment containing dust is dangerous, the following must be considered: the concentration of the dust, the chemical combination of the dust (for example the % free silica content), and the size and shape of the particles. The basic ways in which high dust exposures can be controlled or prevented are as follows [16]:

- Removal of personnel
  - This is the most effective way of preventing exposure to dust. It is mainly applied to dust produced by blasting through insisting on a minimum re-entry period and by arranging a fixed blasting time for each place so that other workers are not exposed to the blasting dust and fumes. When on-shift or multiple-shift blasting is permitted, removal of personnel from the mine is impossible and the dust and fumes must either be taken directly to surface or filtered. Other ways in which workers are kept out of dusty air is by arranging that men travel in downcast shafts and by having all waiting places in fresh air.
- Prevention of dust at its source
  - Every effort should be made to prevent formation of dust at its source, or its liberation into the atmosphere. Water is one of the most widely used means of suppressing dust. In intake airways air velocities should be between 3-5 m/s, not exceeding 5 m/s. Foot-walls should be treated with chemicals to bind dust particles.
- Dilution by ventilation
  - This is essential when the actual suppression of dust at the source has failed. Obviously, if the quantity of air passing a given source of dust is doubled, the dust concentration from that source will be halved. By delivering enough air, the dust concentration can always be reduced to below dangerous limits, but it is not always practical or economical to do this.

- Filtration
    - When dust cannot be controlled by one of the above methods and it has become airborne, it can be removed from the air by filtering the air through a suitable filter, which allows the air to flow through it, but retains the dust particles.

Dilution of contaminants through the supply of additional air is employed quite frequently in underground mines and this aspect should be quantified. OEL's exists for dusts of various types of minerals. These are the minimum guidelines for concentration levels that must not be exceeded, or workers will be exposed to unhealthy conditions. Such a guideline is known as the air quality index (AQI).

The AQI is the dust concentration value for a specific area divided by the OEL value for that particular type of dust. The AQI was introduced as a measure of determining whether a work environment that had dust related problems could be quantified in term of its health status. An area that has an AQI value of less than 1 is regarded as being acceptable and safe to work in. An AQI value between 1 and 5 is seen as one that needs remedial action and an AQI value of more than 5 is unacceptable. Table 2.3.2.1 gives some OEL values for the most important dust related contaminants [17].

**Table 2.3.2.1: Various OEL levels for different types of dust**

| Type of dust | OEL Level ($mg/m^3$) |
|---|---|
| **Silica** | |
| Crystalline silica (all forms) | 0,1 |
| Silica, amorphous inhalable | 6,0 |
| Silica, amorphous respirable | 3,0 |
| **Coal dust** | |
| < 5% crystalline silica (quartz) | 2,0 |
| > 5% crystalline silica (quartz) | 0,1 |
| **Soluble platinum salts** | 0,002 |

### *2.3.2.2 Other dangerous contaminants*

In recent years diesel-related contaminants were highlighted as a contaminant that was detrimental to health. Table 2.3.2.2a shows the OEL levels for diesel related contaminants [18]. Diesel type equipment such as locomotives, load haul dumpers, trucks etc, are commonly used in mining. The constant presence of smoke from this type of equipment makes monitoring and control important.

**Table 2.3.2.2a: OEL for diesel related contaminants**

| Contaminant | OEL (mg/m³) |
|---|---|
| **Diesel**<br>- Exhaust gases containing carbon monoxide (25 ppm) and carbon dioxide (5000 ppm), Nitrogen dioxide (2 ppm)<br>- Diesel particulate matter (DPM)<br>- Respirable carbon particles (RCP) | <br><br>10<br>0,02 (*ACGIH) |

*American Congress for Group Industrial Hygienists

Contaminants that are also detrimental to health are radioative materials. These radioative contaminants also have OEL's, shown in Table 2.3.2.2b [19].

**Table 2.3.2.2b: OEL for radiation in underground mines**

| Contaminant | OEL (mSv/a) |
|---|---|
| Radiation (limit of National Radiation Regulator (NRR)) | 50 |
| Radiation (limit of International Commission for Radiological Protection (ICRP)) | 20 |

A summary of the various ways to deal with these contaminants is as follows:

- By controlling the contaminant at the source (for instance wetting down when dealing with dust)
- Through applicable engineering designs (proper duct design, or filtration methods)
- Through administrative measures (by the removal of employees during high dust creation periods)
- Through dilution by supplying additional air
- Personal protective equipment

### *2.3.2.3 The significance of the available information*

Dilution by ventilation for dust related contaminants are mainly done when the actual suppression of dust at source has failed. Obviously, if the quantity of air passing a given source of dust is doubled the dust concentration from that source will be halved.

By delivering enough air the dust concentration can always be reduced to below dangerous limits, but it is not always practical or economical to do so. Dust dilution is one of the most common methods used to control dust concentrations underground. Here the quantity of air available plays an important role.

An increase in air quantities will lead to improved dust concentration levels, but at a higher cost for air supply (keeping in mind that air velocities must be within certain guidelines to prevent dust creation). The proposed integrated approach of air supply and cooling will have the effect that if the increased air quantity is maintained over a long period, the refrigeration can also be reduced in establishing a productive safe and health environment.

Also for the control of the other contaminants, dilution plays an important role, as control by any other means is not always possible. In Chapter 1 it was also highlighted that if contaminant release rates are high, action plans are put in place to remove or minimise the risk. This is normally done reactively (changing the quantity of air when an area with high contaminant levels have been identified cannot happen instantaneously). The challenge is to be able to vary the air quantity supplied on a "when needed" basis.

## 2.4 Recirculation of air

The potential benefits of recirculating air are great, but this practice has hardly been used in South Africa in the past, largely because of safety concerns. Work carried out by Burton in the early 1980s indicated that recirculation of air can in fact be regarded as a safe, reliable and effective procedure, provided certain precautions are taken [20].

A trial was conducted by Gorges at East Rand Propriety Mines in 1948, when a portion of the up-cast air was cooled and then mixed with the downcast air [21]. In 1973, Holding reported on a recirculation scheme in a single stope [22]. Burton then undertook an intensive investigation into the use of controlled recirculation, which resulted in a trial being conducted at Lorraine Gold Mines Ltd in 1984. A great deal of success was achieved with this trial and other studies followed.

Although there are a considerable number of technical papers available on the use of controlled recirculation in mines, they suffer from two main disadvantages. First, the majority of the papers are concerned with small-scale recirculation systems in British collieries and secondly, each paper tends to deal only with individual aspects of recirculation. Burton and co-workers, in their report in 1984, covered all the relevant aspects of recirculation of air for deep gold mines in full detail [23].

### 2.4.1 The role of controlled recirculation

In hot working environments, chilled water is used to absorb some of the heat load, but the air will absorb most of this heat load. In shallow mines, the effects of auto-compression and heat transfer from the rock are small, and downcast ventilation air, without any refrigeration, is capable of absorbing the heat load, while maintaining reject temperatures at an acceptable level.

As depths increase, this capability is progressively reduced. In summer, at a depth of about 2500 m below surface, the downcast ventilation air reaches a wet-bulb temperature of 28°C. Clearly, if the desired reject temperature is also 28°C, the downcast air has lost all its capacity for cooling. Therefore, below this depth, all the heat produced must be removed by refrigeration. However, although the usefulness of downcast ventilation air decreases with greater depth, air is still required for two cooling purposes: as a medium for distributing the necessary refrigeration, and as a means of removing heat from any refrigeration plant.

The use of controlled recirculation of ventilation air can therefore be defined as the re-introduction of a portion of the return air from an area into the intake of that same area. The term "area" is used in a general sense and can mean a development end, a single stope or a whole section of a mine. For illustration purposes, a simplified "controlled recirculation system" can be seen in Figure 2.4.1 [24].

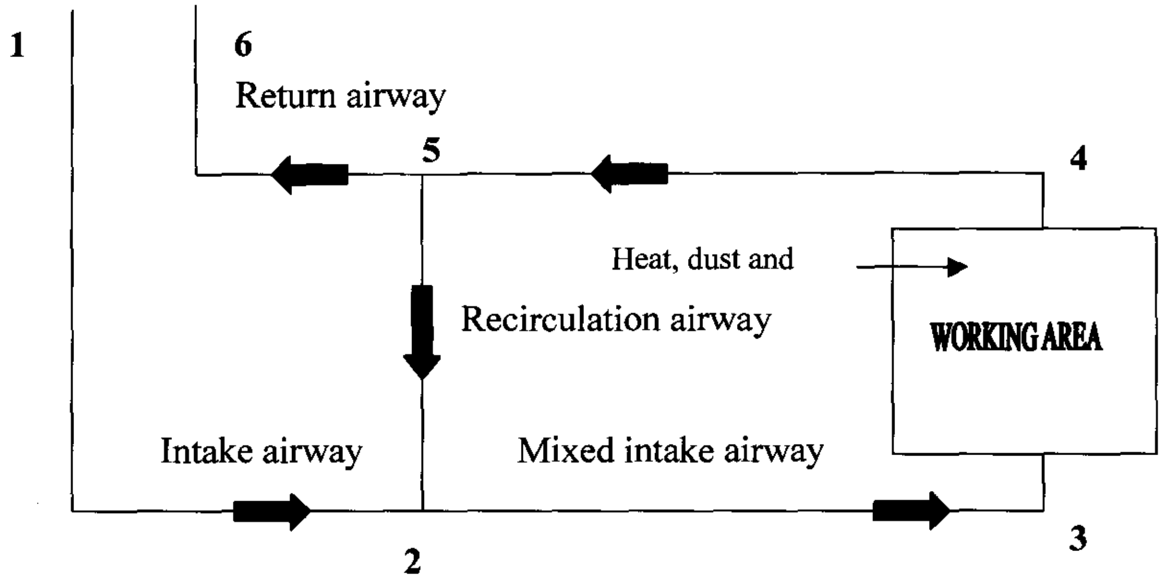



**Figure 2.4.1: Simplified controlled recirculation system for a mine (Webber [24])**

In Figure 2.4.1, "fresh" intake air flows along the path from point 1, passes through the working area and is finally rejected at point 6. Meanwhile, recirculation takes place along the route 2-3-4-5-2. It can be observed that the rate at which air is recirculated is dependent on the quantity of the intake air. Essentially, recirculation is merely the enforced circulation of the fixed volume of air contained in the area 2-3-4-5-2, and this can be done with any quantity of intake air.

It will be apparent that the effect of superimposing recirculation onto the intake airflow is to increase the flow rate of air at point 3. Stewart showed that air velocities will also increase throughout the working area and this increase has two beneficial effects, namely increased values for cooling power without any changes in the actual air temperatures, and increased air velocities, which can also minimise gas layering, as pointed out by Bakke et al. in 1964 [25].

However, the most important advantage of an increased airflow is that it provides a means of more conveniently distributing refrigeration within an area. When airflow is *restricted*, air temperatures will increase rapidly for a given heat load and repeated cooling using small air coolers becomes necessary. With an increased airflow created by recirculation, the rate of temperature rise decreases. The cooling needed for a specific area can then be achieved by means of a single bulk air cooler. It is important to recognise that controlled recirculation can *only be used as a means of distribution and not as a source of refrigeration.* The amount of refrigeration required in an area is virtually independent of any controlled recirculation that may take place.

Controlled recirculation on its own does not affect the return-air dust concentration. This concentration is largely dependent on the intake air quantity and on the amount of dust that is produced and becomes airborne within the working area. However, a situation could arise in which the intake quantity is insufficient to maintain the return-air dust concentration at an acceptable level. Controlled recirculation, with bulk air dust filtration, could then be used as an alternative to increasing the intake air quantity.

Clearly, controlled recirculation cannot provide any additional oxygen that is required. The intake air must supply the oxygen. It is also important to note that the return-air concentrations of any noxious or inflammable gases produced in a working area (excluding those produced by the blast) are not affected by controlled recirculation. Such concentrations are largely dependent on the intake air quantity and the amount of gas produced within the area.

Furthermore, although blasting fumes (such as nitrous fumes, carbon monoxide, carbon dioxide etc.) are a special case for consideration, controlled recirculation has little or no effect on the rate of removal of such fumes. Again, the overriding influence is the intake air quantity. Finally, since controlled recirculation has no effect on the quantity of return air (at point 6, Figure 2.3.1), it can be of no assistance in rejecting heat from any refrigeration plant [20]. This could have an influence on the future use of recirculation.

### 2.4.2 The significance of the available information

Recirculation is mentioned as a means of providing higher air velocities is because it can make a significant contribution in cost saving. It will be much cheaper to *increase the velocity* of the air in a specific portion of a mine through recirculation than to *increase the quantity* of air in the downcast shaft.

It will also make the control of various velocities of air in specific work areas more feasible (the increase or reduction of air velocities, depending on the air cooling power needed). The introduction of a recirculation portion into a design can be easily included in a simulation model. The financial implications of recirculation can then be ascertained.

## 2.5 Heat transfer in the underground mining environment

The major modes of heat transfer from the solid rock to the ventilating air can be summarized as follows [26]:-

**Conduction**

This is a heat transfer process that takes place through the solid rock to the exposed rock surface. The virgin rock temperature is much higher than that of the exposed rock surface, resulting in heat-flow from the solid rock to the exposed rock surface (stope faces, haulages, development end face, etc.)

**Convection**

In this heat transfer process, heat flows from the exposed rock surface to the air layer flowing over the exposed rock surface and eventually into the general air body. The exposed rocks surface is at a higher temperature than the ventilating air, resulting in heat-flow from the exposed rock surface to the ventilating air.

**Radiation**

This is the heat transfer from a hot to a cold body by means of heat rays or waves. This means of heat transfer from the rock in the workings is seldom of great significance. However radiative heat transfer from diesel machinery and large electrical equipment contributes to the total heat load (e.g. diesel LHD's, main sub-station transformers, hoists, winches, etc.).

The same heat transfer processes mentioned above take place between man and the environment. The human body has an effective heat regulating mechanism that strives to keep the body temperature constant at approximately 37,0°C. Thus, through conduction, heat is transferred from the inner body tissue to the skin surface. The rate of evaporation of sweat from the skin surface is dependent on the *velocity of the air* over the body, and is the primary mechanism for cooling the body. As a result of the evaporating sweat (latent heat), the skin surface cools down and more heat flows from the inner tissue to the skin surface, allowing the body to cool down. This evaporating capacity and heat loss is a combined function of the air velocity and temperature difference between the ambient air and the wetted skin.

### 2.5.1 Sources of Heat

There are many sources of heat in mines, but the main sources and an estimate of their relative effects are shown in Table 2.5.1 [27].

**Table 2.5.1: Sources of heat in mines**

| Source of Heat | Approximate percentage allocation (%) |
|---|---|
| Heat-flow from rock (hot mines) | 35% |
| Auto-compression of air (deep mines) | 20% |
| Machinery | 15% |
| Men | 10% |
| Oxidation of timber/materials | 10% |
| Explosives | 8% |
| Hot pipes and electrical cables | 2% |
| Movement of rock | Unknown |

There are also various ways of reducing the effect of heat. They are: reducing heat-flow from rock, removal of machinery, dilution by ventilation, acclimatization and refrigeration. From the above it is clear that the removal of heat by ventilation (dilution) plays an important role in mining and that there is a relationship between the amount of air supplied and the refrigeration required. By increasing the air quantity, the heat removal capacity is also increased, which leads to an improvement of the cooling power of the air.

### 2.5.2 Productivity Effects

The performance of all human tasks is adversely affected at temperatures above 27,0°C wet-bulb. Experiments done by the Chamber of Mines Research Organization (COMRO) have shown that with wet-bulb temperatures of 27,0°C and lower, even with low air velocities, a person's work performance is unaffected. Table 2.5.2 illustrates the approximate combined effect of wet-bulb temperature and air velocity on worker performances [28].

**Table 2.5.2: The effect of heat of worker performance**

| Wet Bulb Temperature (°C) | Velocity (m/s) | Work Performance (%) |
|---|---|---|
| 27,0 | 0,5 | 100 |
| 32,5 | 0,5 | 80 |
| 32,5 | 2,0 | 90 |
| 33,0 | 0.5 | 72 |
| 33,0 | 4.0 | 90 |
| 34,0 | 0,5 | 65 |
| 34,0 | 4,0 | 80 |

### 2.5.3 The significance of the available information

From Table 2.5.2 we see that for a specific air temperature an increase in air velocity would lead to a higher productivity level, but that a colder temperature at a lower velocity could also give the same work performance percentage. There is however a real balance between the costs related to air supply and refrigeration, and there is a definite need for the establishment of an active simulation programme to optimize resources for the various parameters set.

It should be possible to adjust the refrigeration supplied if the air quantity changes. In the current scenario this is not happening (nor is it possible), which leads to large energy wastage and even more important, the fact that working conditions are not optimized.

These considerations underline the need for an integrated simulation programme. Such a programme should be able to show what the effects of any increase or decrease in airflow would be on the refrigeration requirements as well as on the control of contaminants. The actual optimized real-time energy cost can then be determined as well.

## 2.6 Air temperature control methods employed underground

Mines are generally designed to provide a specified workplace air temperature, determined in accordance with worker health, safety, productivity and comfort, legal and regulatory requirements and engineering constraints, which invariably entail financial considerations. The provision of appropriate refrigeration capacity, an essential aspect of environmental control in any hot mine, will depend greatly on the design temperature and also has a critical impact on costs.

Research and experience have indicated that formal controls in the form of a structured heat stress management (HSM) programme are required where the wet-bulb temperature ($T_{wb}$) reaches 27,5°C and this is prescribed in the legislation. Furthermore, it has been recommended that routine work should not be permitted where $T_{wb}$ exceeds 32,5°C or the dry-bulb temperature ($T_{db}$) exceeds 37°C, as was established in a COMRO report in 1991 [28].

The ideal would be to design for and achieve workplace wet-bulb temperatures at least as low as 27,4 °C and dry-bulb temperatures not greater than 37,0 °C. This would minimise the risk of heat illnesses and enhance labour force productivity, without reliance on formal and costly HSM programmes. Such an approach would amount to eliminating the hazard, rather than expending resources to contend with it.

Parsons states that although it is not uncommon, both locally and abroad, for wet-bulb temperatures in workplaces to exceed 32°C, the acceptable limit for design purposes should be between 27°C and 28°C [29], and in 1986 Schutte et al. set the upper limit for routine work at 32,5°C [30]. There is nothing in the way of subsequent research findings to support an expansion of these upper limits.

On the contrary, physiological tolerance criteria, together with the fact that work performance and safety would have a critical impact on the success of ultra-deep mining, may indicate a need for lower wet-bulb temperature limits than those currently applied. Accordingly, decisions relating to the thermal limits ultimately adopted for ultra-deep mining (and for that matter any hot mining environment) should consider the impact of heat stress on workers' performance and cognitive ability.

Given the ranges of relative humidity and air velocity prevailing and those anticipated for deep hot mining, wet-bulb temperature is likely to remain the most useful means of monitoring environmental heat stress. Where these parameters are likely to differ from current norms, air-cooling power (ACP) should prove to be most useful basis for quantifying cooling requirements for deep hot mines, as it includes the effect of the air velocity and the wet bulb temperature and is expressed as Watt/m$^2$. A specific value is normally agreed upon for design purposes.

However, the cost of pursuing the ideal described above can be prohibitive in the case of deep hot mines, and may be particularly so in the case of an ultra-deep mine. Janse van Rensburg states that it is essential to critically evaluate proposed design temperatures for ultra-deep mines in order to balance the requirements of "thermal well-being" (and all that the term implies) with the financial viability of ultra-deep mining [31]. In this lies the real need for an integrated simulation programme that could identify the real-time effect of different heat loads and different contaminants, keeping balancing or optimization of costs in mind.

### 2.6.1 Air temperature control methods employed on South African mines

Air, especially on deep mines, loses some or all of its cooling ability due to the effect of auto-compression of air. By the time the air reaches the workplaces, it needs to be cooled again, through bulk air-cooling. This can also be done on surface. A combination of both underground and surface cooling can also be used to cater for the various associated heat loads. It can also be done through closed-circuit refrigeration units at strategic positions, which therefore only cool the air for specific work areas. In this way, the need for cooling large amounts of air is eliminated.

As discussed, in the planning stages for air supply and cooling specific optimized design figures (physical and financial) for these parameters have been established, but they are normally based on a steady-state scenario (constant heat load, contaminants, etc.), with various "what-if?" runs, to cater for the best and worst case scenarios. A design reject temperature for the various workplaces is therefore set and the cooling needed to ensure this reject temperature is therefore established. As stated earlier, this is dependent on the quantity of air supplied.

Bulk air-cooling on surface or underground is done by passing the air through bulk water sprays. This means that the amount of air-cooling required is directly proportional to the amount of water circulated. This also has a bearing on the chilled water pumping power required and the temperature of the water needed for cooling the air. There is therefore an energy balance between the amount of heat removed from the air and the amount of heat added to the water that has to be cooled again at the refrigeration plant.

In the mining environment, the temperature of the water coming from the refrigeration plant is normally set at a specific design value and this value remains constant for the specific amount of air-cooling required. If the water temperature is much colder, a larger amount of air cooling will be possible for the same amount of airflow and vice versa.

Here the actual need for temperature control on a day-to-day and possibly shift-to-shift basis becomes an issue. The compressor that cools the refrigerant is a critical component of the whole water temperature control process. The costs associated with the compressor power are a matter for further investigation.

Williams notes that Thermal Energy Storage (TES) can be optimized in several ways and highlighted a few design rules for refrigeration equipment [32]:

- While the refrigeration unit and its auxiliary equipment are operating, get the most out of it
- Do not put in any more energy than the system requires or you will just end up wasting it away in another area
- Use variable-speed drives for every pump that uses a variable load, instead of control valves

Williams also notes the following advantages to controlling refrigeration units:

- They provide exact control of the temperature of the leaving water, without losing any refrigeration capacity under all operating conditions
- Loss of normal capacity will be apparent immediately, allowing correction of operating problems before they become severe
- Because the refrigeration unit is operated at maximum capacity, the refrigeration and auxiliary equipment operate for fewer hours per "season" to obtain the same cooling effect

### 2.6.2 The significance of the available information

The amount of cooling of the air that needs to be done is dependent on the flow rate of the water, which is related to the compressor input power required, so that the best way of controlling the temperature of the water would be to manipulate or control the compressor power. This can be done through computerised intervention and optimization of the compressor power.

This means that if storage capacity for chilled water (chilled water dams) is available, the water can be stored in these dams and the compressors will then only have to operate during the time of pre-scheduled cheapest electricity cost. This would reduce the compressor-related electricity cost drastically.

The cold water in the storage dams could then be pumped to the bulk air coolers at significantly lower cost than at the peak time of high electricity cost (at this time the compressors would be idle) and could also be used to pre-cool the water coming from the evaporator spray ponds, which enters the refrigeration units, thus further reducing energy requirements for compressors.

Another aspect that can be considered is the use of VSD motors for the water pumps as well. This will mean that the quantity of water pumped from the chilled water dam can be controlled, which would then make possible the control of the air temperature leaving the bulk air coolers. For the purpose of this investigation, VSD motors for pumps have not been considered, but they should be included in any further investigations pertaining to air temperature control underground.

From the comments made by Williams, it is evident that there are indeed ways in which the energy supplied to the compressor of the refrigeration unit can be optimized to suit current needs. Each refrigeration unit is unique and should be utilised correctly in the required ventilation system.

This means that the temperature of the air cannot be reduced or increased depending on need as easily as in the case of a building, but the amount of energy associated with air cooling can be monitored and controlled, based on the optimized cooling (temperature of air) required. As mentioned above, the use of VSD motors for pumps may solve this problem.

In the building industry, both the amount of air-cooling and the quantity of air supplied are dictated by the actual need in the building. For example, if more people are in the building, the need to replace high levels of carbon dioxide will be higher and therefore the fans will supply fresh air more frequently. In this case the temperature will also increase much quicker, with air-conditioning or cooling of the air then taking place as the need arises.

A mine can also be regarded as a very large building with various other unique factors, such as virgin rock temperature and additional heat loads, associated with it. In principle its air quantity and air quality management needs are the same. The question to answer is to what extent the similarities between these two entities can be utilised to improve air quantity and air quality management underground?

## 2.7 Indicators highlighting the need for integrated optimization

In order to understand the interrelationship between the air quantity/air velocity it is necessary to highlight to which heat stress index it applies most. We must ascertain to what extent this heat stress index can be used as a control and monitoring tool and in the optimization of the resources associated with it. The following section is a brief explanation of the concept of air-cooling power as used in the current South African mining context.

### 2.7.1 Air-cooling power (ACP) applicable to hot mines

The CSIR Division of Mining Technology (or Miningtek) has conducted comprehensive investigations into heat stress in mining. This resulted in a concept which is fundamentally sound, from both an engineering and a physiological perspective, and defines the balance between metabolic heat, and the collective cooling effects of radiation, convection and evaporation, as expressed in the following relation formulated by Stewart [33].

$$M = R + C + E$$

Where: $M$ = Metabolic heat ($W/m^2$)

$R$ = Radiation ($W/m^2$)

$C$ = Convection ($W/m^2$)

$E$ = Evaporation ($W/m^2$)

The units of these parameters are normalised to watts of heat transferred per square metre of skin surface area. Respiratory cooling, conductive heat transfer and mechanical work output are assumed to be negligible. The summation of R + C + E can be regarded as a measure of ACP. Provided this value remains equal to or greater than M, workers will maintain thermal equilibrium.

If, on the other hand, metabolic heat production exceeds the ACP, the skin temperature of the worker will rise. This may be sufficient to increase the ACP until a heat balance is achieved, otherwise the worker's body core temperature will increase. If the latter situation develops and is not alleviated, the worker will exhibit progressive symptoms of heat strain.

Figure 2.7.1a indicates that air velocities of approximately 0,5 and 1,5 m/s are required to achieve an ACP of 300 W/m$^2$ at wet-bulb temperatures of 27 and 29°C, respectively [34]. It must be noted that increasing air velocity from 0,5 to 1,5 m/s at a constant wet-bulb temperature will increase the ACP available by approximately 20%. In contrast, decreasing the wet-bulb temperature from 31 to 25°C for a constant air velocity of 0,5 m/s will increase the ACP by nearly 60%, and a velocity of 1,5 m/s would provide an even greater increase in the ACP.

These figures are applicable to the deep hot mining environment and would have to be re-investigated and redesigned for the shallow "cool" mining environment. When an environmental control system is being designed, ACP can be used to determine the required reject wet-bulb temperature for areas with high air velocities. Non-environmental co-determinants of ACP, such as skin temperature, sweat rate, work rate, etc., are difficult to measure and thus reduce the practicability of applying ACP for monitoring and control purposes.

For design purposes, it is recommended by McPherson that the ACP should not be less than 300 W/m$^2$ [35]. Although lower design and control limits for ACP are in use, most notably in Australia, these are within the context of high levels of mechanisation and air-conditioned operator cabins.

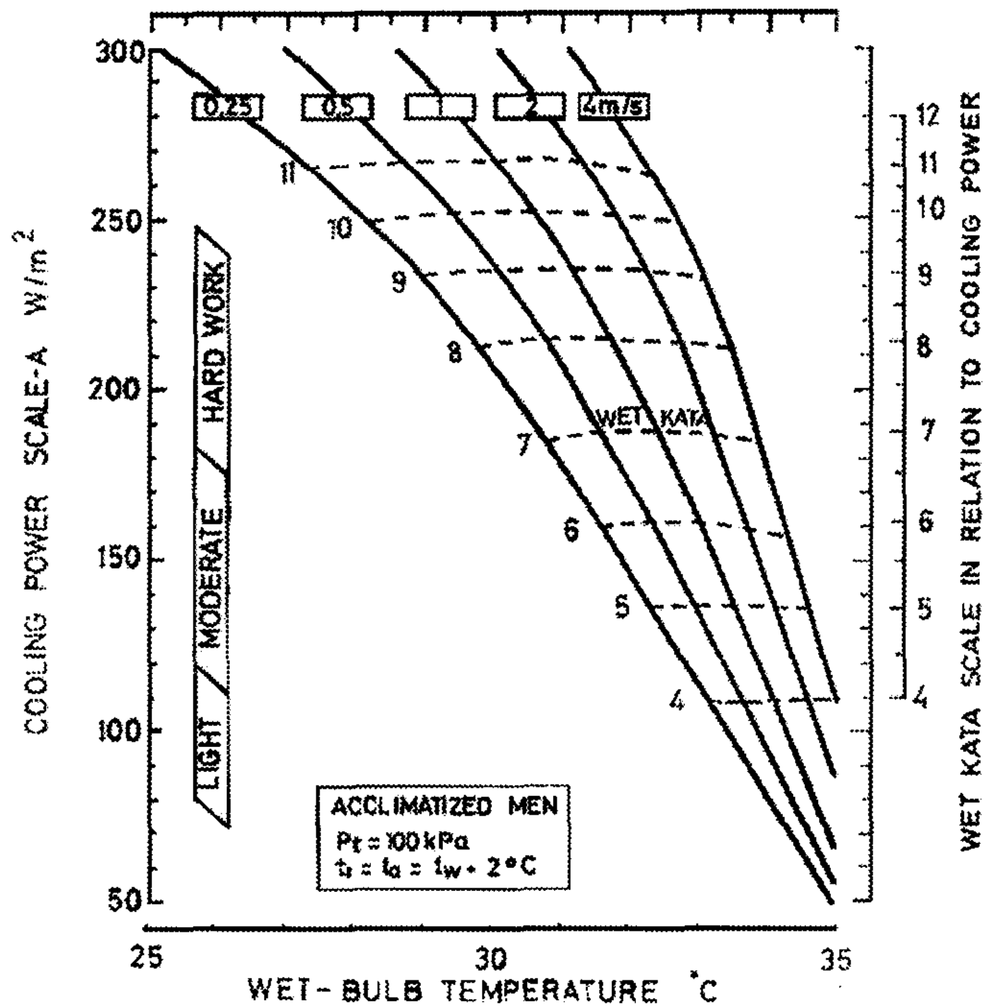



**Figure 2.7.1a: Environmental design parameters in relation to ACP (Webber [34])**

It was also found that for some situations, such as in very deep mines, the high pressure losses incurred would have a major impact on the actual running cost of the fans, and that optimizing the quantity of air required at a specific temperature would be crucial.

The conclusion from previous research pertaining to costs for the supply and cooling of air was that "reducing the design reject wet-bulb temperature, within limits, does not affect ventilation and cooling costs to the same extent as increasing the total airflow quantity" [36].

The optimized combination of air velocity (quantity) and air temperature in establishing a safe and healthy productive working environment is therefore a critical item in the total energy consumption (electricity) of a mine. A higher air velocity would mean the possibility of providing air at a higher wet-bulb temperature, and vice versa for the same amount of air-cooling power available, or necessary for the workers.

In work done for the Deepmine project and also included in Webber's Masters dissertation, it was noted that a given level of ACP in an ultra-deep mine can be provided at a far lower cost by reducing wet-bulb temperature than by increasing air velocity and air quantity.

It follows then that, should health, safety and productivity-related requirements dictate a design reject wet-bulb temperature of, say, 25°C, it should be feasible (for ventilation and cooling costs) to meet that criterion. This only holds true if a design temperature of 31°C was economically viable in the first place.

Figure 2.7.1b shows that designing of air supply and cooling requirements on the basis of the ACP concept will have a major effect on the total costs applicable. What is, however, not dealt with is how this specific air-cooling power should be, as far as possible, maintained to ensure optimum cost-saving possibilities and working conditions [36].

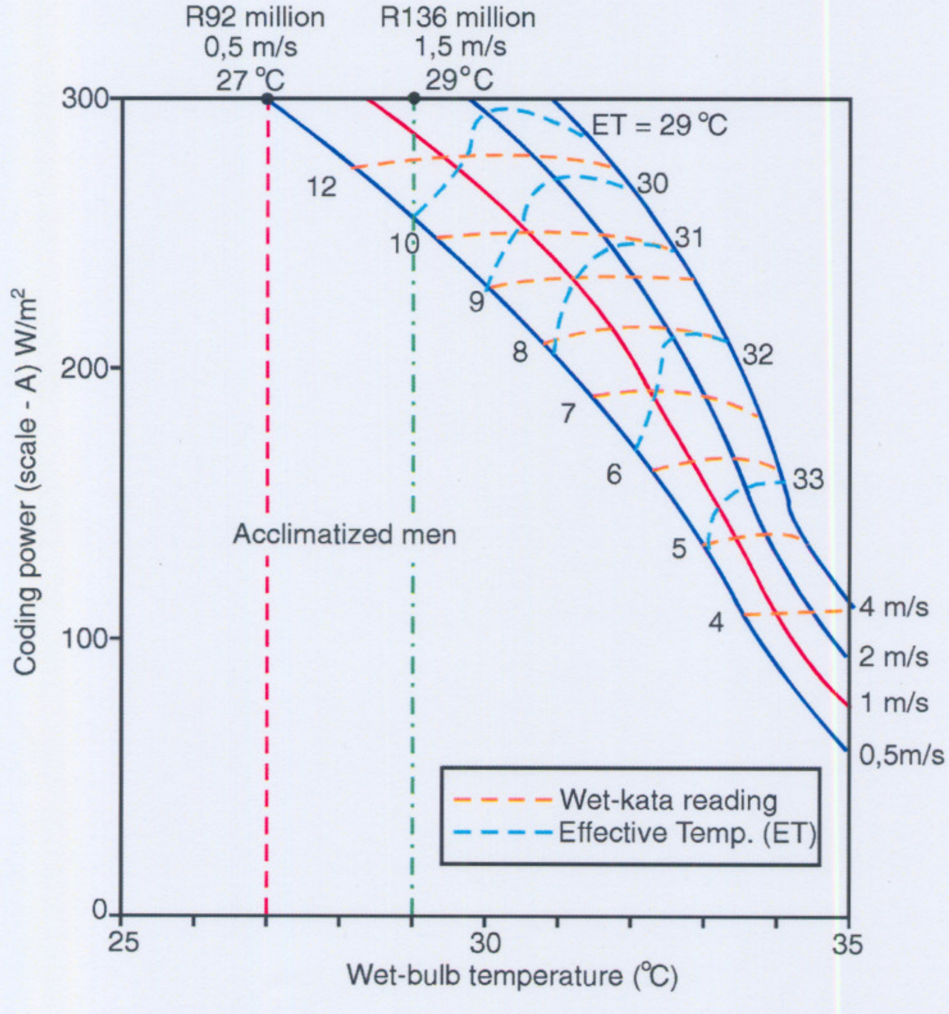



**Figure 2.7.1b: Annual costs $t_{wb}$'s and air velocities for 300 W/m$^2$ ACP (Webber [36])**

Figure 2.7.1b highlights the fact that there is a specific reject temperature (wet-bulb) and air velocity associated with a specific ACP available, and that the capital and running costs associated with air supply and air temperature play an important role in establishing this specific reject temperature (not ignoring the safety and health issues associated with them).

### 2.7.2 Thermal Work Limit (TWL) challenging ACP as heat stress index

Thermal stress, with its attendant problems of heat illness, safety incidents, lowered productivity, poor morale and higher costs, affects many industrial operations. Over the past 80 years many heat stress indices have been developed to assist with the *management* of these problems. Some of these indices have been developed for particular industries and the majority are empirically derived.

More recently, attempts have been made to develop so-called "rational heat stress indices", such as cooling power, air-cooling power and specific air-cooling power. Brake and Bates noted that problems with rational indices become evident when such an index (rational) is introduced into a workplace where workers are geographically mobile and work at varying tasks and metabolic rates during their work shift [37].

Brake and Bates emphasize that if an index *does not take the velocity of the air* over the body of the worker into consideration (such as the wet-bulb globe temperature [WBGT]), it will have *only a narrow range of validity*. They also noted that indices that require estimations of metabolic rates are often not practical, especially with different levels of thermal stress and metabolic rate at each location (even for the same type of activity).

In addition, Brake and Bates highlight some shortcomings pertaining to the term "air cooling power". The heat stress index called the "thermal work limit" (TWL), as an algorithm, builds on work originated in 1972 by Mitchell and Whillier, who developed an index called "specific air-cooling power", which subsequently became known as air-cooling power (ACP) [38].

Early formulations of ACP suffered from problems such as fixed skin temperature and making no allowance for the effect of clothing. Then in 1976 Stewart and van Rensburg proposed a method involving variable skin temperatures [39]. According to Brake and Bates, the term "air-cooling power" can be misleading for the following reasons:

- It is not an independent measure of environmental conditions, which its name implies. Even when the wet-bulb and dry-bulb globe temperatures, the wind speed and the barometric pressure (which together fully describe the state of the air) are all fixed, ACP varies according to the clothing ensemble
- ACP measures the interaction between environmental conditions, human physiology (especially skin and core body temperatures, and sweat rates) and metabolic rates. ACP also depends on the presence of radiant heat, such as the heat from the exposed rock surface
- It is not a cooling power as such. In *reality it considers the net loss or gain of heat between a working human and the environment*, and is therefore more of a heat-balancing equation than a cooling power. Brake and Bates further state that the term ACP creates the same sort of confusion that the term "wind chill factor" continues to create as a measure of cold stress, and they therefore adopted the term "Thermal Work Limit" (TWL) to avoid confusion
- The TWL model created by Brake and Bates also incorporates a new method for calculating variable skin temperatures based on published data. TWL is therefore a reference to a limiting metabolic rate, measured in units of watts of metabolic energy expended per $m^2$ of body surface

A fundamental advantage of the TWL system or index is that it is designed to make use of a comprehensive range of environmental measurements (i.e. dry-bulb, wet-bulb and globe temperatures, wind speed and barometric pressures). The index therefore calculates the maximum metabolic rate in watts of metabolic heat per $m^2$ of body surface area that can be continuously expended in a particular thermal working environment; the higher the TWL number, the higher the safely sustainable work rate (due to thermal conditions) [40].

Brake and Bates also specify some TWL values for different working environments. Workers should be withdrawn from a work area where the TWL is 115 $W/m^2$ for three reasons.

- Firstly, there is practically no benefit in keeping workers in such conditions as productivity is excessively low.

- Secondly, even light work is not continuously sustainable in these conditions and therefore a work/rest cycle would be required; and
- Thirdly, because productivity is so low and frustrating, there is a danger that a worker will not continue to self-pace, which could result in hyperthermia. The authors therefore recommended that a buffer value of 140 W/m$^2$ (TWL) be used for withdrawing workers so as to prevent them from working at the minimum limit value and thus exposing themselves to danger. A limit of 220 W/m$^2$ (TWL) was selected as the acclimatization limit [41]

Brake and Bates also note that some observations could be made by using the TWL index. The first example is the loss of productivity due to thermal stress, and establishing the cost benefit of cooling installations. It was shown that if the metabolic rate for a particular type of work in an environment with low thermal stress is 180 W/m$^2$ and assuming a resting metabolic rate of 60 W/m$^2$, then the productivity when working in an environment with a TWL of 120 W/m$^2$ is given as:

$$\text{Productivity} = \frac{(120-60)}{(180-60)} \text{ x } 100\% = 50\%$$

Brake and Bates also give an example of the cost benefit of cooling installations. TWL is measured in W/m$^2$ and it can therefore easily be compared to watts of refrigeration cooling. For example, if one considers a workplace being ventilated with 10 m$^3$/s of air at 30/38°C, a globe temperature of 38°C, a barometric pressure of 110 kPa and a wind speed of 0,3 m/s, the initial TWL is calculated as 117 W/m$^2$.

When local refrigeration to an amount of 100 kW is installed, it can be proved through standard psychrometric calculations that the temperature will drop to 28,1/30,2°C, which will result in an increase in TWL to 165 W/m$^2$. The capital and operating costs of this engineering intervention (refrigeration) can be directly evaluated against the cost benefit of improved productivity. The *"free" cooling available as a result of increased airflow could also be achieved by increasing the wind speed over the skin to 0,82 m/s, without the need for any refrigeration* [42].

Brake and Bates conclude by stating that in the past it was not always possible or practical to measure the five environmental parameters, namely the wet-bulb, dry-bulb and globe temperatures, the barometric pressure and the air velocity. However, a suitable pocket-sized instrument is now available with the necessary accuracy to measure the parameters, with an Erasable Programmable Read Only Memory (EPROM) to undertake the necessary calculations [43].

### 2.7.3 The significance of the available information

The purpose of this information is to highlight that the air velocity and air temperature, which make up the most important part of this heat stress index, play a significant role in the optimization of the energy resources associated with them. Previously, the use of ACP was limited to design applications, with wet-bulb temperature and air velocity (both of which are readily measured with reasonable accuracy) being used for monitoring the conditions in specific areas and workplaces.

Air velocity and air temperature, which are used to determine the ACP can be varied independently. These two parameters have very different cost profiles. To obtain a specific ACP at lowest cost, it is necessary that the effects of an increase or reduction in both the design temperature and air velocity be considered continuously and simultaneously. The increase or decrease in the air quantity also has a direct impact on the pressure drop in the shaft, and this must be considered as well.

In future, real-time monitoring of the quantity of air supplied and the amount of cooling required will become critical as the depth and extent of work areas increases. The issue of a demand strategy rather than a supply strategy for air supply and cooling requirements will therefore become even more pertinent in years to come. The actual need (day-to-day requirements) will have to be based on real-time need and not, as in the past, on the principle that "that which is available, is used".

In the past, ACP was used as an indicator to determine whether a working environment was safe and healthy (reactive approach), but it was not used as a control method to determine the optimized use of energy resources applicable to air supply and cooling. In earlier simulations, real-time management and control of the energy resources related to the air supply and cooling potential of the air, were seldom considered. The results were based on an optimized steady-state condition and did not take into account the day-to-day (or hour-to-hour) demand (need) for air supply or cooling.

It must be noted that when the actual optimized plan is implemented, the result of having the "wrong ratio" of air and cooling supplied at any stage could have serious financial implications for the life of the mine and could also mean that the project ceases to be feasible. The introduction of TWL was an improvement in the measurement of heat stress in the South African mining industry, since it remedied most, if not all, of the shortcomings of the ACP index. TWL also highlighted the inter-related importance of the air velocity and the temperature of the air in a working environment.

It was shown through some typical examples that the productivity of workers could be improved by supplying refrigeration in work areas, but that an increase in air velocity could also have improved the working environment (and also improves conditions by diluting contaminants through higher air quantities supplied).

The purpose of inclusion of the ACP and the TWL was therefore to indicate that a combination of various parameters would eventually determine the quality of a specific work environment and that it is necessary to establish not only the critical cost parameter, but also what the influence on other set parameters would be.

The inclusion of TWL was not to specify or prove the existence of yet another heat stress limit for ultra-deep mines, but simply to show the importance of the interrelationship between the air temperature and the air velocity and the direct impact this has on energy-related costs.

However, this study revealed shortfalls in using the ACP as a heat stress index. For the purposes of this investigation the term ACP will be used, keeping in mind its shortfalls, but also in the knowledge that it will not dramatically influence the findings. It is therefore assumed that using the concept of optimizing air supply, the temperature of the air and the pumping associated with it, referred to it here as ACP, will give an indication of the possible cost savings associated with this index, which will be established through predictive simulation and active control methods.

What is also of note is that whereas a design figure for ACP of 300 W/m$^2$ is suggested for establishing safe, healthy and productive working environments, the value suggested by Brake and Bates for TWL for establishing a safe and healthy working environment is 220 W/m$^2$. This is encouraging as both the systems devised have upper and lower values associated with good and poor working environments and could be adapted and applied where necessary.

## 2.8 Energy management systems in South Africa

An integrated optimization simulation for the air supply, air cooling and pumping related activities in establishing a safe, productive and healthy environment, includes various parameters, which have been discussed in the document thus far. An important aspect, the energy use and energy management systems associated with these parameters should be included as well.

HVAC International, a Pretoria-based company, designed a Real-time Energy Management System (REMS), which was introduced on Kopanang mine in 2002 for their clear-water pumping activities (Kopanang Mine is an Anglo American gold mine in the North-West Province of South Africa). Claassen noted in his report that the REMS was initially introduced at Kopanang mine not only to optimize pumping, but also to introduce an automated system to control all water-pumping-related activities on the mine.

It was also one of the objectives at Kopanang to design an optimized schedule based on the actual pumping at the mine, and to determine the optimized electricity cost associated with it [44]. The initial implementation at Kopanang mine was for clear-water pumping activities only, but the ultimate objective is to investigate whether in fact it was possible to implement REMS for controlling refrigeration units (compressors) and chilled water pumping (cooling water) as well.

A further objective of this study was therefore to ascertain whether the REMS principle could be applied in establishing a safe and healthy working environment by including air supply and the optimization of all the resources associated with ventilation and air-cooling.

### 2.8.1 Real-time Energy Management System (REMS)

There are many companies that claim the ability to manage and optimize the electricity cost of ventilation, cooling and pumping systems in mines, buildings and industries. Many simply provide a system that measures, balances and reports the energy consumption and cost. These systems are typically used to:

- Reconcile the readings from the various electricity meters of the installation with the reading of the utility that supplies the electricity
- Allocate electricity costs to sub-sections of an installation
- Identify billing problems
- Identify overall trends
- Warn users of peak prices (to adopt peak demand strategies) and select the optimum electricity tariff among those offered.

One such system is disclosed in a U.S. patent issued to Zaloom [45]. According to the author of the patent, 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, in which the system has an extensive web-based communication capability for real-time energy data [46]. A good example of a company that provides a system for automated electricity metering and reporting is IST Otokon (Pty) Ltd in South Africa. The IST Otokon system does remote electricity metering via a data-collection network. The data are mainly used for electricity accounting. A user can access the data by means of his proprietary ecWin™ 5 software [47].

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 so as to optimize energy consumption. Cascia et al. patented a digital controller that implements a control strategy for a cooling and heating plant. The control strategy provides for the calculation of near-optimal global set-points for all the main components in real-time [48].

The controller seeks to optimize 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 optimize the electricity cost of ventilation, cooling and pumping (VCP) system. This system also cannot take thermal storage into account. Alfan et al. patented another system, which minimises energy consumption [49]. The patented apparatus controls the heating source of an absorption cooling system by using the chilled water temperature return signal.

The third approach to energy management involves the measurement, reporting and optimizing of the total electricity cost of an installation. The invention disclosed by Irvin et al. monitors and controls variable-speed pumps and constant speed pumps [50]. 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 human operator.

The system does not use short-term future price and fluid demand information to optimize electricity 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 [51].

This system does not attempt to shift load by making use of some thermal capacitance of the cooling/heating system. Instead, it simply relaxes the set-point dead-band as the electricity price increases. The following needs have been identified that are not satisfied by the devices described thus far:

- A control system that schedules VCP equipment 24 hours in advance. It should optimize the total electricity cost of an installation. The optimization would be based on predicted electrical loads and electricity prices in a 24-hour forward horizon
- A control system that optimizes the VCP schedules remotely from the installation. The optimized schedules would then be sent daily to the mine via any suitable communication network
- A control system that can be easily implemented
- A control system that can be incorporated with any existing control or monitoring system
- A control system that does not change the set-points of the VCP system but that primarily uses the inherent capacitance in the system to shift load
- A control system that can be used for the VCP systems of mines, and for commercial buildings and industries

### 2.8.2 Development of REMS

Claassen discusses a procedure that optimizes the energy cost of mines that are on a time-of-use electricity tariff such as RTP. The optimization uses the principle of load shifting to off-peak periods. This new procedure creates optimized schedules every 24 hours for pumps, turbines, fans and refrigeration units of cooling system and winders. An optimized schedule contains on-off statuses for the relevant equipment hourly.

The procedure includes all the steps necessary to create optimized schedules for a specific hot mine where refrigeration is required. This includes information gathering, simulation and optimization. The procedure is simple and straightforward so that most engineers and technicians in the hot mining environment can use it. The types of equipment discussed in the investigation by Claassen are pumps, dams, fans, water-cooled refrigeration units, cooling towers, hoists and silos. The necessary calculations are performed on a spreadsheet. The procedure consists of four main phases [52]:

- Phase **one** is the collection and identification of the required input data for setting up a complete optimization model. This optimization model is used to calculate the optimized schedules for the relevant equipment on a daily basis
- Phase **two** is the setting up of the mathematical models of the relevant equipment using the input data of phase one. The models are then linked to create an integrated optimization model of the energy cost of the whole heating ventilation and cooling (HVAC) system. All the models are calibrated and verified
- Phase **three** is the automation of the generation of daily schedules
- Phase **four** is a system for calibrating the mathematical models of the relevant equipment. Figure 2.8.2a is a diagram of the four main phases of this procedure

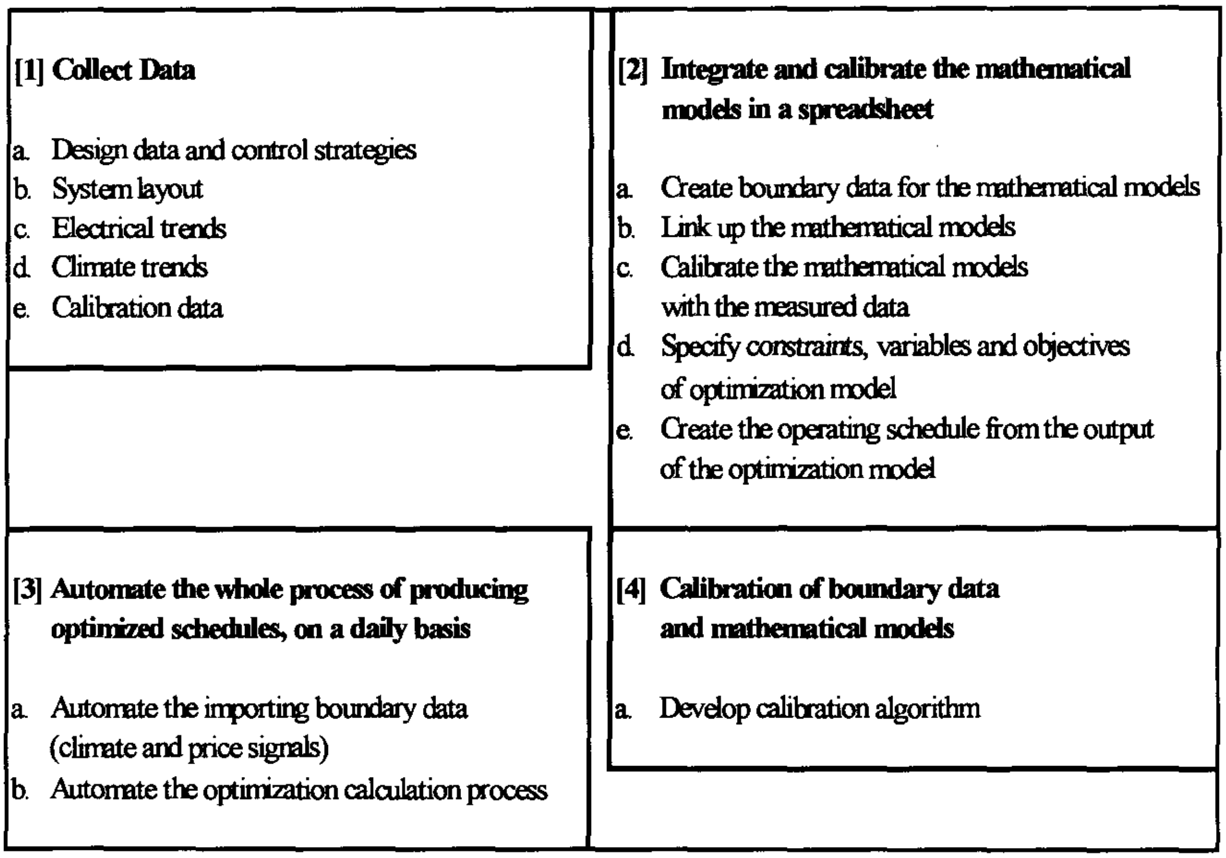



**Figure 2.8.2a: Main phases of energy optimization procedure (Claassen [52])**

Figure 2.8.2b shows diagrammatically the flow of information in REMS. It also shows the relationship between the four components of this invention. In the implementation of REMS for clear-water pumping on Kopanang mine, various issues related to pumping on the mine came to the fore. The details pertaining to the implementation of the REMS for clear-water pumping at Kopanang can be found in Claassens's report [44].

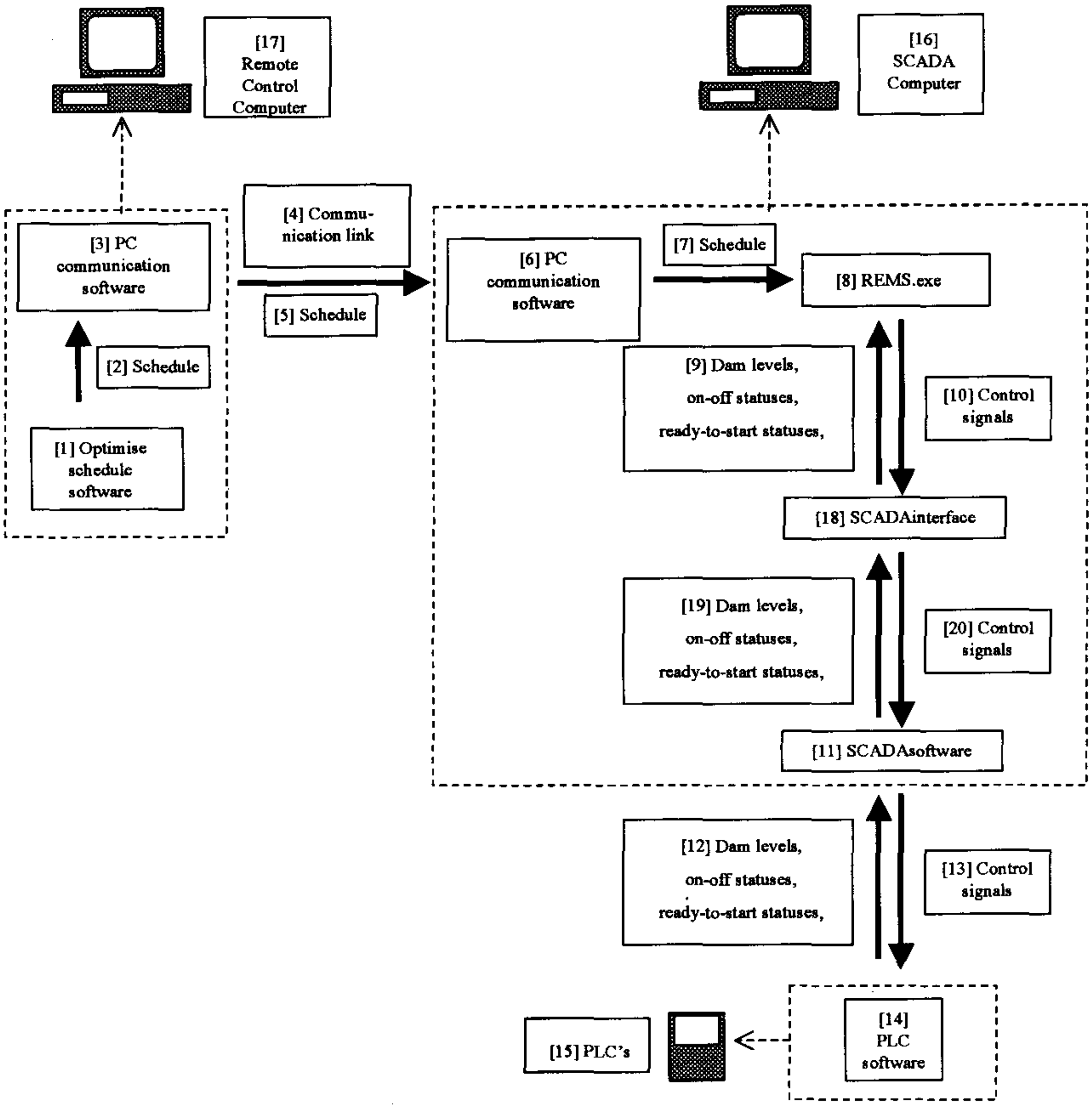



**Figure 2.8.2b: Schematic diagram of information flow of REMS (Claassen [52])**

### 2.8.3 The significance of the available information

South Africa wants to have internationally accepted health and safety standards applicable to all occupations and industries. The various Acts and regulations are being modernised and regularly updated to address this. This progress is gaining momentum but it will still be some time before all the issues of acceptable occupational health and safety for all occupations are adequately addressed.

The trend of legislation is that the protection of employee health and safety is not negotiable and will not be compromised in the interests of creating additional employment, tax revenues, investment or any other agenda. The nature of current legislation also implies that a business must become self-regulating with regard to occupational health and safety. This has advantages and disadvantages depending on how it is perceived.

The major disadvantage for the unwary is that this may confuse the vital issues for effective Risk Management and result in a "Wait and see" attitude. Waiting for some form of prescriptive legislation on exactly "how to do it and when to do it" can have disastrous consequences. Using this as an excuse for not doing what is necessary to protect workers from occupational dangers will not be accepted in a court of law.

If acceptable health and safety is to be maintained, a positive attitude to legislation is required. Effective use and application of the available legislation can achieve this. In the Risk Management Process we first look at the total company operation and identify all the risks.

These risks are then evaluated with regard to establishing consequences (outcomes), the magnitude (seriousness) of these consequences and the frequency of possible events. This will help to establish the Risk Profile. This then has to be assessed to establish the risk priority to identify the appropriate management controls to be put in place.

Risk management cannot begin until risk identification, evaluation and assessment have been completed. This process can be laid out in the following four fundamental steps, namely, identification, evaluation, control and financing. In considering these steps it must be remembered that risk management is a process, not an event. It is a continuous process, forms part of the daily company operations and must be monitored and regularly assessed. Risk control and risk financing means that identified risks can be:

- Terminated (Eliminated or stopped at source)
- Treated (Minimized, reduced)
- Transferred (Insure the risk by self funding or use outside insurance)
- Tolerated (Accepted with due legal compliance for cost effectiveness)

With regard to energy management information and the optimization of the various resources associated with it, it is important to remember that the risk management process mentioned above must to be followed to ensure that the requirements of the Act are met.

Having an integrated predictive simulation process in place that identifies risk trends such as continuous high temperatures and unacceptably high contaminant levels will enhance compliance with the Act (risk will be minimised or reduced). Linking these simulations to an optimization of costs will be an added advantage.

REMS has been successfully developed for clear-water pumping at Kopanang, but even more importantly, it has been implemented as well. Real-time monitoring was done and real-time results used to optimize and schedule future pumping needs at the most cost-effective electricity rates available.

What made this system unique is that any applicable constraints (dam levels, flow rates and so forth) were built into the simulation model. REMS can also be changed at any time to suit different needs. The other advantage of the system is that it can be remote-controlled without any risks, as the system is flexible enough to be overridden in case of emergency.

The challenge is now to apply the same optimized simulation capabilities to other aspects of the whole ventilation, cooling and pumping process. However, for pumping, it should incorporate not only the pumping of clear-water, but also that for chilled water. It should also incorporate the fan parameters (running speed, pressure and quantity delivered) to ensure that the whole ventilation, cooling and water-pumping (VCP) process is integrated. This would mean that the whole VCP process can be optimized with all the applicable constraints and boundaries built into the simulation tool, incorporating electricity optimization as well.

It was found that in various parts of the world air supply is varied by means of several different air-supply control measures, but that in South Africa, air-control measures (instantaneous) have not been extensively employed. Such control, combined with control of the actual air temperature needed, forms the basis for optimizing the energy resources of a deep hot mine, the necessity for which will be proved in this thesis.

The optimization of the conditions for a specific working environment, and the cost associated with it, is a very complicated exercise. It was therefore necessary to establish the feasibility or availability of such a tool in the industry. As indicated above, the tools available could only really be used to establish an optimized design based on the various planning parameters and steady state conditions set. However, controlling and optimizing the day-to-day needs for the working environment (air supplied and temperature of the air), and the optimization of the associated energy costs, there is still a lack of suitable optimization tools.

One of the objectives of this study was therefore to investigate the availability of an appropriate optimization tool to cater for the day-to-day dynamic nature of the mining environment and the associated energy costs, and if necessary, to establish such a tool. Such a tool, named Quick, had been used for the optimized design and control of the environment of buildings [53] and it was necessary to ascertain whether the same approach could be applied in mining.

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# CHAPTER 3

# QUANTIFYING THE IMPORTANCE OF AIR QUANTITY CHANGES

# 3. QUANTIFYING THE IMPORTANCE OF AIR QUANTITY CHANGES

## 3.1 Introduction

The literature search covered all the relevant aspects for an integrated approach towards the optimization of air supply, air-cooling and chilled water pumping. This literature search also established that one of the most important components in an Integrated Predictive Simulation (IPS) programme is a fan able to supply different volumes of air when needed.

This part of the investigation deals with the real-time effects of the change in air quantities on the amount of refrigeration required and the effect on the concentration levels of contaminants such as dust and gases. (Radioative contaminants have not been dealt with, as it is assumed that if there is enough air for dust dilution, these contaminants will be diluted as well.

## 3.2 Dilution of contaminants through additional ventilation

From the literature study various contaminants have been identified, and in this section the effect of air quantity changes on contaminant dilution will be investigated.

### 3.2.1 Gas dilution related calculations

The concentration of gas is dependant on the amount of gas released ($m^3/s$) and the amount of fresh air available to dilute the gas. The basic formula used to determine the gas concentration (expressed as a percentage) is shown in formula 3.1.[1]:

$$\begin{aligned}\%\,\text{gas} &= \frac{\text{total quantity of gas }(q_{gas})}{\text{total quantity of mixture }(q_{mix})} \times 100\% \\ &= \frac{\text{total quantity of gas }(q_{gas})}{\text{total quantity of mixture }(q_{gas} + q_{air})} \times 100\%\end{aligned} \tag{3.1}$$

Either the quantity or the mass flow of the gas ($m^3/s$ or kg/s respectively) can be used, provided the same unit is used for the gas and the air. The mixture refers to the sum of the gas and air quantities or mass flow. The gas concentration can also be expressed in ppm.

The amount of fresh air required for dilution is shown in formula 3.2[2]:

$$Q_{fresh} = \frac{q_{gas} \times 10^6}{MAC - N} - q_{gas} \qquad (3.2)$$

Where: $Q_{fresh}$ = Quantity of fresh air supplied in $m^3/s$

$q_{gas}$ = Rate of pollutant gas emission in $m^3/s$

MAC = Maximum Allowable Concentration pollutant gas in air in ppm

N = Normal concentration of pollutant gas in air in ppm (for $CO_2$ this value is 300 ppm)

The reason for the "- $q_{gas}$" term, is that the amount of fresh air needed will then be the resultant answer. If the gas in question does not appear in normal fresh air, the value of N is zero. For example, there is no carbon monoxide in normal fresh air and therefore the value of N is zero. Table 3.2.1a shows a constant gas release rate for nitrous fumes ($NO_x$) and what effect a 10% variance in air quantity has on the gas concentration.

The same exercise can be repeated for any other gas and will show the same effect, to a lesser or greater extent (the MAC for nitrous fumes is 3 ppm). Nitrous fumes have been chosen for the exercise, as they have low OEL levels for gases found underground and therefore needs more fresh air (than gases with higher OEL levels) to dilute to acceptable limits. Table 3.2.1b shows a constant air quantity and what effect a 10% variance in different release rate of nitrous fumes ($NO_x$) has on the gas concentration.

**Table 3.2.1a: Constant gas release rate, changing air quantities on gas concentrations**

| Fresh air quantity $m^3/s$ | Air Quantity % variance | Gas amount released $m^3/s$ | Gas concentration % | Gas concentration ppm | Gas concentration % variance | OEL ppm |
|---|---|---|---|---|---|---|
| 12.6 | -33 | 0.00005 | 0.0004 | 4.0 | 33 | 3 |
| 13.9 | -21 | 0.00005 | 0.0004 | 3.6 | 21 | 3 |
| 15.2 | -10 | 0.00005 | 0.0003 | 3.3 | 10 | 3 |
| 16.8 | 0 | 0.00005 | 0.0003 | 3.0 | 0 | 3 |
| 18.4 | 10 | 0.00005 | 0.0003 | 2.7 | -10 | 3 |
| 20.3 | 21 | 0.00005 | 0.0002 | 2.5 | -21 | 3 |
| 22.3 | 33 | 0.00005 | 0.0002 | 2.2 | -33 | 3 |

**Table 3.2.1b: Constant air quantities, changing gas release rates on gas concentrations**

| Fresh air quantity $m^3/s$ | Air Quantity %variance | Gas amount released $m^3/s$ | Gas concentration % | Gas concentration ppm | Gas concentration % variance | OEL ppm |
|---|---|---|---|---|---|---|
| 16.8 | 0 | 0.000038 | 0.0002 | 2.2 | -25 | 3 |
| 16.8 | 0 | 0.000041 | 0.0002 | 2.5 | -17 | 3 |
| 16.8 | 0 | 0.000045 | 0.0003 | 2.7 | -9 | 3 |
| 16.8 | 0 | 0.000050 | 0.0003 | 3.0 | 0 | 3 |
| 16.8 | 0 | 0.000055 | 0.0003 | 3.3 | 9 | 3 |
| 16.8 | 0 | 0.000061 | 0.0004 | 3.6 | 17 | 3 |
| 16.8 | 0 | 0.000067 | 0.0004 | 4.0 | 25 | 3 |

In Table 3.2.1a the air quantity variance is 10% and the gas release rate is 0,00005 $m^3/s$. In this example the minimum air quantity required to be within acceptable OEL limits has been determined as 16,8 $m^3/s$.

Figure 3.2.1 shows a sensitivity analysis of a 10% variance in air quantity and a 10% variance in gas release rate. From this graph it can be seen that the gas concentration is more sensitive to the release rate than to the change in air quantity (a steeper curve for air quantity changes than for gas concentration changes). However, it also shows that the gas concentration is indirectly proportional to the air quantity variance. This means that a 10% increase in the air quantity will lead to a 10% decrease in the gas concentration and vice versa. This is a significant finding, as it indicates that the gas concentration levels are sensitive to air quantity changes.

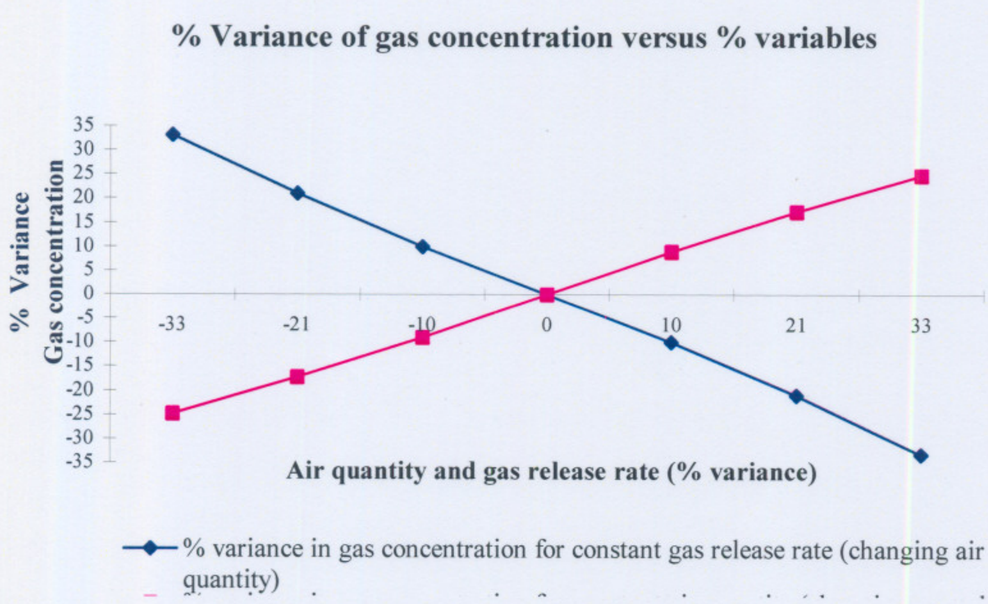


**Figure 3.2.1: % Variance of gas concentration versus % variables**

### 3.2.2 Dust dilution related calculations

The concentration of dust in air is also dependant on the amount of dust released (mg/s) and the amount of fresh air available to dilute the gas. The basic formula used to determine the dust concentration (mg/m$^3$) is shown in formula 3.3 [3]:

$$\text{Dust concentration} = \frac{\text{dust release rate (mg/s)}}{\text{quantity of fresh air (m}^3\text{/s)}} = \text{mg/m}^3 \qquad (3.3)$$

The AQI can be determined by using formula 3.4, where OEL is the occupational exposure level for the dust investigated [4]:

$$\begin{aligned} \text{AQI} &= \frac{\text{dust concentration (mg/m}^3\text{)}}{\text{OEL (mg/m}^3\text{)}} \\ \text{with AQI} &< 1 \quad \text{acceptable conditions} \\ \text{AQI} &= 1\text{-}5 \quad \text{remedial action needed} \\ \text{AQI} &> 5 \quad \text{unacceptable conditions} \end{aligned} \qquad (3.4)$$

Table 3.2.2a shows a constant dust release rate for quartz dust and what effect a variance in air quantity will have on the AQI. The same exercise could be repeated for any other dust and will show the same effect (the OEL for quartz dust is 0,1 mg/m$^3$). Quartz dust was chosen for the exercise, as it has low OEL levels for dusts found underground and is among the most dangerous. It will therefore also need more air to dilute high amounts of dust released. Table 3.2.2b shows a constant air quantity and what effect a variance in different dust release rates will have on the AQI.

**Table 3.2.2a: Effect of constant dust release rate and air quantity increase on the AQI**

| dust release rate mg/s | Air quantity $m^3/s$ | OEL $mg/m^3$ | dust concentration $mg/m^3$ | AQI | % variance Q | % variance AQI |
|---|---|---|---|---|---|---|
| 15 | 26 | 0.1 | 0.6 | 5.7 | -33 | 33 |
| 15 | 29 | 0.1 | 0.5 | 5.2 | -21 | 21 |
| 15 | 32 | 0.1 | 0.5 | 4.7 | -10 | 10 |
| 15 | 35 | 0.1 | 0.4 | 4.3 | 0 | 0 |
| 15 | 39 | 0.1 | 0.4 | 3.9 | 10 | -10 |
| 15 | 42 | 0.1 | 0.4 | 3.5 | 21 | -21 |
| 15 | 47 | 0.1 | 0.3 | 3.2 | 33 | -33 |

In Table 3.2.2a the air quantity variance is 10% and the dust release rate is 15 mg/s. According to the guideline for AQI discussed in Chapter 3, an AQI figure of between 1 and 5 needs remedial action and a figure below 1 is acceptable. In this example the air quantity will have to be even greater than the maximum amount of 47 $m^3/s$ shown in the table. The corresponding AQI is 3.2 (a dimensionless figure), which indicates that remedial action is needed. In Table 3.2.1b the air quantity remains constant at 35 $m^3/s$ and the dust release rate variance is 10%. In this example it appears that the air quantity (47 $m^3/s$) is not sufficient to dilute the dust to within acceptable limits.

Figure 3.2.2 shows a sensitivity analysis of a 10% variance in air quantity and a 10% variance in dust release rate. From this graph we see that the AQI is more sensitive to the change in air quantity than to the change in dust release rate (the curve for a change in air quantity changes is steeper than the curve for a change in dust release rate). However we also see that the AQI is indirectly proportional to the air quantity variance. The means that a 10% increase in the air quantity will lead to a 10% decrease in the AQI and vice versa. This is an important observation as it indicates that the dust concentration levels are also sensitive to air quantity changes.

**Table 3.2.2b: Effect of constant air quantity and changing dust release rate on the AQI**

| dust release rate mg/s | Air quantity $m^3/s$ | **OEL $mg/m^3$ | dust concentration $mg/m^3$ | AQI | % variance Q | % variance AQI |
|---|---|---|---|---|---|---|
| 15 | 35 | 0.1 | 0.4 | 4.3 | 0 | -25 |
| 17 | 35 | 0.1 | 0.5 | 4.7 | 0 | -17 |
| 18 | 35 | 0.1 | 0.5 | 5.2 | 0 | -9 |
| 20 | 35 | 0.1 | 0.6 | 5.7 | 0 | 0 |
| 22 | 35 | 0.1 | 0.6 | 6.3 | 0 | 9 |
| 24 | 35 | 0.1 | 0.7 | 6.9 | 0 | 17 |
| 27 | 35 | 0.1 | 0.8 | 7.6 | 0 | 25 |

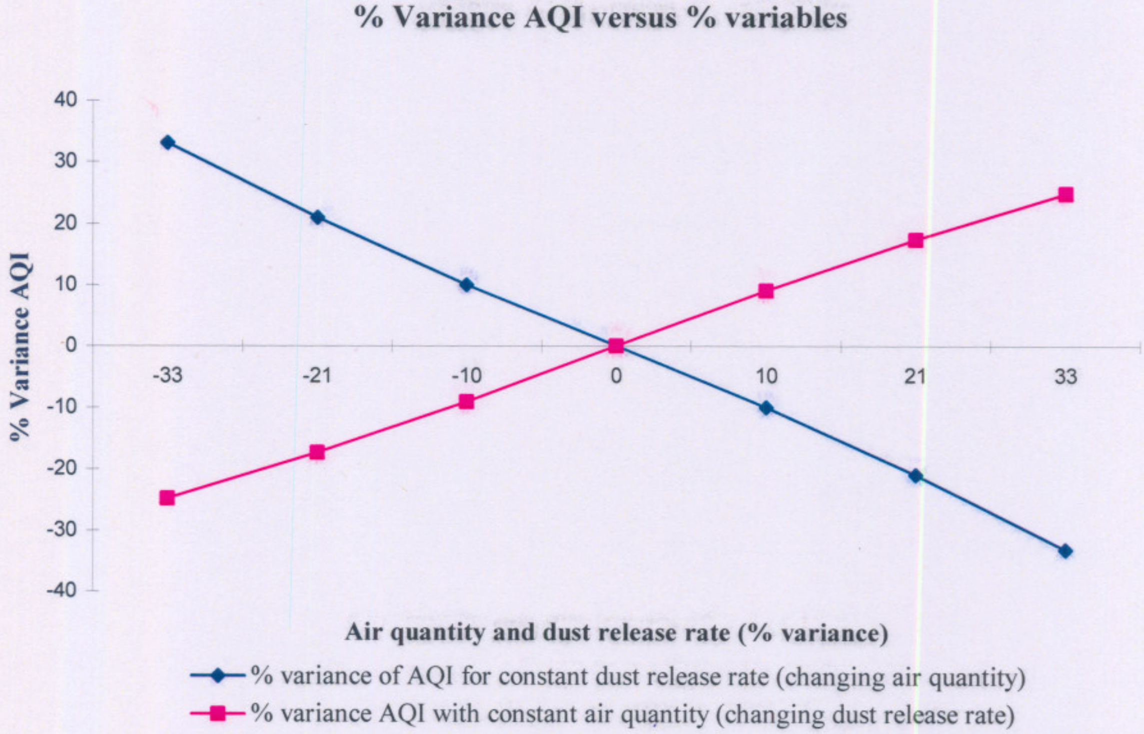


**Figure 3.2.2 : Dust concentration and AQI versus air quantity**

## 3.3 The effect of increased or decreased air quantities on refrigeration requirements

It has been established from the literature search that an increase in air quantity will have an effect on the amount of refrigeration required. This will change from mine to mine and the purpose of inclusion is to show the effect of increase in air quantity on the ventilation planning results for a platinum mine. This investigation was done through personal communication with Mr Jaco Venter, ventilation manager on Waterval Shaft, Rustenburg area, Anglo Platinum [5].

The effect of an increased or decreased air quantity on the refrigeration requirements of a mine is illustrated by the VUMA simulation programme. The results of a sensitivity analysis for air quantity and refrigeration requirements is shown in Table 3.3 and the details of the results shown in Annexures A, B and C. The results in Table 3.3 (only refrigeration, temperature and associated mass flow of air) are shown as a % increase or % decrease of variables shown in the table.

**Table 3.3: VUMA results for platinum mine**

| **Variable** | **% Increase / decrease in variable** | | | |
|---|---|---|---|---|
| **Mass flow** | -33 | -11 | + 20 | + 30 |
| **Heat in branch** | + 8.4 | + 2.7 | -4.4 | -6.1 |
| **Refrigeration** | + 0.03 | + 0.02 | -0.03 | -0.06 |
| **Reject temperature** | -5.1 | -2.8 | + 4.8 | + 6.6 |

The mass flow in the design for the platinum mine has been increased and decreased by 10% and the results shown in Table 3.3 are the cumulative percentage increase/decrease in air quantity. From this change in air quantity different observations were made. From Table 3.3 it can be seen that there is indeed a decrease in refrigeration required if the airflow quantity is increased and also an increase in the refrigeration requirements when the air quantity is reduced. The heat in the design decreases with an increase air quantity and there is a slight increase in reject temperature because there is less refrigeration done. The design reject temperature however, was never exceeded and this is an indication of the savings potential or optimization. The benefits of reduced or increased air quantity cannot be enjoyed in South African mining at present, because variable speed drive motors are not used, for reasons previously mentioned.

Figure 3.3 is the graphical representation of the results shown in Table 3.3. The graph indicates that for this particular type of platinum mine layout, the refrigeration requirements are not sensitive to an increase or decrease in air mass flow. However in this layout the actual increase/decrease in heat for the various branches is more sensitive than the reject temperature in wet-bulb.

From this example it appears that for a 33% decrease in air quantity there will be a 5,1% decrease in the wet-bulb temperature. This makes sense, as with less air quantity available, more refrigeration will be required. This proves the theory that for every mine ventilation layout there are distinct features to be considered in the optimization process. The ability to change the airflow quantity remains essential if real-time airflow optimization is to be incorporated in the design.

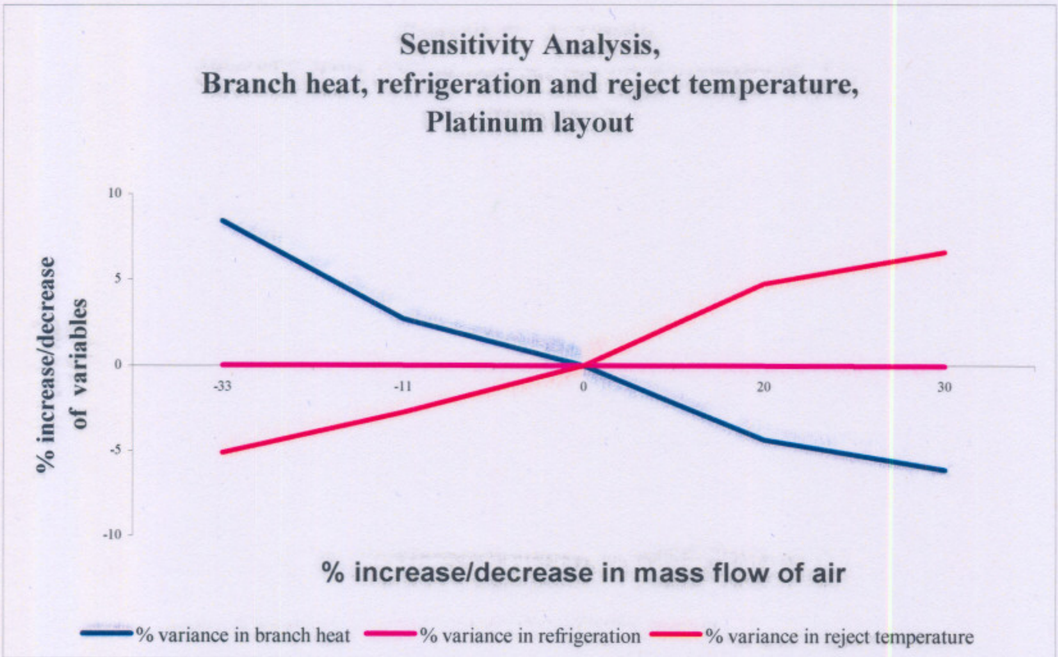


**Figure 3.3: Sensitivity analysis for platinum mine layout using VUMA software**

It is therefore necessary to ascertain what the real financial issues pertaining to variable speed drive motors for fan use are, and to highlight these issues for specific parameters. The most important reasons given for non-use of variable speed drive motors for fans in the past are high capital cost and unreliability. The unreliability argument has been dealt with previously, but it is important to quantify the financial facts.

## 3.4 The significance of the results

From the results shown in this chapter, it is obvious that changing the air quantities does in fact play a significant role in achieving a safe, healthy and productive working environment. This can only occur through varying the air quantity supplied. It also appears that the change in air quantity has an effect on the AQI as well as on the dilution of the dust and gases in the working environment.

What is also shown is that an increase or decrease in the amount of air supplied has an effect on the amount of refrigeration required. This balance ratio is dependent on the type of mining and layout and will therefore differ from mine to mine, but can be quite easily established with the aid of an IPS model. Optimization is therefore dependant on the actual layout, boundaries and restrictions applicable in each case.

The next challenge in establishing a safe, healthy and productive working environment is the ability to change poor conditions to acceptable conditions "instantaneously". Here the ability to supply additional air on a "when needed" basis is important. The ability to revert back to "normal" design air quantities once the conditions have normalised is another challenge posed to the mining fraternity.

Changing the air quantities instantaneously through IPS models can be done with the inclusion of variable speed drives. In Chapter 4 of this thesis, various issues pertaining to VSD's, such as capital cost, running costs and payback periods are discussed in detail. In the literature survey it was shown that VSD's for main air supply were not used in South African mining due to high capital cost and low electricity prices. It was also noted that the robust environment underground was also not conducive to implementing VSD's successfully. This did not make VSD's an attractive option.

An increase in the availability and reliability of VSD's and an expected increase in electricity price and pressure on the availability of electricity, would make it worthwhile to re-investigate the feasibility of introducing VSD motors for fans into South African underground mines.

## REFERENCES

[1] The Intermediate Certificate in Mine Environmental Control, Workbook 2, Chapter 7, Gases, pp. 192-244, The Mine Ventilation Society of South Africa, Johannesburg, South Africa, Updated July 2004.

[2] ibid, p. 245.

[3] The Intermediate Certificate in Mine Environmental Control, Workbook 2, Chapter 8, Dust, pp. 250, The Mine Ventilation Society of South Africa, Johannesburg, South Africa, Updated July 2004.

[4] ibid, p 260.

[5] Venter J, Personal communications, Ventilation Manager, Waterfall shaft, Anglo Platinum, Rustenburg, South Africa.

# CHAPTER 4

# VARIABLE SPEED DRIVES: THE REALITY

# 4. VARIABLE SPEED DRIVES: THE REALITY

## 4.1 Introduction

In the previous Chapters it was shown that an IPS model depends on the ability to vary the amount of air supplied. In this chapter, financial and other issues pertaining to variable speed drives are examined in detail. These include the Net Present Value (NPV), the Internal rate of Return (IRR), and the payback period applicable if a variable speed drive motor is used for driving a fan.

The NPV, IRR and payback periods will be tested against different scenarios such as changes in the electricity price, inflation, and the effect of the rand/euro on the capital cost of the equipment. This chapter is a summary of results from the investigation pertaining to VSD's. Detailed information is shown in the appendices.

The significance of this chapter is the fact that VSD's have not been used extensively in South African mining. The main reason given was that the savings in electrical power (due to the low electricity price) did not warrant the capital outlay for the VSD. Other important reasons mentioned were the unreliability of the VSD drive and the fact that the harsh environment underground did not suit this sensitive type of equipment. It was noted in Chapter 2 that with the change in technology the VSD can be installed remotely from the motor in a dedicated controlled environment, which makes it more attractive to consider (pending other issues to be investigated as well).

It was also important to quantify the financial facts with regard to VSD motors that are currently available and to put in perspective their applicability to mining today's. In the last 10 years technology of VSD drives has changed so much that the reliability of VSD's is almost a hundred percent and the mean time between failures is 20 years (a significant number). These facts were mentioned in Chapter 2 of this document.

## 4.2 Cost comparison of variable speed drive air control and VIV

In Chapter 2 of this document various other issues pertaining to variable speed drive motors were noted. It was shown that higher efficiencies were possible when using variable speed drive motors for fans to control different quantities of air supplied. Howden Safanco provided a fan selection programme to distinguish between costs associated with fans with variable speed drives and variable inlet vane control for reduction in airflow quantities. (Only running costs were considered.)

The results of this comparison are shown in Tables 4.2a and 4.2b respectively. This information is included to highlight how variable speed drives reduce running costs associated with specific duties required. In this example the amount of air supplied by the fan is reduced from 62,5 $m^3/s$ to 56,3 $m^3/s$. An annual electricity cost of R1300 / kW is assumed as reasonable (assuming the fan runs 24 hours per day, 365 days per year).

**Table 4.2a: Running cost savings through the use of variable speed drives**

| Description | Units | Design duty | Duty 1 |
|---|---|---|---|
| Volume | $m^3/s$ | 62.5 | 56.3 |
| Fan static pressure | kPa | 5.00 | 4.05 |
| Air power | kW | 313 | 228 |
| Compressibility | | 0.9835 | 0.9860 |
| Fan speed | r/min | 985 | 884 |
| Fan static efficiency | % | 84.6 | 84.7 |
| Fan shaft power | kW | 363 | 265 |
| Motor efficiency | % | 90 | 90 |
| Fan motor input power | kW | 404 | 295 |
| **Annual electricity cost** | Rand | **R 524,753** | **R 383,064** |
| **Potential savings** | | | **R 141,688** |

Note: details of fan and power curves can be found in Annexure D.

Table 4.2a shows that the fan speed has been reduced from 985 rpm to 884 rpm. The fan's static efficiency remained constant and there is a significant reduction in fan shaft power and fan motor input power. The volume is reduced and there is a 1 kPa reduction in fan static pressure.

**Table 4.2b: Savings through the use of VIV's**

| Description | Units | Design duty | Duty 1 |
|---|---|---|---|
| Volume | $m^3/s$ | 62.5 | 56.3 |
| Fan static pressure | kPa | 5.00 | 4.05 |
| Air power | kW | 313 | 228 |
| Compressibility | | 0.9835 | 0.9864 |
| Fan speed | r/min | 985 | 985 |
| Fan static efficiency | % | 84.6 | 80.5 |
| Fan shaft power | kW | 363 | 279 |
| Motor efficiency | % | 90 | 90 |
| Fan motor input power | kW | 404 | 310 |
| **Annual electricity cost** | Rand | **R 524,753** | **R 403,214** |
| **Potential savings** | | | **R 121,539** |

Note: details of fan and power curves can be found in Annexure E.

Table 4.2b shows that the fan static efficiency has been reduced from 84,6% to 80,5% (in the variable speed option this remained constant). The fan shaft input power is also much higher than for the variable speed drive (310 kW versus 265 kW). The speed of the fan with VIV control remained constant, which means a higher potential for an increase in maintenance cost. The fan motor input power is also slightly higher for VIV control (310 kW versus 295 kW).

This fan selection programme was made available by Howden Safanco to illustrate the real impact of variable speed drive air control versus VIV [1]. It was not the aim to do an in depth investigation with detailed calculations of the different values (the fan selection programme creates the answer immediately on input of certain parameters).

The fan selection programme has been tested and proven successful in recent years. In summary: the two tables above show that the potential savings are quite large, remembering that a reduction of 6,2 $m^3/s$ led to a saving of R141 688 per annum for a variable-speed drive and an amount of R121 539 per annum for VIV's. It must also be noted that the fan efficiency for the variable-speed drive is also higher, which means that a lower input power is required for the same air power.

## 4.3 NPV, IRR and payback period applicable to variable speed drive motors

The following section highlights various real-time figures applicable to VSD motors as supplied by ABB Engineering in Alberton. The advantages and disadvantages of VSD motors have been dealt with in Chapter 2. In personal communications with Mr Arthur Tucker, managing director of ABB Engineering and from the catalogue for various speed drives, some interesting facts were discovered [1]. Table 4.3a summarises the basic financial figures related to a 3 MW variable speed drive motor. These figures have been used as input figures to create various comparisons pertaining to net present values (NPV's), internal rates of return (IRR) and payback periods for VSD motors.

**Table 4.3a: Cost related figures for variable speed drive motors**

| | | | | |
|---|---|---|---|---|
| **Capital cost variable speed** | **Motor** | R 800,000 | R 160,000 (20% rand/euro sensitive) | € 20,000.00 |
| | | | <u>R 640,000</u> (80% of components in RSA) | |
| | | | **R 800,000** | |
| | **Drive** | R 3,200,000 | R 2,560,000 (80% rand/euro sensitive) | € 320,000.00 |
| | | | <u>R 640,000</u> (20% of components in RSA) | |
| | | | **R 3,200,000** | |
| | **Total cost** | **R 4.0 million** | | |
| **Maintenance cost 1** | R 200,000 every 7 years based on current rates | | | |
| **Maintenance cost 2** | R 10,000 per year | | | |

Table 4.3a shows that the basic variable speed drive systems consists of two parts, namely the motor and the drive, which are both partially rand/euro sensitive as some of the parts are imported (the € 20 000 and the € 320 000 are the current euro prices at an exchange rate of R8 to the euro). This is an important aspect and the significance thereof will be dealt with in the sections to follow. For the purpose of this comparison, the following basic assumptions were made:

- The inflation percentage base line is 7%
- The discount rate is 15%
- Electricity cost assumed as 15c/kWh and
- The rand/euro exchange rate assumed as 8,0
- An overall fan efficiency of 70% is assumed
- Maintenance cost as indicated in the table

In today's terms, the capital cost of a variable speed drive motor is R4 million at an exchange rate of R8 to the Euro. If the rand strengthens it will be cheaper to get the variable speed drive motor, and more expensive if the rand weakens. The impact thereof will be highlighted for the NPV, IRR and payback periods applicable to the various parameters set.

Table 4.3b shows the various air quantities used for the calculations. A base case air quantity of 1000 $m^3/s$ (i.e. a constant air quantity supplied for a specific production phase) and a pressure of 3 kPa were assumed. Table 4.3b shows the total running costs (i.e. electricity and maintenance cost) for different air quantities and comparative fan pressure required (calculated by using formula 4.1).

The related electrical input power, electrical cost per annum, maintenance cost and total running cost were determined as a first run and used as base case for the exercise. The reason for the inclusion of various air quantities for a year was to show the difference in total cost if a VSD motor for a fan was used. The figures in bold in the table are the base case figures. These figures relate to a standard motor and fan, where the air quantity cannot be changed instantaneously.

**Table 4.3b: Basic input data and results for running and maintenance cost calculations**

| Quantity Q ($m^3/s$) | Pressure P (Pa) | Air Power (MW) PQ | Electrical input power (MW) PQ/fan efficiency |
|---|---|---|---|
| 750 | 1688 | 1.3 | 1.8 |
| 800 | 1920 | 1.5 | 2.2 |
| 850 | 2168 | 1.8 | 2.6 |
| 900 | 2430 | 2.2 | 3.1 |
| 950 | 2708 | 2.6 | 3.7 |
| **1000** | **3000** | **3.0** | **4.3** |
| 1050 | 3308 | 3.5 | 5.0 |
| 1100 | 3630 | 4.0 | 5.7 |
| 1150 | 3968 | 4.6 | 6.5 |
| 1200 | 4320 | 5.2 | 7.4 |
| 1250 | 4688 | 5.9 | 8.4 |

| Quantity Q | Electrical cost /annum (running cost, Rm) | Maintenance cost per annum(R) | Total running/maintenance cost per annum (Rm) |
|---|---|---|---|
| 750 | R 2.376 | R 38,571 | R 2.414 |
| 800 | R 2.883 | R 38,571 | R 2.922 |
| 850 | R 3.458 | R 38,571 | R 3.497 |
| 900 | R 4.105 | R 38,571 | R 4.144 |
| 950 | R 4.828 | R 38,571 | R 4.867 |
| **1000** | **R 5.631** | **R 10,000** | **R 5.641** |
| 1050 | R 6.519 | R 38,571 | R 6.558 |
| 1100 | R 7.495 | R 38,571 | R 7.534 |
| 1150 | R 8.565 | R 38,571 | R 8.603 |
| 1200 | R 9.731 | R 38,571 | R 9.770 |
| 1250 | R 10.999 | R 38,571 | R 11.037 |

As an example the electrical input power for 850 $m^3/s$ was determined as follows (the effect of compressibility ignored as it is seen as a "common" factor in the comparison and would therefore not effect the outcome of the investigation). According to one of the fan laws, the new pressure at a new air quantity can be determined as follows:

$$P_2 = P_1 \text{ x} \left(\frac{Q_2}{Q_1}\right)^2 \text{, substitute the values accordingly}$$

$$P_2 = P_1 \text{ x} \left(\frac{Q_2}{Q_1}\right)^2$$

$$= 3\,000 \text{ x} \left(\frac{850}{1\,000}\right)^2 \qquad (4.1)$$

$$= 2167{,}5 \text{ say } 2168 \text{ Pa}$$

The air power ($W_a$) required can be determined as follows:

$$W_a = PQ/1000$$

$$= (2168 \text{ x } 850)/1000$$

$$= 1{,}8 \text{ MW}$$

The electricity input power to the motor can be calculated as follows:

$$\text{Power}_1 = \frac{W_a}{\eta_{fan}} = \frac{1,8}{0,7} = 2,6\,\text{MW}$$

The maintenance cost per year is R200 000 every 7 years (R200 000 / 7 = R28 571 for the variable speed drive motor, general maintenance amounts to approximately R10 000 per year.

| | | |
|---|---|---|
| Total maintenance cost per year | = | R28 571 + R10 000 |
| | = | R38 571 |
| Running cost | = | electricity cost x kWh |
| | = | 0,15 / kWh x 2 600 000 Watt x 365 days x 24hrs |
| | = | R3,458 million |
| The total cost per annum | = | R3,458 + R0,038 571 |
| | = | R3,497 million |

The Excel spreadsheet financial programme was used to determine the different values for the IRR and NPV's over a period of 20 years. The payback period were also done. Formula 4.2 is used to determine the payback period for different cash flows and savings in running cost [2].

The running cost associated with 3 MW air power (3 kPa x 1000 $m^3/s$) required was used as base case. If less air power is required (fan running slower), the running cost will be less. The saving is expressed as the difference between the original total cost (maintenance cost included) and the new "cheaper", total fan running cost. (This investigation is a comparison of total fan running costs at different fan speeds. Maintenance cost is assumed as a constant variable, and not changed for different fan speeds).

$$\text{Payback period} = \frac{\log_{10}\left[\dfrac{1}{\left(1-\dfrac{\%\,\text{inflation rate x Capital cost}}{1^{st}\,\text{year saving in running cost}}\right)}\right]}{\log_{10}(1+\%\,\text{inflation rate})} \qquad (4.2)$$

**For example,** Capital = R4 million

Saving in running costs = R2,66 million (first year saving)

Inflation rate = 7%

$$\text{Payback period} = \frac{\log_{10}\left[\dfrac{1}{\left(1-\dfrac{7\%\,\text{x R 4}}{\text{R 2,66}}\right)}\right]}{\log_{10}(1+7\%)}$$

= 1,6 years

The rest of the calculations are based on the above. Annexures F, G (including graph summary), H, I (including graph summary), J, and K (including graph summary) show detailed cash flow and summaries of NPV values for different R/€ rates, inflation rates and change in electricity prices pertaining to variable speed drives. It must be noted that for these graphs a 20-year financial period was considered, meaning that the NPV for each of the air quantities showed, is the NPV for a period of 20 years.

Figure 4.3 shows the results of a sensitivity analysis for the NPV and the three variables discussed thus far, namely the electricity price, inflation and the R/€ exchange rate. This graph shows that for a predetermined change in air quantity (in our example 10%, 21% and 33% increase and decrease in variables), the NPV is more sensitive to the electricity price than to either the inflation rate or the R/€ exchange rate (steeper gradient in graph). This is important to know as it has been mentioned in Chapter 2 and 3 of this document that the electricity price will play an important role in future. The electricity price will influence the running cost of equipment such as fans and refrigeration units and the graph shows this clearly for fans.

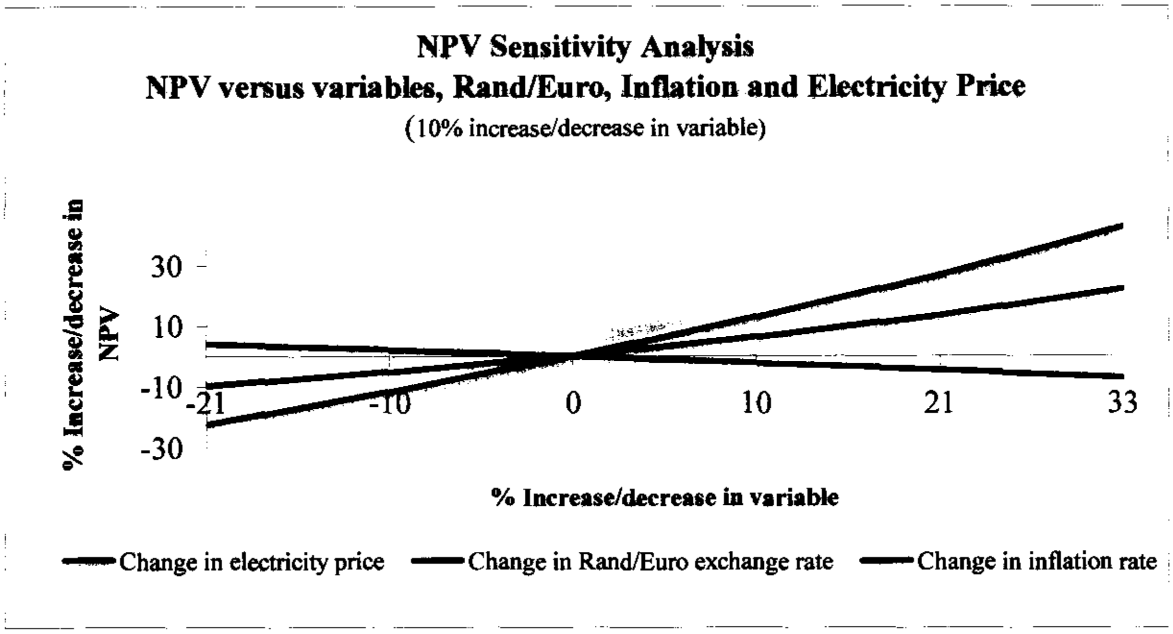


**Figure 4.3: NPV sensitivity analysis**

IRR values were also calculated for the parameters mentioned before and details pertaining to these calculations are shown in Annexures F, G (graph summary included), H, I (graph summary included), J and K (graph summary included). These graphs were included to show that if the fan was running slower than the current design of 1000 $m^3/s$ there will be a significant IRR associated with the three items mentioned before, but the electricity price once again proved to be more sensitive than the other two parameters.

The payback period was also calculated for the abovementioned scenarios. Once again the effect of the three variables discussed so far was investigated. The details pertaining to the calculations for the payback periods are shown in Annexures F, G (including graph summary), H, I (including graph summary), J and K (including graph summary).

From these three graphs it appears that the payback period for air quantities between 750 and 900 $m^3/s$ compared to a base case quantity of 1000 $m^3/s$ will be between 1 and 5 years (for all three the variables considered). The running cost for each of these air quantities has been determined for a year. This figure was then used to determine the payback period if the fan would be running at that slower speed for the next 5 years (to complete the payback).

All the graphs shown thus far have an academic comparative value assigned to them. They show the worst and best case scenarios if these quantities were sustained at 20-year periods as indicated in the assumptions. These figures were given for comparative use only, and showed the financial significance if the fan was able to increase or reduce the quantity of air required. It is important to note that in these financial examples for the VSD motor, the possible effect of a reduction in the amount of refrigeration required was not considered.

In the real life scenario the speed of fans will change according to the need underground, which means that a statistical pattern for air quantity distribution over a period of time may or may not be possible, depending on circumstances. In the next few sections the effect of different air quantity distributions is considered. This is to show the real-time financial effect if a fan's speed can be varied.

## 4.4 NPV, IRR and payback periods for statistical air quantity distributions

When a constant amount of air is supplied during a production phase, it relates to a certain cost profile for a specific period of time. It is obvious that if the fan runs at speeds other than the constant revolutions to deliver the 1000 $m^3/s$ designed, it will have a different total running and maintenance cost.

The reason for looking at statistical air quantity distributions is to ascertain to what extent the NPV, IRR and the payback period will be influenced by these distributions, if the fan was able to supply different amounts of air instantaneously over a specific period of time. Dr Johan Joubert, from the Industrial Engineering Department, University of Pretoria, has created different statistical air quantity distributions for air quantity values between 800 and 1200 $m^3/s$. As mentioned above, 1000 $m^3/s$ was used as a base case all along and in this comparison it will be used too.

In the examples that follow, it was assumed that a fan runs at a specific statistical air quantity distribution during one financial year, and that it will repeat this air quantity distribution throughout the life of the mine. It is obvious that a particular air distribution (i.e. statistical distribution) cannot be sustained over a period of time, let alone 20 years, but for comparison purposes the results can be used.

The statistical distributions identified were categorised as "far left skewed", "right skewed", "normal distribution", "right skewed" and "far right skewed." Figures 4.4a, b, c, d, and e show the type of statistical distributions (showing % probability versus air quantity for each distribution). When compared to the base case annual air quantity supply of 1000 $m^3/s$,for a far left air quantity distribution the probability that the fan will supply an air quantity of 1000 m$^3$/s will be very low. For a far right air quantity distribution the probability of he fan supplying an air quantity less than 1000 m$^3$/s is much less. In this case the dilution of contaminants underground can be improved and refrigeration may possibly be reduced. This however is not dealt with in this financial comparison of statistical air quantity distributions.

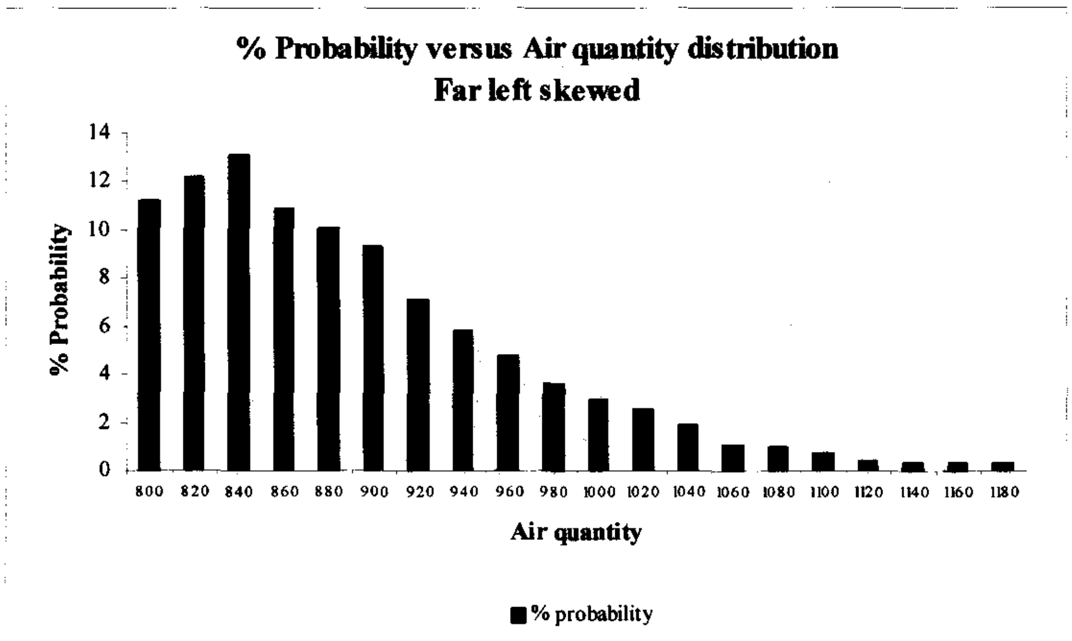


**Figure 4.4a: "Far left skewed" air quantity distributions**

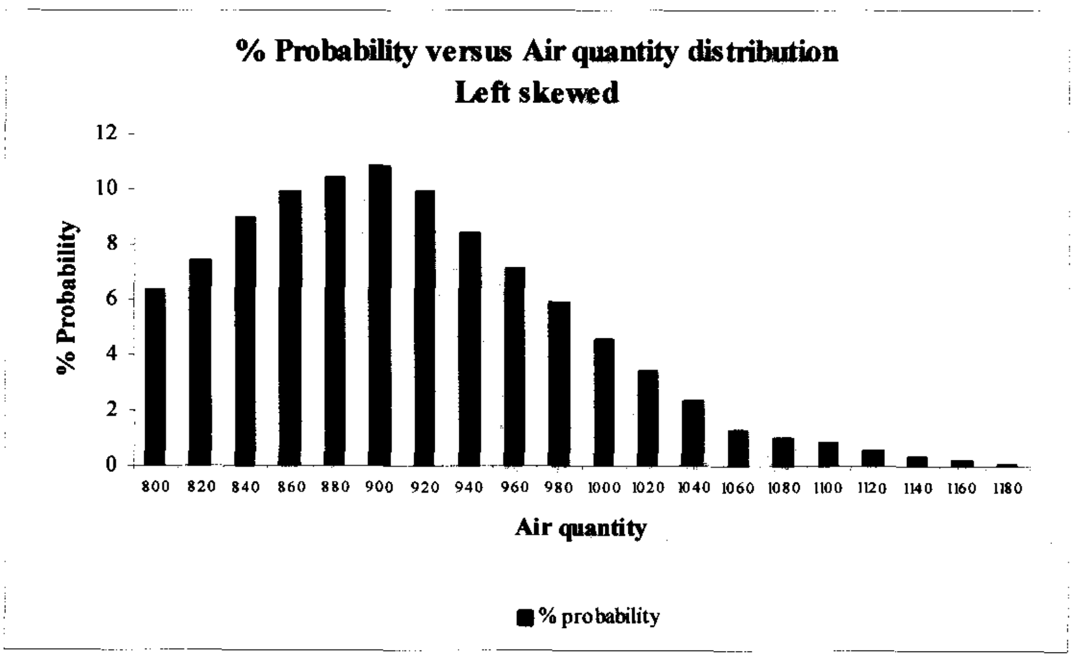


**Figure 4.4b: "Left skewed" air quantity distributions**

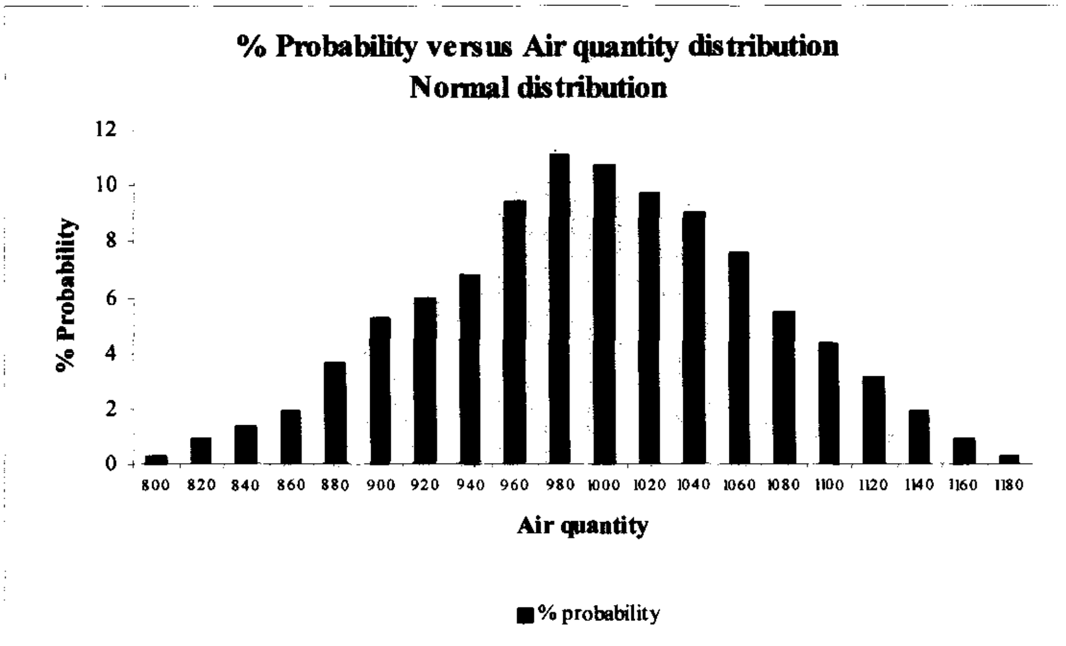


**Figure 4.4c**: Normal distribution air quantity distributions

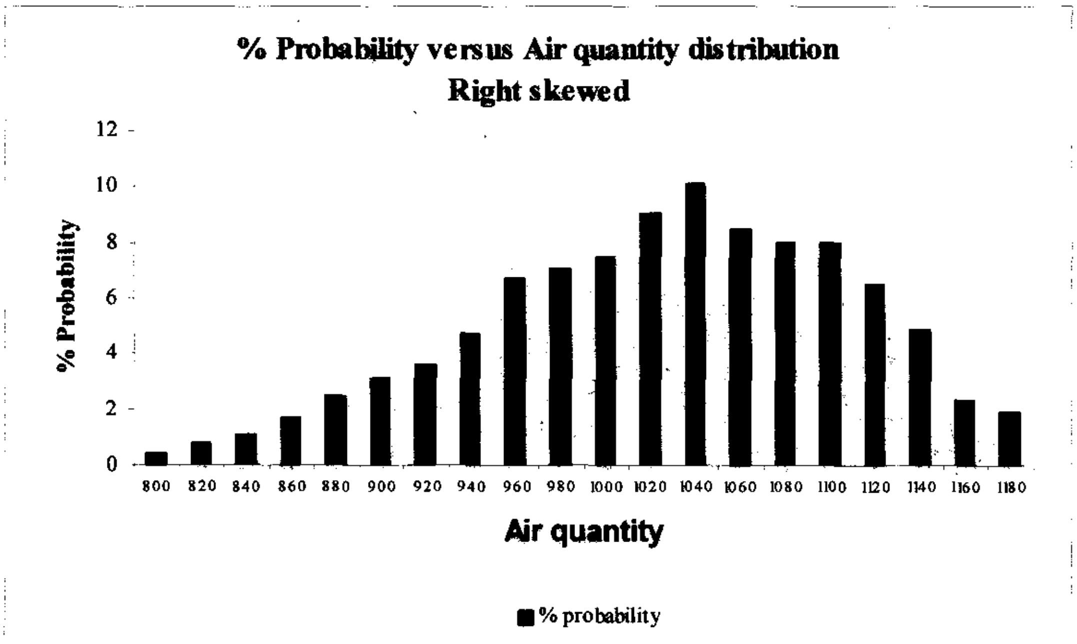


**Figure 4.4d**: "Right skewed" air quantity distributions

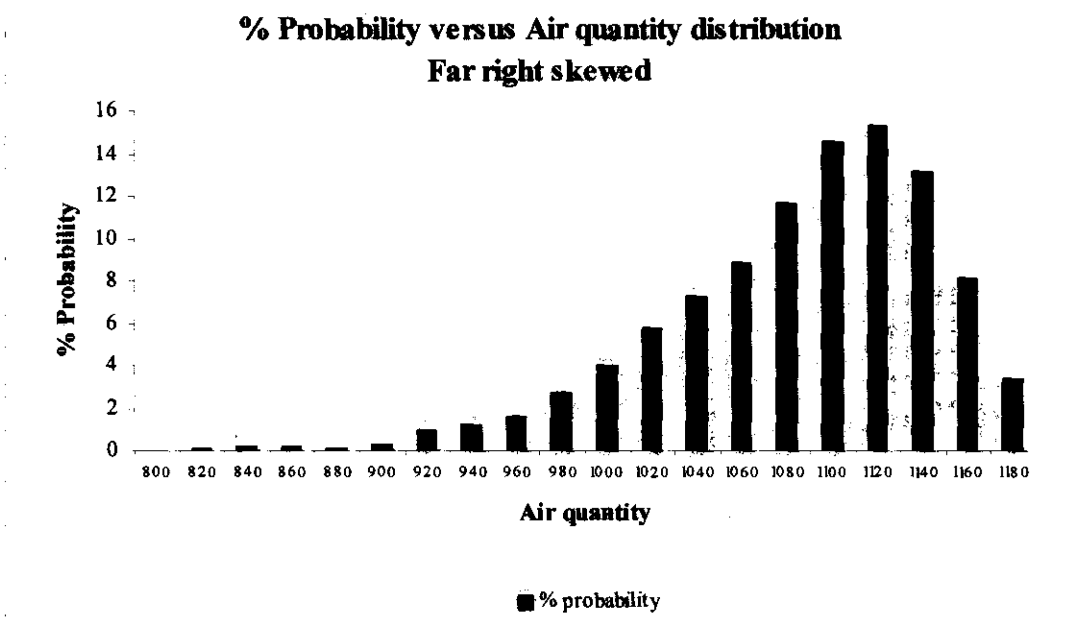


**Figure 4.4e: "Far right skewed" air quantity distributions**

The air quantity distributions therefore include various probability percentages of a fan delivering a specific air quantity in any financial year. In this case the total cost in delivering 1000 $m^3/s$ is also compared to the total costs for each of the statistical distributions. Table 4.4a shows how the actual total annual cost for a "far left" air quantity distribution for a year was determined. The same procedure was repeated for the other statistical air quantity distributions.

**Table 4.4a: Total fan operating cost for "far left" air quantity distribution**

| Quantity (Q) ($m^3/s$) | Total running&maintenance cost per annum, (Rm) | Far left skewed % air distribution | Total cost (Rm) x % distribution |
|---|---|---|---|
| 800 | R2.9 | 11.2% | 0.328 |
| 820 | R3.1 | 12.2% | 0.383 |
| 840 | R3.4 | 13.1% | 0.442 |
| 860 | R3.6 | 10.9% | 0.393 |
| 880 | R3.9 | 10.1% | 0.392 |
| 900 | R4.1 | 9.3% | 0.386 |
| 920 | R4.4 | 7.1% | 0.315 |
| 940 | R4.7 | 5.8% | 0.274 |
| 960 | R5.0 | 4.7% | 0.238 |
| 980 | R5.3 | 3.6% | 0.193 |
| **1000** | R5.6 | 2.9% | 0.165 |
| 1020 | R6.0 | 2.6% | 0.154 |
| 1040 | R6.4 | 1.9% | 0.119 |
| 1060 | R6.7 | 1.1% | 0.072 |
| 1080 | R7.1 | 1.0% | 0.072 |
| 1100 | R7.5 | 0.7% | 0.056 |
| 1120 | R8.0 | 0.4% | 0.030 |
| 1140 | R8.4 | 0.3% | 0.027 |
| 1160 | R8.8 | 0.3% | 0.028 |
| 1180 | R9.3 | 0.3% | 0.030 |
| 1200 | R9.8 | 0.4% | 0.042 |
| | | **Resultant NPV for far left skewed** | **4.14** |

The R4,14 million figure was then used as the total fan operating cost for a year. The detailed calculations for the statistical air distribution annual operating costs for different air quantity distributions are shown in Annexures L, M, N, O, and P. Annexure Q is the detail of the actual 20-year financial flow sheet.

Table 4.4b is a summary of the NPV, IRR and payback period results from these detailed financial cash flow sheets. The significance of these results is that they are the cost summation of a fan running for 20 years at a specific statistical air quantity distribution. The results are all compared with a fan running for 20 years at 1000 $m^3/s$. The different statistical distributions show possibilities in saving cost and also establishing safe, healthy and productive working environments. The flexibility that these variable speed drive fans give is one of their major advantages.

**Table 4.4b: NPV, IRR, payback periods, statistical air quantity distributions**

| | | | |
|---|---|---|---|
| "far left skewed" | 3.0 | R 10.4 | 45 |
| "left skewed" | 3.7 | R 8.0 | 38 |
| normal distribution | | -R 4.4 | |
| "right skewed" | | -10.1 | |
| "far right skewed" | | -20.3 | |

Figures 4.4a, b and c show the NPV, the IRR and the payback periods associated with these statistical air quantity distributions. Figure 4.4a shows that the NPV for the "far left skewed" and "left skewed" air quantity distributions show a positive cash flow compared to the base case of 1000m$^3$/s. Over the life of the project the real airflow need can be established by using the monitored air quantity results and comparing these with the temperatures in the workplaces.

The difference in temperatures into and out of the workplace is an indication of the heat load. Knowing the actual heat load to contend with, an optimized airflow and refrigeration profile can be established. This can also include data about the most important contaminants. This optimization should be through active monitoring and control and simulated computerised intervention.

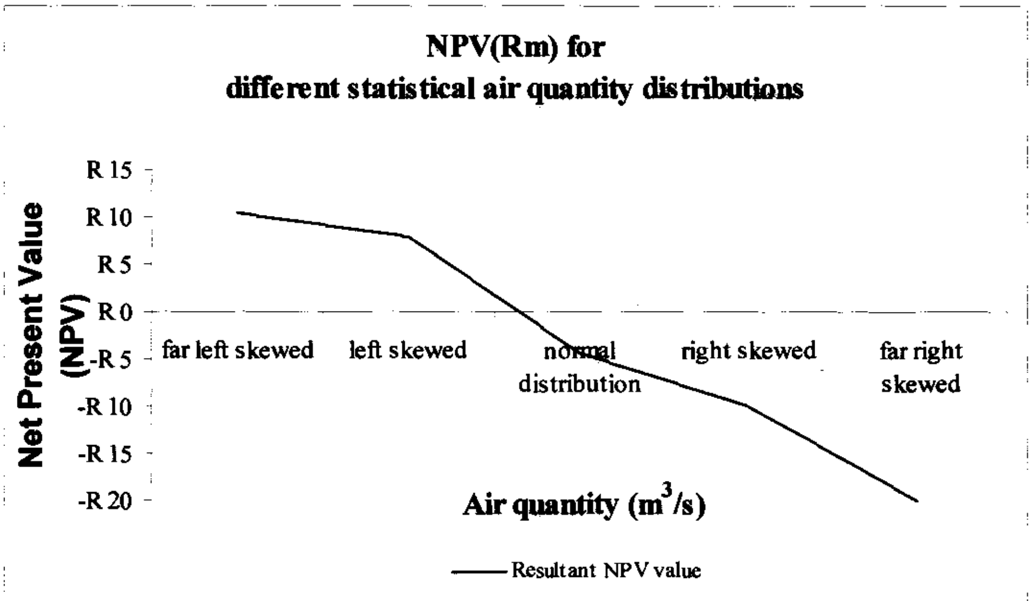


**Figure 4.4a: NPV for different statistical air quantity distributions**

The IRR figures in Figure 4.4b are more realistic and show that for "left skewed" and "far left skewed" air quantity distributions it is financially viable to have a variable speed drive fan in place to manipulate the quantity of air required.

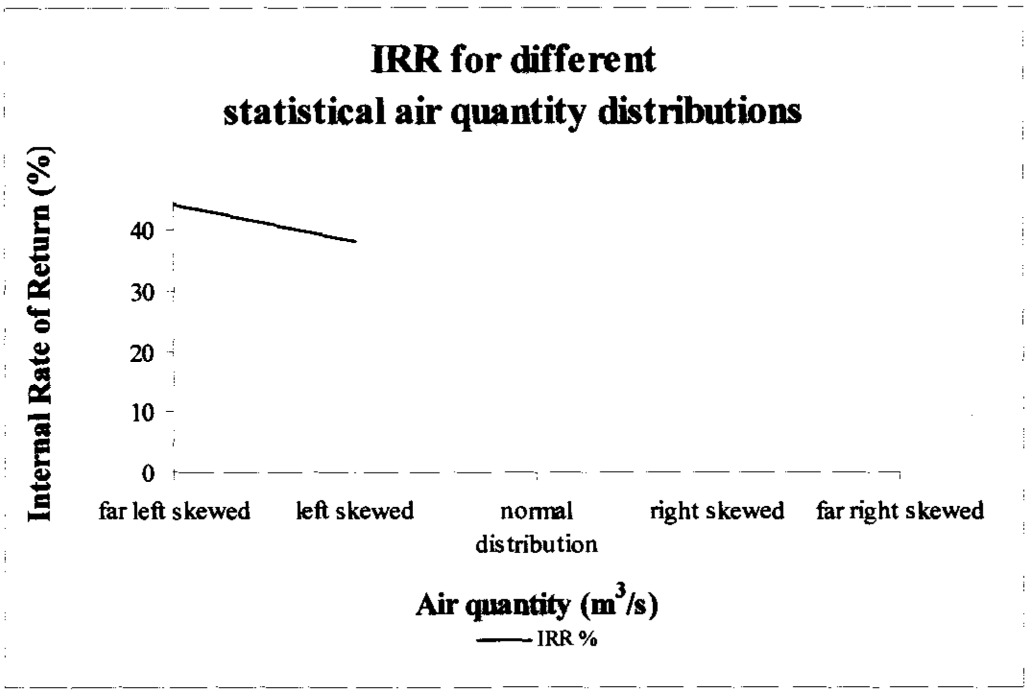


**Figure 4.4b: IRR for different statistical air quantity distributions**

For "far left" and "left skewed" air distributions, the payback period for the fan is not even 4 years, compared to a fan that runs at 1000 $m^3/s$ for 5 years. The payback period increases as the air distribution approaches a normal distribution from the left, and this the reason why the result is not included on the graph in Figure 4.4c. The fact that the air distributions to the right indicate a longer payback period can be offset by the fact that with more air available, less refrigeration is required (this was proven with the platinum mine simulation).

This means that if a real-time IPS optimization is done, a positive cash flow is possible. This will only be possible to prove once a real-time simulation programme for a mine has been created, calibrated and optimized with the incorporation of all the relevant factors involved in air supply, cooling and chilled water pumping.

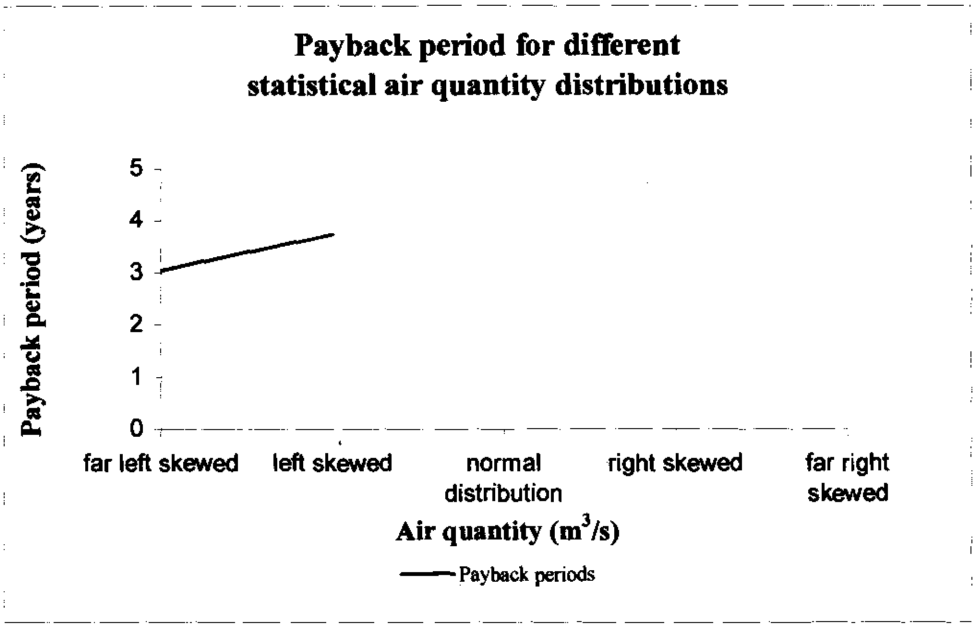


**Figure 4.4c: Payback periods for different statistical air quantity distributions**

## 4.4 Significance of the results

The abovementioned results show that there are various real-time financial advantages in having VSD's incorporated in an integrated approach towards the optimization of air supply and air cooling. The purpose of this chapter was to highlight financial issues pertaining to VSD's. The capital outlay for VSD's versus the possible savings shown for various scenarios (such as change in rand/euro, inflation and electricity price), make a further detailed financial and physical analysis of the use of VSD's for underground mining worthwhile.

Depending on the air quantity distribution over a specific time period, there will be a potential in running cost saving if the cost effect of a reduction in refrigeration is also included in the optimization model. It is one of objectives of this thesis to show that it is indeed possible in a hot mine currently in production.

The inclusion of this chapter was not to make a final decision on the financial applicability of VSD's, but merely to show that what the financial implication of VSD's could be. The results from this part of the investigation can also be used as a guideline when the real implication of the inclusion of VSD's in an IPS model for a mine is considered.

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[2] Cloete C., Personal communication, Ventilation Training Officer, Anglogold Ashanti, Deelkraal, Carletonville, South Africa.

# CHAPTER 5

# DEVELOPING A REAL-TIME INTEGRATED PREDICTIVE SIMULATION MODEL FOR VENTILATION COOLING AND PUMPING AT TARGET MINE

# 5. DEVELOPING A REAL-TIME IPS MODEL FOR VCP AT TARGET MINE

## 5.1 Introduction

It was necessary to identify a mine that could be a case study for this investigation and Target Gold Mine in the Free State was chosen. Target is situated on the western flank of the Witwatersrand Basin, where most of the world's gold has been mined. The then Avgold's exploration efforts focused on the Target area and by 1993 had yielded extremely encouraging results. In 1995 feasibility studies for a 45 000 tons-a-month mine began, but in July 1996 Avgold increased the scope of the project to a 90 000 tons-a-month mine.

Target was a good choice because it has a "simple" underground layout compared to other deep hot gold mines. It has a downcast shaft, a cluster of declines used as intake airways, the workings, a cluster of declines as return airways and an up-cast shaft that removes the contaminated air from underground.

This meant it was fairly easy to simulate the actual mining environment, which would be the base case of the simulation programme. This base case simulation programme was then calibrated by using real-time results of the temperatures and air quantities measured underground. This calibrated simulation programme was then optimized by incorporating the electricity price and optimizing the amount of air supplied and cooling required. A physical analysis of the findings to identify possible savings and real issues pertaining to the simulation followed.

The literature search showed that ACP is a combination of the air velocity and the wet-bulb temperature in a working environment. The inter-relationship between the air velocity and the wet-bulb temperature was also discussed. For a specific design of ACP in $W/m^2$, there are various combinations of air velocities and wet-bulb temperatures.

These combinations are cost sensitive and should be evaluated to determine the optimum cut-off point, both for the *amount* of air supplied and the *temperature* of the environment. It is therefore necessary to test the application of the ACP and the effective utilisation of this concept in a real life mine environment and apply it in an IPS model for VCP.

As part of this investigation it was necessary to establish whether an oversupply or undersupply of ACP was taking place. The ACP values for Target mine were obtained from the mine ventilation annual results for the 2001-02 financial year. These values were audited and approved by mine management and formed part of the mine's annual report. The ACP values obtained were then compared with the design figure of 300 $W/m^2$ previously mentioned.

## 5.2 Data gathering and evaluation of ACP results

Although the ambient temperature on surface changes with the seasons, the effect is negligible in relation to the temperature increase due to auto compression, heat flow from the rock and other secondary heat sources. At Target mine no refrigeration is done on surface – all the cooling of the air is by means of bulk air coolers underground. The air travels long distances and undergoes an increase in temperature due to the auto-compression of the air, the heat flow from the rock and some secondary heat loads in the mine before it reaches the bulk air coolers.

This means that the change in heat load on a day-to-day or area-to-area basis will determine the amount of air-cooling to be provided. Herein lies the opportunity for determining the actual heat loads of specific areas and supplying the optimized quantity of air and temperature to these places.

Table 5.2 shows the average results of air temperatures (wet bulb) and air velocities obtained for development and stoping at Target mine and the actual ACP's associated with them (details of the individual quarterly results for the year are shown in Annexure R). The air-cooling power for the various development ends was estimated by using the ACP and the kata graph previously shown in Figure 2.7.1a.

These results were obtained from the mine's annual reports and based on actual data obtained with ventilation surveys. The purpose of using this data was to ascertain whether energy was indeed being wasted.

## Table 5.2: ACP available for stoping and development in 2002

TARGET DIVISION
YEAR RESULTS 2002
STATISTICAL INFORMATION ON ENVIRONMENTAL CONDITIONS.

1. DEVELOPMENT

| SHAFT / AREA | NO. OF ENDS PLANNED | NO. OF ENDS SURVEYED | WET-BULB TEMP °C NO. OF ENDS IN RANGE ≤ 27.5 | >27.5≤32.0 | >32≤32.5 | >32.5 | WET KATA NO. OF ENDS IN RANGE ≤ 6.0 | >6.0 ≤ 10.0 | > 10.0 | FORCE VOL. DISCHARGE $m^3/s$ | SERVICE WATER TEMP °C | AIR-COOLING POWER $W/m^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| QUARTER 1 TOTAL ENDS | 24 | 17 | 6 | 11 | 0 | 0 | 0 | 2 | 15 | | | |
| AVERAGE | | | 26.5 | 29.1 | 0 | 0 | 0 | 8.8 | 14.1 | 10.70 | 23.3 | 281 |
| QUARTER 2 TOTAL ENDS | 46 | 22 | 6 | 16 | 0 | 0 | 0 | 6 | 16 | | | |
| AVERAGE | | | 26.9 | 29.9 | 0 | 0 | 0 | 8.7 | 11.8 | 8.5 | 21.1 | 272 |
| QUARTER 3 TOTAL ENDS | 41 | 21 | 5 | 16 | 0 | 0 | 0 | 4 | 17 | | | |
| AVERAGE | | | 25.7 | 29.6 | 0 | 0 | 0 | 9.3 | 12.5 | 9.42 | 15.8 | 287 |
| QUARTER 4 TOTAL ENDS | 30 | 15 | 6 | 9 | 0 | 0 | 0 | 2 | 13 | | | |
| AVERAGE | | | 26.1 | 29.1 | 0 | 0 | 0 | 9.6 | 12.9 | 13.5 | 19.4 | 308 |
| YEAR 2002 TOTAL ENDS | 141 | 75 | 23 | 52 | 0 | 0 | 0 | 14 | 61 | | | |
| AVERAGE | | | 26.4 | 29.5 | 0 | 0 | 0 | 9.0 | 12.8 | 10.3 | 19.7 | 277 |

2. STOPING

| SHAFT / AREA | NUMBER OF PANELS PLANNED | NUMBER OF PANELS SURVEYED | WET-BULB TEMP °C NO. OF PANELS IN RANGE ≤ 27.5 | >27.5≤32.0 | >32≤32.5 | >32.5 | WET KATA NO OF PANELS IN RANGE ≤ 6.0 | >6.0≤10.0 | > 10.0 | FACE VELOCITY m/s | SERVICE WATER TEMP °C | AIR-COOLING POWER $W/m^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| QUARTER 1 TOTAL FACES | 42 | 37 | 10 | 27 | 0 | 0 | 1 | 9 | 25 | | | |
| AVERAGE | | | 25.9 | 29.9 | 0 | 0 | 3.0 | 8.9 | 13.8 | 0.9 | 23.2 | 265 |
| QUARTER 2 TOTAL FACES | 44 | 32 | 7 | 25 | 0 | 0 | 1 | 6 | 26 | | | |
| AVERAGE | | | 25.0 | 30.2 | 0 | 0 | 3.0 | 8.0 | 12.6 | 1.2 | 22.3 | 289 |
| QUARTER 3 TOTAL FACES | 32 | 29 | 8 | 21 | 0 | 0 | 0 | 5 | 24 | | | |
| AVERAGE | | | 25.4 | 29.6 | 0 | 0 | 0 | 9.0 | 12.0 | 1.1 | 18.0 | 301 |
| QUARTER 4 TOTAL FACES | 34 | 31 | 15 | 16 | 0 | 0 | 0 | 4 | 27 | | | |
| AVERAGE | | | 26.1 | 29.3 | 0 | 0 | 0 | 6 | 9.3 | 0.84 | 17.9 | 325 |
| YEAR 2002 TOTAL FACES | 152 | 129 | 40 | 89 | 0 | 0 | 2 | 24 | 102 | | | |
| AVERAGE | | | 25.7 | 29.8 | 0 | 0 | 3.0 | 8.0 | 11.9 | 1.0 | 20.5 | 293 |

From the results obtained (quarter to quarter), the ACP varied from workplace to workplace and this in itself is an indication that the temperatures and air supply (and for that matter the heat load), varied from area to area in the mine. Through inspection of the detailed results shown in Annexure R, we see that the ACP supplied to some workplaces is very much lower than in others.

It must also be remembered that these quarterly figures relate to averages from several development ends and stope faces, which means that for an average ACP of over $300W/m^2$ , some areas could have had a very high ACP (oversupply) and other areas a very low one (undersupply).

From these results it can be seen that the almost all the ACP values in the table were below the proposed design value of 300 $W/m^2$. This value could in fact be obtained by an increase in the air quantity supplied or an increase in the refrigeration underground. There is no active simulation programme on the mine that could indicate the airflow and refrigeration combination that would relate to optimized energy use. In establishing a higher ACP, working conditions would be improved and an increase in productivity could be possible.

In addition, this uneven distribution of ACP to the different working areas, would in fact mean higher costs associated with ACP in some areas and lower costs in other areas. This could also imply certain safety risks for the areas with low ACP. The ultimate objective would be to supply, as far as practicably possible, the same ACP to all work areas, in an effort to redistribute the energy resources available as evenly as possible.

At Target mine there is a SCADA monitoring system and the results are documented, but it is basically used as a management system. The areas with poor environmental conditions are identified and remedial actions are then taken re-actively instead of instantaneously. The current resources available are optimized through a "reactive response" approach, and are not energy management-friendly. A system utilising a predictive simulation approach through active control measures would ensure that areas where resources are being oversupplied could be identified, and resources applied differently.

It would therefore be necessary to set up a simulation of the current workings and to calibrate this simulation with actual results from monitoring stations. From this simulation a predictive simulation could follow, incorporating all the various airflow requirements, air temperatures and pollutant occupational exposure limits, and the optimized energy requirements associated with these parameters and constraints.

In this way an integrated optimized system can be designed, calibrated and put in place that will not only meet production, safety and health requirements, but also optimize the various energy resources associated with the system (as suggested by von Glehn).

In establishing acceptable environmental conditions with regard to airflow quantities and air temperatures, Target is meeting its objectives with regards to the required air velocities and wet-bulb temperatures. But there is room for improvement in the amount of energy consumed for air supply and cooling.

In the building industry, there are simulation tools that incorporate any constraints (i.e. $CO_2$ levels, temperature, humidity levels, etc.), and they ensure (through automisation) that only the amount of air and cooling necessary for a healthy environment (based on set constraints) is supplied [1]. This thesis, as mentioned before, attempts to prove that the same principles apply to hot mining environments.

## 5.3 Developing an IPS model for Target mine

In the previous chapters, all the relevant aspects pertaining to an IPS model were dealt with in detail. Claassen highlights the phases of a new procedure in optimization of energy resource as shown in Chapter 2. These phases form the basis of the investigation approach in the establishment of an IPS model for Target mine. The phases as set out by Claassen however, were adapted to the needs of the current investigation [2].

- Phase **one:** the collection and identification of the required input data to set up a complete optimization model. This optimization model was then used to calculate the optimized schedules for the relevant equipment on a daily basis
- Phase **two:** the setting up of the mathematical models of the relevant equipment using the input data of phase one. The models were then linked to create an integrated optimization model of the energy cost of the refrigeration, air supply and pumping components of the system. All the models were calibrated and verified

- Phase **three,**: the generating of daily schedules could not be automated for all the equipment because variable speed drive fans are not available at Target (or any other mine in South Africa). Since the design of the optimization model was a primary objective for the investigation at Target mine, this model did, however, include the effect of a variable speed drive fan in the IPS model
- Phase **four,:**calibrating the mathematical models of the relevant equipment

The on-mine investigation focused on the simultaneous optimization of air supply, cooling and chilled water pumping, and optimizing working conditions (i.e. real-time control of contaminants and temperatures). Historical electrical consumption data of the whole mine was an important part of the investigation, as this data was used for the calibration of the equipment models.

A year's data on the demand profiles and all necessary information to calculate the electricity cost of Target mine was obtained. This data can be considered representative of the load profiles and electricity cost for the mine. This established the cyclical nature of the cooling and pumping through the seasons. This data was used to establish a cost base line for comparison with the new optimized schedule. Data obtained from the SCADA system on the mine was used to design the simulation and optimized simulation models.

In phase two of the procedure of energy optimization, it was important to establish all the boundary data. The boundaries are those values that can be regarded as fixed inputs to the equipment mathematical models or the optimization model as a whole. Typical boundaries are:

- The electricity tariff. The hourly prices directly influence the objective function of the optimization model
- The predicted minimum and maximum ambient temperatures. This drives the refrigeration load
- A water or airflow demand. These are normally constant or predictable flows that constitute input values for the certain mathematical models. An example of such flows is the waterflow from the settlers to the nearest clear-water dam
- Temperatures. For example, fixed or predictable temperature that influences the optimization, but is not influenced by the temperature of the water pumped out of the

mine. This temperature was found to be fairly constant throughout the year

- Electrical base load. All other loads on the mine that will not be influenced by the scheduling of the pumping, refrigeration and air supply were grouped as a base load. The base load is a function of the day of the week

Once the valid simulation model was established, constraints necessary for optimization were added. From the optimized model an "optimized schedule" was created. Some parts of the optimization schedule for Target cannot be automated (for example, no variable speed drive fan), but the optimized schedules can be incorporated manually, if needed, in the application phase.

Claassen states that after the optimization model has been established; it should be automated so as to produce a daily schedule automatically. In the case of Target mine it is only possible to include some items for automation, but the schedule can be used to identify over or undersupply of resources on the mine. Christopher Swart of HVAC International designed the simulation and optimization programme, with input from, and guidance by RCW Webber-Youngman.

Permission by TEMM International to include edited extracts from Report 21308, written by Christopher Swart, is hereby acknowledged [3]. For the purpose of the investigation it was decided to design simulation models for the mine at first excluding contaminant control and then later to include the contaminants and their respective OEL's, as constraints or boundaries in the optimized simulation. It was an initial objective to consider the optimization of the physical components.

### 5.3.1 System layout

The three main components involved in the optimization process are fans, refrigeration units and chilled water pumps. For the sake of completeness a section on clear-water pumping at Target mine is also included in this investigation. The basic system to be considered is airflow, refrigeration and pumping. Each of these elements are unique in their own right, but as mentioned before, are influenced by one another. A fourth component, contaminant control through dilution, is added to this process. This is directly influenced by the amount of air available and was discussed in detail in Chapter 3 of this document.

It is necessary to show the physical layouts and/or descriptions of these items on Target mine. A simplified mine layout of Target is shown in Figure 5.3.1. It consists of a downcast shaft, intake air declines, airflow through the massive ore deposit workings, and the return air through the declines linked to an up-cast shaft, from where the contaminated air is take out of the mine. Air is drawn through the mine by a main fan on surface, assisted by 6 booster fans underground. The air from surface is cooled underground at 255 level before it goes to the workings.

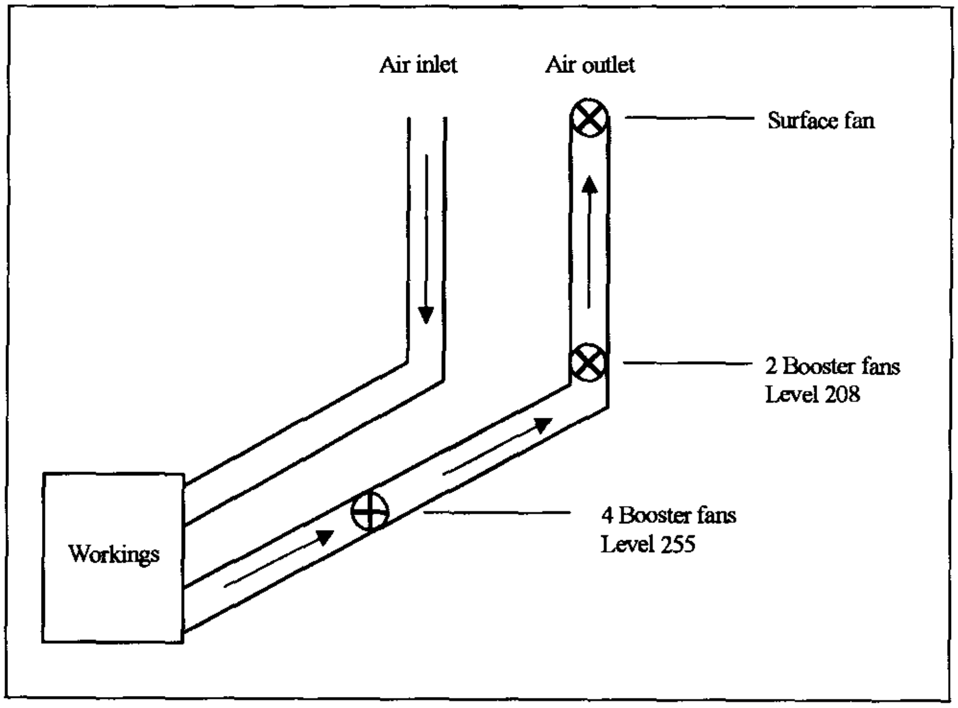


**Figure 5.3.1: Basic layout of Target mine**

### 5.3.2 Underground pumping (clear-water and cooling-related pumping)

It is important to distinguish between clear pumping and chilled water pumping associated with the cooling of the air. Clear-water pumping has no real impact on the establishment of a safe, healthy and productive work environment, but can have considerable costs.

Chilled water pumping, on the other hand, influences conditions underground, as the temperature of the cold water eventually determines the temperature of the air. As indicated before, the temperature of the air is dependent on the quantity of air supplied.

#### *5.3.2.1 Chilled water pumping*

Figure 5.3.2.1 is a schematic diagram of the refrigeration process at Target mine. It shows the pumping activities associated with the refrigeration process. Hot water enters the evaporators and is and then pumped to a chilled water dam. The water is pumped from the chilled water dam to the evaporator spray pond at a rate of 265 litres/second. This water then cools the air that is destined for the workings.

The hot water from the evaporator spray ponds gathers in the hot dam, and is then pumped back to the evaporator in the refrigeration plant. On the condenser side of the refrigeration plant, very hot water is pumped at a flow rate of 800 litres/second to the condenser spray ponds, where the return air from the workings cools the water.

The cooled water leaving the condenser spray ponds is then pumped back to the condenser in the refrigeration plant and the very hot air is then rejected to surface. The water-holding capacity of the chilled water and hot water dams is 2,54 Mega litres and 1,953 Mega litres respectively.

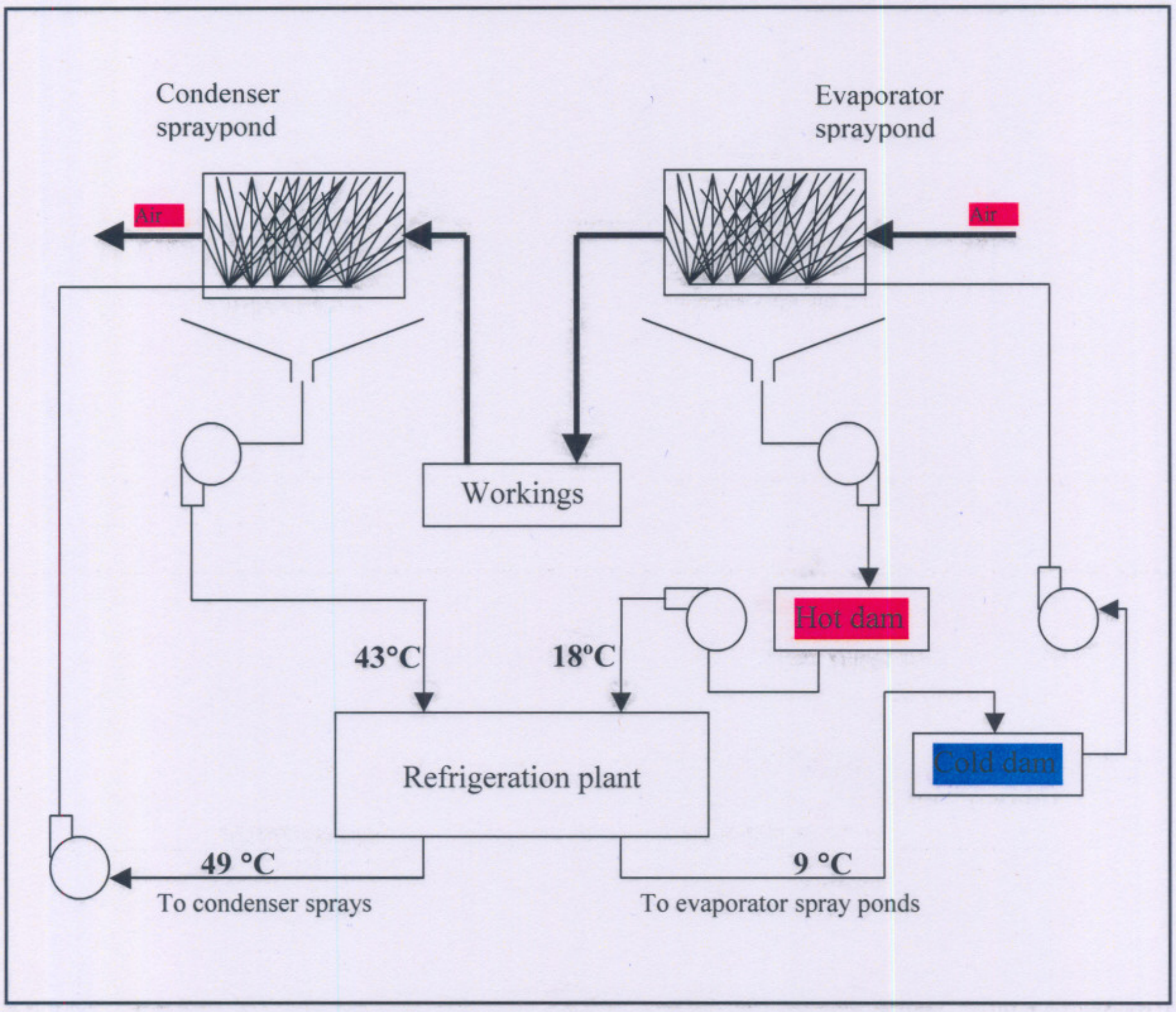


**Figure 5.3.2.1: Schematic diagram showing cooling-associated pumping**

The chilled water dam has an important function. It is currently a six-hour back-up facility. Herein lies the potential for scheduling compressor electrical input power. Cooling of the refrigerant only has to take place at times when the minimum electricity tariff applies, optimizing electricity consumption.

This would mean that chilled water could be pumped from the chilled water dam (with sufficient capacity) while the compressor is not working. In this way the compressor power can be minimized by using this back-up facility.

The chilled water can also be mixed with the hot return water from the evaporator spray ponds, helping to reduce the temperature of the inlet water to the refrigeration plant, thereby reducing the work load on the refrigeration plant. The refrigeration plant is normally designed to deliver water at a specific temperature, which means that if the inlet water temperature can be reduced, the overall cooling duty for a specific flow rate of water can be reduced. The back-up capacity of the dam would, however, determine the feasibility of such a strategy.

#### *5.3.2.2 Underground clear-water pumping*

At Target mine, the water from the workings flows from gullies and haulages underground and eventually gathers at the settlers underground. At the settlers, the "solids" are gravitated from the water and the clear-water is then pumped back to surface with the help of electrical pumps. Target mine has three main pump stations, namely on levels 255, 212 and 142.

Clear-water from the settlers on level 255 flows to the 6 Mega litre clear-water dam on the same level. From here the water is pumped to the 2,1 Mega litre clear-water dam on level 212 via the level 255 pump station. The clear-water is then pumped via pump station 212 to the 1,6 Mega litre clear-water dam on level 142 and from there to the surface dam via pump station 142. The total pumping layout clear-water dams are shown in Figure 5.3.2.2.

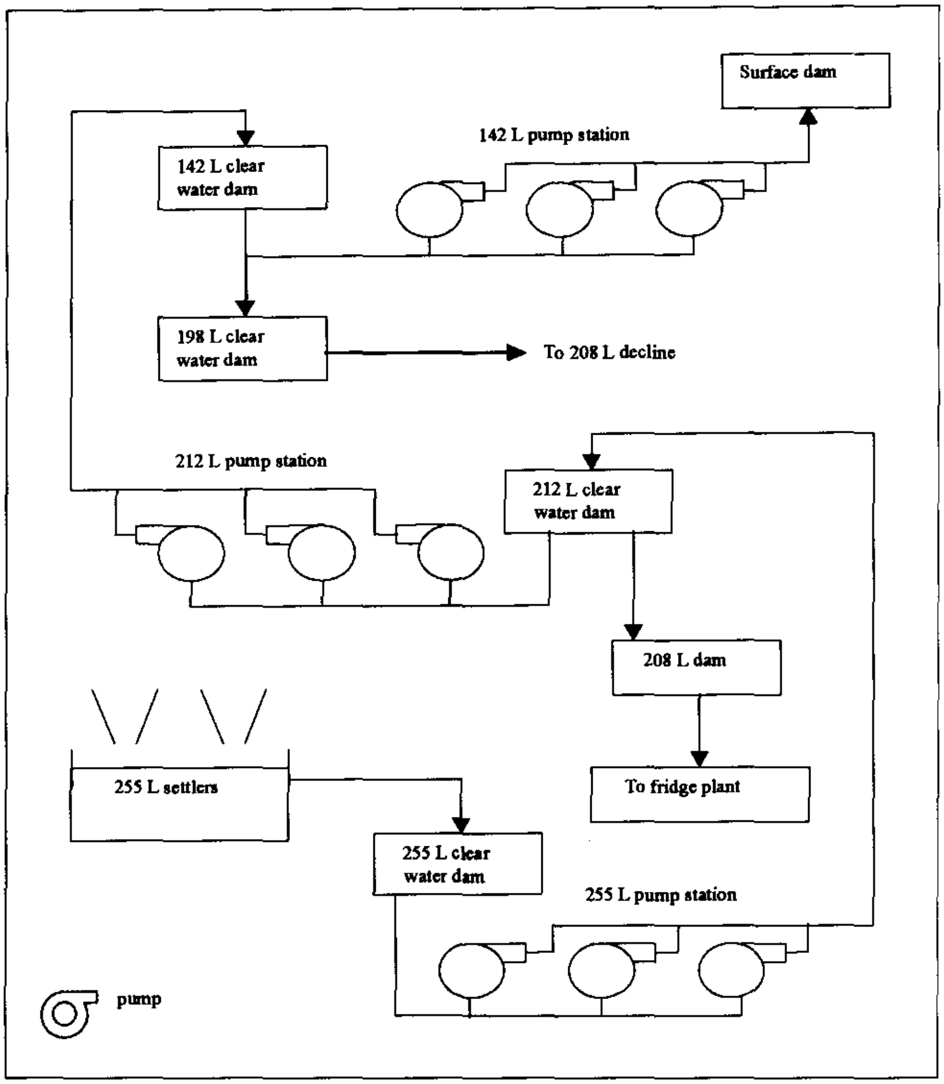


**Figure 5.3.2.2: Schematic diagram of the underground clear-water pumping system**

### 5.3.3 Underground refrigeration

There is no surface refrigeration at Target. All refrigeration takes place underground. The refrigeration plant is situated on level 255 and consists of 10 refrigeration machines, each with a cooling capacity of ± 3 MW, not all of which were operational at the time of the investigation. The main components of the refrigeration units are the evaporators, condensers, compressors and pumps.

Also associated with the refrigeration process are the chilled water and hot water dams and the BAC's. There are four main evaporator spray ponds in parallel on level 255. There are also two smaller secondary evaporator spray ponds on levels 276 and 280, and the condenser spray ponds cooling the return water for the condenser (refer to Figure 5.3.2.2).

Table 5.3.3 shows the different values for the evaporator and condenser duties, and the compressor power. If one considers the Coefficient of Performance (COP) of the plant, which is a direct indication of the ratio of the amount of cooling versus the compressor motor input power, then it can be seen that the COP values for the different units vary considerably, which in itself is an indication of energy waste. Chiller 4 was not commissioned at the time of the investigation.

In discussions with planning officials on the mine, it was found that the future refrigeration requirements for Target mine will be of the order of 30 MW. In considering this figure it must be clear that there is real scope for establishing an energy friendly design for Target mine.

**<u>Table 5.3.3:</u> Evaporator and cooler duties and compressor power at Target mine**

| Description | Chiller 1 | Chiller 2 | Chiller 3 | Chiller 5 | Chiller 6 | Total | Average |
|---|---|---|---|---|---|---|---|
| **Evaporator duty design (kW)** | 3850 | 3232 | 4842 | 2831 | 2672 | 17427 | **3485** |
| **Condenser duty design (kW)** | 4122 | 4533 | 5482 | 3253 | 2708 | 20099 | **4020** |
| **Compressor power actual (kW)** | 839 | 772 | 1233 | 497 | 736 | 4077 | **815** |
| **Evap. duty + Compr. Power (kW)** | | | | | | **21504** | |
| **<u>Evaporator duty actual (kW)</u>** | | | | | | | |
| **Massflow water (kg/s)** | 55.7 | 64.2 | 118.4 | 63.5 | 72.1 | **374.0** | |
| **$T_{in}$ (°C)** | 19.5 | 21.5 | 16.4 | 18.0 | 17.9 | | **18.3** |
| **$T_{out}$(°C)** | 6.6 | 7.4 | 9.1 | 9.2 | 11.5 | | **8.9** |
| **Heat exhanged (kW)** | 3019 | 3814 | 3621 | 2341 | 1942 | **14738** | **2948** |
| **COP** | 3.6 | 4.9 | 2.9 | 4.7 | 2.6 | | |
| **<u>Condenser duty actual (kW)</u>** | | | | | | | |
| **Massflow water (kg/s)** | 134.4 | 147.0 | 182.4 | 137.1 | 137.2 | **738.2** | |
| **$T_{in}$ (°C)** | 49.7 | 47.7 | 49.4 | 48.5 | 47.6 | | **48.6** |
| **$T_{out}$(°C)** | 42.3 | 42.5 | 42.2 | 42.9 | 42.9 | | **42.5** |
| **Heat exchanged (kW)** | 4138 | 3241 | 5500 | 3260 | 2715 | **18854** | **3771** |

If one assumes a COP of 3,6 (from Table 5.3.3) and a total evaporator cooling duty of 14,7MW, the compressor motor input power would be approximately 4 083 kW. If a 24-hour working day, 300 days per year, is assumed for the compressor motors, this means an annual electricity cost of R4 410 000 (at a conservative electricity price of R0,15/kWh). As mentioned before, the eventual cooling capacity at Target is planned to be 30 MW, which indicates a large annual electricity expense for compressors.

The total pump duties (chilled water circuits) at Target are only 1,8 MW, which is much less than the total compressor motor input power required for all the refrigeration units (4 077 kW from Table 5.3.3). If, as mentioned above, thermal energy storage principles (through chilled water dams) can be employed more extensively at Target mine, pumps supplying chilled water to the bulk air coolers can be operated at times of high electricity cost.

A matter not considered here is the inclusion of VSD motors for the pumps as well, in this way optimizing the amount of water supplied to the bulk air coolers. In times of low electricity tariffs, the compressors can then be utilised more effectively. It is therefore a fact that the compressor motor input power is a critical item in the total cost-saving drive.

### 5.3.4 Air supply

A surface fan driven by a 2 100 kW electric motor is responsible for the primary ventilation of the mine. This fan can deliver air at 400 $m^3/s$ at a pressure of 3,5 kPa. There is also one main fan on standby. The main fan is supported by two 275 kW booster fans on level 208 and four 445 kW booster fans on level 255 (refer to Figure 5.3.1). The effect of auxiliary fans is not considered in the optimization process.

## 5.4 Energy audit

The main consumers of electricity on the mine are refrigeration, underground pumping and ventilation (air supply). Refrigeration includes all the compressors and pumps in the refrigeration plant, and the fans and pumps at the condenser and evaporator ponds. The contribution of each of these to the total electricity consumption of the mine can be seen in Figure 5.4.

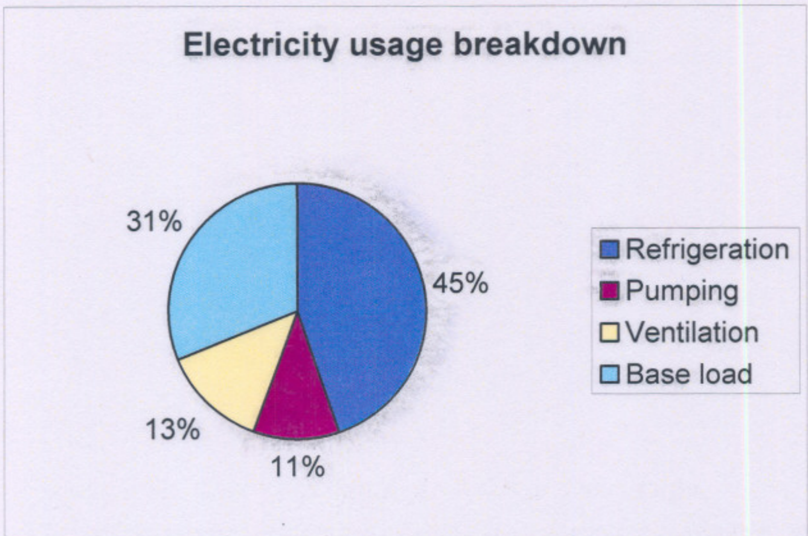


**Figure 5.4: Electricity consumption breakdown at Target mine**

The base load includes all the winders, the general surface, drills and rigs, crushers and conveyor systems. These systems did not form part of the present study due to their stable or unpredictable nature. Rock winding was also excluded. The effect of load shifting and demand side management (DSM) was investigated for the refrigeration (including the chilled water pumping), ventilation and underground clear-water pumping systems.

### 5.4.1 Tariffs and cost

At the time of the investigation, the mine was on the NIGHTSAVE urban tariff structure. This tariff consists of demand and energy charges. The demand charge is only applicable during peak periods, when the mine is billed per kW of maximum demand. The energy charge is calculated by taking the total energy (kWh) consumed by the mine for the month and then multiplying it by the c/kWh "NIGHTSAVE" urban electricity tariff set by Eskom.

The ability to shift energy load from peak to off-peak times will ensure a lower electricity cost when the mine shifts to, for example, the Megaflex tariff structure. These tariff structures imply lower electricity tariffs during off-peak times and higher tariffs during peak times. Eskom's present peak periods are between 07:00 and 10:00 in the morning and between 18:00 and 20:00 in the afternoon/evening. Eskom calculates this price every day for the next day.

## 5.5 Data availability

The mine has a comprehensive Supervisory Control And Data Acquisition (SCADA) system. All underground dam levels and active pumps are logged. At the refrigeration plant, the entering and leaving water temperatures, water mass flows and compressor power are logged for each refrigeration unit. For the ventilation system, all active fans are logged. During the study, the air temperature and relative humidity were measured at all the crucial points in the mine. Measurements were taken per minute over a period of four days. This was done to establish the actual heat load in the mine, so that this could eventually be compared with the results obtained by the simulation.

Knowing the physical components and their layout at target mine, the next phase of the process could begin. It was now necessary to design various simulation models. The simulation models designed were the following:

- An underground heat flow and associated cooling simulation model
- An underground pumping system model
- An underground refrigeration model
- An underground airflow model

The significance of each of these models and the design thereof will be discussed in the sections to follow. The formulas used were all obtained from the theses of Den Boef [4] and Taljaard [5].

## 5.6 Underground heat flow and associated cooling simulation model

The air that flows through the mine is heated by both the rock temperature and the underground diesel equipment. The underground heat-removing capacity of the air at Target depends on the capacity of the underground refrigeration plants and the cooling capacity of the air supplied by the fans. Both the air velocity and the temperature of the air (air-cooling power) therefore have to be controlled so as to ensure that the correct quantity of air is supplied at the required temperature.

Consequently, a further requirement would be to optimize the ratio of quantity to temperature of air supplied so that the minimum amount of energy would be consumed, without sacrificing safety, health and production requirements. It was therefore necessary to know the temperature of the air approaching the workings and to be able to predict accurately the reject wet-bulb temperature at the return from the workings. This is done to establish the actual heat load and then determine the optimized airflow and air temperature requirements.

The actual heat load would determine the quantity of air that must be supplied by the fans (and hence the fan motor input power required), and the compressor power needed to cool the water. The optimized combination of these two parameters will ensure the required reject temperature.

It was for this reason necessary to ascertain the cooling arrangements on the mine (fans in combination with the refrigeration units) and to use this layout as the basis for the optimization model. A schematic underground layout of the mine is shown in Figure 5.6a and was drawn using the information from Figure 5.3.1.

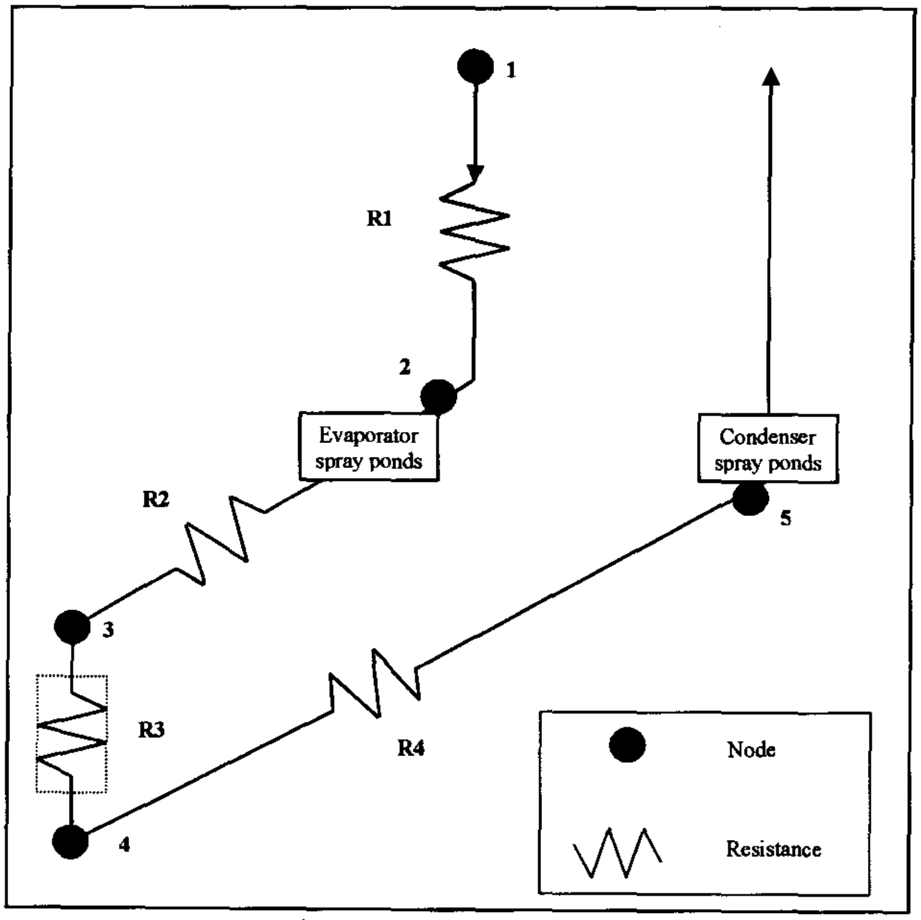


**Figure 5.6a: Schematic diagram of the underground mine layout**

The mine is divided into four main zones, as follows:

| | |
|---|---|
| Node 1 – Node 2: | Represents the shaft from surface through the underground workings/declines to the intake of the evaporator spray ponds |
| Node 2 – Node 3: | Represents the evaporator spray ponds to the intake of the workings via the declines |
| Node 3 – Node 4: | Represents the workings area: the intake to the workings to the return from the workings (through this the actual heat load could be established) |
| Node 4 – Node 5: | Represents the tunnels/declines from the return of the workings to the inlet of the condenser spray ponds |
| R1 through to R4 | Heat flow resistances between every set of nodes |

The thermal performance of each shaft/airway mentioned above was simulated using energy-balance equations. The basic thermal model of the shaft/airways is shown in Figure 5.6b.

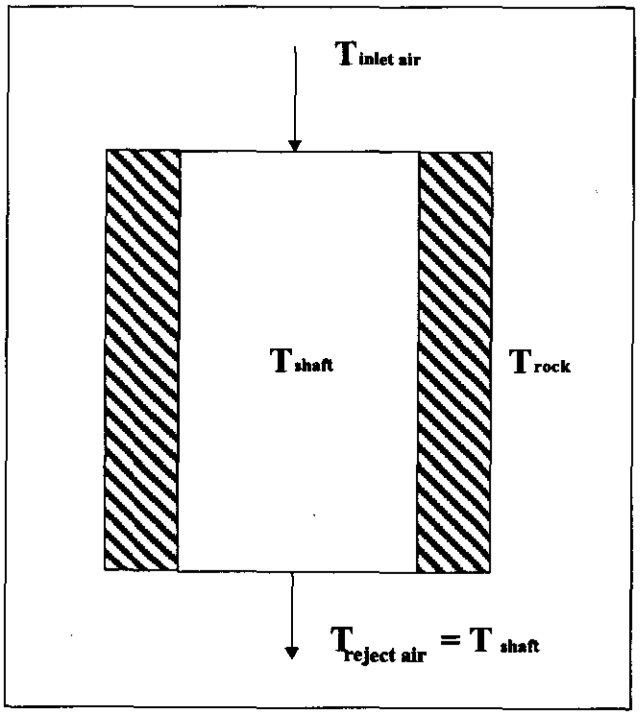


**Figure 5.6b: Schematic diagram of the thermal model of the shaft/airways**

The energy balance of the system in Figure 5.6b can be written as follows:

$$C\frac{dT_{shaft}}{dt} = U_{shaft}A_{shaft}\left(T_{rock} - T_{shaft}\right) + m_{air}cp_{air}\left(T_{inletair} - T_{shaft}\right) \tag{5.1}$$

| | | | |
|---|---|---|---|
| Where: | A | = | Area of the shaft ($m^2$) |
| | U | = | Heat transfer Co-efficient (heat transfer co-efficient, $W/m^{2o}C$) |

By separating the variables and using the initial values $T_{shaft} = T^0_{shaft}$ at $t = 0$, the shaft temperature can be solved using the following equation:

$$T_{shaft} = \frac{1}{a}\left[\left(aT^0_{shaft} - b\right)\exp\left(\frac{-a\delta t}{C}\right) + b\right] \tag{5.2}$$

where $a = U_{shaft}A_{shaft} + m_{air}cp_{air}$ and $b = U_{shaft}A_{shaft}T_{rock} + m_{air}cp_{air}T_{inletair}$

The values of the thermal capacity (C) and the heat transfer coefficient ($U_{shaft}A_{shaft}$) can be calibrated using the measured temperature profiles for each shaft. The model for the workings section (Nodes 3 to 4) is shown in Figure 5.6c. The symbol Q represents the heat generated by mining activities, and the heat transfer from the surrounding rock to the air in the workings. Q will change throughout the day, depending on mining activities, but it was found that there was a standard daily profile. Q consists of two parts: $q_s$ and $q_l$, with $q_s$ being the sensible and $q_l$ the latent heat transfer.

$$Q = q_s + q_l \tag{5.3}$$

with: $q_s = mc_p(t_o - t_i)$ and $q_l = m(W_o - W_i)i_{fg}$

| | | | |
|---|---|---|---|
| where: | m | = | Mass flow of the air through the workings (kg/s) |
| | $c_p$ | = | Heat capacity of the air (kJ/kg.K) |
| | $t_o$ | = | Temperature of the air at the return from the workings (°C) |
| | $t_i$ | = | Temperature of the air at the inlet of the workings (°C) |
| | $W_o$ | = | Humidity ratio of the air at the outlet of the workings (kg/kg) |
| | $W_i$ | = | Humidity ratio of the air at the inlet of the workings (kg/kg) |
| | $i_{fg}$ | = | Enthalpy of the air (kJ/kg) |

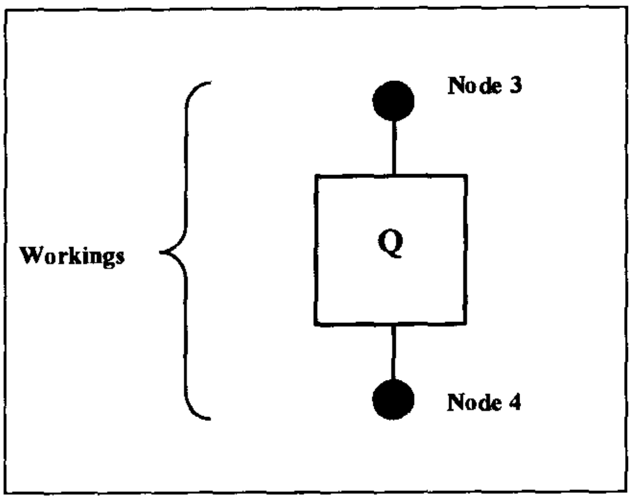


**Figure 5.6c: Schematic diagram of the underground workings area**

By calculating a suitable daily average for Q from the measured data, it was possible to predict the average reject temperature from the workings. The inlet temperatures and humidity ratio are known from the shaft/decline model between Nodes 2 and 3. With the heat generated (Q) known, and with the help of psychrometric formulas, the outlet (reject) temperature (wet- and dry-bulb) and the humidity ratio could be determined. It was assumed that no mass transfer took place.

## 5.7 Underground pumping system model

As mentioned before, the clear-water pumping system, although it did have the potential for saving costs and for having new optimized schedules designed for it, would not have an impact on the establishment of a safe and healthy working environment through the optimization of the resources associated with it. The effect of optimizing clear-water pumping through optimized scheduling was therefore investigated only to show its importance and cost-saving ability, and for the sake of completeness.

Cooling-associated pumping was excluded from this simulation. (In this case it was regarded as negligible, but it can have a large effect, depending on the amount of cooling needed). For the purpose of this exercise, it was assumed that the pumping associated with the refrigeration process would not have a real impact on the actual cost. The optimization of cooling related pump requirements were therefore assumed as complete, and the values of pump power and pump capacities as currently used on the mine were used in the simulation model.

However, as mentioned before, there is potential for load shifting on the clear-water pumping. Accurate prediction of the power consumption of the pumps is essential for any load-shifting calculations. To arrive at a realistic operating schedule for clear-water pumping, the following have to be predicted accurately:

- Settler flows
- All clear-water dam capacities
- Every pump flow

Each of the items mentioned was dealt with and the way in which this was done in the simulation is described. With regard to dam capacities, not all the information was available, and a few assumptions had to be made. These were:

- The settlers had enough capacity to ensure a constant daily flow rate to the level 255 clear-water dam
- The refrigeration plant daily make-up water demand was divided by 24 to find the average flow per hour
- The daily drinking water demand was divided by 24 to find the average flow per hour
- All the pumps at one pump station deliver the same flow. This flow was taken as the average flow of the individual pumps

By using these assumptions, together with the number of pumps active on each level every hour, the dam capacities could be predicted by simulation. The assumptions made above were real indicators of the actual situation underground and could be used as correct for the simulation.

## 5.8 Energy (electrical) consumption

Just as the flow per pump was taken as constant, the energy consumption per pump at a pumping station was taken as the average power consumption of all the pumps at the pumping station. The energy consumption was then calculated by multiplying the power absorption of each pump by the time the pumps were active.

## 5.9 Underground refrigeration system model

It was required that the simulation model must be able to predict the inlet and outlet water temperatures to and from the refrigeration plant accurately. This model included different smaller models, each characterising one of the components of the refrigeration system.

These components are the refrigeration machines (refrigeration plants), the condenser and the evaporator spray ponds. The compressors, which are part of the refrigeration machines, are the only simulation component that consumes electrical energy. The water pumps in the system (as mentioned before) were ignored for the purposes of the simulation, since their power consumption is relatively small.

The accurate prediction of the compressor power consumption of refrigeration plants is essential for any load-shifting calculations. To predict a realistic operating schedule for the refrigeration plants, the thermal performances of the evaporator and condenser spray ponds had to be predicted accurately.

At this stage it should be noted that the type of compressor used was irrelevant (i.e. multistage compression with flash gas by pass, single stage etc) was used. What is relevant is the effect, seen through the simulation, that the compressor had in the total cooling process (in terms of energy and costs).

By using heat flow and mass flow characteristics, formulas and calculations, the cooling capacity of the evaporator spray ponds, the compressor power and the condenser spray ponds were *predicted* and compared with actual measured findings on the mine. The correlation coefficients were calibrated using measured data. Details of the various formulas used are shown in the section that follows. The cooling capacity of the evaporator spray ponds was determined through the following function:

$$Q_e = ((b_1 t_{loe} + b_2) t_{wb} + b_3 t_{loe} + b_4) m_{max}^{0.37} \left( \frac{m_{sp}}{m_{max}} \right) \qquad \ldots\ldots\ldots\ldots\ldots(5.4)$$

Where: $Q_e$ = Cooling capacity of the evaporator spray ponds (kW)

$b$ = Correlation coefficients derived for cooling capacity

$t_{wb}$ = Wet-bulb temperature of the air through the spray ponds (°C)

$t_{loe}$ = Temperature of the water leaving the evaporator (°C)

$m_{max}$ = Maximum waterflow through the spray ponds (kg/s)

$m_{sp}$ = Waterflow through the spray ponds (kg/s)

The compressor power was then determined using the following formula:

$$P_{wr} = \frac{m_{lie} m_{lic} c_p (a_0 + a_1 t_{lic} + a_2 t_{lie}) - Q_e (m_{lic} c_p m_{lie} - m_{lie} a_1 - a_2 m_{lie})}{m_{lie} a_1} \tag{5.5}$$

where $P_{wr}$ = Compressor power (kW)

$m_{lie}$ = Mass flow of the water entering the evaporator (kg/s)

$m_{lic}$ = Mass flow of the water entering the condenser (kg/s)

$c_p$ = Specific heat capacity of the water (J/kg.K)

$a$ = Correlation coefficients derived for compressor power

$t_{lic}$ = Temperature of the water entering the condenser (°C)

$t_{lie}$ = Temperature of the water entering the evaporator (°C)

To complete the cycle, the cooling capacity of the condenser spray ponds was calculated as follows:

$$Q_c = ((c_1 t_{loc} + c_2) t_{wb} + c_3 t_{loc} + c_4) m_{max}^{0.525} \left( \frac{m_{sp}}{m_{max}} \right) \tag{5.6}$$

where: $Q_c$ = Cooling capacity of the condenser spray ponds (kW)

$c$ = Correlation coefficients derived for cooling capacity

$t_{wb}$ = Wet-bulb temperature of the air through the spray ponds (°C)

$t_{loc}$ = Temperature of the water leaving the condenser (°C)

$m_{max}$ = Maximum water low through the spray ponds (kg/s)

$m_{sp}$ = Waterflow through the spray ponds (kg/s)

where:

$$t_{lec} = t_{lic} - \frac{Q_e + Pwr}{m_{lic} c_p} \quad \text{and} \quad t_{lee} = t_{lie} - \frac{Q_e}{m_{lic} c_p}$$

## 5.10 Airflow model

A certain airflow is needed in the mine to maintain the correct amount of fresh air for a safe, healthy and productive working environment. The ventilation fans are responsible for the airflow through the mine. To be able to calculate the potential saving in electricity on the fan power, it was necessary to develop a simulation model that could predict underground airflow under changing fan conditions (variable speed drive fans).

The airflow network underground was simplified and represented by a flow diagram. This flow diagram works on the same principle as an electrical circuit. The electrical resistances "replace" the airflow resistances through the shafts and airways. The pressure created by the fans "replaces" the power sources. The layout of the airflow circuit is shown in Figure 5.10.

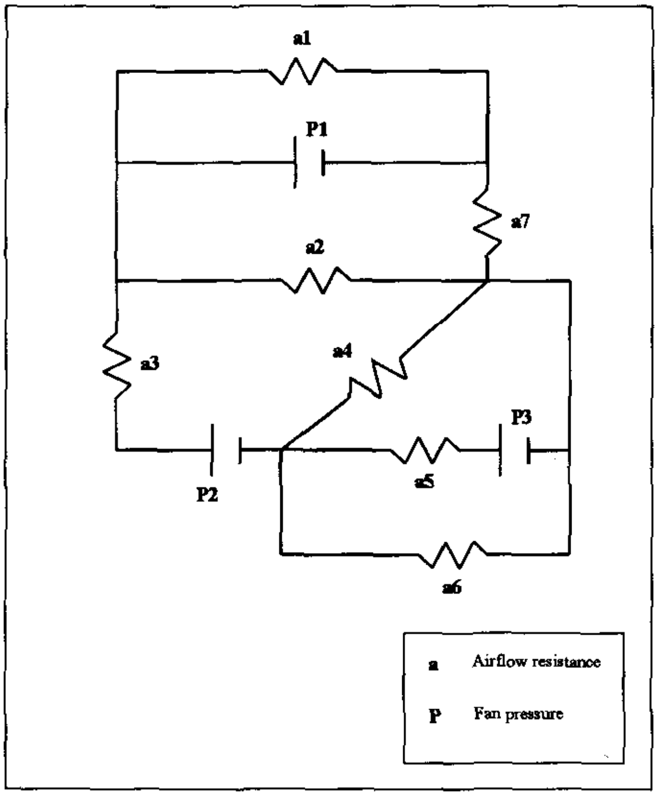


**Figure 5.10: Schematic diagram, underground airflow simulation model for Target**

The symbols shown in Figure 5.10 represent the following:

| | | |
|---|---|---|
| P1 | = | Pressure difference created by the surface fan |
| P2 | = | Pressure difference created by the level 255 booster fans at the evaporator spray ponds |
| P3 | = | Pressure difference created by the level 208 booster fans |
| a | = | Airflow resistance of the airways between each node in the circuit (A node is where two or more airways come together at one point) |

As with any electrical circuit, it was now possible to generate a series of equations that could be solved simultaneously and, in that way, to calculate all the airflows and fan pressures in the circuit. This was done by using Kirchhoff's current laws for electricity flow, revised for airflow and air pressures. These pressure drops through each airway must then be overcome by the pressure created by the ventilation fans.

The pressure differences created by the ventilation fans were calculated using a fan model for each of the ventilation fans, taking into account the rotational speed of the fan, impeller diameter, pressure head coefficient, correlation coefficient, flow coefficient, mass flow of the air and fan efficiency. By these means the air power required (pQ) could be determined and, through that, the electrical input power of the fan motor. The airflow and air pressures at all the strategic places in the mine could now be solved by using Kirchhoff's current laws on the circuit shown in Figure 5.10.

For the airflow, the algebraic sum of all the airflow quantities at any node in a circuit equals zero and for the air pressure, the algebraic sum of all the pressure differences around any closed path in a circuit equals zero as well. The pressure drop through each airway is a function of the resistance of the airway and the quantity of air that flows through the airway.

Pressure drop:

$$\Delta P = RQ^2 \tag{5.7}$$

where: R = Resistance of the airway ($Ns^2/m^8$)

Q = Quantity of air through the airway ($m^3/s$)

Fan model:

$$P = K_h N^2 D^2 \tag{5.8}$$

where: P = Pressure created by the fan (kPa)

$K_h$ = Dimensionless pressure head coefficient

N = Rotational speed of the fan (r/min)

D = Impeller diameter of the fan (m)

and $K_h = a_0 + a_1 K_f + a_2 K_f^2$ and $K_f = \frac{m_a}{ND^3}$

where: a = Correlation coefficients for $K_h$

$K_f$ = Dimensionless flow coefficient

$m_a$ = Mass flow of the air (kg/s); derived from $\rho Q = kg/m^3 \times m^3/s = kg/s$

and the fan efficiency

$$\eta = b_0 + b_1 K_f + b_2 K_f^2$$

where b = Correlation coefficients for fan efficiency

The fan power can now be determined as follows (meaning of symbols as used before):

$$Power_{fan} = \frac{QP}{\eta} \tag{5.9}$$

In designing the above, the minimum air velocity requirements for stopes and development ends was dealt with as follows: as a guideline, the velocity in stopes was considered to be 1 m/s and in development ends not less than 0,15 $m^3/s/m^2$.

In the case of Target mine, the temperature of the air flowing into the entire underground workings and the return temperature from the workings were to be considered for the simulation. This meant that the effect of the various air velocities in the stopes and development ends was included in the final return temperature. For the purpose of this simulation, the total amount of airflow supplied to the whole work area was considered, which had an impact on the conditions set underground (the heat-removal capacity and the eventual design reject temperature).

The four items described above (heat flow and cooling, pumping, refrigeration and air supply) combine all the parameters applicable in the design of a safe and healthy working environment. It is the interaction of these parameters and the interrelated costs associated with each that have to be optimized by developing a predictive simulation tool, using active control measures (such as for air temperature, waterflow rates and airflow quantities). It was now necessary to look at detail pertaining to the air-cooling power and to what extent it could be incorporated in the actual optimization.

## 5.11 Boundaries and constraints associated with simulation optimization

Various boundaries and constraints are associated with the basic elements of optimization, some of which have been mentioned before. These are briefly discussed in the section that follows. This will confirm their importance in the integrated optimization process. The main boundaries and constraints are minimum air temperatures, minimum and maximum air velocities, dam capacities, air losses, variables, Eskom tariffs and the objective function. As a conclusion to the total integrated approach, the effects of contaminant control on the optimization will be included as well.

### 5.11.1 Boundaries

The boundaries are those values that are not dependent on any of the outputs of the models, but do influence the models directly or indirectly. The boundaries are values that have to be calibrated from time to time. The boundaries in this case are the number of air leaks through the airways and Eskom's electricity tariffs.

### 5.11.2 Constraints

The constraints are the values that impose the physical operational limits of the system on the optimization. The accurate implementation of these limits is essential to ensure that the outputs of the optimization are practical and can be implemented. The constraints applicable to every system will now be discussed.

#### *5.11.2.1 Constraints applicable to the refrigeration plant*

The constraints on a refrigeration plant are the number of refrigeration units available and their refrigeration capacity. Other constraints are the maximum waterflow and airflow through the spray ponds. At Target, at the time of the investigation, there were 5 active refrigeration units. The total maximum refrigeration capacity of these is 18 MW. The maximum waterflow rate through the evaporator spray ponds is 380 ℓ/s. The maximum waterflow through the condenser spray ponds is 740 ℓ/s and there are four condenser spray ponds and four evaporator spray ponds available.

##### *5.11.2.2 Constraints applicable to underground conditions*

The suggested (ideal) reject temperature at the return from the workings was given as 25,5°C (wet-bulb). The maximum temperature at the outlet of the workings during the trial was 27,5°C. The ideal airflow through the workings was suggested as 240 $m^3/s$. However, these figures were only based on the physical heat-removal capacity of the air and the setting of a comfortable working temperature (25,5°C). In planning the airflow requirements for Target mine, it was suggested that a minimum of 225 $m^3/s$ was advisable to be able to cater for heat removal and deal with pollutants such as diesel fumes, gases, dust and radiation. The minimum air-cooling power to design for was set at 300 $W/m^2$.

### 5.11.3 Variables

The variables are the values that are changed to minimise or maximise the objective function, while still satisfying the constraints. In the optimization model, the fan speeds and the set point of the refrigeration units are variables.

### 5.11.4 Objective function

The objective function is the value that is dependent on all the variables that must be optimized. In this case, the total energy consumption (kW) for one hour is the value that must be minimised, while still satisfying all the constraints.

## 5.12 Savings potential

With the completion of the real-time simulation the optimized simulation can be done on the basis of the original simulation. It will be possible to compare the actual electricity costs (running costs) associated with the original simulation and the optimized schedule.

### 5.12.1 Savings calculation

All the savings calculations were based on Eskom's NIGHTSAVE energy tariff. The optimum cost was compared with the cost on the actual daily energy profile as measured in 2002. These savings were extrapolated to calculate the monthly savings and then multiplied to determine the possible annual savings.

The simulation model was set up to simulate actual conditions on the mine (i.e., air temperature, airflow, compressor power, heat flow and heat exchanged in the evaporator and condenser ponds) exactly. The current actual cost of energy was then calculated. After optimization, the cost of energy was calculated again and these two values compared. The savings potential was the difference between the current and optimized energy costs.

## 5.13 Formula for air-cooling power

Previous sections in this thesis dealt with all the aspects relevant to the definition of ACP: how the term originated, its use as a heat stress index, its shortcomings and the need to use it to optimize the energy requirements for the optimum supply of temperature-controlled air underground. Stewart used several temperature and airflow results to derive a graph for establishing the ACP related to each combination of air velocity and air temperature [6].

The results from his report (the table with various air temperatures and air velocities) are shown in Table 5.13a. The ACP was calculated for wet-bulb temperatures and air velocities in the ranges of 25 °C to 35 °C and 0,2 to 4,5 m/s – the ranges that are normally encountered in the underground working environment.

Stewart showed the results in increments of 0,1 for temperature and velocity, but for the purpose of this thesis, temperature increases in increments of 1°C are shown and air velocity increases in increments of 0,5 m/s. Stewart also noted that if the work rate of a worker exceeded the limit value of cooling power as specified in his results, there was potential danger. From these results (obtained from calculations) an ACP graph, shown above as Figure 2.6.1a, was derived. Details of Stewart's ACP results are shown in Annexure S.

**Table 5.13a: Summary of ACP results (Stewart [6])**

| Wet-bulb temperature (°C) | Air velocity (m/s) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0.5 | 1.0 | 1.5 | 2.0 | 2.6 | 3.0 | 3.5 | 4.0 | 4.5 |
| 25.0 | 335 | 376 | 402 | 421 | 438 | 447 | 457 | 465 | 472 |
| 26.0 | 317 | 356 | 381 | 399 | 415 | 424 | 433 | 440 | 447 |
| 27.0 | 299 | 335 | 359 | 376 | 391 | 399 | 408 | 415 | 421 |
| 28.0 | 280 | 314 | 336 | 352 | 366 | 374 | 382 | 389 | 395 |
| 29.0 | 260 | 291 | 314 | 327 | 340 | 347 | 355 | 361 | 367 |
| 30.0 | 240 | 268 | 287 | 301 | 313 | 328 | 327 | 333 | 338 |
| 31.0 | 206 | 244 | 262 | 274 | 285 | 291 | 298 | 303 | 308 |
| 32.0 | 171 | 206 | 232 | 246 | 256 | 261 | 267 | 272 | 276 |
| 33.0 | 134 | 162 | 183 | 199 | 215 | 224 | 233 | 240 | 243 |
| 34.0 | 100 | 116 | 131 | 143 | 155 | 161 | 168 | 174 | 180 |

On the basis of Stewart's calculations, it was necessary to derive a simplified formula, which could be used in the optimized simulation model. This was done to incorporate the idea of optimizing the ACP supplied for a specific work area. Table 5.13b shows some of the results for the ACP as derived from this new formula by Swart and a comparison with Stewart's results [3]:

**Table 5.13b: Correlation of ACP results with simplified formula**

| Wet-bulb temperature (°C) | Air velocity (m/s) | ACP | | % fault |
|---|---|---|---|---|
| | | Stewart | "simulation" | |
| 25.0 | 1.0 | 376 | 377 | 0.3 |
| 26.0 | 1.5 | 381 | 382 | 0.3 |
| 27.0 | 4.0 | 415 | 421 | 1.4 |
| 28.0 | 3.0 | 374 | 382 | 2.1 |
| 29.0 | 2.0 | 327 | 333 | 1.8 |
| 30.0 | 3.0 | 320 | 324 | 1.2 |
| 31.0 | 2.6 | 285 | 283 | 0.7 |
| 32.0 | 4.0 | 272 | 264 | 2.9 |
| 32.5 | 3.0 | 240 | 230 | 4.2 |

From the above it can be seen that the differences in ACP values read off Stewart's graph and those derived from the new formula are within acceptable limits. The "new" formula could thus be used in the simulation model.

The investigation was now at the stage where the simulation models for cooling, airflow and pumping (with cooling-related pumping assumed to be optimized) could be integrated by applying the concept of optimization of the ACP using the formula derived by Swart. *Herein lies the uniqueness of the investigation – ACP has never before been used in a simulation model for the optimization of air supply and temperature, incorporating the electricity consumption associated with it.*

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# CHAPTER 6

# ANALYSIS AND VERIFICATION OF THE SIMULATION RESULTS

# 6. ANALYSIS AND VERIFICATION OF SIMULATION RESULTS

## 6.1 Introduction

In this chapter the results of the simulation, and of the optimized simulation results, will be discussed in detail. The fact that the workings are reached by two declines and the air is returned through declines as well, makes it simple to monitor the intake and return temperatures from the workings. Due to the relatively high virgin rock temperatures, the air reaches the evaporator spray ponds on 255 level at a fairly constant temperature, independently of the surface ambient air temperature. This was confirmed by the temperature readings taken underground.

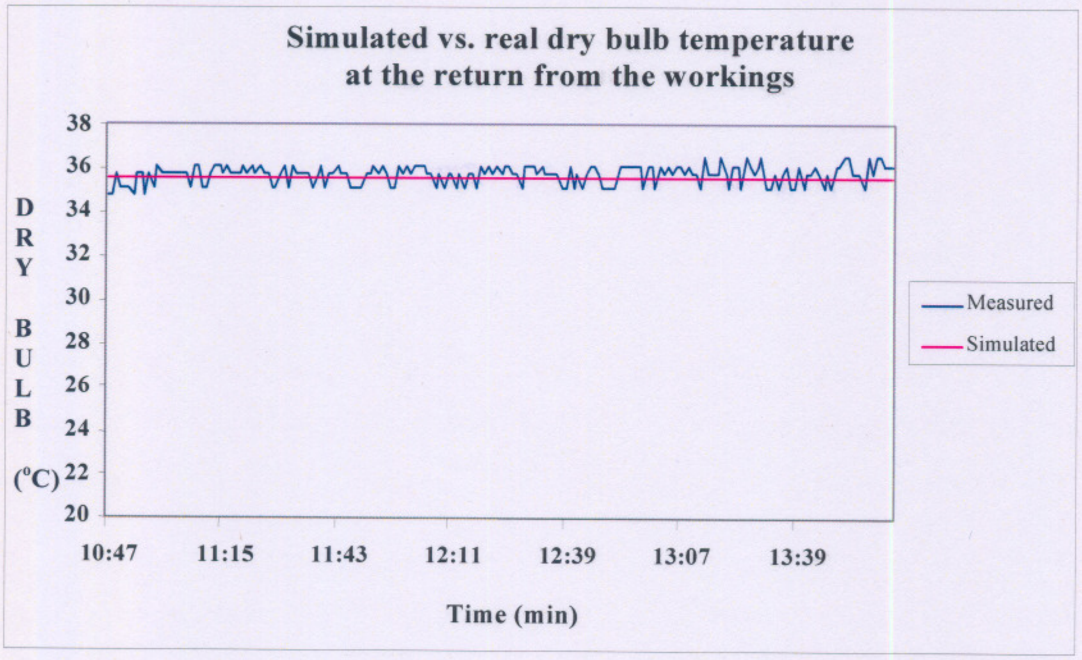
Knowing this, it was possible to simplify the simulation model to turn it into a steady-state model. This means that the simulation needs to be run only once in a day to predict the temperatures underground. The temperature of the air supply reaching the evaporator spray ponds could therefore be accepted as constant throughout the day. It was expected that the wet-bulb temperatures of the return air from the workings would change, due to different mining activities taking place at different times [1].

The simulation was done while one of the condenser spray ponds was shut down. This was an ideal time to test the model as the underground conditions are then different from what they would normally be. The model was calibrated with measurements taken under normal conditions and then verified under abnormal underground conditions.

## 6.2 Simulation results highlighting temperature comparison

The reject wet-bulb and dry-bulb temperatures were measured at the main return from the workings. The simulated reject temperature (temperature of the air from the workings) was dependent on the results obtained from the airflow model and refrigeration model. The two models were integrated after they had been calibrated with measured data. After the calibration and integration of the models, the simulation results were obtained and these were compared with new measured data from underground.

The simulated values compared well with the actual measured values at the return from the workings. The comparison was made for a period of three hours. The maximum deviation of the simulated dry-bulb temperature from the actual measurement was 1,01°C. This represents an error of 2,8% and is acceptable. Figure 6.2a shows the results of the simulated dry-bulb temperatures versus the actual dry-bulb temperatures measured.




**<u>Figure 6.2a</u>: Simulated versus actual dry-bulb temperatures**

Figure 6.2b shows the simulated versus measured results of the wet-bulb temperature of the return air from the workings. This comparison was also made for three hours. The maximum deviation was 1,87°C, which is equal to an error of 5,6%. This proved to be acceptable as well. The simulation model predicted the return air wet-bulb temperature well, but this temperature was on average a little lower than what was measured, as can be seen in Figure 6.2b.

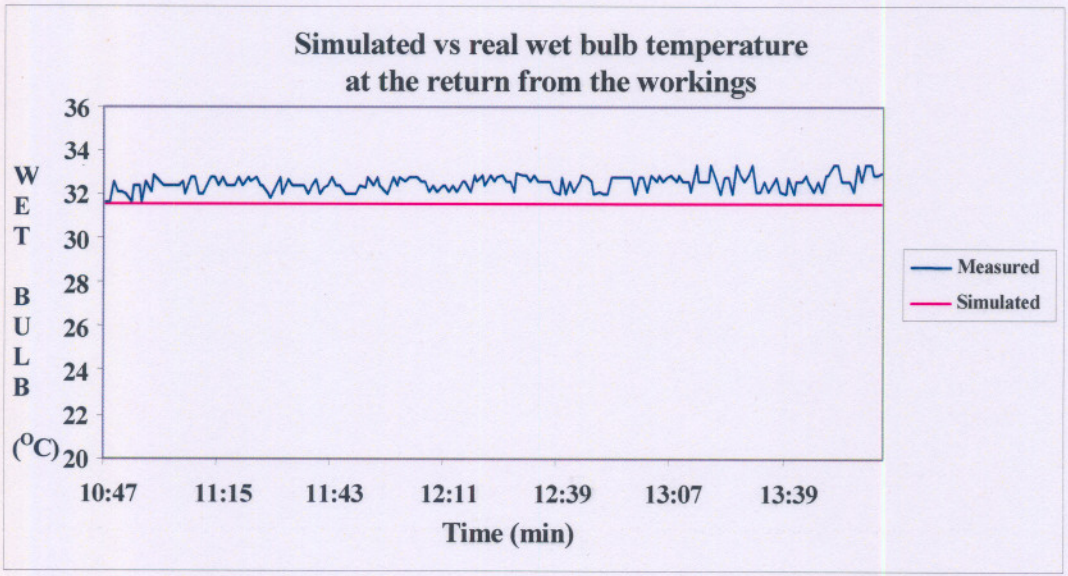



**Figure 6.2b: Simulated versus actual wet-bulb temperatures**

The above wet-bulb and dry-bulb temperatures were all predicted at an air quantity of 190m$^3$/s through the workings, which was the same airflow measured when the temperatures were taken.

## 6.3 Simulation results highlighting compressor power comparison

The compressors were also simulated at Target mine. The correlation coefficients were calibrated using measured data. The simulation results of the compressor power are shown in Figure 6.3. The average error was 1,15% and the maximum error was 2,58%. This is acceptable as an error of less than 10% for 80% of the time is the norm.

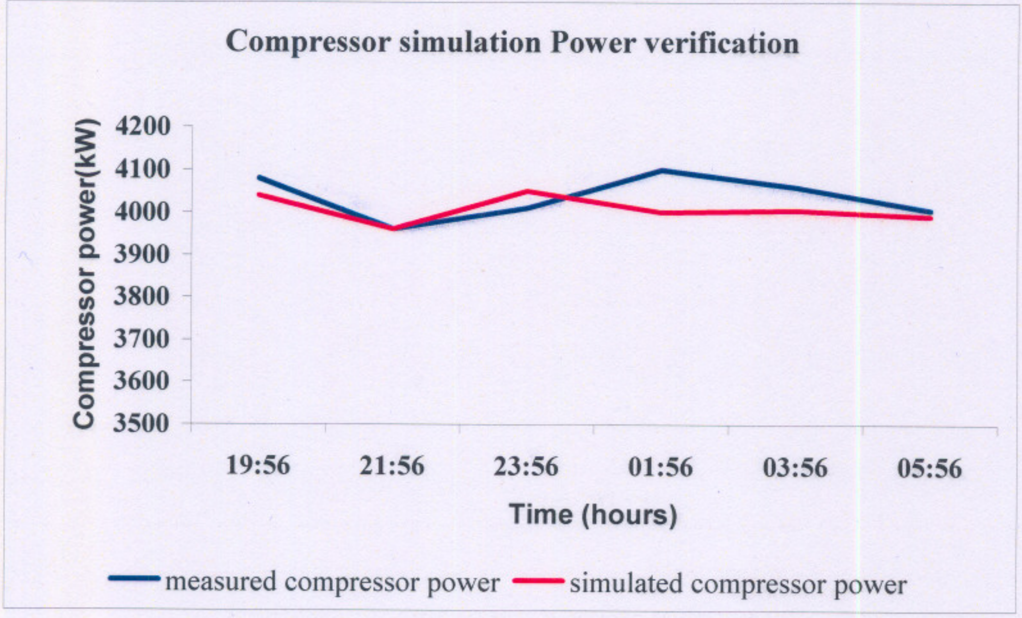


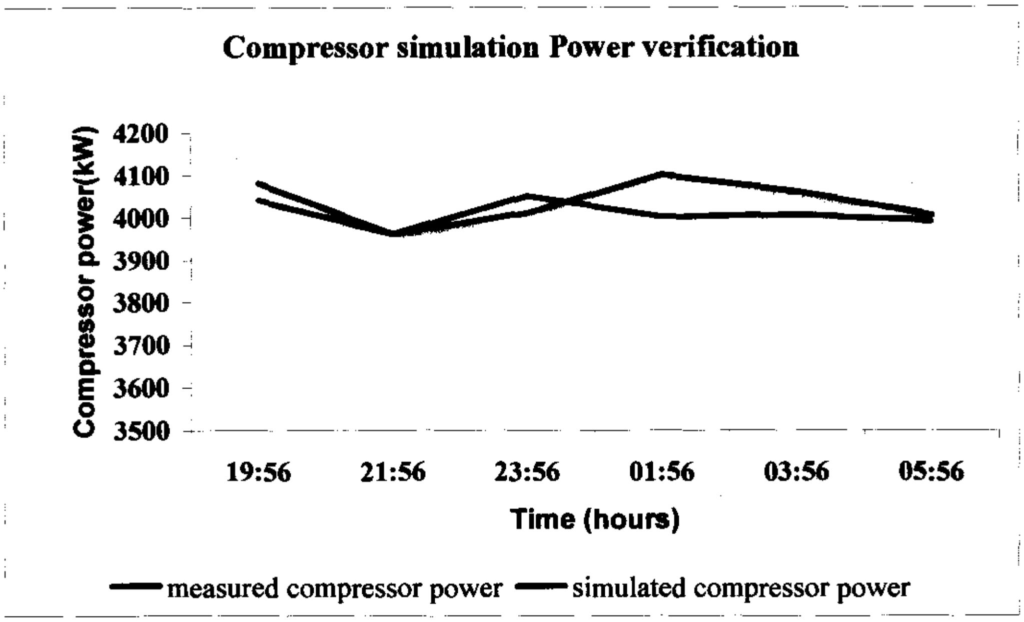

**Figure 6.3: Simulation of refrigeration plant compressor power**

## 6.4 Overview of the optimization model

The above findings show that it is indeed possible to simulate the real-time conditions underground accurately, and that the simulation yielded temperature and airflow parameters that would give reject temperatures of acceptable accuracy. The temperature of the air leaving the workings is a direct result of the inter-relationship between the quantity of the air and the actual refrigeration that takes place. These two parameters are also closely related with regard to the cost of providing them.

The actual operating costs (with specific reference to electricity-related costs) associated with establishing the said conditions can now be confirmed through the simulation model. The running costs to establish acceptable thermal conditions will be for the fans and the fridge plant.

The fridge plant cost relates to the cost of the electrical input power to the compressor. Having established the simulation model on the basis of the relevant parameters, it was now possible through optimized simulation design to establish what the actual preferred conditions would be like, and to compare these new optimized conditions for their cost-saving potential.

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The objective of the optimization simulation is to maximise the use of the refrigeration unit by optimizing the compressor electrical input power and the electrical input power to the fan. The design reject temperature for the underground conditions has been set at 25,5°C. This temperature is dependent on the air quantity available for heat removal, and the amount of refrigeration supplied. The main objective is to provide this required design at a minimum cost. This can be done by manipulation of the fan rotational speed and the set point of the refrigeration unit.

The optimum would be the point where the combination of air quantity (through changing fan speed) and the refrigeration unit set point, produce a resultant 25,5°C reject temperature from the workings, at optimized energy cost, without sacrificing health and safety objectives.

A further optimization study was done to limit the air-cooling power in the workings to 300 $W/m^2$. This value of 300 $W/m^2$ was identified through previous research as an acceptable guideline for establishing a safe and healthy environment in its ability to counteract the effect of heat on a worker. It was also noted that as long as the metabolic work rate of a worker remained below the ACP supplied, there would be no danger of the worker falling victim to heat-related illnesses. This value would be the minimum design air-cooling power available in the workings

The objective of this simulation was to ensure a minimum air-cooling power of 300 $W/m^2$ at the return from the workings by optimizing the fan speeds and the refrigeration unit set point, which would result in the minimisation of the energy cost. It was at no time the intention to reduce airflow quantities below acceptable amounts, or to increase temperature to reduce costs, but rather to confirm that there was a definite optimum point in terms of the quantity and temperature of the air supplied.

The point was to prove not only that the actual conditions could be simulated successfully, but also that in certain circumstances there was an oversupply of resources. It was therefore possible for these resources to be optimized in terms of certain physical requirements (in this case temperatures and air velocities) and the running costs associated with them.

## 6.5 Results of optimized simulations

From the original simulation model for Target, it was now possible to optimize the model by the inclusion of certain design requirements. The first optimization that was done was to optimize the airflow and cooling based on current settings on the mine. The second optimization that was done was to optimize the ACP, and the third was the optimization of the clear-water pumping at Target mine.

### 6.5.1 Optimizing airflow and cooling

The first optimization study was done on the optimization of the compressor motor input power of the refrigeration plants and the motor input power of the ventilation fans. The reject temperature of the return air was kept at a wet-bulb temperature of 25,5°C. The airflow quantity as designed was 225 $m^3/s$, but through the optimized simulation it was shown that the quantity could be lowered to 197,5 $m^3/s$ if the temperature of the water delivered at the evaporator was lower, which would mean cooler temperatures in the work areas.

About 1 400 kW of energy could be saved through this optimization This saving was arrived at from an increase in the kW usage of the original refrigeration plant from 3 900 kW to 4 400 kW, and a decrease in the kW usage of the fans (because of the better efficiencies possible through better air-control methods) from 4 300 kW (the original fan motor input power consumption) to 2 113 kW.

Figure 6.5.1 shows how Target can use less energy to maintain the ideal wet-bulb reject temperature of 25,5°C at the return from the workings by optimizing the energy usage of the refrigeration plant and fans. The optimization was done for a 24-hour period. This saving of ±1 400 kW throughout the day results in a possible saving of approximately R1,5 million per annum, based on Eskom's NIGHTSAVE tariff for 2002.

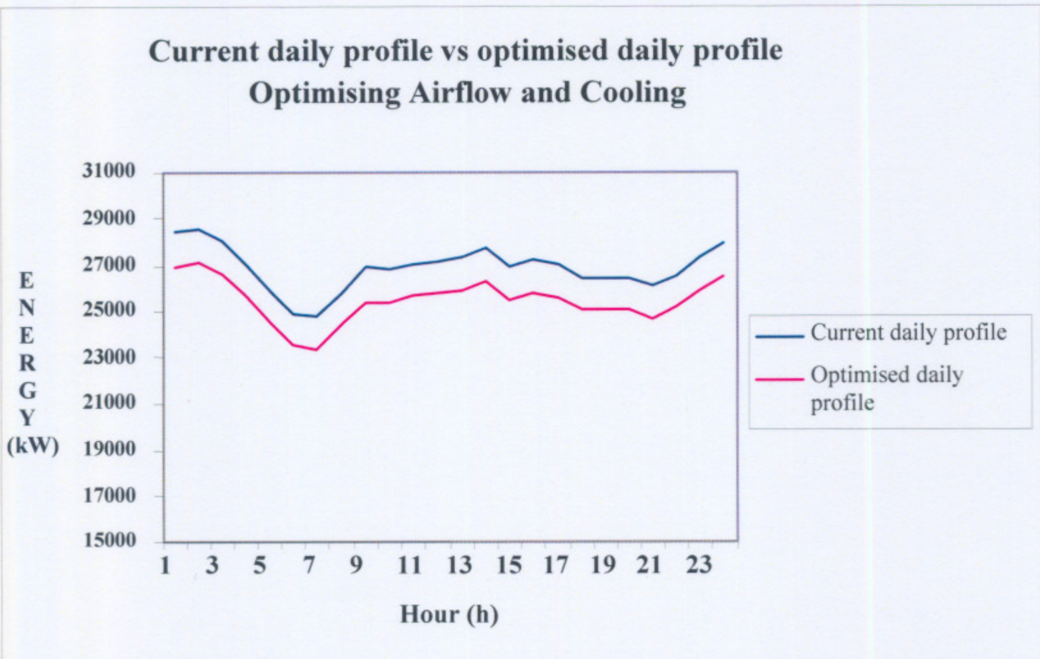


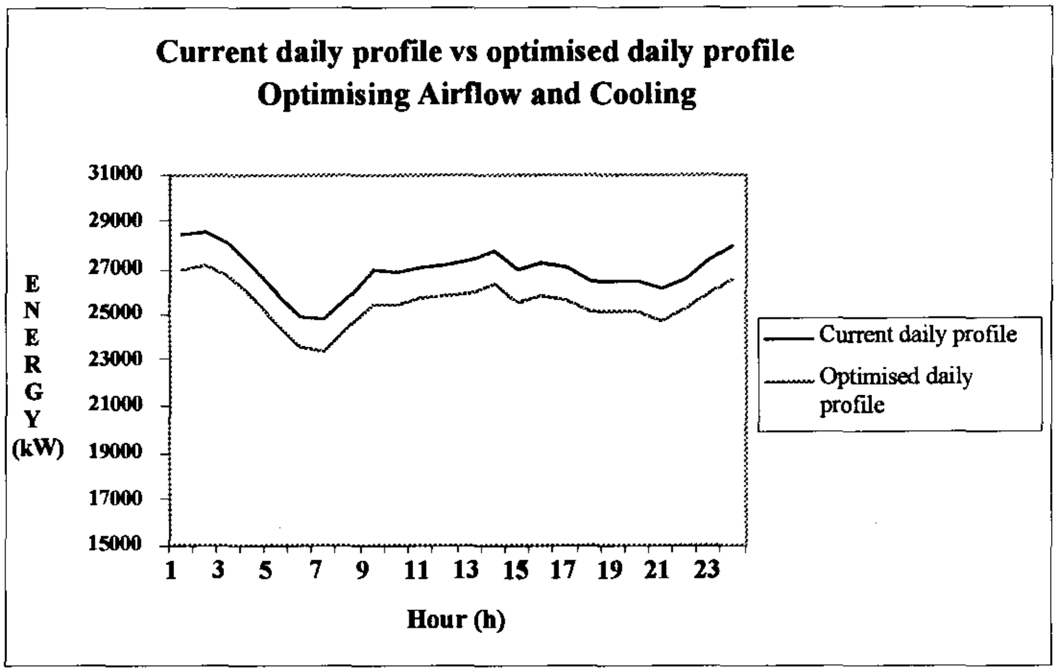

**Figure 6.5.1: Simulated actual profile versus optimized profile for airflow and cooling**

### 6.5.2 Optimizing air-cooling power

The concept of ACP was discussed in detail in previous sections. It is now necessary to establish how this concept could be incorporated into the optimized simulation. The average refrigeration consumption per refrigeration unit was taken as 3 900 kW and the fan power consumption as 4 300 kW.

One of the components of ACP, air velocity, had to be included in the simulation and it was therefore necessary to establish the average velocity through the workings. It was also important to remember that development ends and stopes have different velocities associated with them. An average workplace area for the workings was obtained as 93 $m^2$, which was based on the 210 $m^3/s$ of air available, giving an air velocity of 2,2 m/s for that area.

At this stage it should also be noted that auxiliary fans could be incorporated into specific work areas (not necessarily development ends), which would increase the air velocity and therefore "allow" a higher wet-bulb temperature for the workplace. The airflow through the area (in $m^2$) of each individual workplace is normally easily determined (either through stope faces or in development ends), but in this case the global approach was taken.

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This was necessary to establish an average air velocity through all the workings. This in itself is not necessarily correct for all the work areas, but it gave a starting point for including the concept of ACP in the optimization simulation model. It must be noted that if accurate velocities and areas for specific workplaces are available, the optimization could be even more accurate (through active monitoring and control systems).

This simulation showed a possible reduction of fan motor power (from 4 300 kW to 2 416 kW) and refrigeration compressor power (from 3 900 kW to 3 093 kW), giving a total possible saving of 2 691 kW per day. The reject wet-bulb temperature at the return from the workings was set at 30,3°C, but with airflow of 209 $m^3/s$, the minimum air-cooling power of 300 $W/m^2$ could still be realised.

Figure 6.5.2 shows the potential energy savings through optimizing the airflow and cooling in the mine to maintain a minimum air-cooling power of 300 $W/m^2$ at the return from the workings. It was found that the mine had an unnecessarily high air-cooling power available at the return from the workings. This equates to a saving of R2,6 million per annum, based on the NIGHTSAVE energy tariff from Eskom for 2002.

It must be noted that for an air quantity/refrigeration combination simulation to work, the speed of the fan must be adjustable according to need. In this simulation ACP was used to optimize the cost. If a variable speed drive motor was in fact available, the optimization potential becomes even more feasible. Almost any optimization in which air quantity plays a role can then be built into the simulation and the results can be optimized with the inclusion of any type of constraint.

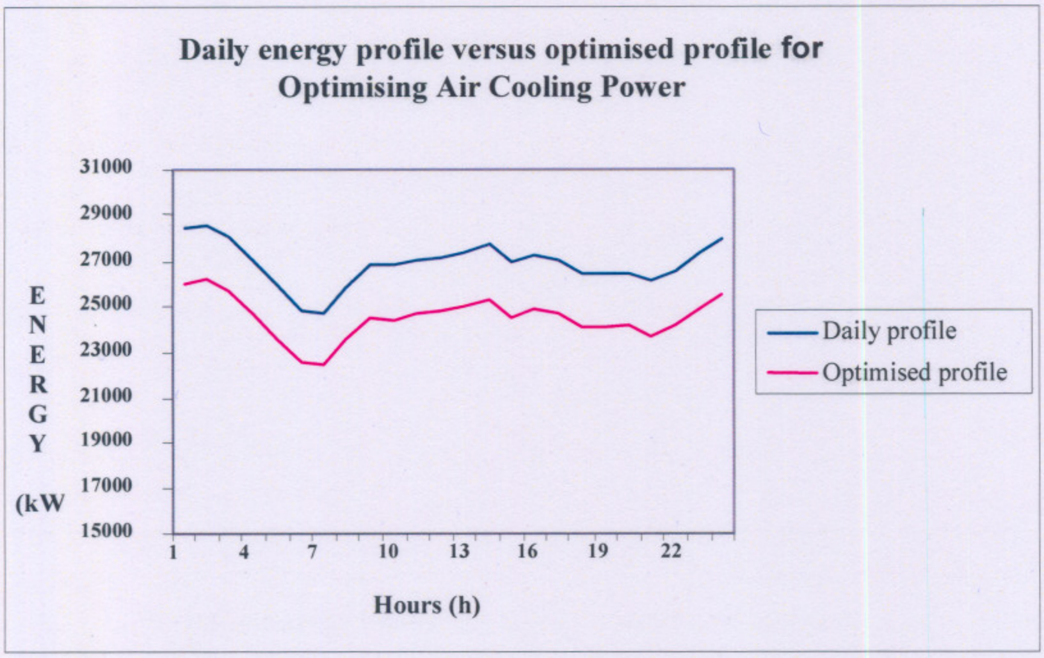



**Figure 6.5.2: Simulated actual profile versus profile optimizing ACP**

## 6.6 Optimizing the clear-water pumping at Target

In a follow-up study done by HVAC International (under the guidance of Christopher Swart), the simulation model and the subsequent optimization model were updated and improved for the clear-water pumping at the mine. The simulation model highlighted deficiencies in the current system and also showed the savings potential. It also showed that if Target were to change to the Megaflex tariff structure, more load-shifting would be possible for the underground clear-water pumping system. Figure 6.6 shows how the load can be shifted from the Megaflex peak periods to the off-peak periods by using optimization.

A total of approximately 12,4 MWh can be shifted daily. This will result in a potential electricity cost saving of R1,65 million per year. In total, this will amount to a saving of from 2 to 4% on their total electricity bill per annum [2]. This saving, however, is subject to Eskom's conversion surcharge. It will also be possible to run this system through an REMS, as at Kopanang mine, because the mine has the infrastructure to proceed with such a system.

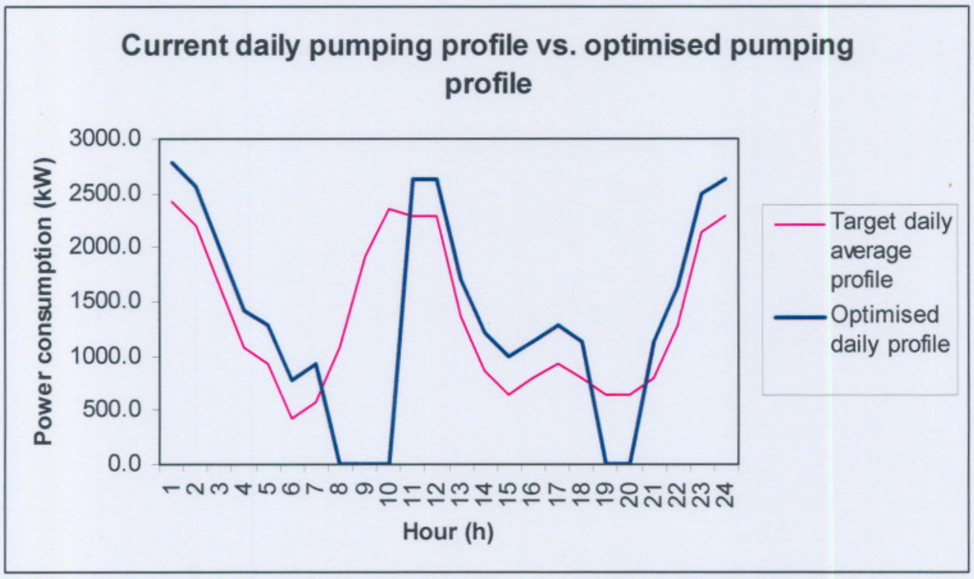



**Figure 6.6: Clear-water pumping optimization**

## 6.7 The inclusion of contaminant constraints in the simulation

At present the requirements for supplying sufficient air to dilute pollutants (such as diesel fumes, gases, etc.) and to remove blasting fumes have not been built into the simulation. However, it would be easy to incorporate them into the simulation model. This will only apply if the mine has a variable speed drive fan. In Chapters 2, 3 and 4 of this thesis several aspects pertaining to variable speed drive fans have been dealt with.

Once a simulation model for a mine has been created, it will be possible to include in the optimization model the various OEL's for specific pollutants. For the simulation programme it just means another constraint to be considered in the optimization process. This is all possible through active monitoring and control.

If through this active monitoring it is detected that conditions are deteriorating (with regard to temperature or contaminant conditions), the simulation model could then readdress the situation by sending an activating signal to the fan motor to increase the speed. This will have the effect of supplying more air and the unacceptable conditions can be dealt with instantaneously.

In South African mines a stage has now been reached where the introduction of variable speed drives should be considered, especially for new mine ventilation planning. This gives much more flexibility in establishing not only a safe and healthy productive environment, but also optimizing the costs associated with it.

With all the active monitoring in mining today, the actual shortfall in the design for ventilation and cooling can be identified much sooner. The most important advantage however, is that with an active simulation programme "linked" to the real-time monitor results, undesirable conditions can be responded too much quicker. This is invaluable for the establishment of safe, healthy and productive working environments.

With these monitored results certain trends can also be established and design guidelines changed before major costs are incurred. These results can then all be incorporated in the real-time integrated predictive simulation model for the optimization of all the relevant parameters assigned to it.

The required quantity of air found through the simulation model and used by Target was sufficient to dilute the normal quantity of air pollutants underground. Personnel on the mine confirmed this. The optimized simulation model however could have confirmed this as well, or showed deficiencies in the design, if contaminant constraints were included in the optimization model.

It is therefore possible that where work areas have to be closely monitored for heat conditions or contaminants, that active control measures could provide the optimized quantity of air (set within certain limits) at the correct temperature as soon as a need was identified. This would give a powerful advantage in the sense that not only would workplaces be *designed* to be safe and healthy, but they would also, through the use of predictive simulation software, be *kept* safe and healthy.

In the past, unsafe and unhealthy work environments were only identified through routine measurement of underground workplaces, but such situations were only attended to in a reactive manner. The most desirable idea of having a model that could actually simulate real-time conditions underground and predict future optimized schedules is now a reality.

In the simulation model designed for Target, it must be noted that the workings referred to were the total mine production area, which made for a unique situation in which to test the simulation since the results would reflect total mine conditions at the return. This could also be regarded as a “macro approach”.

The ultimate goal of the simulation model is to monitor conditions at various strategic positions underground and to include the results from these monitoring stations in the simulation to give real-time results. These results can then be used for calibration purposes. In this way the conditions in the different working areas could be optimized, not only by establishing safe and healthy working conditions, but also in optimizing the running costs associated with the resources that provide these conditions.

## REFERENCES

[1] Swart, C., Development of a Dynamic Computer Simulation System, Minetoolbox, to Reduce the Cost of Cooling in Deep Mines: Additional Case Study 2, TEMM International, G. A. Fourie and Associates, Mining Consultants cc, Synergy, November 2002.

[2] Swart, C., Target Electricity Cost Saving Report, with Emphasis on the Clear-Water Pump System, HVAC International, July 2003.

# CHAPTER 7

# CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER WORK

# 7. CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER WORK

## 7.1 Introduction

In this investigation some real issues with regard to mine environmental engineering have been covered and relevant contributions have been made. In particular, the use of VSD's for motors for fans has been analysed. An integrated approach towards the optimization of air supply, air-cooling and pumping requirements for hot mines has been proposed.

## 7.2 Conclusions

This investigation showed that the simulation and optimization of the energy resources associated with establishing safe, healthy and productive working environments for South African hot mines is entirely possible. The main objective of this study was to prove that it is possible to simulate real-time conditions for an underground deep mine (in terms of air supply and temperature) and through this to identify associated savings possibilities.

Continuous airflow-control measures (through variable speed drives) have not been applied extensively in the South African mining industry. The various aspects pertaining to variable speed drives have been shown extensively in this document and should be explored further by those companies that can benefit from inclusion of a variable speed drive fan. It must, however, be stated that it was the purpose of this investigation to prove that day-to-day real-time simulation and optimization was possible and that calibration through continuous real-time results is also possible. *These possibilities have been proved and verified.*

In the optimization it was shown that air velocities would have to be adapted through changes in the fan motor speeds and through variable inlet vanes (VIV's). No mine in South Africa has variable-speed drive motors for fans, and this possibility was not previously considered because of the high capital cost. VIV's were normally only used when entering a higher or lower production phase. Much energy was and still is being wasted underground.

Through an extensive literature search all aspects pertaining to fan airflow monitoring and control, basic airflow control measures, power saving associated with airflow control measures and a comparison of power saving potential of various airflow control measures have been ascertained.

All aspects pertaining to variable speed drives, including costs, and reasons for non-use in South African mining have been noted. An important part of this investigation is the fact that all financial issues pertaining to variable speed drive motors have been covered. Some of the other basic conclusions for the variable speed drive motor are:

1. The expected increase in the electricity cost above inflation and subsequent higher running cost for fans now makes consideration of variable-speed drives more attractive
2. The capital cost of the variable speed drive for changes in air quantities is less sensitive than an increase in electricity price in future. In the financial analysis for the variable speed drive motor fan, it was also concluded that higher NPV values could be possible, when compared to a fan without the capacity to change speed when needed
3. The components associated with the variable speed drive are rand/euro sensitive (80% of the variable speed drive has to be imported from Europe, which means a strong rand will favour imports
4. The components associated with the motor for the variable speed drive variable speed drive are also rand/euro sensitive, but less so (20% of the motor components have to be imported from Europe)
5. Squirrel cage motors currently used on mines can be converted to include variable speed drives, which will then exclude the cost for the motor (which is approximately R1 million)
6. Various advantages of the variable speed drive motor have been highlighted, of which the most important are:
   - It can be easily introduced in an IPS simulation model package, as it is possible to control the speed of the fan through computerised intervention
   - The flexibility of the variable speed drive in adjusting to changing airflow needs is important
   - The fact that the fan speed can be varied, plays an important role in the IPS process
7. Various payback periods, NPV's, and IRR's have been established for different air quantity distributions. The indications are that even without optimization built into the equation, payback periods of less than 5 years are possible. Positive cash flows are

indeed possible, as over or under utilisation of the fan can be eliminated. With the inclusion of the VSD drive fan in an IPS simulation model, the prospects are even more promising

The characteristics of the most important contaminants found underground have been shown. The effect of different air quantities on contaminant dilution has been highlighted through sensitivity analyses. It was found that dust and gas concentration are sensitive to the amount of air supplied. This was highlighted as important in the establishment of an IPS simulation for mines.

Re-circulation of air was included as an additional method to optimize airflow costs, but it was not included in the IPS model. With a simulation model created for a mine, various options pertaining to re-circulation strategies can also be built into the simulation model and optimized.

Heat removal or rejection is important underground. The amount of heat removed depends on the amount of air available for heat removal and the temperature of the air. In optimizing these two entities (air supply and refrigeration), there is a distinct balance in financial terms. Through the IPS model for Target it was shown that there was indeed a cut-off point for these two entities. To prove this point even further, VUMA results for the ventilation design of a platinum mine in the Rustenburg area were evaluated, and some interesting facts emerged (these results only applicable to this specific layout and design):

1. There is indeed a reduction in branch heat in the production components of the design
2. An increase in air quantity has a small effect on the refrigeration requirements (shows less sensitive for this design)
3. The increase in air quantity is more sensitive to the actual wet-bulb temperature and if the air quantity is reduced, more refrigeration is needed to maintain conditions. This has the effect that the wet bulb temperature reject decreases as the air quantity decreases, because more refrigeration is supplied
4. With an increase in the air quantity, there is also a reduction in the heat for the various branches in the design

Air temperature control methods currently employed on South African mines were shown to be dependent on the amount of air supplied, and on the chilled water temperature supplied by the evaporator. It is highlighted in this investigation that instantaneous air temperature changes will not be as easily possible as in the built environment, unless VSD's for water pumps also form part of the design. In this way the waterflow rates can be controlled according to need. An in depth investigation into this matter was not part of the scope of this thesis.

The inability to change air temperatures instantaneously when needed, however, can be counteracted through active monitoring and control. If an increase in underground reject temperature is identified, it is normally an indication that production has increased. It can also mean that the heat load underground has increased through the use of additional mechanised diesel equipment. Once it has been established where the problem lies, remedial action can be taken. This, however, as mentioned before, is not the ideal way to deal with the situation

Increases in temperature over a period normally show a trend and this information can be included in an IPS model. This will mean that design for substandard temperatures can be included much quicker that anticipated. This once again highlights the inter-relationship between air supply and refrigeration in establishing acceptable underground temperatures.

ACP or TWL is an indicator of comfort level for workers underground, and depends on air velocity and air temperature. It was shown in this investigation that various combinations of air velocity and wet-bulb temperature for a specific design ACP exist.

Although an ACP design figure is used in the optimization, it does not exclude the possibility of including air quantities for specific areas at specific temperatures independent of the ACP required. It is in fact an optimization of air supply and refrigeration on a continuous basis. Wastage through oversupply of air supply and/or refrigeration can be eliminated through the IPS model.

An important part of this investigation was the REMS currently employed in South Africa. It was found that extensive work has been done in the field of real-time energy management for clear-water pumping on some South African gold mines. Research is also currently taking place that considers REMS for other high electricity consumers on mines, such as compressors for refrigeration units, fans, hoists, and metallurgical plants.

For the current investigation, it was necessary to establish to what extent an IPS for ventilation cooling and pumping could be done. This investigation has shown that, varying the air supply plays a significant role in the optimization VCP process.

In the investigation it was also mentioned that one of the objectives of REMS is to eventually have the system automated. In the investigation done for Target, automation of resources pertaining to air supply was found not to be possible yet, but the IPS model can propose optimization schedules, which can be applied manually. This is not the ideal, but will be a step in the right direction. The implementation of REMS for the clear-water pumping at Target, however, can go ahead and it will be possible to automate it as for Kopanang mine.

It was necessary to apply the above findings to a real-time (on-mine) study. The best way to do this was to use a mine in operation and to compare the simulation results with actual results on the mine. From these real-time results, a predictive simulation model was designed that optimized current resources in terms of electricity cost. It was also noted that there was indeed an oversupply of energy for certain work areas on Target mine, and that an investigation into energy wastage was justified.

An important question is now raised. If a VSD is not available, has the investigation served its purpose? The answer is yes, as a real-time simulation model was created and calibrated by using on-mine results. From the simulation results obtained, it was found that real-time conditions underground could in fact be simulated quite accurately (in terms of the temperature of the return air from the workings).

The dry-bulb temperature was simulated within 2,8% of the measured temperature and the wet-bulb temperature to within 5,6% of the measured temperature. The simulation model used the same airflow as was measured at that time. From this simulation, the actual running costs for establishing the prevailing conditions (air supply and cooling) could be determined. This formed the basis for the design of the optimization model. The availability of a VSD fan will therefore enhance the optimization possibilities.

From the optimization model it was proved that an annual saving of R1,5 million (1 400 kW/day) in air supply and cooling (maintaining a wet-bulb reject temperature of 25,5°C at a lower a supply velocity), was possible. If the design was based on establishing an ACP not exceeding 300 W/m$^2$, an annual saving of R2,6 million (2 691 kW/day) would be possible. If this figure is compared with the capital outlay for a VSD, it shows that the payback could be within two years.

It was also proved that by optimizing the clear-water pumping schedule, an annual saving of approximately R1,65 million (1 700 kW) could be realised. The groundwork has been done at Target mine, and REMS for the clearwater pumping can be implemented

It was also shown that there is more potential for load shifting at the refrigeration plant at Target mine, and preliminary studies showed that a realistic amount of 12 MWh could be shifted daily. Furthermore, it was shown that energy wastage is taking place at the refrigeration plant and that large savings are indeed possible. Target mine is currently upgrading its refrigeration plant, after which the matter can be reinvestigated.

This investigation has shown that the REMS developed and implemented for Kopanang mine in the North West Province is a unique mechanism in controlling the scheduling and optimization process. One of its most relevant features is that it can be operated from a control station remote from the mine, with the further capability of overriding the system in the event of an emergency.

Once a simulation model for a mine has been prepared, the OEL's for specific pollutants can be included in the optimization model. For the simulation programme it just means another constraint to be considered in the optimization process. This is all possible through active monitoring and control. If through this active monitoring it is detected that conditions are deteriorating (with regard to temperature or contaminant conditions), the simulation model could then readdress the situation by sending an activating signal to the fan motor to increase the speed. The fan will supply more air and the unacceptable conditions can be dealt with instantaneously. In the current South African mining context this is not possible, as no variable speed drive fans are employed anywhere in the country for reasons discussed before.

The work done in this thesis addressed the issues raised by the Mine Health and Safety Act. It is now indeed in the hands of the companies concerned to evaluate their own systems in terms of the requirements of the Act, but also to optimize the energy resources associated with them.

## 7.3 Recommendations

1. Mines in South Africa can no longer ignore the importance of REMS. The use of simulation tools forms a significant part of the energy-management process and its applicability to other mines should be investigated. This practice could benefit, not only the mines concerned, but also help in energy savings initiatives in South Africa at large.
2. The results of this investigation have indicated that an integrated approach towards the optimization of air supply and cooling demand strategy versus a supply strategy for ventilation, air cooling and pumping requirements for South African hot mines is indeed possible and should be investigated and implemented on mines needing energy saving and optimization.
3. Hot mines in South Africa and the rest of the world should have active simulation programmes in place. These models must relate to real-time conditions underground on a 24-hour basis.
4. It is important to evaluate the information from the SCADA systems on mines and establish trend lines pertaining to temperatures, heat loads and contaminants underground. This information can then be used to update and recalibrate the simulation model continuously.
5. It is important to have an integrated approach towards the optimization of the various resources applicable to ventilation, air cooling and pumping requirements for deep mines, not only from a financial perspective, but also in providing safe, healthy and productive working environments.

## 7.4 Suggestions for further work

In order to extend the work done, the following work should be pursued:

1. More detailed studies on the introduction of variable speed drive fans in specific South African mines. This applies not only to deep hot mines, but to other mines, such as coal mines, as well
2. At present the requirements for supplying sufficient air to dilute pollutants (such as diesel fumes, gases, etc.) and to remove blasting fumes have not been built into the simulation, but it would be easy to incorporate them into the simulation model. These will however be dependent on the mine having a variable speed drive fan

# APPENDICES

# APPENDIX A

**DETAILED VUMA RESULTS FOR PLATINUM MINE LAYOUT**
(Mass flow for different main airflow quantities)

| Branch number | Workplace description | Work area | massflow for different main flows (kg/s) | | | | |
|---|---|---|---|---|---|---|---|
| 18 | LEDGE-2W(BOT) | prod zone | 45 | 44 | 44 | 44 | 43 |
| 21 | ST2-2W(BOT) | prod zone | 35 | 49 | 57 | 75 | 83 |
| 23 | ST3-2W(BOT) | prod zone | 35 | 48 | 57 | 74 | 83 |
| 25 | LEDGE-2W(TOP) | prod zone | 45 | 44 | 44 | 44 | 43 |
| 27 | ST3-2W(TOP) | prod zone | 35 | 48 | 57 | 74 | 83 |
| 30 | ST2-2W(TOP) | prod zone | 35 | 49 | 57 | 75 | 83 |
| 60 | ST1-2E(BOT) | prod zone | 37 | 49 | 58 | 75 | 84 |
| 61 | ST2-2E(BOT) | prod zone | 36 | 49 | 58 | 75 | 84 |
| 62 | ST3-2E(BOT) | prod zone | 36 | 49 | 58 | 75 | 83 |
| 63 | LEDGE - 2E(BOT) | prod zone | 49 | 48 | 47 | 46 | 45 |
| 70 | ST1-2E(TOP) | prod zone | 37 | 49 | 58 | 75 | 84 |
| 72 | ST2-2E(TOP) | prod zone | 36 | 49 | 58 | 75 | 84 |
| 74 | ST3-2E(TOP) | prod zone | 36 | 49 | 58 | 75 | 83 |
| 76 | LEDGE-2E(TOP) | prod zone | 49 | 48 | 47 | 46 | 45 |
| 108 | ST1-2W(BOT) | prod zone | 36 | 49 | 58 | 75 | 84 |
| 110 | ST1-2W(TOP) | prod zone | 36 | 49 | 58 | 75 | 84 |
| 129 | ST1-4W(BOT) | prod zone | 36 | 49 | 58 | 75 | 83 |
| 130 | ST2-4W(BOT) | prod zone | 36 | 49 | 58 | 75 | 83 |
| 131 | ST3-4W(BOT) | prod zone | 36 | 49 | 57 | 74 | 83 |
| 132 | LEDGE-4W(BOT) | prod zone | 50 | 49 | 48 | 47 | 46 |
| 138 | LEDGE-4W(TOP) | prod zone | 50 | 49 | 48 | 47 | 46 |
| 139 | ST3-4W(TOP) | prod zone | 36 | 49 | 57 | 74 | 83 |
| 142 | ST2-4W(TOP) | prod zone | 36 | 49 | 58 | 75 | 83 |
| 144 | ST1-4W(TOP) | prod zone | 36 | 49 | 58 | 75 | 83 |
| 171 | ST1-4E(BOT) | prod zone | 37 | 50 | 58 | 75 | 84 |
| 172 | ST2-4E(BOT) | prod zone | 36 | 49 | 58 | 75 | 84 |
| 173 | ST3-4E(BOT) | prod zone | 36 | 49 | 57 | 75 | 83 |
| 174 | LEDGE 4E(BOT) | prod zone | 50 | 49 | 48 | 47 | 46 |
| 181 | ST1-4E(TOP) | prod zone | 37 | 50 | 58 | 75 | 84 |
| 182 | ST2-4E(TOP) | prod zone | 36 | 49 | 58 | 75 | 84 |
| 183 | ST3-4E(TOP) | prod zone | 36 | 49 | 57 | 75 | 83 |
| 184 | LEDGE-4E(TOP) | prod zone | 50 | 49 | 48 | 47 | 46 |
| 199 | BAC 1 | control man | 750 | 900 | 1000 | 1200 | 1300 kg/s |

# APPENDIX B

**DETAILED VUMA RESULTS FOR PLATINUM MINE LAYOUT**
(Different branch heats for different main air flow quantities)

| Branch number | Workplace description | Work area | Branch heat (kW) | | | | |
|---|---|---|---|---|---|---|---|
| 18 | LEDGE-2W (BOT) | prod zone | 427 | 430 | 433 | 435 | 437 |
| 21 | ST2-2W (BOT) | prod zone | 1320 | 1249 | 1215 | 1158 | 1135 |
| 23 | ST3-2W (BOT) | prod zone | 1311 | 1242 | 1209 | 1153 | 1130 |
| 25 | LEDGE-2W (TOP) | prod zone | 485 | 488 | 490 | 492 | 494 |
| 27 | ST3-2W (TOP) | prod zone | 1383 | 1321 | 1292 | 1249 | 1232 |
| 30 | ST2-2W (TOP) | prod zone | 1390 | 1326 | 1297 | 1253 | 1236 |
| 60 | ST1-2E (BOT) | prod zone | 1255 | 1179 | 1143 | 1085 | 1062 |
| 61 | ST2-2E (BOT) | prod zone | 1249 | 1175 | 1139 | 1083 | 1059 |
| 62 | ST3-2E (BOT) | prod zone | 1241 | 1169 | 1134 | 1078 | 1056 |
| 63 | LEDGE - 2E (BOT) | prod zone | 626 | 571 | 545 | 512 | 501 |
| 70 | ST1-2E (TOP) | prod zone | 1337 | 1265 | 1233 | 1185 | 1168 |
| 72 | ST2-2E (TOP) | prod zone | 1332 | 1261 | 1229 | 1183 | 1165 |
| 74 | ST3-2E (TOP) | prod zone | 1326 | 1256 | 1225 | 1179 | 1162 |
| 76 | LEDGE-2E (TOP) | prod zone | 676 | 625 | 600 | 567 | 556 |
| 108 | ST1-2W (BOT) | prod zone | 1249 | 1177 | 1142 | 1085 | 1061 |
| 110 | ST1-2W (TOP) | prod zone | 1052 | 1070 | 1071 | 1066 | 1063 |
| 129 | ST1-4W (BOT) | prod zone | 1377 | 1296 | 1257 | 1195 | 1170 |
| 130 | ST2-4W (BOT) | prod zone | 1310 | 1237 | 1201 | 1143 | 1119 |
| 131 | ST3-4W (BOT) | prod zone | 1311 | 1236 | 1201 | 1142 | 1118 |
| 132 | LEDGE-4W (BOT) | prod zone | 1340 | 1251 | 1207 | 1150 | 1131 |
| 138 | LEDGE-4W (TOP) | prod zone | 641 | 597 | 575 | 545 | 534 |
| 139 | ST3-4W (TOP) | prod zone | 1381 | 1314 | 1283 | 1236 | 1219 |
| 142 | ST2-4W (TOP) | prod zone | 1381 | 1315 | 1285 | 1238 | 1221 |
| 144 | ST1-4W (TOP) | prod zone | 1381 | 1316 | 1286 | 1239 | 1222 |
| 171 | ST1-4E (BOT) | prod zone | 1328 | 1249 | 1211 | 1150 | 1125 |
| 172 | ST2-4E (BOT) | prod zone | 1332 | 1251 | 1212 | 1151 | 1126 |
| 173 | ST3-4E (BOT) | prod zone | 1312 | 1237 | 1201 | 1143 | 1119 |
| 174 | LEDGE 4E (BOT) | prod zone | 664 | 606 | 578 | 541 | 528 |
| 181 | ST1-4E (TOP) | prod zone | 1394 | 1324 | 1292 | 1244 | 1226 |
| 182 | ST2-4E (TOP) | prod zone | 1397 | 1326 | 1294 | 1245 | 1226 |
| 183 | ST3-4E (TOP) | prod zone | 1382 | 1315 | 1284 | 1237 | 1220 |
| 184 | LEDGE-4E (TOP) | prod zone | 711 | 657 | 630 | 594 | 582 |
| 199 | BAC 1 | control man | -19990 | -19988 | -19984 | -19977 | -19973 |
| | | | 750 | 900 | 1000 | 1200 | 1300 kg/s |

## APPENDIX C

### DETAILED VUMA RESULTS FOR PLATINUM MINE LAYOUT
(Wet-bulb temperatures for different main airflow quantities)

| Branch number | Workplace description | Work area | Wetbulb temperatures (°C) | | | | | |
|---|---|---|---|---|---|---|---|---|
| 18 | LEDGE-2W (BOT) | prod zone | 29.9 | 29.6 | 29.5 | 29.2 | 29.1 | |
| 21 | ST2-2W (BOT) | prod zone | 23.0 | 22.9 | 23.2 | 24.1 | 24.5 | |
| 23 | ST3-2W (BOT) | prod zone | 23.4 | 23.1 | 23.5 | 24.3 | 24.7 | |
| 25 | LEDGE-2W (TOP) | prod zone | 28.2 | 28.0 | 27.9 | 27.6 | 27.5 | |
| 27 | ST3-2W (TOP) | prod zone | 22.2 | 21.7 | 22.1 | 22.8 | 23.1 | |
| 30 | ST2-2W (TOP) | prod zone | 21.9 | 21.5 | 21.9 | 22.6 | 23.0 | |
| 60 | ST1-2E (BOT) | prod zone | 21.8 | 22.1 | 22.7 | 23.7 | 24.2 | |
| 61 | ST2-2E (BOT) | prod zone | 22.1 | 22.3 | 22.8 | 23.8 | 24.3 | |
| 62 | ST3-2E (BOT) | prod zone | 22.4 | 22.6 | 23.0 | 24.0 | 24.4 | |
| 63 | LEDGE - 2E (BOT) | prod zone | 15.1 | 19.0 | 20.9 | 23.4 | 24.2 | |
| 70 | ST1-2E (TOP) | prod zone | 20.2 | 20.4 | 20.9 | 21.9 | 22.4 | |
| 72 | ST2-2E (TOP) | prod zone | 20.4 | 20.5 | 21.1 | 22.1 | 22.5 | |
| 74 | ST3-2E (TOP) | prod zone | 20.7 | 20.7 | 21.3 | 22.2 | 22.6 | |
| 76 | LEDGE-2E (TOP) | prod zone | 14.3 | 18.0 | 19.7 | 22.1 | 22.8 | |
| 108 | ST1-2W (BOT) | prod zone | 22.2 | 22.2 | 22.7 | 23.8 | 24.2 | |
| 110 | ST1-2W (TOP) | prod zone | 30.1 | 28.2 | 27.7 | 27.2 | 27.0 | |
| 129 | ST1-4W (BOT) | prod zone | 22.5 | 22.5 | 23.0 | 24.0 | 24.5 | |
| 130 | ST2-4W (BOT) | prod zone | 22.6 | 22.6 | 23.1 | 24.1 | 24.6 | |
| 131 | ST3-4W (BOT) | prod zone | 22.6 | 22.7 | 23.1 | 24.2 | 24.6 | |
| 132 | LEDGE-4W (BOT) | prod zone | 18.6 | 22.2 | 23.9 | 26.2 | 27.0 | |
| 138 | LEDGE-4W (TOP) | prod zone | 18.8 | 22.0 | 23.6 | 25.7 | 26.4 | |
| 139 | ST3-4W (TOP) | prod zone | 21.5 | 21.3 | 21.7 | 22.6 | 23.0 | |
| 142 | ST2-4W (TOP) | prod zone | 21.4 | 21.2 | 21.6 | 22.6 | 23.0 | |
| 144 | ST1-4W (TOP) | prod zone | 21.3 | 21.1 | 21.5 | 22.5 | 22.9 | |
| 171 | ST1-4E (BOT) | prod zone | 22.0 | 22.1 | 22.7 | 23.8 | 24.3 | |
| 172 | ST2-4E (BOT) | prod zone | 21.9 | 22.1 | 22.6 | 23.8 | 24.3 | |
| 173 | ST3-4E (BOT) | prod zone | 22.6 | 22.6 | 23.1 | 24.1 | 24.6 | |
| 174 | LEDGE 4E (BOT) | prod zone | 14.4 | 18.6 | 20.6 | 23.3 | 24.2 | |
| 181 | ST1-4E (TOP) | prod zone | 20.9 | 20.8 | 21.3 | 22.3 | 22.7 | |
| 182 | ST2-4E (TOP) | prod zone | 20.8 | 20.7 | 21.2 | 22.3 | 22.7 | |
| 183 | ST3-4E (TOP) | prod zone | 21.4 | 21.2 | 21.6 | 22.6 | 23.0 | |
| 184 | LEDGE-4E (TOP) | prod zone | 14.0 | 17.8 | 19.7 | 22.2 | 23.0 | |
| 199 | BAC 1 | control man | 13.5 | 15.1 | 15.8 | 17.0 | 17.5 | |
| | | | 750 | 900 | 1000 | 1200 | 1300 | kg/s |

## APPENDIX D

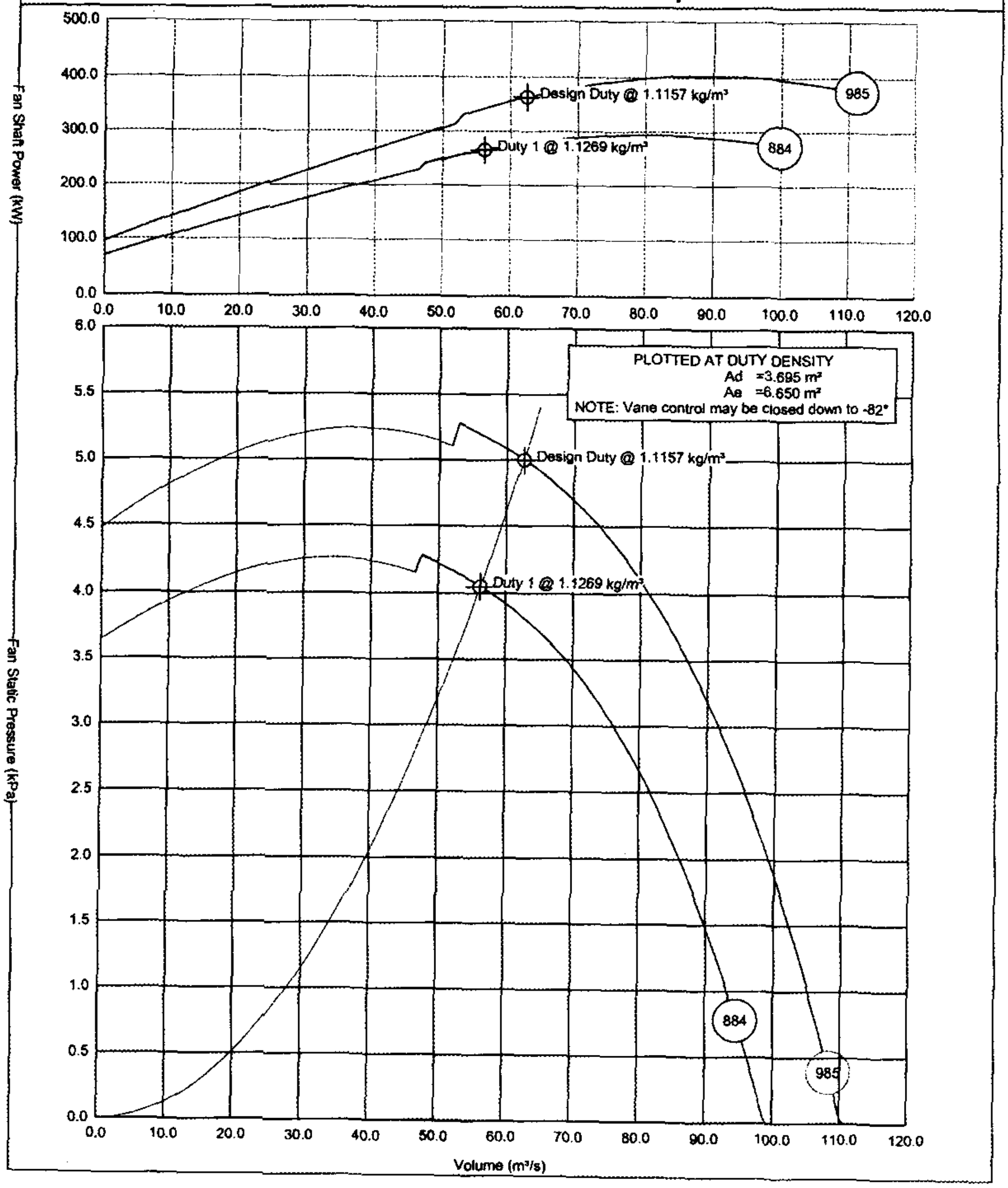
### FAN AND POWER CURVES FOR VARIABLE-SPEED DRIVE FAN

**Howden Fan Equipment**
**CENTRIFUGAL FAN PROGRAM - VERSION 3.1.0.1**
**PERFORMANCE CURVE**

Howden

| | | | |
|---|---|---|---|
| Client | : Ronny Webber | Date | : Thursday, August 21, 2003 |
| Clients Ref | : 11111 | Application | : Induced Draught |
| Our Ref | : 11111 | Destination | : Target |
| File | : untitled.cfs | | |

**Z9B 1588.10.85 DOV6T, Variable Speed**

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# Howden Fan Equipment
## CENTRIFUGAL FAN PROGRAM - VERSION 3.1.0.1
## PART LOADS

Howden

| | | | | |
|---|---|---|---|---|
| Client | : Ronny Webber | Date | : Thursday, August 21, 2003 | Page 3 |
| Clients Ref | : 11111 | Application | : Induced Draught | |
| Our Ref | : 11111 | Destination | : Target | |
| File | : untitled.cfs | | | |

## PART LOADS

Design Description Z9B 1588.10.85 DOV6T

Fan Speed 985.0 rpm

| Duty Name | | Design Duty | Duty 1 |
|---|---|---|---|
| Volume | $m^3/s$ | 62.500 | 56.250 |
| a. Fan Static Pressure | kPa | 5.000 | 4.050 |
| b. Inlet Losses | kPa | 0.000 | 0.000 |
| c. Discharge Losses | kPa | 0.000 | 0.000 |
| a + b + c | kPa | 5.000 | 4.050 |
| Inlet Pressure | kPa | -5.000 | -4.050 |
| Inlet Temperature | °C | 20.0 | 20.0 |
| Inlet Density (Actual) | $kg/m^3$ | 1.1157 | 1.1269 |
| Compressibility | | 0.9835 | 0.9860 |
| Fan Speed | r.p.m. | 985 | 884 |
| Fan Shaft Power | kW | 363 | 265 |
| Static Efficiency | % | 84.6 | 84.7 |
| Vane Setting | ° | 0 | 0 |
| Discharge Temperature | °C | 25.1 | 24.1 |
| Discharge Density | $kg/m^3$ | 1.1542 | 1.1581 |

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# APPENDIX E

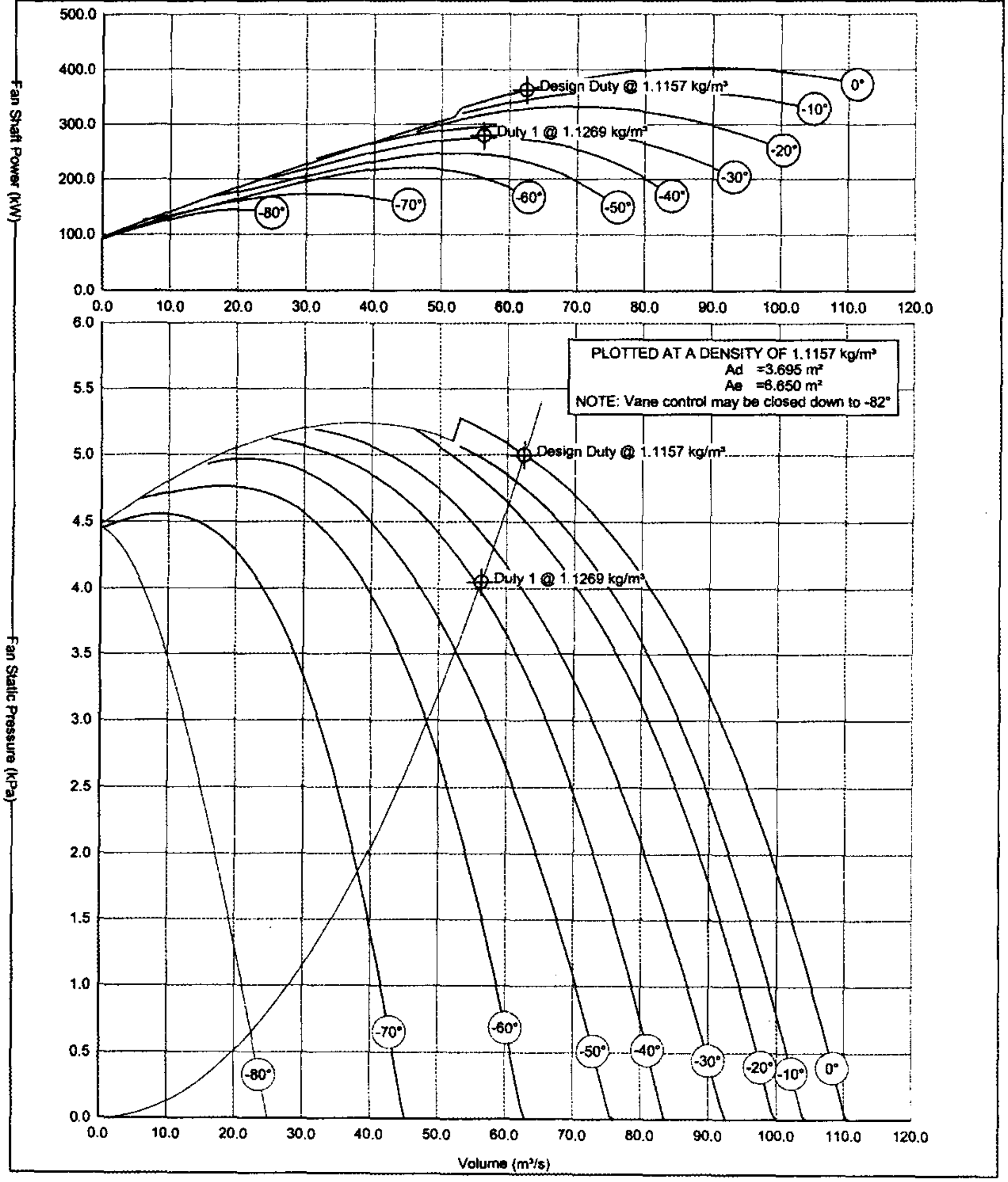
## FAN AND POWER CURVES FOR VARIABLE INLET VANE CONTROL

# Howden Fan Equipment
## CENTRIFUGAL FAN PROGRAM - VERSION 3.1.0.1
## PERFORMANCE CURVE

Howden

| | | | |
|---|---|---|---|
| Client | : Ronny Webber | Date | : Thursday, August 21, 2003 |
| Clients Ref | : 11111 | Application | : Induced Draught |
| Our Ref | : 11111 | Destination | : Target |
| File | : untitled.cfs | | |

**Z9B 1588.10.85 DOV6T, Constant Speed at 985 rpm**

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# Howden Fan Equipment
## CENTRIFUGAL FAN PROGRAM - VERSION 3.1.0.1
## PART LOADS

Howden

| | | | | |
|---|---|---|---|---|
| Client | : Ronny Webber | Date | : Thursday, August 21, 2003 | Page 3 |
| Clients Ref | : 11111 | Application | : Induced Draught | |
| Our Ref | : 11111 | Destination | : Target | |
| File | : untitled.cfs | | | |

## PART LOADS

Design Description Z9B 1588.10.85 DOV6T
Fan Speed 985.0 rpm

| Duty Name | | Design Duty | Duty 1 |
|---|---|---|---|
| **Volume** | m³/s | 62.500 | 56.250 |
| **a. Fan Static Pressure** | kPa | 5.000 | 4.050 |
| **b. Inlet Losses** | kPa | 0.000 | 0.000 |
| **c. Discharge Losses** | kPa | 0.000 | 0.000 |
| **a + b + c** | kPa | 5.000 | 4.050 |
| **Inlet Pressure** | kPa | -5.000 | -4.050 |
| **Inlet Temperature** | °C | 20.0 | 20.0 |
| **Inlet Density (Actual)** | kg/m³ | 1.1157 | 1.1269 |
| **Compressibility** | | 0.9827 | 0.9864 |
| **Fan Speed** | r.p.m. | 985 | 985 |
| **Fan Shaft Power** | kW | 363 | 279 |
| **Static Efficiency** | % | 84.6 | 80.5 |
| **Vane Setting** | ° | 0 | -39 |
| **Discharge Temperature** | °C | 25.1 | 21.1 |
| **Discharge Density** | kg/m³ | 1.1542 | 1.1701 |

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## APPENDIX F

**DETAILED CASH FLOW SHEETS FOR VARIABLE SPEED DRIVE MOTOR**
(Changes in the rand/euro exchange rate)

**Cash Flow Analyses** **R/Euro** **6.61**
**20 years period**
**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -3.42 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -3.42 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -3.42 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -3.42 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -3.42 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -3.42 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.59 | 14.55 | 15.56 | 16.65 | 17.82 | 19.07 | 20.40 |
| -3.42 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -3.42 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.46 | 27.25 |
| -3.42 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.81 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -3.42 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.86 | 33.02 | 35.33 |
| -3.42 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.58 | 34.87 | 37.31 | 39.92 |

**Net cash flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -3.42 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -3.42 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -3.42 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -3.42 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -3.42 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -3.42 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -3.42 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -3.42 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -3.42 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -3.42 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.64 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -3.42 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.66 | -9.27 | -9.92 | -10.61 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.51 |

**Cash Flow Analyses** **R/Euro** **7.27**
**20 years period**
**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -3.69 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -3.69 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -3.69 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -3.69 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -3.69 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -3.69 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.59 | 14.55 | 15.56 | 16.65 | 17.82 | 19.07 | 20.40 |
| -3.69 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -3.69 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.46 | 27.25 |
| -3.69 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.81 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -3.69 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.86 | 33.02 | 35.33 |
| -3.69 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.58 | 34.87 | 37.31 | 39.92 |

**Net cash flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -3.69 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -3.69 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -3.69 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -3.69 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -3.69 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -3.69 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -3.69 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -3.69 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -3.69 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -3.69 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.64 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -3.69 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.66 | -9.27 | -9.92 | -10.61 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.51 |

**Cash Flow Analyses** **R/Euro** **8.00**

**20 years period**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -4.00 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -4.00 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -4.00 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -4.00 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -4.00 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.59 | 14.55 | 15.56 | 16.65 | 17.82 | 19.07 | 20.40 |
| -4.00 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -4.00 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.46 | 27.25 |
| -4.00 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.81 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -4.00 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.86 | 33.02 | 35.33 |
| -4.00 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.58 | 34.87 | 37.31 | 39.92 |

**Net cash flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -4.00 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -4.00 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -4.00 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -4.00 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -4.00 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -4.00 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -4.00 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.64 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -4.00 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.66 | -9.27 | -9.92 | -10.61 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.51 |

**Cash Flow Analyses** **R/Euro** **8.80**
**20 years period**

**Year**

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.34 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -4.34 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -4.34 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -4.34 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -4.34 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -4.34 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.59 | 14.55 | 15.56 | 16.65 | 17.82 | 19.07 | 20.40 |
| -4.34 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -4.34 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.46 | 27.25 |
| -4.34 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.81 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -4.34 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.86 | 33.02 | 35.33 |
| -4.34 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.58 | 34.87 | 37.31 | 39.92 |

**Net cash flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.34 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -4.34 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -4.34 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -4.34 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -4.34 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -4.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.34 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -4.34 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -4.34 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -4.34 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.64 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -4.34 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.66 | -9.27 | -9.92 | -10.61 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.51 |

**Cash Flow Analyses** **R/Euro** **9.68**

**20 years period**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.71 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -4.71 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -4.71 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -4.71 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -4.71 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -4.71 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.59 | 14.55 | 15.56 | 16.65 | 17.82 | 19.07 | 20.40 |
| -4.71 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -4.71 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.46 | 27.25 |
| -4.71 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.81 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -4.71 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.86 | 33.02 | 35.33 |
| -4.71 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.58 | 34.87 | 37.31 | 39.92 |

**Net cash flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.71 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -4.71 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -4.71 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -4.71 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -4.71 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -4.71 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.71 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -4.71 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -4.71 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -4.71 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.64 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -4.71 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.66 | -9.27 | -9.92 | -10.61 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.51 |

**Cash Flow Analyses** R/Euro 10.65

**20 years period**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -5.11 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -5.11 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -5.11 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -5.11 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -5.11 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -5.11 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.59 | 14.55 | 15.56 | 16.65 | 17.82 | 19.07 | 20.40 |
| -5.11 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -5.11 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.46 | 27.25 |
| -5.11 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.81 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -5.11 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.86 | 33.02 | 35.33 |
| -5.11 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.58 | 34.87 | 37.31 | 39.92 |

**Net cash flow**

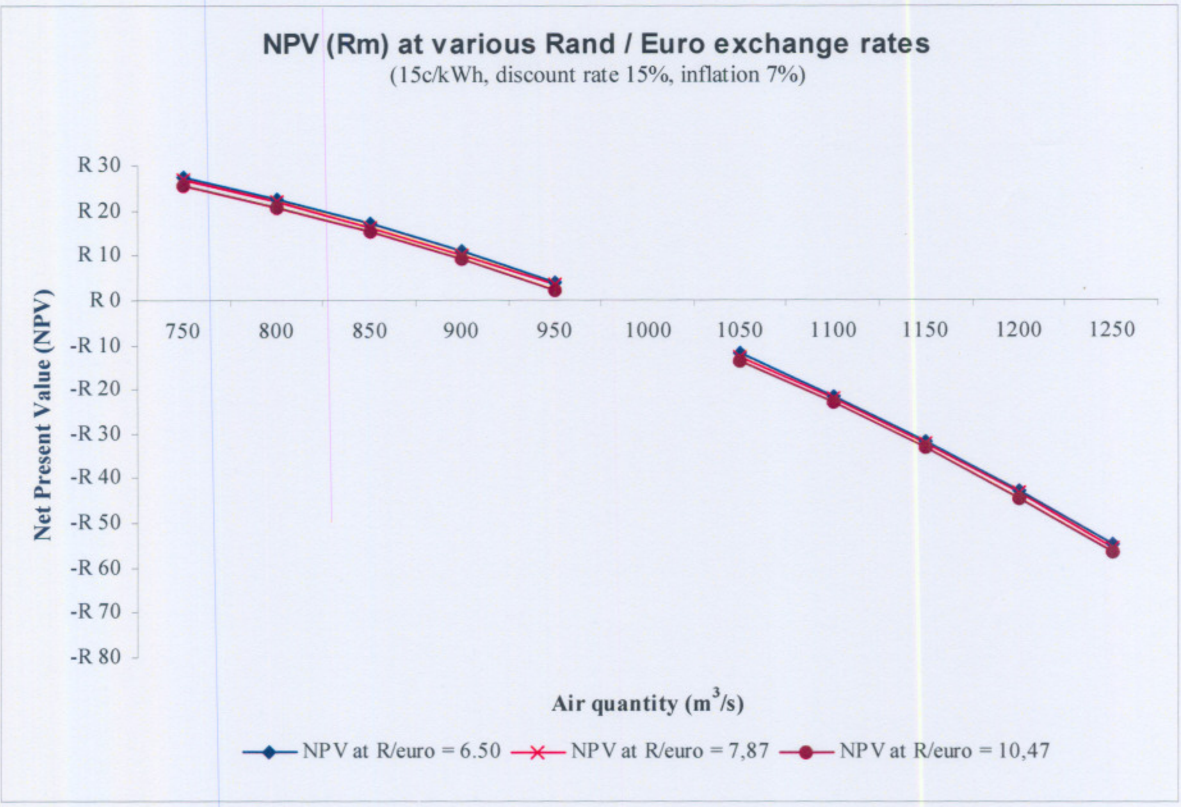
| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -5.11 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -5.11 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -5.11 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -5.11 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -5.11 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -5.11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -5.11 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -5.11 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -5.11 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -5.11 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.64 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -5.11 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.66 | -9.27 | -9.92 | -10.61 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.51 |

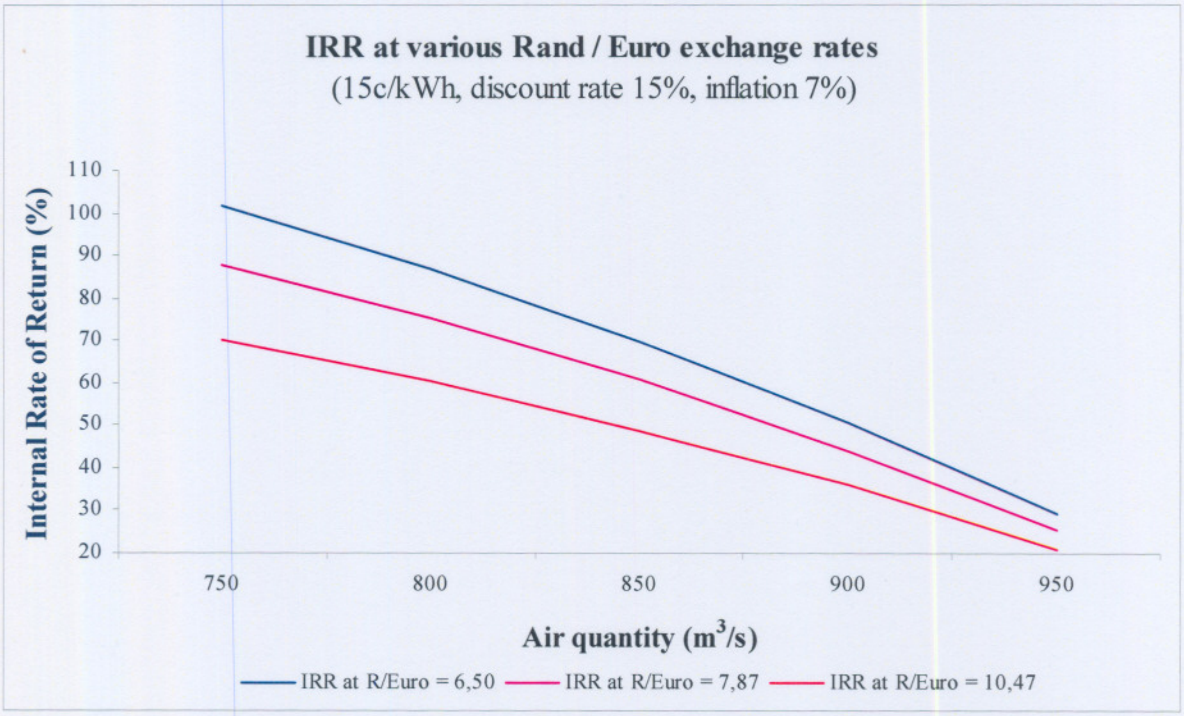
## APPENDIX G

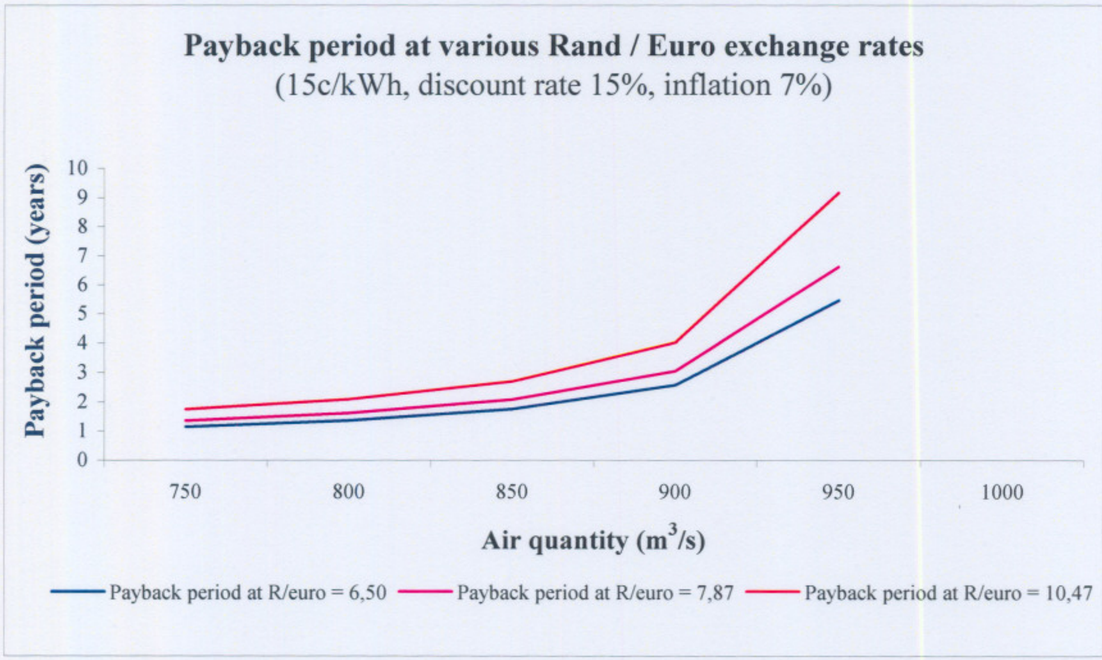
**DETAILED CASH FLOW SHEETS FOR VARIABLE SPEED DRIVE MOTOR**
(Summary of cash flow sheets for changes in the Rand/Euro exchange rate)

## NPV, IRR and Payback periods for changes in the Rand/Euro exchange rate

| Rand / Euro Exchange rate | Q ($m^3/s$) | Payback period (years) | NPV (R m) | IRR (%) |
|---|---|---|---|---|
| 6.61 | 750 | 1.1 | 27.38 | 101 |
| | 800 | 1.4 | 22.54 | 87 |
| | 850 | 1.7 | 17.05 | 70 |
| | 900 | 2.6 | 10.88 | 51 |
| | 950 | 5.5 | 3.98 | 29 |
| | 1000 | | | |
| | 1050 | 0.0 | -12.16 | 0 |
| | 1100 | 0.0 | -21.48 | 0 |
| | 1150 | 0.0 | -31.69 | 0 |
| | 1200 | 0.0 | -42.82 | 0 |
| | 1250 | 0.0 | -54.92 | 0 |
| 7.27 | 750 | 1.2 | 27.11 | 94 |
| | 800 | 1.5 | 22.26 | 81 |
| | 850 | 1.9 | 16.77 | 65 |
| | 900 | 2.8 | 10.60 | 47 |
| | 950 | 6.0 | 3.70 | 27 |
| | 1000 | | | |
| | 1050 | 0.0 | -12.44 | 0 |
| | 1100 | 0.0 | -21.76 | 0 |
| | 1150 | 0.0 | -31.96 | 0 |
| | 1200 | 0.0 | -43.10 | 0 |
| | 1250 | 0.0 | -55.20 | 0 |
| 8.00 | 750 | 1.3 | 26.80 | 88 |
| | 800 | 1.6 | 21.96 | 75 |
| | 850 | 2.1 | 16.47 | 61 |
| | 900 | 3.1 | 10.29 | 44 |
| | 950 | 6.6 | 3.39 | 26 |
| | 1000 | | | |
| | 1050 | 0.0 | -12.74 | 0 |
| | 1100 | 0.0 | -22.06 | 0 |
| | 1150 | 0.0 | -32.27 | 0 |
| | 1200 | 0.0 | -43.40 | 0 |
| | 1250 | 0.0 | -55.50 | 0 |
| 8.80 | 750 | 1.5 | 26.47 | 81 |
| | 800 | 1.7 | 21.62 | 70 |
| | 850 | 2.3 | 16.13 | 56 |
| | 900 | 3.3 | 9.96 | 41 |
| | 950 | 7.4 | 3.06 | 24 |
| | 1000 | | | |
| | 1050 | 0.0 | -13.08 | 0 |
| | 1100 | 0.0 | -22.40 | 0 |
| | 1150 | 0.0 | -32.61 | 0 |
| | 1200 | 0.0 | -43.74 | 0 |
| | 1250 | 0.0 | -55.84 | 0 |
| 9.68 | 750 | 1.6 | 26.10 | 76 |
| | 800 | 1.9 | 21.25 | 65 |
| | 850 | 2.5 | 15.76 | 53 |
| | 900 | 3.7 | 9.59 | 39 |
| | 950 | 8.2 | 2.69 | 22 |
| | 1000 | | | |
| | 1050 | 0.0 | -13.45 | 0 |
| | 1100 | 0.0 | -22.77 | 0 |
| | 1150 | 0.0 | -32.97 | 0 |
| | 1200 | 0.0 | -44.11 | 0 |
| | 1250 | 0.0 | -56.21 | 0 |
| 10.65 | 750 | 1.7 | 25.69 | 70 |
| | 800 | 2.1 | 20.84 | 60 |
| | 850 | 2.7 | 15.36 | 49 |
| | 900 | 4.0 | 9.18 | 36 |
| | 950 | 9.2 | 2.28 | 21 |
| | 1000 | | | |
| | 1050 | 0.0 | -13.86 | 0 |
| | 1100 | 0.0 | -23.18 | 0 |
| | 1150 | 0.0 | -33.38 | 0 |
| | 1200 | 0.0 | -44.51 | 0 |
| | 1250 | 0.0 | -56.61 | 0 |


NPV (Rm) at various Rand / Euro exchange rates
(15c/kWh, discount rate 15%, inflation 7%)
Net Present Value (NPV)
R 30
R 20
R 10
R 0
-R 10
-R 20
-R 30
-R 40
-R 50
-R 60
-R 70
-R 80
750
800
850
900
950
1000
1050
1100
1150
1200
1250
Air quantity (m3/s)
NPV at R/euro = 6.50
NPV at R/euro = 7,87
NPV at R/euro = 10,47


IRR at various Rand / Euro exchange rates
(15c/kWh, discount rate 15%, inflation 7%)
Internal Rate of Return (%)
110
100
90
80
70
60
50
40
30
20
750
800
850
900
950
Air quantity (m3/s)
IRR at R/Euro = 6,50
IRR at R/Euro = 7,87
IRR at R/Euro = 10,47



Payback period at various Rand / Euro exchange rates
(15c/kWh, discount rate 15%, inflation 7%)
Payback period (years)
0
1
2
3
4
5
6
7
8
9
10
750
800
850
900
950
1000
Air quantity (m³/s)
Payback period at R/euro = 6,50
Payback period at R/euro = 7,87
Payback period at R/euro = 10,47

# APPENDIX H

**DETAILED CASH FLOW SHEETS FOR VARIABLE SPEED DRIVE MOTOR**
(Changes in the inflation rate)

**Cash Flow Analysis** **Inflation** **5.8%**
**(20 year period)**
**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.55 | 2.70 | 2.86 | 3.02 | 3.20 | 3.38 | 3.58 | 3.79 | 4.01 | 4.24 | 4.48 | 4.74 | 5.02 | 5.31 | 5.61 | 5.94 | 6.28 | 6.64 | 7.03 |
| -4.00 | 2.92 | 3.09 | 3.27 | 3.46 | 3.66 | 3.87 | 4.09 | 4.33 | 4.58 | 4.85 | 5.13 | 5.42 | 5.74 | 6.07 | 6.42 | 6.79 | 7.19 | 7.60 | 8.04 | 8.51 |
| -4.00 | 3.50 | 3.70 | 3.91 | 4.14 | 4.38 | 4.63 | 4.90 | 5.18 | 5.48 | 5.80 | 6.14 | 6.49 | 6.87 | 7.26 | 7.68 | 8.13 | 8.60 | 9.10 | 9.62 | 10.18 |
| -4.00 | 4.14 | 4.38 | 4.64 | 4.91 | 5.19 | 5.49 | 5.81 | 6.14 | 6.50 | 6.87 | 7.27 | 7.69 | 8.14 | 8.61 | 9.11 | 9.63 | 10.19 | 10.78 | 11.40 | 12.06 |
| -4.00 | 4.87 | 5.15 | 5.45 | 5.76 | 6.09 | 6.45 | 6.82 | 7.21 | 7.63 | 8.07 | 8.54 | 9.03 | 9.56 | 10.11 | 10.70 | 11.31 | 11.97 | 12.66 | 13.39 | 14.17 |
| -4.00 | 5.64 | 5.97 | 6.31 | 6.68 | 7.06 | 7.47 | 7.91 | 8.36 | 8.85 | 9.36 | 9.90 | 10.47 | 11.08 | 11.72 | 12.40 | 13.11 | 13.87 | 14.68 | 15.52 | 16.42 |
| -4.00 | 6.56 | 6.94 | 7.34 | 7.76 | 8.21 | 8.69 | 9.19 | 9.72 | 10.28 | 10.88 | 11.51 | 12.17 | 12.88 | 13.62 | 14.41 | 15.24 | 16.13 | 17.06 | 18.05 | 19.09 |
| -4.00 | 7.53 | 7.97 | 8.43 | 8.92 | 9.43 | 9.98 | 10.56 | 11.17 | 11.81 | 12.50 | 13.22 | 13.99 | 14.80 | 15.65 | 16.56 | 17.51 | 18.53 | 19.60 | 20.73 | 21.93 |
| -4.00 | 8.60 | 9.10 | 9.63 | 10.18 | 10.77 | 11.40 | 12.06 | 12.75 | 13.49 | 14.27 | 15.10 | 15.97 | 16.90 | 17.87 | 18.91 | 20.00 | 21.16 | 22.38 | 23.68 | 25.05 |
| -4.00 | 9.77 | 10.33 | 10.93 | 11.57 | 12.23 | 12.94 | 13.69 | 14.48 | 15.32 | 16.21 | 17.14 | 18.14 | 19.19 | 20.30 | 21.47 | 22.71 | 24.03 | 25.42 | 26.89 | 28.44 |
| -4.00 | 11.04 | 11.68 | 12.35 | 13.07 | 13.82 | 14.62 | 15.47 | 16.36 | 17.31 | 18.31 | 19.37 | 20.49 | 21.68 | 22.93 | 24.26 | 25.66 | 27.14 | 28.71 | 30.37 | 32.13 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.41 | 3.61 | 3.82 | 4.04 | 4.27 | 4.52 | 4.78 | 5.06 | 5.35 | 5.66 | 5.99 | 6.34 | 6.70 | 7.09 | 7.50 | 7.94 | 8.40 | 8.88 | 9.39 |
| -4.00 | 2.72 | 2.88 | 3.04 | 3.22 | 3.41 | 3.60 | 3.81 | 4.03 | 4.26 | 4.51 | 4.77 | 5.05 | 5.34 | 5.65 | 5.98 | 6.32 | 6.69 | 7.07 | 7.48 | 7.92 |
| -4.00 | 2.14 | 2.27 | 2.40 | 2.54 | 2.69 | 2.84 | 3.01 | 3.18 | 3.36 | 3.56 | 3.76 | 3.98 | 4.21 | 4.45 | 4.71 | 4.99 | 5.27 | 5.58 | 5.90 | 6.24 |
| -4.00 | 1.50 | 1.58 | 1.68 | 1.77 | 1.88 | 1.98 | 2.10 | 2.22 | 2.35 | 2.48 | 2.63 | 2.78 | 2.94 | 3.11 | 3.29 | 3.48 | 3.68 | 3.90 | 4.12 | 4.36 |
| -4.00 | 0.77 | 0.82 | 0.87 | 0.92 | 0.97 | 1.03 | 1.09 | 1.15 | 1.21 | 1.29 | 1.36 | 1.44 | 1.52 | 1.61 | 1.70 | 1.80 | 1.90 | 2.02 | 2.13 | 2.26 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -0.97 | -1.03 | -1.08 | -1.15 | -1.21 | -1.28 | -1.36 | -1.44 | -1.52 | -1.61 | -1.70 | -1.80 | -1.90 | -2.01 | -2.13 | -2.25 | -2.38 | -2.52 | -2.67 |
| -4.00 | -1.89 | -2.00 | -2.12 | -2.24 | -2.37 | -2.51 | -2.65 | -2.81 | -2.97 | -3.14 | -3.32 | -3.51 | -3.72 | -3.93 | -4.16 | -4.40 | -4.65 | -4.92 | -5.21 | -5.51 |
| -4.00 | -2.96 | -3.13 | -3.31 | -3.51 | -3.71 | -3.92 | -4.15 | -4.39 | -4.64 | -4.91 | -5.20 | -5.50 | -5.82 | -6.15 | -6.51 | -6.89 | -7.28 | -7.71 | -8.15 | -8.62 |
| -4.00 | -4.13 | -4.37 | -4.62 | -4.89 | -5.17 | -5.47 | -5.79 | -6.12 | -6.47 | -6.85 | -7.24 | -7.66 | -8.11 | -8.58 | -9.07 | -9.60 | -10.15 | -10.74 | -11.36 | -12.02 |
| -4.00 | -5.40 | -5.71 | -6.04 | -6.39 | -6.76 | -7.15 | -7.56 | -8.00 | -8.46 | -8.95 | -9.47 | -10.02 | -10.60 | -11.21 | -11.86 | -12.54 | -13.27 | -14.04 | -14.85 | -15.71 |

**Cash Flow Analysis** **Inflation** **6.4%**
**(20 year period)**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.57 | 2.73 | 2.91 | 3.09 | 3.29 | 3.50 | 3.72 | 3.95 | 4.21 | 4.47 | 4.76 | 5.06 | 5.38 | 5.73 | 6.09 | 6.48 | 6.89 | 7.33 | 7.80 |
| -4.00 | 2.92 | 3.11 | 3.31 | 3.52 | 3.74 | 3.98 | 4.23 | 4.50 | 4.79 | 5.09 | 5.41 | 5.76 | 6.13 | 6.52 | 6.93 | 7.37 | 7.84 | 8.34 | 8.87 | 9.43 |
| -4.00 | 3.50 | 3.72 | 3.96 | 4.21 | 4.48 | 4.76 | 5.06 | 5.39 | 5.73 | 6.09 | 6.48 | 6.89 | 7.33 | 7.80 | 8.29 | 8.82 | 9.38 | 9.98 | 10.62 | 11.29 |
| -4.00 | 4.14 | 4.41 | 4.69 | 4.99 | 5.30 | 5.64 | 6.00 | 6.38 | 6.79 | 7.22 | 7.68 | 8.17 | 8.69 | 9.24 | 9.83 | 10.45 | 11.12 | 11.83 | 12.58 | 13.38 |
| -4.00 | 4.87 | 5.18 | 5.51 | 5.86 | 6.23 | 6.63 | 7.05 | 7.50 | 7.97 | 8.48 | 9.02 | 9.59 | 10.20 | 10.85 | 11.54 | 12.28 | 13.06 | 13.89 | 14.77 | 15.72 |
| -4.00 | 5.64 | 6.00 | 6.38 | 6.79 | 7.22 | 7.68 | 8.17 | 8.69 | 9.24 | 9.83 | 10.45 | 11.12 | 11.83 | 12.58 | 13.38 | 14.23 | 15.14 | 16.10 | 17.13 | 18.22 |
| -4.00 | 6.56 | 6.97 | 7.42 | 7.89 | 8.39 | 8.93 | 9.50 | 10.10 | 10.74 | 11.43 | 12.15 | 12.93 | 13.75 | 14.62 | 15.55 | 16.54 | 17.60 | 18.72 | 19.91 | 21.17 |
| -4.00 | 7.53 | 8.01 | 8.52 | 9.07 | 9.64 | 10.26 | 10.91 | 11.60 | 12.34 | 13.13 | 13.96 | 14.85 | 15.80 | 16.80 | 17.87 | 19.01 | 20.22 | 21.50 | 22.87 | 24.33 |
| -4.00 | 8.60 | 9.15 | 9.73 | 10.35 | 11.01 | 11.71 | 12.46 | 13.25 | 14.09 | 14.99 | 15.94 | 16.96 | 18.04 | 19.19 | 20.41 | 21.71 | 23.09 | 24.56 | 26.12 | 27.78 |
| -4.00 | 9.77 | 10.39 | 11.05 | 11.76 | 12.50 | 13.30 | 14.15 | 15.05 | 16.00 | 17.02 | 18.11 | 19.26 | 20.48 | 21.79 | 23.17 | 24.65 | 26.22 | 27.88 | 29.66 | 31.55 |
| -4.00 | 11.04 | 11.74 | 12.49 | 13.28 | 14.13 | 15.03 | 15.98 | 17.00 | 18.08 | 19.23 | 20.46 | 21.76 | 23.14 | 24.61 | 26.18 | 27.85 | 29.62 | 31.50 | 33.51 | 35.64 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.43 | 3.65 | 3.88 | 4.13 | 4.39 | 4.67 | 4.97 | 5.29 | 5.62 | 5.98 | 6.36 | 6.77 | 7.20 | 7.65 | 8.14 | 8.66 | 9.21 | 9.80 | 10.42 |
| -4.00 | 2.72 | 2.89 | 3.08 | 3.27 | 3.48 | 3.70 | 3.94 | 4.19 | 4.45 | 4.74 | 5.04 | 5.36 | 5.70 | 6.06 | 6.45 | 6.86 | 7.30 | 7.76 | 8.26 | 8.78 |
| -4.00 | 2.14 | 2.28 | 2.43 | 2.58 | 2.74 | 2.92 | 3.11 | 3.30 | 3.51 | 3.74 | 3.97 | 4.23 | 4.50 | 4.78 | 5.09 | 5.41 | 5.75 | 6.12 | 6.51 | 6.92 |
| -4.00 | 1.50 | 1.59 | 1.69 | 1.80 | 1.92 | 2.04 | 2.17 | 2.31 | 2.45 | 2.61 | 2.78 | 2.95 | 3.14 | 3.34 | 3.55 | 3.78 | 4.02 | 4.27 | 4.55 | 4.84 |
| -4.00 | 0.77 | 0.82 | 0.88 | 0.93 | 0.99 | 1.05 | 1.12 | 1.19 | 1.27 | 1.35 | 1.44 | 1.53 | 1.62 | 1.73 | 1.84 | 1.95 | 2.08 | 2.21 | 2.35 | 2.50 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -0.97 | -1.04 | -1.10 | -1.17 | -1.25 | -1.33 | -1.41 | -1.50 | -1.60 | -1.70 | -1.81 | -1.92 | -2.04 | -2.17 | -2.31 | -2.46 | -2.62 | -2.78 | -2.96 |
| -4.00 | -1.89 | -2.01 | -2.14 | -2.28 | -2.42 | -2.58 | -2.74 | -2.91 | -3.10 | -3.30 | -3.51 | -3.73 | -3.97 | -4.22 | -4.49 | -4.77 | -5.08 | -5.40 | -5.75 | -6.11 |
| -4.00 | -2.96 | -3.15 | -3.35 | -3.56 | -3.79 | -4.03 | -4.29 | -4.56 | -4.85 | -5.16 | -5.49 | -5.84 | -6.21 | -6.61 | -7.03 | -7.47 | -7.95 | -8.45 | -8.99 | -9.56 |
| -4.00 | -4.13 | -4.39 | -4.67 | -4.97 | -5.28 | -5.62 | -5.98 | -6.36 | -6.76 | -7.19 | -7.65 | -8.14 | -8.66 | -9.21 | -9.79 | -10.42 | -11.08 | -11.78 | -12.53 | -13.33 |
| -4.00 | -5.40 | -5.74 | -6.10 | -6.49 | -6.91 | -7.35 | -7.81 | -8.31 | -8.84 | -9.40 | -10.00 | -10.64 | -11.31 | -12.03 | -12.80 | -13.61 | -14.48 | -15.40 | -16.38 | -17.42 |

**Cash Flow Analysis** **Inflation** **7.0%**
**(20 year period)**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -4.00 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -4.00 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -4.00 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -4.00 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -4.00 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.59 | 14.55 | 15.56 | 16.65 | 17.82 | 19.07 | 20.40 |
| -4.00 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -4.00 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.46 | 27.25 |
| -4.00 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.81 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -4.00 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.86 | 33.02 | 35.33 |
| -4.00 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.58 | 34.87 | 37.31 | 39.92 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -4.00 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -4.00 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -4.00 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -4.00 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -4.00 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -4.00 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -4.00 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.64 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -4.00 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.66 | -9.27 | -9.92 | -10.61 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.51 |

**Cash Flow Analysis** **Inflation** **7.7%**
**(20 year period)**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.60 | 2.80 | 3.02 | 3.25 | 3.50 | 3.77 | 4.06 | 4.37 | 4.71 | 5.07 | 5.46 | 5.88 | 6.33 | 6.82 | 7.35 | 7.91 | 8.52 | 9.18 | 9.88 |
| -4.00 | 2.92 | 3.15 | 3.39 | 3.65 | 3.93 | 4.23 | 4.56 | 4.91 | 5.29 | 5.70 | 6.14 | 6.61 | 7.12 | 7.66 | 8.25 | 8.89 | 9.57 | 10.31 | 11.11 | 11.96 |
| -4.00 | 3.50 | 3.77 | 4.06 | 4.37 | 4.70 | 5.07 | 5.46 | 5.88 | 6.33 | 6.82 | 7.34 | 7.91 | 8.52 | 9.17 | 9.88 | 10.64 | 11.46 | 12.34 | 13.29 | 14.31 |
| -4.00 | 4.14 | 4.46 | 4.81 | 5.18 | 5.58 | 6.00 | 6.47 | 6.96 | 7.50 | 8.08 | 8.70 | 9.37 | 10.09 | 10.87 | 11.71 | 12.61 | 13.58 | 14.62 | 15.75 | 16.96 |
| -4.00 | 4.87 | 5.24 | 5.65 | 6.08 | 6.55 | 7.05 | 7.60 | 8.18 | 8.81 | 9.49 | 10.22 | 11.01 | 11.85 | 12.77 | 13.75 | 14.81 | 15.95 | 17.18 | 18.50 | 19.92 |
| -4.00 | 5.64 | 6.08 | 6.54 | 7.05 | 7.59 | 8.17 | 8.80 | 9.48 | 10.21 | 11.00 | 11.85 | 12.76 | 13.74 | 14.80 | 15.94 | 17.16 | 18.49 | 19.91 | 21.44 | 23.09 |
| -4.00 | 6.56 | 7.06 | 7.61 | 8.19 | 8.82 | 9.50 | 10.23 | 11.02 | 11.87 | 12.78 | 13.77 | 14.83 | 15.97 | 17.20 | 18.53 | 19.95 | 21.49 | 23.14 | 24.92 | 26.84 |
| -4.00 | 7.53 | 8.11 | 8.74 | 9.41 | 10.14 | 10.92 | 11.76 | 12.66 | 13.64 | 14.69 | 15.82 | 17.04 | 18.35 | 19.76 | 21.28 | 22.92 | 24.69 | 26.59 | 28.64 | 30.84 |
| -4.00 | 8.60 | 9.27 | 9.98 | 10.75 | 11.58 | 12.47 | 13.43 | 14.46 | 15.57 | 16.77 | 18.06 | 19.46 | 20.95 | 22.57 | 24.30 | 26.18 | 28.19 | 30.36 | 32.70 | 35.22 |
| -4.00 | 9.77 | 10.52 | 11.33 | 12.20 | 13.14 | 14.16 | 15.25 | 16.42 | 17.69 | 19.05 | 20.51 | 22.09 | 23.79 | 25.63 | 27.60 | 29.72 | 32.01 | 34.48 | 37.13 | 39.99 |
| -4.00 | 11.04 | 11.89 | 12.80 | 13.79 | 14.85 | 15.99 | 17.23 | 18.55 | 19.98 | 21.52 | 23.18 | 24.96 | 26.88 | 28.95 | 31.18 | 33.58 | 36.17 | 38.95 | 41.95 | 45.18 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.48 | 3.74 | 4.03 | 4.34 | 4.68 | 5.04 | 5.42 | 5.84 | 6.29 | 6.78 | 7.30 | 7.86 | 8.46 | 9.12 | 9.82 | 10.57 | 11.39 | 12.27 | 13.21 |
| -4.00 | 2.72 | 2.93 | 3.15 | 3.40 | 3.66 | 3.94 | 4.24 | 4.57 | 4.92 | 5.30 | 5.71 | 6.15 | 6.62 | 7.13 | 7.68 | 8.27 | 8.91 | 9.60 | 10.34 | 11.13 |
| -4.00 | 2.14 | 2.31 | 2.49 | 2.68 | 2.89 | 3.11 | 3.35 | 3.60 | 3.88 | 4.18 | 4.50 | 4.85 | 5.22 | 5.62 | 6.06 | 6.52 | 7.03 | 7.57 | 8.15 | 8.78 |
| -4.00 | 1.50 | 1.61 | 1.74 | 1.87 | 2.01 | 2.17 | 2.34 | 2.52 | 2.71 | 2.92 | 3.14 | 3.39 | 3.65 | 3.93 | 4.23 | 4.56 | 4.91 | 5.29 | 5.69 | 6.13 |
| -4.00 | 0.77 | 0.83 | 0.90 | 0.97 | 1.04 | 1.12 | 1.21 | 1.30 | 1.40 | 1.51 | 1.63 | 1.75 | 1.89 | 2.03 | 2.19 | 2.36 | 2.54 | 2.73 | 2.94 | 3.17 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -0.99 | -1.06 | -1.14 | -1.23 | -1.33 | -1.43 | -1.54 | -1.66 | -1.79 | -1.92 | -2.07 | -2.23 | -2.40 | -2.59 | -2.79 | -3.00 | -3.23 | -3.48 | -3.75 |
| -4.00 | -1.89 | -2.04 | -2.20 | -2.36 | -2.55 | -2.74 | -2.95 | -3.18 | -3.43 | -3.69 | -3.97 | -4.28 | -4.61 | -4.96 | -5.35 | -5.76 | -6.20 | -6.68 | -7.19 | -7.75 |
| -4.00 | -2.96 | -3.19 | -3.44 | -3.70 | -3.98 | -4.29 | -4.62 | -4.98 | -5.36 | -5.77 | -6.22 | -6.70 | -7.21 | -7.77 | -8.37 | -9.01 | -9.71 | -10.45 | -11.26 | -12.12 |
| -4.00 | -4.13 | -4.45 | -4.79 | -5.16 | -5.55 | -5.98 | -6.44 | -6.94 | -7.47 | -8.05 | -8.67 | -9.34 | -10.05 | -10.83 | -11.66 | -12.56 | -13.53 | -14.57 | -15.69 | -16.90 |
| -4.00 | -5.40 | -5.81 | -6.26 | -6.74 | -7.26 | -7.82 | -8.42 | -9.07 | -9.77 | -10.52 | -11.33 | -12.20 | -13.14 | -14.15 | -15.24 | -16.42 | -17.68 | -19.04 | -20.51 | -22.09 |

**Cash Flow Analysis** **Inflation** **8.5%**
**(20 year period)**
**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.62 | 2.84 | 3.08 | 3.34 | 3.63 | 3.93 | 4.27 | 4.63 | 5.02 | 5.44 | 5.90 | 6.40 | 6.95 | 7.54 | 8.17 | 8.87 | 9.62 | 10.43 | 11.32 |
| -4.00 | 2.92 | 3.17 | 3.44 | 3.73 | 4.04 | 4.39 | 4.76 | 5.16 | 5.60 | 6.07 | 6.59 | 7.15 | 7.75 | 8.41 | 9.12 | 9.89 | 10.73 | 11.64 | 12.63 | 13.69 |
| -4.00 | 3.50 | 3.79 | 4.11 | 4.46 | 4.84 | 5.25 | 5.70 | 6.18 | 6.70 | 7.27 | 7.88 | 8.55 | 9.28 | 10.06 | 10.92 | 11.84 | 12.84 | 13.93 | 15.11 | 16.39 |
| -4.00 | 4.14 | 4.49 | 4.88 | 5.29 | 5.74 | 6.22 | 6.75 | 7.32 | 7.94 | 8.61 | 9.34 | 10.13 | 10.99 | 11.92 | 12.93 | 14.03 | 15.22 | 16.51 | 17.91 | 19.42 |
| -4.00 | 4.87 | 5.28 | 5.73 | 6.21 | 6.74 | 7.31 | 7.93 | 8.60 | 9.33 | 10.12 | 10.97 | 11.90 | 12.91 | 14.00 | 15.19 | 16.48 | 17.87 | 19.39 | 21.03 | 22.81 |
| -4.00 | 5.64 | 6.12 | 6.64 | 7.20 | 7.81 | 8.47 | 9.19 | 9.97 | 10.81 | 11.73 | 12.72 | 13.80 | 14.97 | 16.23 | 17.61 | 19.10 | 20.72 | 22.47 | 24.38 | 26.44 |
| -4.00 | 6.56 | 7.11 | 7.72 | 8.37 | 9.08 | 9.85 | 10.68 | 11.59 | 12.57 | 13.63 | 14.79 | 16.04 | 17.40 | 18.87 | 20.47 | 22.20 | 24.08 | 26.12 | 28.33 | 30.73 |
| -4.00 | 7.53 | 8.17 | 8.86 | 9.62 | 10.43 | 11.31 | 12.27 | 13.31 | 14.44 | 15.66 | 16.99 | 18.43 | 19.99 | 21.68 | 23.52 | 25.51 | 27.67 | 30.01 | 32.55 | 35.31 |
| -4.00 | 8.60 | 9.33 | 10.12 | 10.98 | 11.91 | 12.92 | 14.01 | 15.20 | 16.49 | 17.88 | 19.40 | 21.04 | 22.82 | 24.76 | 26.85 | 29.13 | 31.59 | 34.27 | 37.17 | 40.32 |
| -4.00 | 9.77 | 10.60 | 11.49 | 12.47 | 13.52 | 14.67 | 15.91 | 17.26 | 18.72 | 20.31 | 22.03 | 23.89 | 25.92 | 28.11 | 30.49 | 33.08 | 35.88 | 38.92 | 42.21 | 45.79 |
| -4.00 | 11.04 | 11.97 | 12.99 | 14.09 | 15.28 | 16.57 | 17.98 | 19.50 | 21.15 | 22.94 | 24.89 | 26.99 | 29.28 | 31.76 | 34.45 | 37.37 | 40.53 | 43.97 | 47.69 | 51.73 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.50 | 3.80 | 4.12 | 4.47 | 4.85 | 5.26 | 5.70 | 6.18 | 6.71 | 7.28 | 7.89 | 8.56 | 9.29 | 10.07 | 10.93 | 11.85 | 12.86 | 13.94 | 15.12 |
| -4.00 | 2.72 | 2.95 | 3.20 | 3.47 | 3.76 | 4.08 | 4.43 | 4.80 | 5.21 | 5.65 | 6.13 | 6.65 | 7.21 | 7.83 | 8.49 | 9.21 | 9.99 | 10.83 | 11.75 | 12.75 |
| -4.00 | 2.14 | 2.33 | 2.52 | 2.74 | 2.97 | 3.22 | 3.49 | 3.79 | 4.11 | 4.46 | 4.84 | 5.24 | 5.69 | 6.17 | 6.69 | 7.26 | 7.88 | 8.54 | 9.27 | 10.05 |
| -4.00 | 1.50 | 1.62 | 1.76 | 1.91 | 2.07 | 2.25 | 2.44 | 2.65 | 2.87 | 3.11 | 3.38 | 3.66 | 3.97 | 4.31 | 4.67 | 5.07 | 5.50 | 5.97 | 6.47 | 7.02 |
| -4.00 | 0.77 | 0.84 | 0.91 | 0.99 | 1.07 | 1.16 | 1.26 | 1.37 | 1.48 | 1.61 | 1.75 | 1.89 | 2.05 | 2.23 | 2.42 | 2.62 | 2.84 | 3.09 | 3.35 | 3.63 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -0.99 | -1.08 | -1.17 | -1.27 | -1.38 | -1.49 | -1.62 | -1.76 | -1.90 | -2.07 | -2.24 | -2.43 | -2.64 | -2.86 | -3.10 | -3.36 | -3.65 | -3.96 | -4.29 |
| -4.00 | -1.89 | -2.05 | -2.23 | -2.42 | -2.62 | -2.84 | -3.08 | -3.34 | -3.63 | -3.93 | -4.27 | -4.63 | -5.02 | -5.45 | -5.91 | -6.41 | -6.95 | -7.54 | -8.18 | -8.87 |
| -4.00 | -2.96 | -3.21 | -3.48 | -3.78 | -4.10 | -4.45 | -4.82 | -5.23 | -5.68 | -6.16 | -6.68 | -7.24 | -7.86 | -8.52 | -9.24 | -10.03 | -10.88 | -11.80 | -12.80 | -13.88 |
| -4.00 | -4.13 | -4.48 | -4.86 | -5.27 | -5.71 | -6.20 | -6.72 | -7.29 | -7.91 | -8.58 | -9.31 | -10.10 | -10.95 | -11.88 | -12.89 | -13.98 | -15.16 | -16.44 | -17.84 | -19.35 |
| -4.00 | -5.40 | -5.85 | -6.35 | -6.89 | -7.47 | -8.10 | -8.79 | -9.53 | -10.34 | -11.22 | -12.17 | -13.20 | -14.31 | -15.53 | -16.84 | -18.27 | -19.82 | -21.50 | -23.32 | -25.29 |

**Cash Flow Analysis** **Inflation** **9.3%**
**(20 year period)**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.64 | 2.89 | 3.15 | 3.45 | 3.77 | 4.12 | 4.50 | 4.92 | 5.38 | 5.88 | 6.43 | 7.03 | 7.69 | 8.40 | 9.19 | 10.04 | 10.98 | 12.00 | 13.12 |
| -4.00 | 2.92 | 3.19 | 3.49 | 3.82 | 4.17 | 4.56 | 4.99 | 5.45 | 5.96 | 6.51 | 7.12 | 7.78 | 8.51 | 9.30 | 10.17 | 11.12 | 12.15 | 13.28 | 14.52 | 15.88 |
| -4.00 | 3.50 | 3.82 | 4.18 | 4.57 | 4.99 | 5.46 | 5.97 | 6.52 | 7.13 | 7.80 | 8.52 | 9.32 | 10.18 | 11.13 | 12.17 | 13.30 | 14.54 | 15.90 | 17.38 | 19.00 |
| -4.00 | 4.14 | 4.53 | 4.95 | 5.41 | 5.92 | 6.47 | 7.07 | 7.73 | 8.45 | 9.24 | 10.10 | 11.04 | 12.07 | 13.19 | 14.42 | 15.77 | 17.23 | 18.84 | 20.60 | 22.52 |
| -4.00 | 4.87 | 5.32 | 5.82 | 6.36 | 6.95 | 7.60 | 8.31 | 9.08 | 9.93 | 10.85 | 11.86 | 12.97 | 14.17 | 15.49 | 16.94 | 18.52 | 20.24 | 22.13 | 24.19 | 26.44 |
| -4.00 | 5.64 | 6.17 | 6.74 | 7.37 | 8.06 | 8.81 | 9.63 | 10.52 | 11.51 | 12.58 | 13.75 | 15.03 | 16.43 | 17.96 | 19.63 | 21.46 | 23.46 | 25.65 | 28.04 | 30.65 |
| -4.00 | 6.56 | 7.17 | 7.84 | 8.57 | 9.36 | 10.24 | 11.19 | 12.23 | 13.37 | 14.62 | 15.98 | 17.47 | 19.10 | 20.88 | 22.82 | 24.95 | 27.27 | 29.82 | 32.59 | 35.63 |
| -4.00 | 7.53 | 8.24 | 9.00 | 9.84 | 10.76 | 11.76 | 12.86 | 14.06 | 15.36 | 16.80 | 18.36 | 20.07 | 21.94 | 23.99 | 26.22 | 28.66 | 31.33 | 34.25 | 37.45 | 40.93 |
| -4.00 | 8.60 | 9.40 | 10.28 | 11.24 | 12.29 | 13.43 | 14.68 | 16.05 | 17.55 | 19.18 | 20.97 | 22.92 | 25.06 | 27.39 | 29.94 | 32.73 | 35.78 | 39.12 | 42.76 | 46.74 |
| -4.00 | 9.77 | 10.68 | 11.67 | 12.76 | 13.95 | 15.25 | 16.67 | 18.23 | 19.92 | 21.78 | 23.81 | 26.03 | 28.45 | 31.10 | 34.00 | 37.17 | 40.63 | 44.42 | 48.56 | 53.08 |
| -4.00 | 11.04 | 12.07 | 13.19 | 14.42 | 15.76 | 17.23 | 18.84 | 20.59 | 22.51 | 24.61 | 26.90 | 29.41 | 32.15 | 35.14 | 38.41 | 41.99 | 45.91 | 50.18 | 54.86 | 59.97 |

**Net Cash Flow**

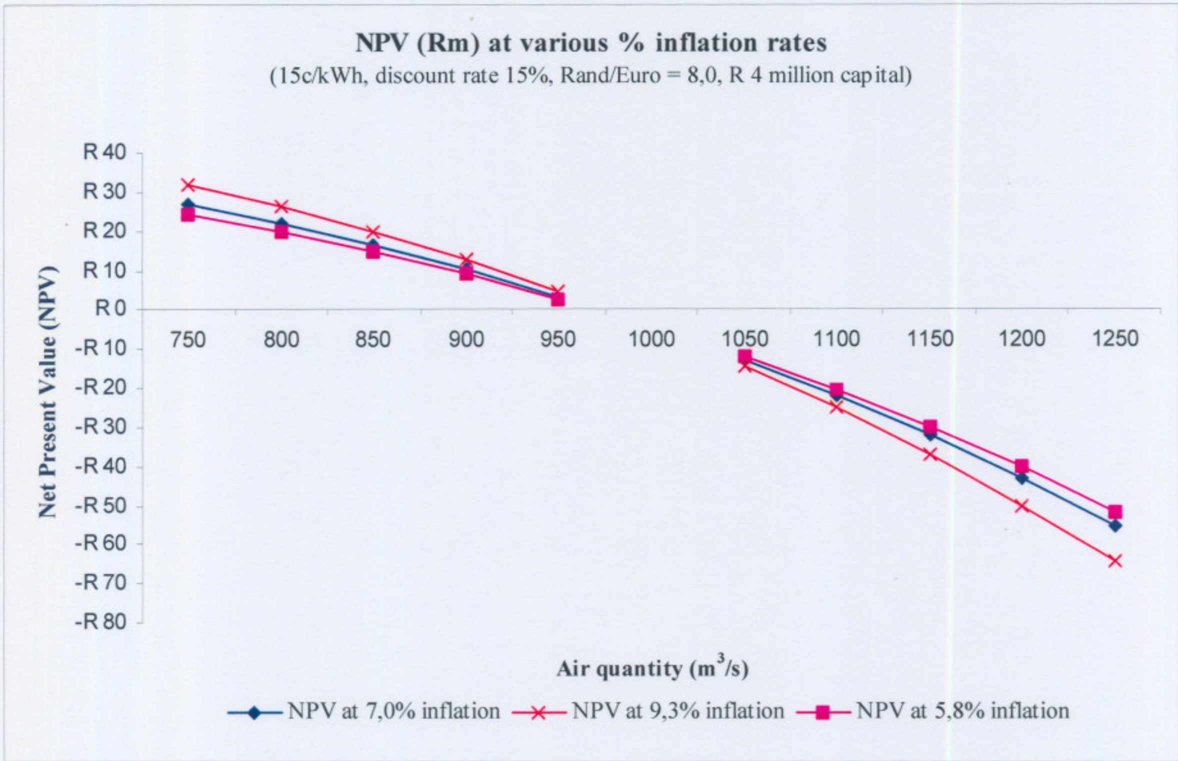
| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.53 | 3.86 | 4.22 | 4.61 | 5.04 | 5.51 | 6.02 | 6.58 | 7.19 | 7.86 | 8.60 | 9.40 | 10.27 | 11.23 | 12.28 | 13.42 | 14.67 | 16.04 | 17.53 |
| -4.00 | 2.72 | 2.97 | 3.25 | 3.55 | 3.88 | 4.25 | 4.64 | 5.07 | 5.55 | 6.06 | 6.63 | 7.25 | 7.92 | 8.66 | 9.47 | 10.35 | 11.31 | 12.36 | 13.52 | 14.78 |
| -4.00 | 2.14 | 2.34 | 2.56 | 2.80 | 3.06 | 3.35 | 3.66 | 4.00 | 4.37 | 4.78 | 5.23 | 5.71 | 6.25 | 6.83 | 7.46 | 8.16 | 8.92 | 9.75 | 10.66 | 11.65 |
| -4.00 | 1.50 | 1.64 | 1.79 | 1.96 | 2.14 | 2.34 | 2.56 | 2.79 | 3.05 | 3.34 | 3.65 | 3.99 | 4.36 | 4.77 | 5.21 | 5.70 | 6.23 | 6.81 | 7.44 | 8.14 |
| -4.00 | 0.77 | 0.85 | 0.93 | 1.01 | 1.11 | 1.21 | 1.32 | 1.45 | 1.58 | 1.73 | 1.89 | 2.06 | 2.26 | 2.47 | 2.70 | 2.95 | 3.22 | 3.52 | 3.85 | 4.21 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -1.00 | -1.09 | -1.20 | -1.31 | -1.43 | -1.56 | -1.71 | -1.87 | -2.04 | -2.23 | -2.44 | -2.67 | -2.92 | -3.19 | -3.49 | -3.81 | -4.17 | -4.55 | -4.98 |
| -4.00 | -1.89 | -2.07 | -2.26 | -2.47 | -2.70 | -2.95 | -3.23 | -3.53 | -3.86 | -4.22 | -4.61 | -5.04 | -5.51 | -6.03 | -6.59 | -7.20 | -7.87 | -8.60 | -9.41 | -10.28 |
| -4.00 | -2.96 | -3.24 | -3.54 | -3.87 | -4.23 | -4.62 | -5.05 | -5.53 | -6.04 | -6.60 | -7.22 | -7.89 | -8.63 | -9.43 | -10.31 | -11.27 | -12.32 | -13.47 | -14.72 | -16.09 |
| -4.00 | -4.13 | -4.51 | -4.93 | -5.39 | -5.90 | -6.44 | -7.05 | -7.70 | -8.42 | -9.20 | -10.06 | -11.00 | -12.02 | -13.14 | -14.37 | -15.71 | -17.17 | -18.77 | -20.52 | -22.43 |
| -4.00 | -5.40 | -5.90 | -6.45 | -7.05 | -7.71 | -8.42 | -9.21 | -10.07 | -11.00 | -12.03 | -13.15 | -14.38 | -15.72 | -17.18 | -18.78 | -20.53 | -22.44 | -24.53 | -26.82 | -29.32 |

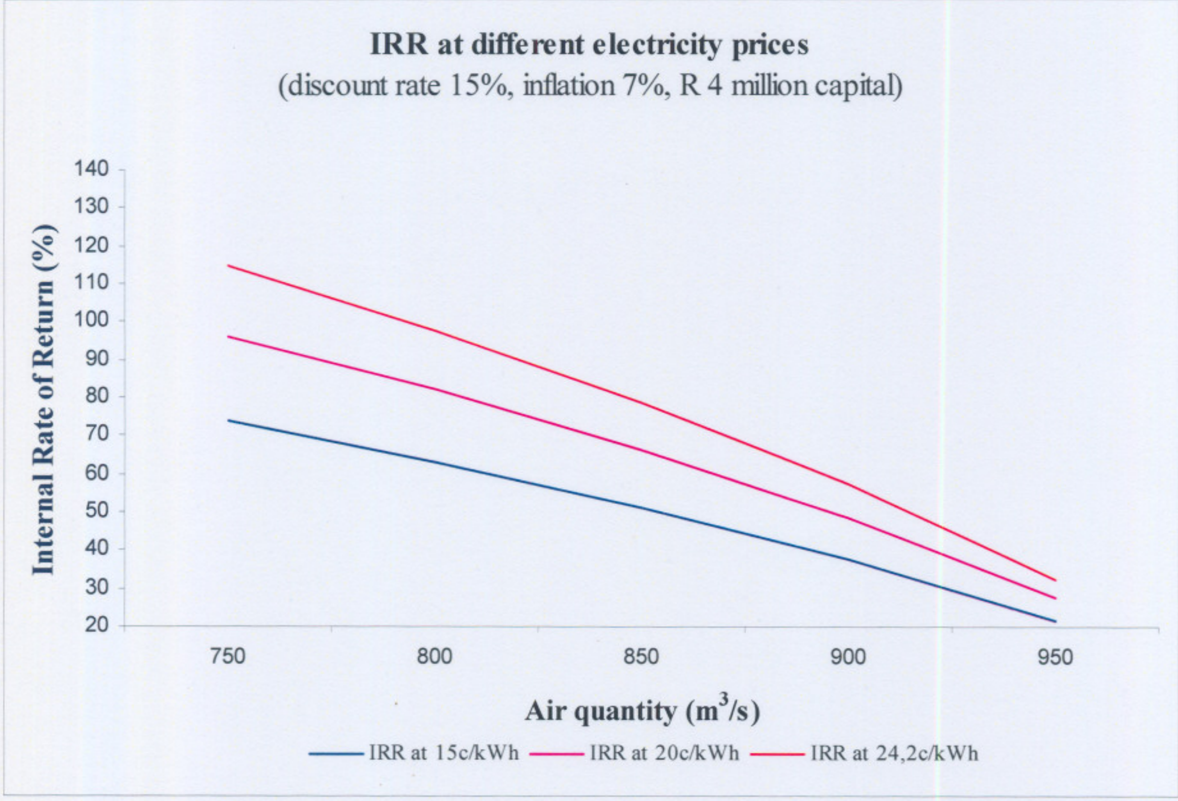
# APPENDIX I

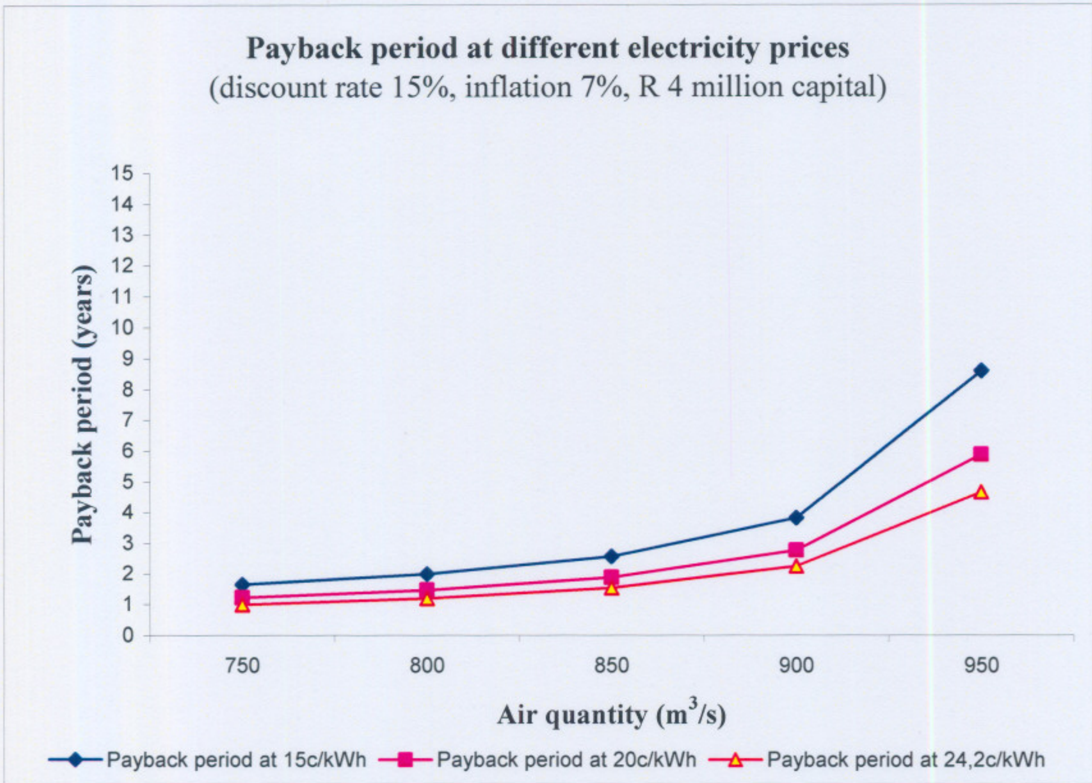
**DETAILED CASH FLOW SHEETS FOR VARIABLE SPEED DRIVE MOTOR**
(Summary of cash flow sheets for changes in the inflation rate)

## NPV, IRR and Payback periods for inflation rate %

| Inflation rate % | Q ($m^3/s$) | Payback period (years) | NPV (R m) | IRR (%) |
|---|---|---|---|---|
| 5.79% | 750 | 1.3 | 24.43 | 86 |
| | 800 | 1.6 | 19.96 | 74 |
| | 850 | 2.0 | 14.89 | 59 |
| | 900 | 3.0 | 9.19 | 43 |
| | 950 | 6.3 | 2.82 | 24 |
| | 1000 | | | |
| | 1050 | 0.0 | -12.07 | 0 |
| | 1100 | 0.0 | -20.67 | 0 |
| | 1150 | 0.0 | -30.09 | 0 |
| | 1200 | 0.0 | -40.37 | 0 |
| | 1250 | 0.0 | -51.54 | 0 |
| 6.36% | 750 | 1.3 | 25.53 | 87 |
| | 800 | 1.6 | 20.88 | 74 |
| | 850 | 2.0 | 15.62 | 60 |
| | 900 | 3.0 | 9.70 | 44 |
| | 950 | 6.5 | 3.09 | 25 |
| | 1000 | | | |
| | 1050 | 0.0 | -12.38 | 0 |
| | 1100 | 0.0 | -21.32 | 0 |
| | 1150 | 0.0 | -31.10 | 0 |
| | 1200 | 0.0 | -41.77 | 0 |
| | 1250 | 0.0 | -53.37 | 0 |
| 7.00% | 750 | 1.3 | 26.80 | 88 |
| | 800 | 1.6 | 21.96 | 75 |
| | 850 | 2.1 | 16.47 | 61 |
| | 900 | 3.1 | 10.29 | 44 |
| | 950 | 6.6 | 3.39 | 26 |
| | 1000 | | | |
| | 1050 | 0.0 | -12.74 | 0 |
| | 1100 | 0.0 | -22.06 | 0 |
| | 1150 | 0.0 | -32.27 | 0 |
| | 1200 | 0.0 | -43.40 | 0 |
| | 1250 | 0.0 | -55.50 | 0 |
| 7.70% | 750 | 1.4 | 28.30 | 88 |
| | 800 | 1.6 | 23.22 | 76 |
| | 850 | 2.1 | 17.46 | 61 |
| | 900 | 3.1 | 10.99 | 45 |
| | 950 | 6.8 | 3.75 | 26 |
| | 1000 | | | |
| | 1050 | 0.0 | -13.17 | 0 |
| | 1100 | 0.0 | -22.94 | 0 |
| | 1150 | 0.0 | -33.64 | 0 |
| | 1200 | 0.0 | -45.32 | 0 |
| | 1250 | 0.0 | -58.01 | 0 |
| 8.47% | 750 | 1.4 | 30.07 | 89 |
| | 800 | 1.6 | 24.71 | 76 |
| | 850 | 2.1 | 18.64 | 62 |
| | 900 | 3.2 | 11.81 | 46 |
| | 950 | 7.1 | 4.18 | 27 |
| | 1000 | | | |
| | 1050 | 0.0 | -13.67 | 0 |
| | 1100 | 0.0 | -23.98 | 0 |
| | 1150 | 0.0 | -35.27 | 0 |
| | 1200 | 0.0 | -47.58 | 0 |
| | 1250 | 0.0 | -60.97 | 0 |
| 9.32% | 750 | 1.4 | 32.18 | 90 |
| | 800 | 1.7 | 26.49 | 77 |
| | 850 | 2.1 | 20.04 | 63 |
| | 900 | 3.2 | 12.79 | 47 |
| | 950 | 7.4 | 4.68 | 28 |
| | 1000 | | | |
| | 1050 | 0.0 | -14.27 | 0 |
| | 1100 | 0.0 | -25.22 | 0 |
| | 1150 | 0.0 | -37.20 | 0 |
| | 1200 | 0.0 | -50.28 | 0 |
| | 1250 | 0.0 | -64.49 | 0 |


NPV (Rm) at various % inflation rates
(15c/kWh, discount rate 15%, Rand/Euro = 8,0, R 4 million capital)
Net Present Value (NPV)
R 40
R 30
R 20
R 10
R 0
-R 10
-R 20
-R 30
-R 40
-R 50
-R 60
-R 70
-R 80
750
800
850
900
950
1000
1050
1100
1150
1200
1250
Air quantity (m3/s)
NPV at 7,0% inflation
NPV at 9,3% inflation
NPV at 5,8% inflation


IRR at different electricity prices
(discount rate 15%, inflation 7%, R 4 million capital)
Internal Rate of Return (%)
140
130
120
110
100
90
80
70
60
50
40
30
20
750
800
850
900
950
Air quantity (m3/s)
IRR at 15c/kWh
IRR at 20c/kWh
IRR at 24,2c/kWh


Payback period at different electricity prices
(discount rate 15%, inflation 7%, R 4 million capital)
Payback period (years)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
750
800
850
900
950
Air quantity (m3/s)
Payback period at 15c/kWh
Payback period at 20c/kWh
Payback period at 24,2c/kWh

# APPENDIX J

**DETAILED CASH FLOW SHEETS FOR VARIABLE SPEED DRIVE MOTOR**
(Changes in the electricity price)

**Cash Flow Analysis** **Electricity price** **0.124** **R/kWh**
**(20 year period)**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.81 | 3.00 | 3.21 | 3.44 | 3.68 | 3.94 | 4.21 | 4.51 | 4.82 | 5.16 | 5.52 | 5.91 | 6.32 | 6.77 | 7.24 |
| -4.00 | 2.42 | 2.59 | 2.77 | 2.97 | 3.17 | 3.40 | 3.63 | 3.89 | 4.16 | 4.45 | 4.76 | 5.10 | 5.45 | 5.84 | 6.24 | 6.68 | 7.15 | 7.65 | 8.18 | 8.76 |
| -4.00 | 2.90 | 3.10 | 3.32 | 3.55 | 3.80 | 4.06 | 4.35 | 4.65 | 4.98 | 5.33 | 5.70 | 6.10 | 6.52 | 6.98 | 7.47 | 7.99 | 8.55 | 9.15 | 9.79 | 10.48 |
| -4.00 | 3.43 | 3.67 | 3.93 | 4.20 | 4.50 | 4.81 | 5.15 | 5.51 | 5.90 | 6.31 | 6.75 | 7.22 | 7.73 | 8.27 | 8.85 | 9.47 | 10.13 | 10.84 | 11.60 | 12.41 |
| -4.00 | 4.03 | 4.31 | 4.61 | 4.94 | 5.28 | 5.65 | 6.05 | 6.47 | 6.92 | 7.41 | 7.93 | 8.48 | 9.07 | 9.71 | 10.39 | 11.12 | 11.89 | 12.73 | 13.62 | 14.57 |
| -4.00 | 4.66 | 4.99 | 5.34 | 5.71 | 6.11 | 6.54 | 7.00 | 7.49 | 8.01 | 8.57 | 9.18 | 9.82 | 10.50 | 11.24 | 12.03 | 12.87 | 13.77 | 14.73 | 15.76 | 16.87 |
| -4.00 | 5.43 | 5.81 | 6.21 | 6.65 | 7.11 | 7.61 | 8.14 | 8.71 | 9.32 | 9.98 | 10.67 | 11.42 | 12.22 | 13.08 | 13.99 | 14.97 | 16.02 | 17.14 | 18.34 | 19.62 |
| -4.00 | 6.23 | 6.67 | 7.14 | 7.64 | 8.17 | 8.74 | 9.35 | 10.01 | 10.71 | 11.46 | 12.26 | 13.12 | 14.04 | 15.02 | 16.07 | 17.20 | 18.40 | 19.69 | 21.07 | 22.54 |
| -4.00 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.98 | 10.68 | 11.43 | 12.23 | 13.08 | 14.00 | 14.98 | 16.03 | 17.15 | 18.35 | 19.64 | 21.01 | 22.48 | 24.06 | 25.74 |
| -4.00 | 8.08 | 8.65 | 9.25 | 9.90 | 10.59 | 11.33 | 12.13 | 12.98 | 13.88 | 14.86 | 15.90 | 17.01 | 18.20 | 19.47 | 20.84 | 22.30 | 23.86 | 25.53 | 27.31 | 29.23 |
| -4.00 | 9.13 | 9.77 | 10.45 | 11.18 | 11.97 | 12.80 | 13.70 | 14.66 | 15.68 | 16.78 | 17.96 | 19.21 | 20.56 | 22.00 | 23.54 | 25.19 | 26.95 | 28.84 | 30.85 | 33.01 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.66 | 2.85 | 3.05 | 3.26 | 3.49 | 3.73 | 4.00 | 4.27 | 4.57 | 4.89 | 5.24 | 5.60 | 6.00 | 6.42 | 6.86 | 7.34 | 7.86 | 8.41 | 9.00 | 9.63 |
| -4.00 | 2.24 | 2.40 | 2.57 | 2.75 | 2.94 | 3.15 | 3.37 | 3.60 | 3.85 | 4.12 | 4.41 | 4.72 | 5.05 | 5.40 | 5.78 | 6.19 | 6.62 | 7.08 | 7.58 | 8.11 |
| -4.00 | 1.77 | 1.89 | 2.02 | 2.17 | 2.32 | 2.48 | 2.65 | 2.84 | 3.04 | 3.25 | 3.48 | 3.72 | 3.98 | 4.26 | 4.56 | 4.88 | 5.22 | 5.58 | 5.97 | 6.39 |
| -4.00 | 1.23 | 1.32 | 1.41 | 1.51 | 1.62 | 1.73 | 1.85 | 1.98 | 2.12 | 2.27 | 2.42 | 2.59 | 2.78 | 2.97 | 3.18 | 3.40 | 3.64 | 3.89 | 4.17 | 4.46 |
| -4.00 | 0.64 | 0.68 | 0.73 | 0.78 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.17 | 1.25 | 1.34 | 1.43 | 1.53 | 1.64 | 1.75 | 1.88 | 2.01 | 2.15 | 2.30 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.76 | -0.82 | -0.87 | -0.93 | -1.00 | -1.07 | -1.14 | -1.22 | -1.31 | -1.40 | -1.50 | -1.60 | -1.72 | -1.84 | -1.97 | -2.10 | -2.25 | -2.41 | -2.58 | -2.76 |
| -4.00 | -1.57 | -1.68 | -1.80 | -1.92 | -2.06 | -2.20 | -2.35 | -2.52 | -2.70 | -2.88 | -3.09 | -3.30 | -3.53 | -3.78 | -4.05 | -4.33 | -4.63 | -4.96 | -5.30 | -5.67 |
| -4.00 | -2.45 | -2.62 | -2.81 | -3.00 | -3.22 | -3.44 | -3.68 | -3.94 | -4.21 | -4.51 | -4.83 | -5.16 | -5.52 | -5.91 | -6.32 | -6.77 | -7.24 | -7.75 | -8.29 | -8.87 |
| -4.00 | -3.42 | -3.66 | -3.91 | -4.19 | -4.48 | -4.79 | -5.13 | -5.49 | -5.87 | -6.28 | -6.72 | -7.19 | -7.70 | -8.23 | -8.81 | -9.43 | -10.09 | -10.79 | -11.55 | -12.36 |
| -4.00 | -4.46 | -4.78 | -5.11 | -5.47 | -5.85 | -6.26 | -6.70 | -7.17 | -7.67 | -8.21 | -8.78 | -9.40 | -10.06 | -10.76 | -11.51 | -12.32 | -13.18 | -14.10 | -15.09 | -16.15 |

**Cash Flow Analysis (20 year period)** **Electricity price 0.136 R/kWh**

**Year**

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.20 | 2.35 | 2.52 | 2.69 | 2.88 | 3.08 | 3.30 | 3.53 | 3.78 | 4.04 | 4.32 | 4.63 | 4.95 | 5.30 | 5.67 | 6.07 | 6.49 | 6.94 | 7.43 | 7.95 |
| -4.00 | 2.66 | 2.85 | 3.05 | 3.26 | 3.49 | 3.73 | 3.99 | 4.27 | 4.57 | 4.89 | 5.23 | 5.60 | 5.99 | 6.41 | 6.86 | 7.34 | 7.85 | 8.40 | 8.99 | 9.62 |
| -4.00 | 3.18 | 3.41 | 3.64 | 3.90 | 4.17 | 4.46 | 4.78 | 5.11 | 5.47 | 5.85 | 6.26 | 6.70 | 7.17 | 7.67 | 8.21 | 8.78 | 9.40 | 10.05 | 10.76 | 11.51 |
| -4.00 | 3.77 | 4.03 | 4.32 | 4.62 | 4.94 | 5.29 | 5.66 | 6.06 | 6.48 | 6.93 | 7.42 | 7.94 | 8.49 | 9.09 | 9.72 | 10.40 | 11.13 | 11.91 | 12.74 | 13.64 |
| -4.00 | 4.43 | 4.74 | 5.07 | 5.42 | 5.80 | 6.21 | 6.65 | 7.11 | 7.61 | 8.14 | 8.71 | 9.32 | 9.97 | 10.67 | 11.42 | 12.22 | 13.07 | 13.99 | 14.97 | 16.01 |
| -4.00 | 5.13 | 5.49 | 5.87 | 6.28 | 6.72 | 7.19 | 7.70 | 8.24 | 8.81 | 9.43 | 10.09 | 10.80 | 11.55 | 12.36 | 13.23 | 14.15 | 15.14 | 16.20 | 17.34 | 18.55 |
| -4.00 | 5.97 | 6.38 | 6.83 | 7.31 | 7.82 | 8.37 | 8.95 | 9.58 | 10.25 | 10.97 | 11.73 | 12.56 | 13.43 | 14.38 | 15.38 | 16.46 | 17.61 | 18.84 | 20.16 | 21.57 |
| -4.00 | 6.85 | 7.33 | 7.85 | 8.39 | 8.98 | 9.61 | 10.28 | 11.00 | 11.77 | 12.60 | 13.48 | 14.42 | 15.43 | 16.51 | 17.67 | 18.91 | 20.23 | 21.65 | 23.16 | 24.78 |
| -4.00 | 7.82 | 8.37 | 8.96 | 9.59 | 10.26 | 10.97 | 11.74 | 12.57 | 13.44 | 14.39 | 15.39 | 16.47 | 17.62 | 18.86 | 20.18 | 21.59 | 23.10 | 24.72 | 26.45 | 28.30 |
| -4.00 | 8.89 | 9.51 | 10.17 | 10.88 | 11.65 | 12.46 | 13.33 | 14.27 | 15.27 | 16.34 | 17.48 | 18.70 | 20.01 | 21.41 | 22.91 | 24.51 | 26.23 | 28.07 | 30.03 | 32.13 |
| -4.00 | 10.04 | 10.74 | 11.49 | 12.30 | 13.16 | 14.08 | 15.06 | 16.12 | 17.25 | 18.45 | 19.75 | 21.13 | 22.61 | 24.19 | 25.88 | 27.69 | 29.63 | 31.71 | 33.93 | 36.30 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.93 | 3.14 | 3.36 | 3.59 | 3.84 | 4.11 | 4.40 | 4.71 | 5.04 | 5.39 | 5.77 | 6.17 | 6.60 | 7.06 | 7.56 | 8.09 | 8.65 | 9.26 | 9.91 | 10.60 |
| -4.00 | 2.47 | 2.64 | 2.83 | 3.03 | 3.24 | 3.46 | 3.71 | 3.97 | 4.24 | 4.54 | 4.86 | 5.20 | 5.56 | 5.95 | 6.37 | 6.81 | 7.29 | 7.80 | 8.35 | 8.93 |
| -4.00 | 1.95 | 2.08 | 2.23 | 2.39 | 2.55 | 2.73 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 |
| -4.00 | 1.36 | 1.45 | 1.56 | 1.66 | 1.78 | 1.91 | 2.04 | 2.18 | 2.33 | 2.50 | 2.67 | 2.86 | 3.06 | 3.27 | 3.50 | 3.75 | 4.01 | 4.29 | 4.59 | 4.91 |
| -4.00 | 0.70 | 0.75 | 0.80 | 0.86 | 0.92 | 0.98 | 1.05 | 1.13 | 1.21 | 1.29 | 1.38 | 1.48 | 1.58 | 1.69 | 1.81 | 1.94 | 2.07 | 2.22 | 2.37 | 2.54 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.84 | -0.89 | -0.96 | -1.02 | -1.10 | -1.17 | -1.25 | -1.34 | -1.44 | -1.54 | -1.64 | -1.76 | -1.88 | -2.01 | -2.15 | -2.31 | -2.47 | -2.64 | -2.82 | -3.02 |
| -4.00 | -1.72 | -1.84 | -1.97 | -2.11 | -2.26 | -2.42 | -2.59 | -2.77 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.44 | -4.75 | -5.09 | -5.44 | -5.82 | -6.23 |
| -4.00 | -2.70 | -2.88 | -3.09 | -3.30 | -3.53 | -3.78 | -4.04 | -4.33 | -4.63 | -4.96 | -5.30 | -5.67 | -6.07 | -6.50 | -6.95 | -7.44 | -7.96 | -8.51 | -9.11 | -9.75 |
| -4.00 | -3.76 | -4.02 | -4.30 | -4.60 | -4.92 | -5.27 | -5.64 | -6.03 | -6.45 | -6.90 | -7.39 | -7.91 | -8.46 | -9.05 | -9.68 | -10.36 | -11.09 | -11.86 | -12.69 | -13.58 |
| -4.00 | -4.91 | -5.25 | -5.62 | -6.01 | -6.43 | -6.88 | -7.37 | -7.88 | -8.43 | -9.02 | -9.66 | -10.33 | -11.05 | -11.83 | -12.66 | -13.54 | -14.49 | -15.50 | -16.59 | -17.75 |

**Cash Flow Analysis** **Electricity price 0.150 R/kWh**
**(20 year period)**

**Year**

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.41 | 2.58 | 2.76 | 2.96 | 3.16 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.23 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 |
| -4.00 | 2.92 | 3.13 | 3.35 | 3.58 | 3.83 | 4.10 | 4.39 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 |
| -4.00 | 3.50 | 3.74 | 4.00 | 4.28 | 4.58 | 4.90 | 5.25 | 5.62 | 6.01 | 6.43 | 6.88 | 7.36 | 7.88 | 8.43 | 9.02 | 9.65 | 10.32 | 11.05 | 11.82 | 12.65 |
| -4.00 | 4.14 | 4.43 | 4.74 | 5.08 | 5.43 | 5.81 | 6.22 | 6.65 | 7.12 | 7.62 | 8.15 | 8.72 | 9.33 | 9.99 | 10.69 | 11.43 | 12.23 | 13.09 | 14.01 | 14.99 |
| -4.00 | 4.87 | 5.21 | 5.57 | 5.96 | 6.38 | 6.83 | 7.30 | 7.82 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.43 | 14.37 | 15.37 | 16.45 | 17.60 |
| -4.00 | 5.64 | 6.04 | 6.46 | 6.91 | 7.39 | 7.91 | 8.47 | 9.06 | 9.69 | 10.37 | 11.10 | 11.87 | 12.71 | 13.60 | 14.55 | 15.57 | 16.65 | 17.82 | 19.07 | 20.40 |
| -4.00 | 6.56 | 7.02 | 7.51 | 8.03 | 8.60 | 9.20 | 9.84 | 10.53 | 11.27 | 12.06 | 12.90 | 13.80 | 14.77 | 15.80 | 16.91 | 18.09 | 19.36 | 20.71 | 22.16 | 23.72 |
| -4.00 | 7.53 | 8.06 | 8.63 | 9.23 | 9.88 | 10.57 | 11.31 | 12.10 | 12.95 | 13.85 | 14.82 | 15.86 | 16.97 | 18.16 | 19.43 | 20.79 | 22.24 | 23.80 | 25.47 | 27.25 |
| -4.00 | 8.60 | 9.21 | 9.85 | 10.54 | 11.28 | 12.07 | 12.91 | 13.82 | 14.78 | 15.82 | 16.92 | 18.11 | 19.38 | 20.73 | 22.18 | 23.74 | 25.40 | 27.18 | 29.08 | 31.11 |
| -4.00 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 | 17.96 | 19.22 | 20.56 | 22.00 | 23.54 | 25.19 | 26.96 | 28.84 | 30.86 | 33.02 | 35.33 |
| -4.00 | 11.04 | 11.81 | 12.64 | 13.52 | 14.47 | 15.48 | 16.56 | 17.72 | 18.96 | 20.29 | 21.71 | 23.23 | 24.86 | 26.60 | 28.46 | 30.45 | 32.59 | 34.87 | 37.31 | 39.92 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.23 | 3.45 | 3.69 | 3.95 | 4.23 | 4.53 | 4.84 | 5.18 | 5.54 | 5.93 | 6.35 | 6.79 | 7.27 | 7.78 | 8.32 | 8.90 | 9.53 | 10.19 | 10.91 | 11.67 |
| -4.00 | 2.72 | 2.91 | 3.11 | 3.33 | 3.56 | 3.81 | 4.08 | 4.37 | 4.67 | 5.00 | 5.35 | 5.72 | 6.13 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 |
| -4.00 | 2.14 | 2.29 | 2.46 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.17 | 5.53 | 5.92 | 6.33 | 6.77 | 7.25 | 7.76 |
| -4.00 | 1.50 | 1.60 | 1.71 | 1.83 | 1.96 | 2.10 | 2.25 | 2.40 | 2.57 | 2.75 | 2.95 | 3.15 | 3.37 | 3.61 | 3.86 | 4.13 | 4.42 | 4.73 | 5.06 | 5.42 |
| -4.00 | 0.77 | 0.83 | 0.89 | 0.95 | 1.02 | 1.09 | 1.16 | 1.24 | 1.33 | 1.42 | 1.52 | 1.63 | 1.74 | 1.87 | 2.00 | 2.14 | 2.29 | 2.45 | 2.62 | 2.80 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -0.92 | -0.98 | -1.05 | -1.12 | -1.20 | -1.29 | -1.38 | -1.47 | -1.57 | -1.68 | -1.80 | -1.93 | -2.06 | -2.21 | -2.36 | -2.53 | -2.70 | -2.89 | -3.10 | -3.31 |
| -4.00 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.65 | -2.84 | -3.04 | -3.25 | -3.48 | -3.72 | -3.98 | -4.26 | -4.56 | -4.88 | -5.22 | -5.59 | -5.98 | -6.40 | -6.84 |
| -4.00 | -2.96 | -3.17 | -3.39 | -3.63 | -3.88 | -4.15 | -4.45 | -4.76 | -5.09 | -5.45 | -5.83 | -6.23 | -6.67 | -7.14 | -7.64 | -8.17 | -8.74 | -9.36 | -10.01 | -10.71 |
| -4.00 | -4.13 | -4.42 | -4.73 | -5.06 | -5.41 | -5.79 | -6.20 | -6.63 | -7.09 | -7.59 | -8.12 | -8.69 | -9.30 | -9.95 | -10.65 | -11.39 | -12.19 | -13.04 | -13.95 | -14.93 |
| -4.00 | -5.40 | -5.77 | -6.18 | -6.61 | -7.07 | -7.57 | -8.10 | -8.67 | -9.27 | -9.92 | -10.62 | -11.36 | -12.15 | -13.00 | -13.91 | -14.89 | -15.93 | -17.05 | -18.24 | -19.52 |

**Cash Flow Analysis** **Electricity price 0.165 R/kWh**
**(20 year period)**

| Year | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
| -4.00 | 2.65 | 2.84 | 3.04 | 3.25 | 3.48 | 3.72 | 3.98 | 4.26 | 4.56 | 4.88 | 5.22 | 5.58 | 5.97 | 6.39 | 6.84 | 7.32 | 7.83 | 8.38 | 8.96 | 9.59 |
| -4.00 | 3.21 | 3.43 | 3.68 | 3.93 | 4.21 | 4.50 | 4.82 | 5.15 | 5.52 | 5.90 | 6.32 | 6.76 | 7.23 | 7.74 | 8.28 | 8.86 | 9.48 | 10.14 | 10.85 | 11.61 |
| -4.00 | 3.84 | 4.11 | 4.40 | 4.71 | 5.04 | 5.39 | 5.77 | 6.17 | 6.60 | 7.07 | 7.56 | 8.09 | 8.65 | 9.26 | 9.91 | 10.60 | 11.34 | 12.14 | 12.99 | 13.90 |
| -4.00 | 4.55 | 4.87 | 5.21 | 5.58 | 5.97 | 6.39 | 6.84 | 7.31 | 7.83 | 8.37 | 8.96 | 9.59 | 10.26 | 10.98 | 11.74 | 12.57 | 13.45 | 14.39 | 15.39 | 16.47 |
| -4.00 | 5.35 | 5.72 | 6.12 | 6.55 | 7.01 | 7.50 | 8.03 | 8.59 | 9.19 | 9.84 | 10.52 | 11.26 | 12.05 | 12.89 | 13.79 | 14.76 | 15.79 | 16.90 | 18.08 | 19.35 |
| -4.00 | 6.20 | 6.64 | 7.10 | 7.60 | 8.13 | 8.70 | 9.31 | 9.96 | 10.66 | 11.41 | 12.21 | 13.06 | 13.97 | 14.95 | 16.00 | 17.12 | 18.32 | 19.60 | 20.97 | 22.44 |
| -4.00 | 7.21 | 7.71 | 8.25 | 8.83 | 9.45 | 10.11 | 10.82 | 11.58 | 12.39 | 13.25 | 14.18 | 15.18 | 16.24 | 17.37 | 18.59 | 19.89 | 21.28 | 22.77 | 24.37 | 26.07 |
| -4.00 | 8.28 | 8.86 | 9.48 | 10.15 | 10.86 | 11.62 | 12.43 | 13.30 | 14.23 | 15.23 | 16.30 | 17.44 | 18.66 | 19.96 | 21.36 | 22.86 | 24.45 | 26.17 | 28.00 | 29.96 |
| -4.00 | 9.46 | 10.12 | 10.83 | 11.59 | 12.40 | 13.27 | 14.20 | 15.19 | 16.25 | 17.39 | 18.61 | 19.91 | 21.31 | 22.80 | 24.39 | 26.10 | 27.93 | 29.88 | 31.97 | 34.21 |
| -4.00 | 10.74 | 11.50 | 12.30 | 13.16 | 14.08 | 15.07 | 16.12 | 17.25 | 18.46 | 19.75 | 21.13 | 22.61 | 24.20 | 25.89 | 27.70 | 29.64 | 31.72 | 33.94 | 36.31 | 38.85 |
| -4.00 | 12.14 | 12.99 | 13.90 | 14.87 | 15.91 | 17.02 | 18.22 | 19.49 | 20.85 | 22.31 | 23.88 | 25.55 | 27.34 | 29.25 | 31.30 | 33.49 | 35.83 | 38.34 | 41.02 | 43.90 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.55 | 3.80 | 4.07 | 4.35 | 4.66 | 4.98 | 5.33 | 5.70 | 6.10 | 6.53 | 6.99 | 7.48 | 8.00 | 8.56 | 9.16 | 9.80 | 10.49 | 11.22 | 12.01 | 12.85 |
| -4.00 | 2.99 | 3.20 | 3.43 | 3.67 | 3.93 | 4.20 | 4.49 | 4.81 | 5.15 | 5.51 | 5.89 | 6.30 | 6.74 | 7.22 | 7.72 | 8.26 | 8.84 | 9.46 | 10.12 | 10.83 |
| -4.00 | 2.36 | 2.53 | 2.70 | 2.89 | 3.10 | 3.31 | 3.54 | 3.79 | 4.06 | 4.34 | 4.65 | 4.97 | 5.32 | 5.69 | 6.09 | 6.52 | 6.97 | 7.46 | 7.98 | 8.54 |
| -4.00 | 1.65 | 1.77 | 1.89 | 2.02 | 2.16 | 2.31 | 2.48 | 2.65 | 2.84 | 3.03 | 3.25 | 3.47 | 3.72 | 3.98 | 4.26 | 4.55 | 4.87 | 5.21 | 5.58 | 5.97 |
| -4.00 | 0.85 | 0.91 | 0.98 | 1.05 | 1.12 | 1.20 | 1.28 | 1.37 | 1.47 | 1.57 | 1.68 | 1.80 | 1.93 | 2.06 | 2.20 | 2.36 | 2.52 | 2.70 | 2.89 | 3.09 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -1.01 | -1.08 | -1.15 | -1.23 | -1.32 | -1.41 | -1.51 | -1.61 | -1.73 | -1.85 | -1.98 | -2.12 | -2.26 | -2.42 | -2.59 | -2.77 | -2.97 | -3.17 | -3.40 | -3.63 |
| -4.00 | -2.08 | -2.22 | -2.38 | -2.55 | -2.73 | -2.92 | -3.12 | -3.34 | -3.57 | -3.82 | -4.09 | -4.38 | -4.68 | -5.01 | -5.36 | -5.74 | -6.14 | -6.57 | -7.03 | -7.52 |
| -4.00 | -3.26 | -3.48 | -3.73 | -3.99 | -4.27 | -4.57 | -4.89 | -5.23 | -5.59 | -5.98 | -6.40 | -6.85 | -7.33 | -7.84 | -8.39 | -8.98 | -9.61 | -10.28 | -11.00 | -11.77 |
| -4.00 | -4.54 | -4.86 | -5.20 | -5.56 | -5.95 | -6.37 | -6.81 | -7.29 | -7.80 | -8.34 | -8.93 | -9.55 | -10.22 | -10.94 | -11.70 | -12.52 | -13.40 | -14.34 | -15.34 | -16.41 |
| -4.00 | -5.93 | -6.35 | -6.79 | -7.27 | -7.78 | -8.32 | -8.90 | -9.53 | -10.19 | -10.91 | -11.67 | -12.49 | -13.36 | -14.30 | -15.30 | -16.37 | -17.51 | -18.74 | -20.05 | -21.46 |

**Cash Flow Analysis (20 year period)** **Electricity price 0.182 R/kWh**

**Year**

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 2.91 | 3.12 | 3.34 | 3.57 | 3.82 | 4.09 | 4.37 | 4.68 | 5.01 | 5.36 | 5.73 | 6.13 | 6.56 | 7.02 | 7.51 | 8.04 | 8.60 | 9.20 | 9.85 | 10.54 |
| -4.00 | 3.53 | 3.77 | 4.04 | 4.32 | 4.62 | 4.95 | 5.29 | 5.66 | 6.06 | 6.49 | 6.94 | 7.42 | 7.94 | 8.50 | 9.10 | 9.73 | 10.41 | 11.14 | 11.92 | 12.76 |
| -4.00 | 4.22 | 4.52 | 4.84 | 5.17 | 5.54 | 5.92 | 6.34 | 6.78 | 7.26 | 7.76 | 8.31 | 8.89 | 9.51 | 10.18 | 10.89 | 11.65 | 12.47 | 13.34 | 14.27 | 15.27 |
| -4.00 | 5.01 | 5.36 | 5.73 | 6.13 | 6.56 | 7.02 | 7.51 | 8.04 | 8.60 | 9.20 | 9.85 | 10.54 | 11.27 | 12.06 | 12.91 | 13.81 | 14.78 | 15.81 | 16.92 | 18.10 |
| -4.00 | 5.88 | 6.29 | 6.73 | 7.20 | 7.71 | 8.25 | 8.83 | 9.44 | 10.10 | 10.81 | 11.57 | 12.38 | 13.24 | 14.17 | 15.16 | 16.23 | 17.36 | 18.58 | 19.88 | 21.27 |
| -4.00 | 6.82 | 7.30 | 7.81 | 8.36 | 8.95 | 9.57 | 10.24 | 10.96 | 11.73 | 12.55 | 13.42 | 14.36 | 15.37 | 16.45 | 17.60 | 18.83 | 20.15 | 21.56 | 23.07 | 24.68 |
| -4.00 | 7.93 | 8.48 | 9.08 | 9.71 | 10.39 | 11.12 | 11.90 | 12.73 | 13.62 | 14.57 | 15.59 | 16.68 | 17.85 | 19.10 | 20.44 | 21.87 | 23.40 | 25.04 | 26.79 | 28.67 |
| -4.00 | 9.11 | 9.75 | 10.43 | 11.16 | 11.94 | 12.77 | 13.67 | 14.63 | 15.65 | 16.75 | 17.92 | 19.17 | 20.51 | 21.95 | 23.49 | 25.13 | 26.89 | 28.77 | 30.79 | 32.94 |
| -4.00 | 10.40 | 11.13 | 11.91 | 12.74 | 13.64 | 14.59 | 15.61 | 16.70 | 17.87 | 19.12 | 20.46 | 21.89 | 23.43 | 25.07 | 26.82 | 28.70 | 30.71 | 32.86 | 35.16 | 37.62 |
| -4.00 | 11.81 | 12.64 | 13.53 | 14.47 | 15.49 | 16.57 | 17.73 | 18.97 | 20.30 | 21.72 | 23.24 | 24.87 | 26.61 | 28.47 | 30.46 | 32.59 | 34.88 | 37.32 | 39.93 | 42.72 |
| -4.00 | 13.35 | 14.28 | 15.28 | 16.35 | 17.50 | 18.72 | 20.03 | 21.43 | 22.93 | 24.54 | 26.26 | 28.09 | 30.06 | 32.17 | 34.42 | 36.83 | 39.40 | 42.16 | 45.11 | 48.27 |

**Net Cash Flow**

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.91 | 4.18 | 4.48 | 4.79 | 5.13 | 5.49 | 5.87 | 6.28 | 6.72 | 7.19 | 7.69 | 8.23 | 8.81 | 9.42 | 10.08 | 10.79 | 11.55 | 12.35 | 13.22 | 14.14 |
| -4.00 | 3.30 | 3.53 | 3.77 | 4.04 | 4.32 | 4.62 | 4.95 | 5.29 | 5.66 | 6.06 | 6.49 | 6.94 | 7.42 | 7.94 | 8.50 | 9.10 | 9.73 | 10.41 | 11.14 | 11.92 |
| -4.00 | 2.60 | 2.78 | 2.98 | 3.19 | 3.41 | 3.65 | 3.90 | 4.18 | 4.47 | 4.78 | 5.12 | 5.47 | 5.86 | 6.27 | 6.71 | 7.18 | 7.68 | 8.22 | 8.79 | 9.41 |
| -4.00 | 1.82 | 1.95 | 2.08 | 2.23 | 2.38 | 2.55 | 2.73 | 2.92 | 3.12 | 3.34 | 3.58 | 3.83 | 4.09 | 4.38 | 4.69 | 5.02 | 5.37 | 5.74 | 6.14 | 6.58 |
| -4.00 | 0.94 | 1.01 | 1.08 | 1.16 | 1.24 | 1.32 | 1.42 | 1.51 | 1.62 | 1.73 | 1.86 | 1.99 | 2.12 | 2.27 | 2.43 | 2.60 | 2.78 | 2.98 | 3.19 | 3.41 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -1.10 | -1.18 | -1.26 | -1.35 | -1.45 | -1.55 | -1.65 | -1.77 | -1.89 | -2.03 | -2.17 | -2.32 | -2.48 | -2.66 | -2.84 | -3.04 | -3.26 | -3.48 | -3.73 | -3.99 |
| -4.00 | -2.28 | -2.44 | -2.62 | -2.80 | -2.99 | -3.20 | -3.43 | -3.67 | -3.92 | -4.20 | -4.49 | -4.81 | -5.14 | -5.50 | -5.89 | -6.30 | -6.74 | -7.21 | -7.72 | -8.26 |
| -4.00 | -3.58 | -3.83 | -4.10 | -4.38 | -4.69 | -5.02 | -5.37 | -5.75 | -6.15 | -6.58 | -7.04 | -7.53 | -8.06 | -8.62 | -9.23 | -9.87 | -10.56 | -11.30 | -12.09 | -12.94 |
| -4.00 | -4.99 | -5.34 | -5.71 | -6.11 | -6.54 | -7.00 | -7.49 | -8.01 | -8.57 | -9.17 | -9.81 | -10.50 | -11.24 | -12.02 | -12.87 | -13.77 | -14.73 | -15.76 | -16.86 | -18.04 |
| -4.00 | -6.52 | -6.98 | -7.47 | -7.99 | -8.55 | -9.15 | -9.79 | -10.48 | -11.21 | -11.99 | -12.83 | -13.73 | -14.69 | -15.72 | -16.82 | -18.00 | -19.26 | -20.61 | -22.05 | -23.59 |

**Cash Flow Analysis (20 year period)** **Electricity price 0.200 R/kWh**

**Year**

| **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 3.20 | 3.42 | 3.66 | 3.92 | 4.20 | 4.49 | 4.80 | 5.14 | 5.50 | 5.88 | 6.30 | 6.74 | 7.21 | 7.71 | 8.25 | 8.83 | 9.45 | 10.11 | 10.82 | 11.58 |
| -4.00 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 | 5.82 | 6.22 | 6.66 | 7.13 | 7.63 | 8.16 | 8.73 | 9.34 | 10.00 | 10.69 | 11.44 | 12.24 | 13.10 | 14.02 |
| -4.00 | 4.64 | 4.97 | 5.31 | 5.69 | 6.08 | 6.51 | 6.97 | 7.45 | 7.98 | 8.53 | 9.13 | 9.77 | 10.45 | 11.19 | 11.97 | 12.81 | 13.70 | 14.66 | 15.69 | 16.79 |
| -4.00 | 5.50 | 5.89 | 6.30 | 6.74 | 7.21 | 7.72 | 8.26 | 8.84 | 9.45 | 10.12 | 10.82 | 11.58 | 12.39 | 13.26 | 14.19 | 15.18 | 16.25 | 17.38 | 18.60 | 19.90 |
| -4.00 | 6.47 | 6.92 | 7.40 | 7.92 | 8.47 | 9.07 | 9.70 | 10.38 | 11.11 | 11.89 | 12.72 | 13.61 | 14.56 | 15.58 | 16.67 | 17.84 | 19.09 | 20.42 | 21.85 | 23.38 |
| -4.00 | 7.51 | 8.03 | 8.59 | 9.19 | 9.84 | 10.53 | 11.26 | 12.05 | 12.90 | 13.80 | 14.76 | 15.80 | 16.90 | 18.09 | 19.35 | 20.71 | 22.16 | 23.71 | 25.37 | 27.14 |
| -4.00 | 8.72 | 9.33 | 9.98 | 10.68 | 11.42 | 12.22 | 13.08 | 14.00 | 14.98 | 16.02 | 17.15 | 18.35 | 19.63 | 21.00 | 22.47 | 24.05 | 25.73 | 27.53 | 29.46 | 31.52 |
| -4.00 | 10.02 | 10.72 | 11.47 | 12.27 | 13.13 | 14.05 | 15.03 | 16.08 | 17.21 | 18.41 | 19.70 | 21.08 | 22.56 | 24.14 | 25.82 | 27.63 | 29.57 | 31.64 | 33.85 | 36.22 |
| -4.00 | 11.44 | 12.24 | 13.10 | 14.01 | 14.99 | 16.04 | 17.17 | 18.37 | 19.65 | 21.03 | 22.50 | 24.08 | 25.76 | 27.56 | 29.49 | 31.56 | 33.77 | 36.13 | 38.66 | 41.37 |
| -4.00 | 12.99 | 13.90 | 14.87 | 15.91 | 17.03 | 18.22 | 19.50 | 20.86 | 22.32 | 23.88 | 25.56 | 27.34 | 29.26 | 31.31 | 33.50 | 35.84 | 38.35 | 41.04 | 43.91 | 46.98 |
| -4.00 | 14.68 | 15.71 | 16.81 | 17.98 | 19.24 | 20.59 | 22.03 | 23.57 | 25.22 | 26.99 | 28.87 | 30.90 | 33.06 | 35.37 | 37.85 | 40.50 | 43.33 | 46.37 | 49.61 | 53.09 |

**Net Cash Flow**

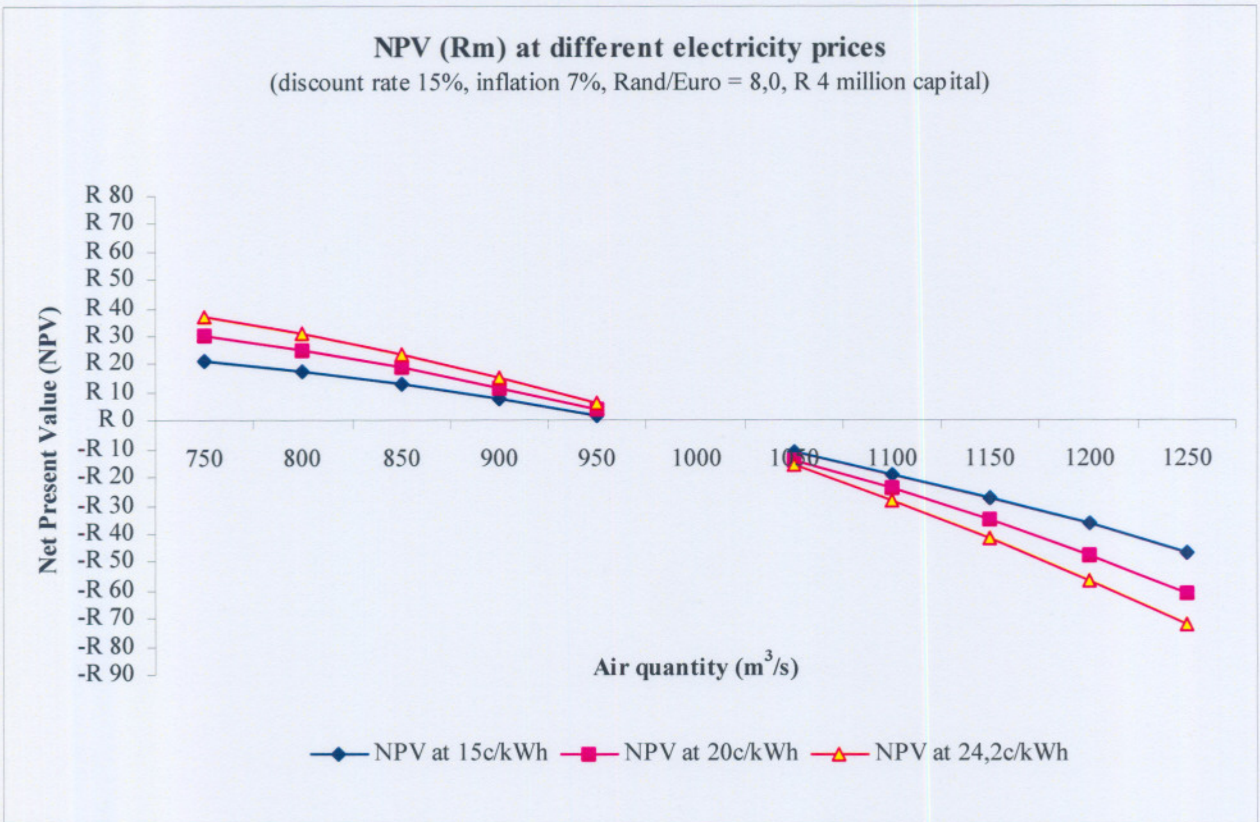
| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -4.00 | 4.30 | 4.61 | 4.93 | 5.27 | 5.64 | 6.04 | 6.46 | 6.91 | 7.40 | 7.91 | 8.47 | 9.06 | 9.70 | 10.37 | 11.10 | 11.88 | 12.71 | 13.60 | 14.55 | 15.57 |
| -4.00 | 3.63 | 3.88 | 4.16 | 4.45 | 4.76 | 5.09 | 5.45 | 5.83 | 6.24 | 6.67 | 7.14 | 7.64 | 8.17 | 8.75 | 9.36 | 10.01 | 10.71 | 11.46 | 12.27 | 13.13 |
| -4.00 | 2.86 | 3.06 | 3.28 | 3.51 | 3.75 | 4.02 | 4.30 | 4.60 | 4.92 | 5.26 | 5.63 | 6.03 | 6.45 | 6.90 | 7.38 | 7.90 | 8.45 | 9.05 | 9.68 | 10.36 |
| -4.00 | 2.00 | 2.14 | 2.29 | 2.45 | 2.63 | 2.81 | 3.01 | 3.22 | 3.44 | 3.68 | 3.94 | 4.22 | 4.51 | 4.83 | 5.16 | 5.53 | 5.91 | 6.33 | 6.77 | 7.24 |
| -4.00 | 1.04 | 1.11 | 1.19 | 1.27 | 1.36 | 1.46 | 1.56 | 1.67 | 1.79 | 1.91 | 2.05 | 2.19 | 2.34 | 2.51 | 2.68 | 2.87 | 3.07 | 3.29 | 3.52 | 3.76 |
| -4.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -4.00 | -1.21 | -1.29 | -1.39 | -1.48 | -1.59 | -1.70 | -1.82 | -1.94 | -2.08 | -2.22 | -2.38 | -2.55 | -2.73 | -2.92 | -3.12 | -3.34 | -3.57 | -3.82 | -4.09 | -4.38 |
| -4.00 | -2.51 | -2.69 | -2.87 | -3.07 | -3.29 | -3.52 | -3.77 | -4.03 | -4.31 | -4.61 | -4.94 | -5.28 | -5.65 | -6.05 | -6.47 | -6.92 | -7.41 | -7.93 | -8.48 | -9.08 |
| -4.00 | -3.93 | -4.21 | -4.50 | -4.82 | -5.16 | -5.52 | -5.90 | -6.32 | -6.76 | -7.23 | -7.74 | -8.28 | -8.86 | -9.48 | -10.14 | -10.85 | -11.61 | -12.42 | -13.29 | -14.22 |
| -4.00 | -5.49 | -5.87 | -6.28 | -6.72 | -7.19 | -7.69 | -8.23 | -8.81 | -9.42 | -10.08 | -10.79 | -11.55 | -12.35 | -13.22 | -14.14 | -15.13 | -16.19 | -17.33 | -18.54 | -19.84 |
| -4.00 | -7.17 | -7.67 | -8.21 | -8.79 | -9.40 | -10.06 | -10.76 | -11.52 | -12.32 | -13.19 | -14.11 | -15.10 | -16.15 | -17.29 | -18.50 | -19.79 | -21.18 | -22.66 | -24.24 | -25.94 |

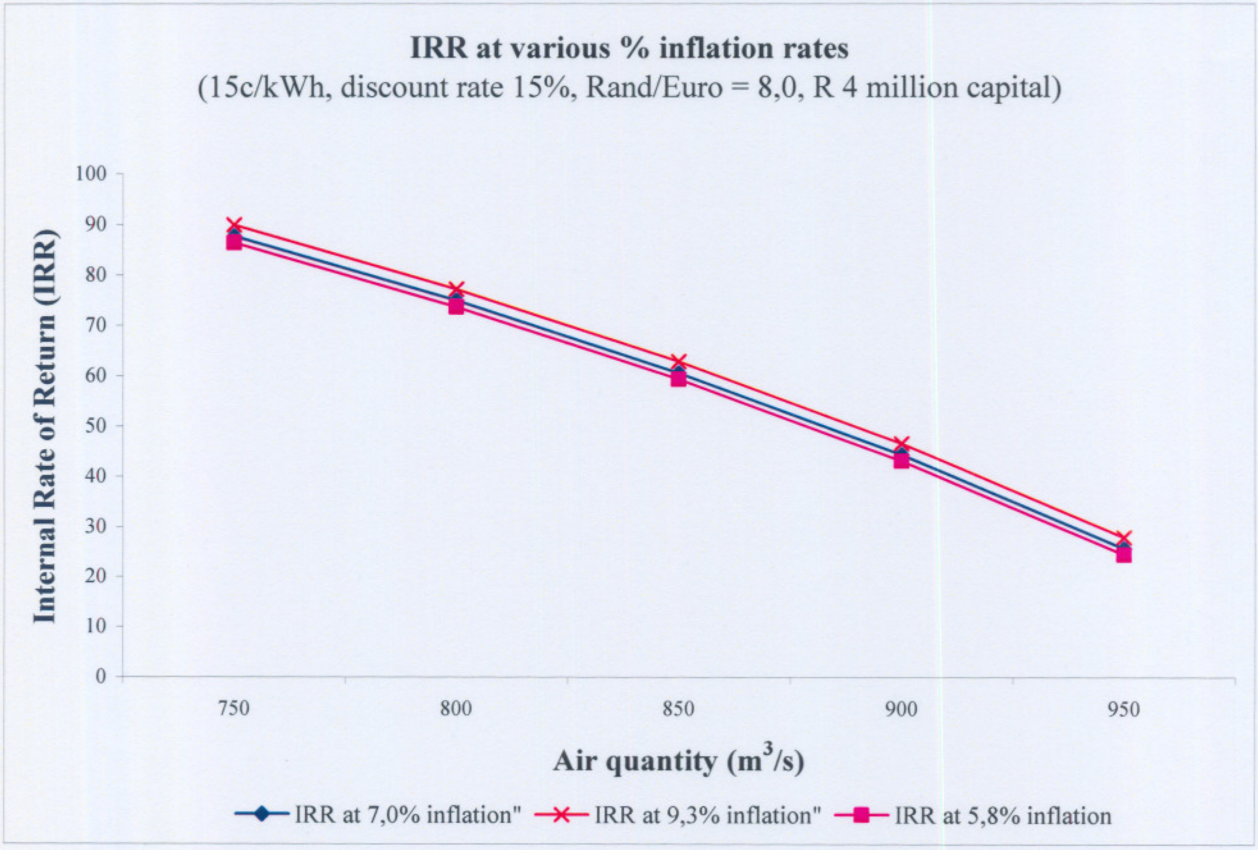
# APPENDIX K

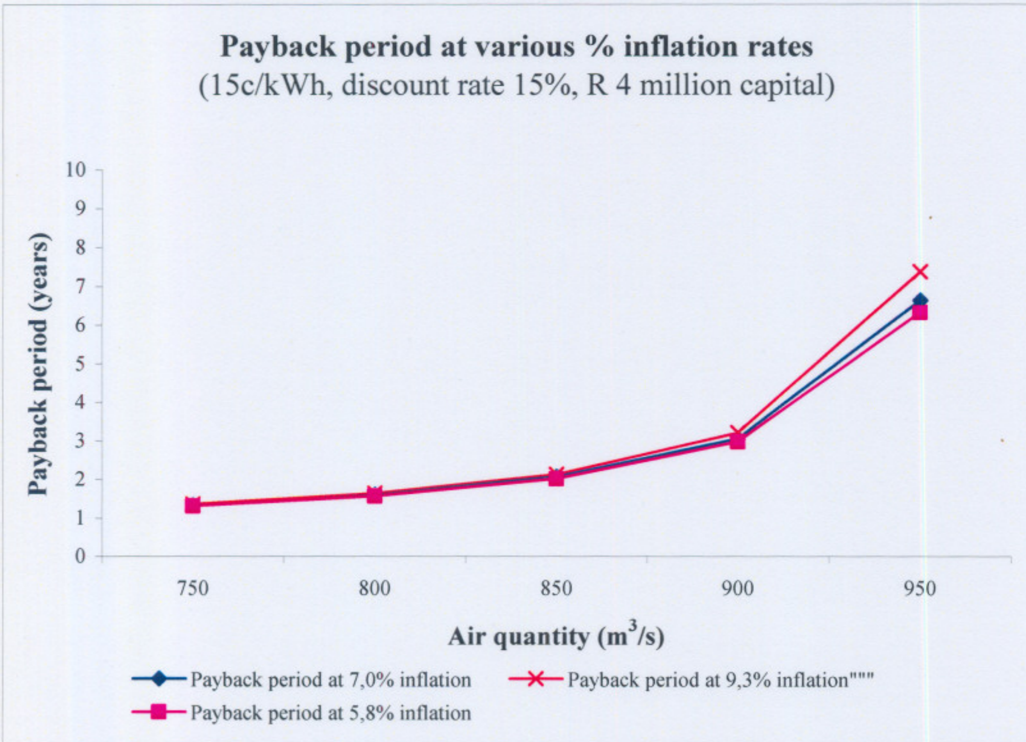
**DETAILED CASH FLOW SHEETS FOR VARIABLE SPEED DRIVE MOTOR**
(Summary of cash flow sheets for changes in electricity price)

**NPV, IRR and Payback periods for different electricity prices**

| Electricity price change (c/kWh) | Q ($m^3/s$) | Payback period (years) | NPV (Rm) | IRR (%) |
|---|---|---|---|---|
| 0.12 | 750 | 1.6 | 21.41 | 74 |
| | 800 | 2.0 | 17.41 | 63 |
| | 850 | 2.5 | 12.87 | 51 |
| | 900 | 3.8 | 7.77 | 38 |
| | 950 | 8.6 | 2.06 | 22 |
| | 1000 | | | |
| | 1050 | 0.0 | -11.27 | 0 |
| | 1100 | 0.0 | -18.98 | 0 |
| | 1150 | 0.0 | -27.41 | 0 |
| | 1200 | 0.0 | -36.61 | 0 |
| | 1250 | 0.0 | -46.61 | 0 |
| 0.14 | 750 | 1.5 | 23.98 | 80 |
| | 800 | 1.8 | 19.57 | 69 |
| | 850 | 2.3 | 14.58 | 56 |
| | 900 | 3.4 | 8.97 | 41 |
| | 950 | 7.5 | 2.70 | 24 |
| | 1000 | | | |
| | 1050 | 0.0 | -11.97 | 0 |
| | 1100 | 0.0 | -20.45 | 0 |
| | 1150 | 0.0 | -29.72 | 0 |
| | 1200 | 0.0 | -39.85 | 0 |
| | 1250 | 0.0 | -50.85 | 0 |
| 0.15 | 750 | 1.3 | 26.80 | 88 |
| | 800 | 1.6 | 21.96 | 75 |
| | 850 | 2.1 | 16.47 | 61 |
| | 900 | 3.1 | 10.29 | 44 |
| | 950 | 6.6 | 3.39 | 26 |
| | 1000 | | | |
| | 1050 | 0.0 | -12.75 | 0 |
| | 1100 | 0.0 | -22.06 | 0 |
| | 1150 | 0.0 | -32.27 | 0 |
| | 1200 | 0.0 | -43.40 | 0 |
| | 1250 | 0.0 | -55.50 | 0 |
| 0.17 | 750 | 1.2 | 29.91 | 96 |
| | 800 | 1.5 | 24.58 | 82 |
| | 850 | 1.9 | 18.54 | 66 |
| | 900 | 2.7 | 11.75 | 48 |
| | 950 | 5.9 | 4.16 | 28 |
| | 1000 | | | |
| | 1050 | 0.0 | -13.59 | 0 |
| | 1100 | 0.0 | -23.84 | 0 |
| | 1150 | 0.0 | -35.07 | 0 |
| | 1200 | 0.0 | -47.32 | 0 |
| | 1250 | 0.0 | -60.63 | 0 |
| 0.18 | 750 | 1.1 | 33.33 | 105 |
| | 800 | 1.3 | 27.47 | 89 |
| | 850 | 1.7 | 20.82 | 72 |
| | 900 | 2.5 | 13.35 | 52 |
| | 950 | 5.2 | 5.00 | 30 |
| | 1000 | | | |
| | 1050 | 0.0 | -14.52 | 0 |
| | 1100 | 0.0 | -25.80 | 0 |
| | 1150 | 0.0 | -38.15 | 0 |
| | 1200 | 0.0 | -51.62 | 0 |
| | 1250 | 0.0 | -66.26 | 0 |
| 0.20 | 750 | 1.0 | 37.09 | 115 |
| | 800 | 1.2 | 30.64 | 98 |
| | 850 | 1.5 | 23.33 | 79 |
| | 900 | 2.2 | 15.12 | 57 |
| | 950 | 4.6 | 5.93 | 33 |
| | 1000 | | | |
| | 1050 | 0.0 | -15.55 | 0 |
| | 1100 | 0.0 | -27.95 | 0 |
| | 1150 | 0.0 | -41.54 | 0 |
| | 1200 | 0.0 | -56.36 | 0 |
| | 1250 | 0.0 | -72.46 | 0 |


NPV (Rm) at different electricity prices
(discount rate 15%, inflation 7%, Rand/Euro = 8,0, R 4 million capital)
Net Present Value (NPV)
R 80
R 70
R 60
R 50
R 40
R 30
R 20
R 10
R 0
-R 10
-R 20
-R 30
-R 40
-R 50
-R 60
-R 70
-R 80
-R 90
750
800
850
900
950
1000
1050
1100
1150
1200
1250
Air quantity (m³/s)
NPV at 15c/kWh
NPV at 20c/kWh
NPV at 24,2c/kWh


IRR at various % inflation rates
(15c/kWh, discount rate 15%, Rand/Euro = 8,0, R 4 million capital)
Internal Rate of Return (IRR)
100
90
80
70
60
50
40
30
20
10
0
750
800
850
900
950
Air quantity (m³/s)
IRR at 7,0% inflation"
IRR at 9,3% inflation"
IRR at 5,8% inflation



Payback period at various % inflation rates
(15c/kWh, discount rate 15%, R 4 million capital)
Payback period (years)
0
1
2
3
4
5
6
7
8
9
10
750
800
850
900
950
Air quantity (m³/s)
Payback period at 7,0% inflation
Payback period at 9,3% inflation"""
Payback period at 5,8% inflation

# APPENDIX L

**DETAILED TOTAL ANNUAL COST CALCULATIONS**
(FAR LEFT SKEWED AIR QUANTITY DISTRIBUTIONS)

**Actual total costs far left skewed distribution**
(15c/kWh, discount rate 15%, inflation rate 7%, R 4 million capital)

| Quantity (Q) ($m^3/s$) | Pressure (P) (Pa) | Air Power (PQ) (MW) | Electrical input power PQ/fan efficiency (MW) | Electrical cost /annum running cost, (Rm) | Maintenance cost per annum, (Rm) | Total running&maintenance cost per annum, (Rm) | Far left skewed % air distribution | Total cost (Rm) x % distribution |
|---|---|---|---|---|---|---|---|---|
| 800 | 1920 | 1.5 | 2.2 | R 2.9 | R 0.04 | R 2.9 | 11% | 0.328 |
| 820 | 2017 | 1.7 | 2.4 | R 3.1 | R 0.04 | R 3.1 | 12% | 0.383 |
| 840 | 2117 | 1.8 | 2.5 | R 3.3 | R 0.04 | R 3.4 | 13% | 0.442 |
| 860 | 2219 | 1.9 | 2.7 | R 3.6 | R 0.04 | R 3.6 | 11% | 0.393 |
| 880 | 2323 | 2.0 | 2.9 | R 3.8 | R 0.04 | R 3.9 | 10% | 0.392 |
| 900 | 2430 | 2.2 | 3.1 | R 4.1 | R 0.04 | R 4.1 | 9% | 0.386 |
| 920 | 2539 | 2.3 | 3.3 | R 4.4 | R 0.04 | R 4.4 | 7% | 0.315 |
| 940 | 2651 | 2.5 | 3.6 | R 4.7 | R 0.04 | R 4.7 | 6% | 0.274 |
| 960 | 2765 | 2.7 | 3.8 | R 5.0 | R 0.04 | R 5.0 | 5% | 0.238 |
| 980 | 2881 | 2.8 | 4.0 | R 5.3 | R 0.04 | R 5.3 | 4% | 0.193 |
| **1000** | **3000** | **3.0** | **4.3** | **R 5.6** | **R 0.01** | R 5.6 | 3% | 0.165 |
| 1020 | 3121 | 3.2 | 4.5 | R 6.0 | R 0.04 | R 6.0 | 3% | 0.154 |
| 1040 | 3245 | 3.4 | 4.8 | R 6.3 | R 0.04 | R 6.4 | 2% | 0.119 |
| 1060 | 3371 | 3.6 | 5.1 | R 6.7 | R 0.04 | R 6.7 | 1% | 0.072 |
| 1080 | 3499 | 3.8 | 5.4 | R 7.1 | R 0.04 | R 7.1 | 1% | 0.072 |
| 1100 | 3630 | 4.0 | 5.7 | R 7.5 | R 0.04 | R 7.5 | 1% | 0.056 |
| 1120 | 3763 | 4.2 | 6.0 | R 7.9 | R 0.04 | R 8.0 | 0% | 0.030 |
| 1140 | 3899 | 4.4 | 6.3 | R 8.3 | R 0.04 | R 8.4 | 0% | 0.027 |
| 1160 | 4037 | 4.7 | 6.7 | R 8.8 | R 0.04 | R 8.8 | 0% | 0.028 |
| 1180 | 4177 | 4.9 | 7.0 | R 9.3 | R 0.04 | R 9.3 | 0% | 0.030 |
| 1200 | 4320 | 5.2 | 7.4 | R 9.7 | R 0.04 | R 9.8 | 0% | 0.042 |
| | | | | | | | **Resultant NPV for far left skewed** | **4.138** |

# APPENDIX M

**DETAILED TOTAL ANNUAL COST CALCULATIONS**
(LEFT SKEWED AIR QUANTITY DISTRIBUTIONS)

**Actual total costs left skewed distribution**
(15c/kWh, discount rate 15%, inflation rate 7%, R 4 million capital)

| Quantity (Q) ($m^3/s$) | Pressure (P) (Pa) | Air Power (PQ) (MW) | Electrical input power PQ/fan efficiency (MW) | Electrical cost /annum running cost, (Rm) | Maintenance cost per annum, (Rm) | Total running&maintenance cost per annum, (Rm) | Left skewed % air distribution | Total cost (Rm) x % distribution |
|---|---|---|---|---|---|---|---|---|
| 800 | 1920 | 1.5 | 2.2 | R 2.9 | R 0.04 | R 2.9 | 6% | 0.185 |
| 820 | 2017 | 1.7 | 2.4 | R 3.1 | R 0.04 | R 3.1 | 7% | 0.233 |
| 840 | 2117 | 1.8 | 2.5 | R 3.3 | R 0.04 | R 3.4 | 9% | 0.302 |
| 860 | 2219 | 1.9 | 2.7 | R 3.6 | R 0.04 | R 3.6 | 10% | 0.358 |
| 880 | 2323 | 2.0 | 2.9 | R 3.8 | R 0.04 | R 3.9 | 10% | 0.405 |
| 900 | 2430 | 2.2 | 3.1 | R 4.1 | R 0.04 | R 4.1 | 11% | 0.450 |
| 920 | 2539 | 2.3 | 3.3 | R 4.4 | R 0.04 | R 4.4 | 10% | 0.439 |
| 940 | 2651 | 2.5 | 3.6 | R 4.7 | R 0.04 | R 4.7 | 8% | 0.398 |
| 960 | 2765 | 2.7 | 3.8 | R 5.0 | R 0.04 | R 5.0 | 7% | 0.357 |
| 980 | 2881 | 2.8 | 4.0 | R 5.3 | R 0.04 | R 5.3 | 6% | 0.316 |
| **1000** | **3000** | **3.0** | **4.3** | **R 5.6** | **R 0.01** | R 5.6 | 5% | 0.256 |
| 1020 | 3121 | 3.2 | 4.5 | R 6.0 | R 0.04 | R 6.0 | 3% | 0.204 |
| 1040 | 3245 | 3.4 | 4.8 | R 6.3 | R 0.04 | R 6.4 | 2% | 0.151 |
| 1060 | 3371 | 3.6 | 5.1 | R 6.7 | R 0.04 | R 6.7 | 1% | 0.087 |
| 1080 | 3499 | 3.8 | 5.4 | R 7.1 | R 0.04 | R 7.1 | 1% | 0.070 |
| 1100 | 3630 | 4.0 | 5.7 | R 7.5 | R 0.04 | R 7.5 | 1% | 0.066 |
| 1120 | 3763 | 4.2 | 6.0 | R 7.9 | R 0.04 | R 8.0 | 1% | 0.045 |
| 1140 | 3899 | 4.4 | 6.3 | R 8.3 | R 0.04 | R 8.4 | 0% | 0.030 |
| 1160 | 4037 | 4.7 | 6.7 | R 8.8 | R 0.04 | R 8.8 | 0% | 0.018 |
| 1180 | 4177 | 4.9 | 7.0 | R 9.3 | R 0.04 | R 9.3 | 0% | 0.010 |
| 1200 | 4320 | 5.2 | 7.4 | R 9.7 | R 0.04 | R 9.8 | 0% | 0.005 |
| | | | | | | | **Resultant NPV for left skewed** | **4.384** |

# APPENDIX N

## DETAILED TOTAL ANNUAL COST CALCULATIONS
(NORMAL DISTRIBUTION AIR QUANTITY DISTRIBUTIONS)

**Actual total costs normal distribution air quantity distribution**
(15c/kWh, discount rate 15%, inflation rate 7%, R 4 million capital)

| Quantity (Q) ($m^3/s$) | Pressure (P) (Pa) | Air Power (PQ) (MW) | Electrical input power PQ/fan efficiency (MW) | Electrical cost /annum running cost, (Rm) | Maintenance cost per annum, (Rm) | Total running&maintenance cost per annum, (Rm) | Normal % air distribution | Total cost (Rm) x % distribution |
|---|---|---|---|---|---|---|---|---|
| 800 | 1920 | 1.5 | 2.2 | R 2.9 | R 0.04 | R 2.9 | 0% | 0.009 |
| 820 | 2017 | 1.7 | 2.4 | R 3.1 | R 0.04 | R 3.1 | 1% | 0.028 |
| 840 | 2117 | 1.8 | 2.5 | R 3.3 | R 0.04 | R 3.4 | 1% | 0.046 |
| 860 | 2219 | 1.9 | 2.7 | R 3.6 | R 0.04 | R 3.6 | 2% | 0.071 |
| 880 | 2323 | 2.0 | 2.9 | R 3.8 | R 0.04 | R 3.9 | 4% | 0.140 |
| 900 | 2430 | 2.2 | 3.1 | R 4.1 | R 0.04 | R 4.1 | 5% | 0.218 |
| 920 | 2539 | 2.3 | 3.3 | R 4.4 | R 0.04 | R 4.4 | 6% | 0.266 |
| 940 | 2651 | 2.5 | 3.6 | R 4.7 | R 0.04 | R 4.7 | 7% | 0.324 |
| 960 | 2765 | 2.7 | 3.8 | R 5.0 | R 0.04 | R 5.0 | 9% | 0.475 |
| 980 | 2881 | 2.8 | 4.0 | R 5.3 | R 0.04 | R 5.3 | 11% | 0.594 |
| **1000** | **3000** | **3.0** | **4.3** | **R 5.6** | **R 0.01** | R 5.6 | 11% | 0.607 |
| 1020 | 3121 | 3.2 | 4.5 | R 6.0 | R 0.04 | R 6.0 | 10% | 0.584 |
| 1040 | 3245 | 3.4 | 4.8 | R 6.3 | R 0.04 | R 6.4 | 9% | 0.574 |
| 1060 | 3371 | 3.6 | 5.1 | R 6.7 | R 0.04 | R 6.7 | 8% | 0.513 |
| 1080 | 3499 | 3.8 | 5.4 | R 7.1 | R 0.04 | R 7.1 | 5% | 0.389 |
| 1100 | 3630 | 4.0 | 5.7 | R 7.5 | R 0.04 | R 7.5 | 4% | 0.328 |
| 1120 | 3763 | 4.2 | 6.0 | R 7.9 | R 0.04 | R 8.0 | 3% | 0.247 |
| 1140 | 3899 | 4.4 | 6.3 | R 8.3 | R 0.04 | R 8.4 | 2% | 0.159 |
| 1160 | 4037 | 4.7 | 6.7 | R 8.8 | R 0.04 | R 8.8 | 1% | 0.080 |
| 1180 | 4177 | 4.9 | 7.0 | R 9.3 | R 0.04 | R 9.3 | 0% | 0.023 |
| 1200 | 4320 | 5.2 | 7.4 | R 9.7 | R 0.04 | R 9.8 | 0% | 0.010 |
| | | | | | | | **Resultant NPV for normal distribution** | **5.685** |

# APPENDIX O

## DETAILED TOTAL ANNUAL COST CALCULATIONS
(RIGHT SKEWED AIR QUANTITY DISTRIBUTIONS)

**Actual total costs right skewed air quantity distribution**
(15c/kWh, discount rate 15%, inflation rate 7%, R 4 million capital)

| Quantity (Q) ($m^3/s$) | Pressure (P) (Pa) | Air Power (PQ) (MW) | Electrical input power PQ/fan efficiency (MW) | Electrical cost /annum running cost, (Rm) | Maintenance cost per annum, (Rm) | Total running&maintenance cost per annum, (Rm) | Far right skewed % air distribution | Total cost (Rm) x % distribution |
|---|---|---|---|---|---|---|---|---|
| 800 | 1920 | 1.5 | 2.2 | R 2.9 | R 0.04 | R 2.9 | 0% | 0.000 |
| 820 | 2017 | 1.7 | 2.4 | R 3.1 | R 0.04 | R 3.1 | 0% | 0.002 |
| 840 | 2117 | 1.8 | 2.5 | R 3.3 | R 0.04 | R 3.4 | 0% | 0.005 |
| 860 | 2219 | 1.9 | 2.7 | R 3.6 | R 0.04 | R 3.6 | 0% | 0.005 |
| 880 | 2323 | 2.0 | 2.9 | R 3.8 | R 0.04 | R 3.9 | 0% | 0.004 |
| 900 | 2430 | 2.2 | 3.1 | R 4.1 | R 0.04 | R 4.1 | 0% | 0.012 |
| 920 | 2539 | 2.3 | 3.3 | R 4.4 | R 0.04 | R 4.4 | 1% | 0.040 |
| 940 | 2651 | 2.5 | 3.6 | R 4.7 | R 0.04 | R 4.7 | 1% | 0.057 |
| 960 | 2765 | 2.7 | 3.8 | R 5.0 | R 0.04 | R 5.0 | 2% | 0.078 |
| 980 | 2881 | 2.8 | 4.0 | R 5.3 | R 0.04 | R 5.3 | 3% | 0.145 |
| **1000** | **3000** | **3.0** | **4.3** | **R 5.6** | **0.01** | R 5.6 | 4% | 0.226 |
| 1020 | 3121 | 3.2 | 4.5 | R 6.0 | R 0.04 | R 6.0 | 6% | 0.347 |
| 1040 | 3245 | 3.4 | 4.8 | R 6.3 | R 0.04 | R 6.4 | 7% | 0.460 |
| 1060 | 3371 | 3.6 | 5.1 | R 6.7 | R 0.04 | R 6.7 | 9% | 0.592 |
| 1080 | 3499 | 3.8 | 5.4 | R 7.1 | R 0.04 | R 7.1 | 12% | 0.826 |
| 1100 | 3630 | 4.0 | 5.7 | R 7.5 | R 0.04 | R 7.5 | 14% | 1.092 |
| 1120 | 3763 | 4.2 | 6.0 | R 7.9 | R 0.04 | R 8.0 | 15% | 1.208 |
| 1140 | 3899 | 4.4 | 6.3 | R 8.3 | R 0.04 | R 8.4 | 13% | 1.097 |
| 1160 | 4037 | 4.7 | 6.7 | R 8.8 | R 0.04 | R 8.8 | 8% | 0.713 |
| 1180 | 4177 | 4.9 | 7.0 | R 9.3 | R 0.04 | R 9.3 | 3% | 0.308 |
| 1200 | 4320 | 5.2 | 7.4 | R 9.7 | R 0.04 | R 9.8 | 1% | 0.132 |
| | | | | | | | **Resultant NPV for far right skewed** | **7.349** |

# APPENDIX P

## DETAILED TOTAL ANNUAL COST CALCULATIONS
(FAR RIGHT SKEWED AIR QUANTITY DISTRIBUTIONS)

**Actual total costs right skewed air quantity distribution**
(15c/kWh, discount rate 15%, inflation rate 7%, R 4 million capital)

| Quantity (Q) ($m^3/s$) | Pressure (P) (Pa) | Air Power (PQ) (MW) | Electrical input power PQ/fan efficiency (MW) | Electrical cost /annum running cost, (Rm) | Maintenance cost per annum, (Rm) | Total running&maintenance cost per annum, (Rm) | Far right skewed % air distribution | Total cost (Rm) x % distribution |
|---|---|---|---|---|---|---|---|---|
| 800 | 1920 | 1.5 | 2.2 | R 2.9 | R 0.04 | R 2.9 | 0% | 0.000 |
| 820 | 2017 | 1.7 | 2.4 | R 3.1 | R 0.04 | R 3.1 | 0% | 0.002 |
| 840 | 2117 | 1.8 | 2.5 | R 3.3 | R 0.04 | R 3.4 | 0% | 0.005 |
| 860 | 2219 | 1.9 | 2.7 | R 3.6 | R 0.04 | R 3.6 | 0% | 0.005 |
| 880 | 2323 | 2.0 | 2.9 | R 3.8 | R 0.04 | R 3.9 | 0% | 0.004 |
| 900 | 2430 | 2.2 | 3.1 | R 4.1 | R 0.04 | R 4.1 | 0% | 0.012 |
| 920 | 2539 | 2.3 | 3.3 | R 4.4 | R 0.04 | R 4.4 | 1% | 0.040 |
| 940 | 2651 | 2.5 | 3.6 | R 4.7 | R 0.04 | R 4.7 | 1% | 0.057 |
| 960 | 2765 | 2.7 | 3.8 | R 5.0 | R 0.04 | R 5.0 | 2% | 0.078 |
| 980 | 2881 | 2.8 | 4.0 | R 5.3 | R 0.04 | R 5.3 | 3% | 0.145 |
| **1000** | **3000** | **3.0** | **4.3** | **R 5.6** | **0.01** | R 5.6 | 4% | 0.226 |
| 1020 | 3121 | 3.2 | 4.5 | R 6.0 | R 0.04 | R 6.0 | 6% | 0.347 |
| 1040 | 3245 | 3.4 | 4.8 | R 6.3 | R 0.04 | R 6.4 | 7% | 0.460 |
| 1060 | 3371 | 3.6 | 5.1 | R 6.7 | R 0.04 | R 6.7 | 9% | 0.592 |
| 1080 | 3499 | 3.8 | 5.4 | R 7.1 | R 0.04 | R 7.1 | 12% | 0.826 |
| 1100 | 3630 | 4.0 | 5.7 | R 7.5 | R 0.04 | R 7.5 | 14% | 1.092 |
| 1120 | 3763 | 4.2 | 6.0 | R 7.9 | R 0.04 | R 8.0 | 15% | 1.208 |
| 1140 | 3899 | 4.4 | 6.3 | R 8.3 | R 0.04 | R 8.4 | 13% | 1.097 |
| 1160 | 4037 | 4.7 | 6.7 | R 8.8 | R 0.04 | R 8.8 | 8% | 0.713 |
| 1180 | 4177 | 4.9 | 7.0 | R 9.3 | R 0.04 | R 9.3 | 3% | 0.308 |
| 1200 | 4320 | 5.2 | 7.4 | R 9.7 | R 0.04 | R 9.8 | 1% | 0.132 |
| | | | | | | | **Resultant NPV for far right skewed** | 7.349 |

# APPENDIX Q

**DETAILED CASH FLOW SHEET**
(DIFFERENT STATISTICAL AIR QUANTITY DISTRIBUTIONS)

## Detailed cash flow sheet for different statistical air quantity distributions

| Distribution type | Cash Flow Analysis | | | (20 year period) | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Year | | | | | | | | | | | | | | | | | | | | |
| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| Far left skewed | -4.00 | 4.14 | 4.43 | 4.74 | 5.07 | 5.42 | 5.80 | 6.21 | 6.64 | 7.11 | 7.61 | 8.14 | 8.71 | 9.32 | 9.97 | 10.67 | 11.42 | 12.22 | 13.07 | 13.99 | 14.96 |
| net cash flow | -4.00 | 1.50 | 1.61 | 1.72 | 1.84 | 1.97 | 2.11 | 2.26 | 2.41 | 2.58 | 2.76 | 2.96 | 3.17 | 3.39 | 3.62 | 3.88 | 4.15 | 4.44 | 4.75 | 5.08 | 5.44 |
| Left skewed | -4.00 | 4.38 | 4.69 | 5.02 | 5.37 | 5.75 | 6.15 | 6.58 | 7.04 | 7.53 | 8.06 | 8.62 | 9.23 | 9.87 | 10.57 | 11.30 | 12.10 | 12.94 | 13.85 | 14.82 | 15.86 |
| net cash flow | -4.00 | 1.26 | 1.35 | 1.44 | 1.54 | 1.65 | 1.76 | 1.89 | 2.02 | 2.16 | 2.31 | 2.47 | 2.65 | 2.83 | 3.03 | 3.24 | 3.47 | 3.71 | 3.97 | 4.25 | 4.55 |
| Normal distribution | -4.00 | 5.69 | 6.08 | 6.51 | 6.96 | 7.45 | 7.97 | 8.53 | 9.13 | 9.77 | 10.45 | 11.18 | 11.97 | 12.80 | 13.70 | 14.66 | 15.69 | 16.78 | 17.96 | 19.22 | 20.56 |
| | -4.00 | -0.04 | -0.05 | -0.05 | -0.05 | -0.06 | -0.06 | -0.07 | -0.07 | -0.08 | -0.08 | -0.09 | -0.09 | -0.10 | -0.11 | -0.11 | -0.12 | -0.13 | -0.14 | -0.15 | -0.16 |
| Right skewed | -4.00 | 6.28 | 6.72 | 7.19 | 7.69 | 8.23 | 8.81 | 9.42 | 10.08 | 10.79 | 11.54 | 12.35 | 13.22 | 14.14 | 15.13 | 16.19 | 17.33 | 18.54 | 19.84 | 21.22 | 22.71 |
| net cash flow | -4.00 | -0.64 | -0.68 | -0.73 | -0.78 | -0.84 | -0.90 | -0.96 | -1.02 | -1.10 | -1.17 | -1.26 | -1.34 | -1.44 | -1.54 | -1.65 | -1.76 | -1.88 | -2.02 | -2.16 | -2.31 |
| Far right skewed | -4.00 | 7.35 | 7.86 | 8.41 | 9.00 | 9.63 | 10.31 | 11.03 | 11.80 | 12.63 | 13.51 | 14.46 | 15.47 | 16.55 | 17.71 | 18.95 | 20.28 | 21.70 | 23.22 | 24.84 | 26.58 |
| net cash flow | -4.00 | -1.71 | -1.83 | -1.96 | -2.09 | -2.24 | -2.40 | -2.56 | -2.74 | -2.93 | -3.14 | -3.36 | -3.60 | -3.85 | -4.12 | -4.40 | -4.71 | -5.04 | -5.40 | -5.77 | -6.18 |

# APPENDIX R

## TARGET MINE – ACTUAL DETAILED ENVIRONMENTAL RESULTS, 2002

**TARGET DIVISION – QUARTER 1-2002**

**QUARTER ENDING SEPTEMBER 2002**

**STATISTICAL INFORMATION On ENVIRONMENTAL CONDITIONS.**

**1. DEVELOPMENT**

| NUMBER OF ENDS | | | WET-BULB TEMP °C | | | | WET KATA | | | FORCE VOL. | SERVICE | AIR-COOLING |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHAFT / AREA | PLANNED | SURVEYED | NO. OF ENDS IN RANGE | | | | NO. OF ENDS IN RANGE | | | DISCHARGE | WATER | POWER |
| | | | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□1.0 | > 10.0 | $m^3/s$ | TEMP °C | $W/m^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 271 to 272 Level | 7 | 6 | 0 | 6 | 0 | 0 | 0 | 1 | 5 | 14.78 | 23.22 | 250 |
| 273 - 274 Level | 7 | 4 | 2 | 2 | 0 | 0 | 0 | 0 | 4 | 11.95 | 23.93 | 300 |
| 275 - 276 Level | 5 | 4 | 1 | 3 | 0 | 0 | 0 | 1 | 3 | 4.78 | 22.35 | 280 |
| 277 - 278 Level | 3 | 3 | 3 | 0 | 0 | 0 | 0 | 0 | 3 | 8.79 | 23.80 | 320 |
| 279 to 282 Level | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| TOTAL | 24 | 17 | 6 | 11 | 0 | 0 | 0 | 2 | 15 | | | |
| AVERAGE | | | 26.5 | 29.1 | 0.0 | 0.0 | 0.0 | 8.8 | 14.1 | 10.70 | 23.28 | 281 |

**2. STOPING**

| NO. OF PANELS | | | WET-BULB TEMP °C | | | | WET KATA | | | FACE | SERVICE | AIR-COOLING |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHAFT / AREA | PLANNED | SURVEYED | NO. OF PANELS IN RANGE | | | | NO. OF PANELS IN RANGE | | | VELOCITY | WATER | POWER |
| | | | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□1.0 | > 10.0 | m/s | TEMP °C | $W/m^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 6 | 6 | 6 | 0 | 0 | 0 | 0 | 0 | 4 | 0.38 | 14.60 | 219 |
| 271 to 272 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0.00 | 0.00 | 0 |
| 273 - 274 Level | 36 | 31 | 4 | 27 | 0 | 0 | 1 | 9 | 19 | 1.00 | 24.80 | 274 |
| 275 - 276 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 277 - 278 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 279 to 282 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| TOTAL | 42 | 37 | 10 | 27 | 0 | 0 | 1 | 9 | 25 | | | |
| AVERAGE | | | 25.9 | 29.9 | 0.0 | 0.0 | 6.0 | 8.9 | 13.8 | 0.90 | 23.15 | 265 |

**TARGET DIVISION – QUARTER 2-2002**

**QUARTER ENDING DECEMBER 2002**

**STATISTICAL INFORMATION ON ENVIRONMENTAL CONDITIONS.**

**1. DEVELOPMENT**

| NO. OF ENDS SHAFT / AREA | PLANNED | SURVEYED | WET-BULB TEMP °C NO. OF ENDS IN RANGE | | | | WET KATA NO. OF ENDS IN RANGE | | | FORCE VOL DISCHARGE | SERVICE WATER TEMP °C | AIR-COOLING POWER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□1.0 | > 10.0 | $m^3/s$ | | $W/m^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0 |
| 256 to 270 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0 |
| 271 to 272 Level | 13 | 7 | 2 | 5 | 0 | 0 | 0 | 3 | 4 | 12.4 | 21.4 | 260 |
| 273 - 274 Level | 17 | 5 | 0 | 5 | 0 | 0 | 0 | 2 | 3 | 8.5 | 19.4 | 250 |
| 275 - 276 Level | 6 | 5 | 0 | 5 | 0 | 0 | 0 | 1 | 4 | 5.0 | 22.8 | 270 |
| 277 - 278 Level | 9 | 4 | 4 | 0 | 0 | 0 | 0 | 0 | 4 | 4.9 | 20.2 | 320 |
| 279 to 282 Level | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 12.7 | 23.7 | 280 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0 |
| **TOTAL** | 46 | 22 | 6 | 16 | 0 | 0 | 0 | 6 | 16 | | | |
| **AVERAGE** | | | 26.9 | 29.9 | 0.0 | 0.0 | 0.0 | 8.7 | 11.8 | 8.5 | 21.1 | 272 |

**2. STOPING**

| NO. OF PANELS SHAFT / AREA | PLANNED | SURVEYED | WET-BULB TEMP °C NO OF PANELS IN RANGE | | | | WET KATA NO OF PANELS IN RANGE | | | FACE VELOCITY | SERVICE WATER TEMP °C | AIR-COOLING POWER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□1.0 | > 10.0 | m/s | | $W/m^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 3 | 4 | 4 | 0 | 0 | 0 | 0 | 0 | 4 | 0.62 | 20.55 | 348 |
| 271 to 272 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 273 - 274 Level | 39 | 26 | 1 | 25 | 0 | 0 | 1 | 6 | 20 | 1.25 | 22.50 | 274 |
| 275 - 276 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 277 - 278 Level | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 0.83 | 22.70 | 356 |
| 279 to 282 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| **TOTAL** | 44 | 32 | 7 | 25 | 0 | 0 | 1 | 6 | 26 | | | |
| **AVERAGE** | | | 25.0 | 30.2 | 0.0 | 0.0 | 0.0 | 8.0 | 12.6 | 1.15 | 22.27 | 289 |

**TARGET DIVISION – QUARTER 3-2002**

**QUARTER ENDING MARCH 2002**

**STATISTICAL INFORMATION ON ENVIRONMENTAL CONDITIONS.**

**1. DEVELOPMENT**

| NUMBER OF ENDS | | | WET-BULB TEMP °C | | | | WET KATA | | | FORCE VOL | SERVICE | AIR-COOLING |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHAFT / AREA | PLANNED | SURVEYED | NO. OF ENDS IN RANGE | | | | NO. OF ENDS IN RANGE | | | DISCHARGE | WATER | POWER |
| | | | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□ı.0 | > 10.0 | $m^3/s$ | TEMP °C | $W/m^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 271 to 272 Level | 8 | 5 | 1 | 4 | 0 | 0 | 0 | 0 | 5 | 15.06 | 16.96 | 280 |
| 273 - 274 Level | 18 | 10 | 0 | 10 | 0 | 0 | 0 | 4 | 6 | 9.16 | 19.10 | 270 |
| 275 - 276 Level | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 277 - 278 Level | 13 | 6 | 4 | 2 | 0 | 0 | 0 | 0 | 6 | 5.15 | 8.72 | 320 |
| 279 to 282 Level | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| **TOTAL** | 41 | 21 | 5 | 16 | 0 | 0 | 0 | 4 | 17 | | | |
| **AVERAGE** | | | 25.7 | 29.6 | 0.0 | 0.0 | 0.0 | 9.3 | 12.5 | 9.42 | 15.62 | 287 |

**2. STOPING**

| NO. OF PANELS | | | WET-BULB TEMP °C | | | | WET KATA | | | FACE | SERVICE | AIR-COOL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHAFT / AREA | PLANNED | SURVEYED | NO OF PANELS IN RANGE | | | | NO OF PANELS IN RANGE | | | VELOCITY | WATER | POWER |
| | | | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□ı.0 | > 10.0 | m/s | TEMP °C | $W/m^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 6 | 6 | 4 | 2 | 0 | 0 | 0 | 0 | 6 | 0.64 | 13.43 | 306 |
| 271 to 272 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 273 - 274 Level | 22 | 19 | 0 | 19 | 0 | 0 | 0 | 4 | 15 | 1.22 | 18.37 | 281 |
| 275 - 276 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 277 - 278 Level | 4 | 4 | 4 | 0 | 0 | 0 | 0 | 1 | 3 | 1.44 | 22.70 | 384 |
| 279 to 282 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| **TOTAL** | 32 | 29 | 8 | 21 | 0 | 0 | 0 | 5 | 24 | | | |
| **AVERAGE** | | | 25.4 | 29.6 | 0.0 | 0.0 | 0.0 | 9.0 | 12.0 | 1.13 | 17.95 | 301 |

**TARGET DIVISION – QUARTER 4-2002**

**QUARTER ENDING JUNE 2002**

**STATISTICAL INFORMATION ON ENVIRONMENTAL CONDITIONS.**

**1. DEVELOPMENT**

| NO. OF ENDS | | | WET-BULB TEMP $^0$C NO. OF ENDS IN RANGE | | | | WET KATA NO. OF ENDS IN RANGE | | | FORCE VOL DISCHARGE | SERVICE WATER | AIR-COOLING POWER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHAFT / AREA | PLANNED | SURVEYED | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□1.0 | > 10.0 | m$^3$/s | TEMP $^0$C | W/m$^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 271 to 272 Level | 6 | 3 | 0 | 3 | 0 | 0 | 0 | 1 | 2 | 15.50 | 19.40 | 300 |
| 273 - 274 Level | 3 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 10.50 | 20.30 | 270 |
| 275 - 276 Level | 7 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 9.50 | 19.00 | 350 |
| 277 - 278 Level | 11 | 10 | 5 | 5 | 0 | 0 | 0 | 1 | 9 | 13.59 | 19.30 | 310 |
| 279 to 282 Level | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| **TOTAL** | 30 | 15 | 6 | 9 | 0 | 0 | 0 | 2 | 13 | | | |
| **AVERAGE** | | | 26.1 | 29.1 | 0.0 | 0.0 | 0.0 | 9.6 | 12.9 | 13.49 | 19.37 | 308 |

**2. STOPING**

| NO. OF PANELS | | | WET-BULB TEMP $^0$C NO OF PANELS IN RANGE | | | | WET KATA NO. OF PANELS IN RANGE | | | FACE VELOCITY | SERVICE WATER | AIR-COOLING POWER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHAFT / AREA | PLANNED | SURVEYED | □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | □□.0 | □□.0□1.0 | > 10.0 | m/s | TEMP $^0$C | W/m$^2$ |
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 2 | 0.40 | 0.00 | 320 |
| 271 to 272 Level | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0.27 | 18.80 | 280 |
| 273 - 274 Level | 28 | 23 | 8 | 15 | 0 | 0 | 0 | 3 | 20 | 0.74 | 19.01 | 320 |
| 275 - 276 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 277 - 278 Level | 4 | 4 | 4 | 0 | 0 | 0 | 0 | 0 | 4 | 1.88 | 18.35 | 380 |
| 279 to 282 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| **TOTAL** | 34 | 31 | 15 | 16 | 0 | 0 | 0 | 4 | 27 | | | |
| **AVERAGE** | | | 26.1 | 29.3 | 0.0 | 0.0 | 0.0 | 5.0 | 9.3 | 0.84 | 17.68 | 325 |

**TARGET DIVISION – ACTUAL YEAR TOTALS, 2002**

**YEAR ENDING JUNE 2002**

**STATISTICAL INFORMATION OF ENVIRONMENTAL CONDITIONS.**

**1. DEVELOPMENT**

| NO. OF ENDS SHAFT / AREA | PLANNED | SURVEYED | WET-BULB TEMP °C N0. OF ENDS IN RANGE □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | WET KATA NO. OF ENDS IN RANGE □□.0 | □□.0□1.0 | > 10.0 | FORCE VOL DISCHARGE $m^3/s$ | SERVICE WATER TEMP °C | AIR-COOLING POWER $W/m^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 271 to 272 Level | 34 | 21 | 3 | 18 | 0 | 0 | 0 | 5 | 16 | 14.17 | 20.59 | 273 |
| 273 - 274 Level | 45 | 20 | 2 | 18 | 0 | 0 | 0 | 6 | 14 | 9.63 | 20.19 | 273 |
| 275 - 276 Level | 19 | 10 | 2 | 8 | 0 | 0 | 0 | 2 | 8 | 5.35 | 22.23 | 225 |
| 277 - 278 Level | 36 | 23 | 16 | 7 | 0 | 0 | 0 | 1 | 22 | 9.26 | 17.29 | 318 |
| 279 to 282 Level | 7 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 12.70 | 23.70 | 70 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| TOTAL | 141 | 75 | 23 | 52 | 0 | 0 | 0 | 14 | 61 | | | |
| AVERAGE | | | 26.4 | 29.5 | 0.0 | 0.0 | 0.0 | 9.0 | 12.8 | 10.26 | 19.73 | 277 |

**2. STOPING**

| NO. OF PANELS SHAFT / AREA | PLANNED | SURVEYED | WET-BULB TEMP °C NO OF PANELS IN RANGE □27.5 | □27.5□32.0 | □32□32.5 | □32.5 | WET KATA NO OF PANELS IN RANGE □□.0 | □□.0□1.0 | > 10.0 | FACE VELOCITY m/s | SERVICE WATER TEMP °C | AIR-COOLING POWER $W/m^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 208 to 255 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 256 to 270 Level | 17 | 18 | 16 | 2 | 0 | 0 | 0 | 0 | 16 | 0.52 | 13.91 | 288 |
| 271 to 272 Level | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 1 | 3 | 0.27 | 18.80 | 280 |
| 273 - 274 Level | 125 | 99 | 13 | 86 | 0 | 0 | 2 | 22 | 74 | 1.05 | 21.62 | 286 |
| 275 - 276 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| 277 - 278 Level | 10 | 10 | 10 | 0 | 0 | 0 | 0 | 1 | 9 | 1.49 | 20.96 | 377 |
| 279 to 282 Level | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0.00 | 0 |
| TOTAL | 152 | 129 | 40 | 89 | 0 | 0 | 2 | 24 | 102 | | | |
| AVERAGE | | | 25.7 | 29.8 | 0.0 | 0.0 | 3.0 | 8.0 | 11.9 | 1.00 | 20.45 | 293 |

## APPENDIX S

**RESULTS OF ACP INVESTIGATION BY J. M. STEWART, 1981**

WIND SPEED m/s

| WET-BULB TEMPERATURE (°C) | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 | 3.5 | 4.0 | 4.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25.0 | 296 | 311 | 324 | 335 | 345 | 354 | 362 | 369 | 376 | 382 | 387 | 392 | 397 | 402 | 406 | 410 | 414 | 417 | 421 | 427 | 433 | 438 | 443 | 447 | 457 | 465 | 472 |
| 25.1 | 294 | 309 | 322 | 333 | 343 | 352 | 360 | 367 | 374 | 380 | 385 | 390 | 395 | 400 | 404 | 408 | 412 | 415 | 419 | 425 | 430 | 436 | 440 | 445 | 454 | 462 | 469 |
| 25.2 | 293 | 308 | 321 | 332 | 341 | 350 | 358 | 365 | 372 | 378 | 383 | 388 | 393 | 398 | 402 | 406 | 409 | 413 | 416 | 423 | 428 | 433 | 438 | 442 | 452 | 460 | 467 |
| 25.3 | 291 | 306 | 319 | 330 | 340 | 348 | 356 | 363 | 370 | 376 | 381 | 386 | 391 | 395 | 400 | 404 | 407 | 411 | 414 | 420 | 426 | 431 | 436 | 440 | 450 | 458 | 465 |
| 25.4 | 290 | 305 | 317 | 328 | 338 | 346 | 354 | 361 | 368 | 374 | 379 | 384 | 389 | 393 | 398 | 401 | 405 | 409 | 412 | 418 | 424 | 429 | 433 | 438 | 447 | 455 | 462 |
| 25.5 | 288 | 303 | 315 | 326 | 336 | 345 | 352 | 359 | 366 | 372 | 377 | 382 | 387 | 391 | 395 | 399 | 403 | 406 | 410 | 416 | 421 | 426 | 431 | 435 | 445 | 453 | 460 |
| 25.6 | 287 | 301 | 314 | 325 | 334 | 343 | 350 | 357 | 364 | 370 | 375 | 380 | 385 | 389 | 393 | 397 | 401 | 404 | 408 | 414 | 419 | 424 | 429 | 433 | 442 | 450 | 457 |
| 25.7 | 285 | 300 | 312 | 323 | 332 | 341 | 348 | 355 | 362 | 368 | 373 | 378 | 383 | 387 | 391 | 395 | 399 | 402 | 405 | 411 | 417 | 422 | 426 | 431 | 440 | 448 | 455 |
| 25.8 | 283 | 298 | 310 | 321 | 330 | 339 | 347 | 353 | 360 | 366 | 371 | 376 | 381 | 385 | 389 | 393 | 396 | 400 | 403 | 409 | 415 | 419 | 424 | 428 | 438 | 445 | 452 |
| 25.9 | 282 | 296 | 308 | 319 | 329 | 337 | 345 | 351 | 358 | 364 | 369 | 374 | 378 | 383 | 387 | 391 | 394 | 398 | 401 | 407 | 412 | 417 | 422 | 426 | 435 | 443 | 450 |
| 26.0 | 280 | 294 | 307 | 317 | 327 | 335 | 343 | 349 | 356 | 361 | 367 | 372 | 376 | 381 | 385 | 388 | 392 | 395 | 399 | 404 | 410 | 415 | 419 | 424 | 433 | 440 | 447 |
| 26.1 | 278 | 293 | 305 | 316 | 325 | 333 | 341 | 348 | 354 | 359 | 365 | 370 | 374 | 378 | 382 | 386 | 390 | 393 | 396 | 402 | 408 | 412 | 417 | 421 | 430 | 438 | 445 |
| 26.2 | 277 | 291 | 303 | 314 | 323 | 331 | 339 | 346 | 352 | 357 | 363 | 367 | 372 | 376 | 380 | 384 | 388 | 391 | 394 | 400 | 405 | 410 | 415 | 419 | 428 | 435 | 442 |
| 26.3 | 275 | 289 | 301 | 312 | 321 | 329 | 337 | 343 | 350 | 355 | 361 | 365 | 370 | 374 | 378 | 382 | 385 | 389 | 392 | 398 | 403 | 408 | 412 | 416 | 425 | 433 | 440 |
| 26.4 | 274 | 288 | 300 | 310 | 319 | 327 | 335 | 341 | 348 | 353 | 358 | 363 | 368 | 372 | 376 | 380 | 383 | 386 | 389 | 395 | 401 | 405 | 410 | 414 | 423 | 430 | 437 |
| 26.5 | 272 | 286 | 298 | 308 | 317 | 325 | 333 | 339 | 346 | 351 | 356 | 361 | 366 | 370 | 374 | 377 | 381 | 384 | 387 | 393 | 398 | 403 | 407 | 411 | 420 | 428 | 434 |
| 26.6 | 270 | 284 | 296 | 306 | 315 | 324 | 331 | 337 | 343 | 349 | 354 | 359 | 363 | 368 | 371 | 375 | 379 | 382 | 385 | 391 | 396 | 401 | 405 | 409 | 418 | 425 | 432 |
| 26.7 | 269 | 283 | 294 | 305 | 314 | 322 | 329 | 335 | 341 | 347 | 352 | 357 | 361 | 365 | 369 | 373 | 376 | 379 | 383 | 388 | 393 | 398 | 403 | 407 | 415 | 423 | 429 |
| 26.8 | 267 | 281 | 292 | 303 | 312 | 320 | 327 | 333 | 339 | 345 | 350 | 355 | 359 | 363 | 367 | 371 | 374 | 377 | 380 | 386 | 391 | 396 | 400 | 404 | 413 | 420 | 427 |
| 26.9 | 265 | 279 | 291 | 301 | 310 | 318 | 325 | 331 | 337 | 343 | 348 | 352 | 357 | 361 | 365 | 368 | 372 | 375 | 378 | 384 | 389 | 393 | 398 | 402 | 410 | 418 | 424 |
| 27.0 | 264 | 277 | 289 | 299 | 308 | 316 | 323 | 329 | 335 | 341 | 346 | 350 | 355 | 359 | 362 | 366 | 369 | 373 | 376 | 381 | 386 | 391 | 395 | 399 | 408 | 415 | 421 |
| 27.1 | 262 | 276 | 287 | 297 | 306 | 314 | 321 | 327 | 333 | 338 | 343 | 348 | 352 | 356 | 360 | 364 | 367 | 370 | 373 | 379 | 384 | 388 | 393 | 397 | 405 | 413 | 419 |
| 27.2 | 260 | 274 | 285 | 295 | 304 | 312 | 319 | 325 | 331 | 336 | 341 | 346 | 350 | 354 | 358 | 361 | 365 | 368 | 371 | 376 | 381 | 386 | 390 | 394 | 403 | 410 | 416 |
| 27.3 | 259 | 272 | 283 | 293 | 302 | 310 | 317 | 323 | 329 | 334 | 339 | 344 | 348 | 352 | 356 | 359 | 362 | 366 | 368 | 374 | 379 | 384 | 388 | 392 | 400 | 407 | 413 |
| 27.4 | 257 | 270 | 282 | 291 | 300 | 308 | 315 | 321 | 327 | 332 | 337 | 341 | 346 | 350 | 353 | 357 | 360 | 363 | 366 | 372 | 377 | 381 | 385 | 389 | 398 | 405 | 411 |
| 27.5 | 255 | 268 | 280 | 289 | 298 | 306 | 313 | 319 | 325 | 330 | 335 | 339 | 343 | 347 | 351 | 354 | 358 | 361 | 364 | 369 | 374 | 379 | 383 | 387 | 395 | 402 | 408 |
| 27.6 | 254 | 267 | 278 | 287 | 296 | 304 | 310 | 317 | 322 | 328 | 332 | 337 | 341 | 345 | 349 | 352 | 355 | 358 | 361 | 367 | 372 | 376 | 380 | 384 | 392 | 399 | 405 |
| 27.7 | 252 | 265 | 276 | 286 | 294 | 302 | 308 | 315 | 320 | 325 | 330 | 335 | 339 | 343 | 346 | 350 | 353 | 356 | 359 | 364 | 369 | 374 | 378 | 381 | 390 | 397 | 403 |
| 27.8 | 250 | 263 | 274 | 284 | 292 | 300 | 306 | 312 | 318 | 323 | 328 | 332 | 337 | 340 | 344 | 347 | 351 | 354 | 357 | 362 | 367 | 371 | 375 | 379 | 387 | 394 | 400 |
| 27.9 | 248 | 261 | 272 | 282 | 290 | 298 | 304 | 310 | 316 | 321 | 326 | 330 | 334 | 338 | 342 | 345 | 348 | 351 | 354 | 359 | 364 | 369 | 373 | 376 | 385 | 391 | 397 |
| 28.0 | 247 | 259 | 270 | 280 | 289 | 295 | 302 | 308 | 314 | 319 | 324 | 328 | 332 | 336 | 339 | 343 | 346 | 349 | 352 | 357 | 362 | 366 | 370 | 374 | 382 | 389 | 395 |
| 28.1 | 245 | 258 | 268 | 278 | 286 | 293 | 300 | 306 | 312 | 317 | 321 | 326 | 330 | 333 | 337 | 340 | 343 | 346 | 349 | 354 | 359 | 364 | 367 | 371 | 379 | 386 | 392 |
| 28.2 | 243 | 256 | 266 | 276 | 284 | 291 | 298 | 304 | 309 | 314 | 319 | 323 | 327 | 331 | 335 | 338 | 341 | 344 | 347 | 352 | 357 | 361 | 365 | 369 | 377 | 383 | 389 |
| 28.3 | 241 | 254 | 265 | 274 | 282 | 289 | 296 | 302 | 307 | 312 | 317 | 321 | 325 | 329 | 332 | 336 | 339 | 342 | 344 | 349 | 354 | 358 | 362 | 366 | 374 | 381 | 386 |
| 28.4 | 240 | 252 | 263 | 272 | 280 | 287 | 294 | 300 | 305 | 310 | 314 | 319 | 323 | 326 | 330 | 333 | 336 | 339 | 342 | 347 | 352 | 356 | 360 | 363 | 371 | 378 | 384 |
| 28.5 | 238 | 250 | 261 | 270 | 278 | 285 | 292 | 297 | 303 | 308 | 312 | 316 | 320 | 324 | 327 | 331 | 334 | 337 | 339 | 344 | 349 | 353 | 357 | 361 | 369 | 375 | 381 |
| 28.6 | 235 | 248 | 259 | 268 | 276 | 283 | 289 | 295 | 300 | 305 | 310 | 314 | 318 | 322 | 325 | 328 | 331 | 334 | 337 | 342 | 346 | 351 | 354 | 358 | 366 | 372 | 378 |
| 28.7 | 233 | 247 | 257 | 266 | 274 | 281 | 287 | 293 | 298 | 303 | 308 | 312 | 316 | 319 | 323 | 326 | 329 | 332 | 334 | 339 | 344 | 348 | 352 | 355 | 363 | 370 | 375 |
| 28.8 | 230 | 245 | 255 | 264 | 272 | 279 | 285 | 291 | 296 | 301 | 305 | 309 | 313 | 317 | 320 | 323 | 326 | 329 | 332 | 337 | 341 | 345 | 349 | 353 | 360 | 367 | 372 |
| 28.9 | 227 | 243 | 253 | 262 | 270 | 277 | 283 | 289 | 294 | 299 | 303 | 307 | 311 | 314 | 318 | 321 | 324 | 327 | 329 | 334 | 339 | 343 | 347 | 350 | 358 | 364 | 370 |
| 29.0 | 225 | 241 | 251 | 260 | 268 | 274 | 281 | 286 | 291 | 296 | 301 | 305 | 308 | 312 | 315 | 318 | 321 | 324 | 327 | 332 | 336 | 340 | 344 | 347 | 355 | 361 | 367 |
| 29.1 | 222 | 240 | 249 | 258 | 265 | 272 | 278 | 284 | 289 | 294 | 298 | 302 | 306 | 310 | 313 | 316 | 319 | 322 | 324 | 329 | 334 | 338 | 341 | 345 | 352 | 358 | 364 |
| 29.2 | 220 | 237 | 247 | 256 | 263 | 270 | 276 | 282 | 287 | 292 | 296 | 300 | 304 | 307 | 310 | 313 | 316 | 319 | 322 | 327 | 331 | 335 | 339 | 342 | 349 | 356 | 361 |
| 29.3 | 217 | 234 | 245 | 254 | 261 | 268 | 274 | 280 | 285 | 289 | 294 | 298 | 301 | 305 | 308 | 311 | 314 | 317 | 319 | 324 | 328 | 332 | 336 | 339 | 347 | 353 | 358 |
| 29.4 | 214 | 231 | 243 | 252 | 259 | 266 | 272 | 277 | 282 | 287 | 291 | 295 | 299 | 302 | 305 | 308 | 311 | 314 | 317 | 321 | 326 | 330 | 333 | 336 | 344 | 350 | 355 |
| 29.5 | 211 | 228 | 241 | 250 | 257 | 264 | 270 | 275 | 280 | 285 | 289 | 293 | 296 | 300 | 303 | 306 | 309 | 311 | 314 | 319 | 323 | 327 | 330 | 334 | 341 | 347 | 352 |
| 29.6 | 209 | 225 | 240 | 247 | 255 | 261 | 267 | 273 | 278 | 282 | 286 | 290 | 294 | 297 | 300 | 303 | 306 | 309 | 311 | 316 | 320 | 324 | 328 | 331 | 338 | 344 | 350 |
| 29.7 | 206 | 222 | 237 | 245 | 253 | 259 | 265 | 271 | 275 | 280 | 284 | 288 | 291 | 295 | 298 | 301 | 304 | 306 | 309 | 313 | 318 | 321 | 325 | 328 | 335 | 341 | 347 |
| 29.8 | 203 | 219 | 234 | 243 | 251 | 257 | 263 | 268 | 273 | 277 | 282 | 285 | 289 | 292 | 295 | 298 | 301 | 304 | 306 | 311 | 315 | 319 | 322 | 325 | 333 | 339 | 344 |
| 29.9 | 201 | 216 | 230 | 241 | 248 | 255 | 261 | 266 | 271 | 275 | 279 | 283 | 286 | 290 | 293 | 296 | 299 | 301 | 304 | 308 | 312 | 316 | 319 | 323 | 330 | 336 | 341 |
| 30.0 | 198 | 213 | 227 | 240 | 246 | 253 | 258 | 264 | 268 | 273 | 277 | 281 | 284 | 287 | 290 | 293 | 296 | 298 | 301 | 305 | 310 | 313 | 317 | 320 | 327 | 333 | 338 |
| 30.1 | 195 | 210 | 224 | 237 | 244 | 250 | 256 | 261 | 266 | 270 | 274 | 278 | 282 | 285 | 288 | 291 | 293 | 296 | 298 | 303 | 307 | 311 | 314 | 317 | 324 | 330 | 335 |
| 30.2 | 192 | 207 | 221 | 233 | 242 | 248 | 254 | 259 | 264 | 268 | 272 | 276 | 279 | 282 | 285 | 288 | 291 | 293 | 296 | 300 | 304 | 308 | 311 | 314 | 321 | 327 | 332 |
| 30.3 | 189 | 204 | 218 | 230 | 240 | 246 | 252 | 257 | 261 | 265 | 269 | 273 | 276 | 280 | 283 | 285 | 288 | 291 | 293 | 297 | 301 | 305 | 308 | 311 | 318 | 324 | 329 |
| 30.4 | 187 | 201 | 215 | 226 | 237 | 244 | 249 | 254 | 259 | 263 | 267 | 271 | 274 | 277 | 280 | 283 | 285 | 288 | 290 | 295 | 299 | 302 | 306 | 309 | 315 | 321 | 326 |
| 30.5 | 184 | 198 | 211 | 223 | 234 | 241 | 247 | 252 | 256 | 261 | 264 | 268 | 271 | 275 | 277 | 280 | 283 | 285 | 288 | 292 | 296 | 299 | 303 | 306 | 312 | 318 | 323 |
| 30.6 | 181 | 195 | 208 | 220 | 230 | 240 | 245 | 249 | 254 | 258 | 262 | 266 | 269 | 272 | 275 | 278 | 280 | 283 | 285 | 289 | 293 | 297 | 300 | 303 | 309 | 315 | 320 |
| 30.7 | 178 | 192 | 205 | 216 | 227 | 236 | 242 | 247 | 252 | 256 | 259 | 263 | 266 | 269 | 272 | 275 | 277 | 280 | 282 | 286 | 290 | 294 | 297 | 300 | 307 | 312 | 317 |
| 30.8 | 175 | 189 | 202 | 213 | 223 | 233 | 240 | 245 | 249 | 253 | 257 | 260 | 264 | 267 | 270 | 272 | 275 | 277 | 279 | 284 | 287 | 291 | 294 | 297 | 304 | 309 | 314 |
| 30.9 | 172 | 186 | 198 | 209 | 220 | 229 | 237 | 242 | 247 | 251 | 254 | 258 | 261 | 264 | 267 | 270 | 272 | 274 | 277 | 281 | 285 | 288 | 291 | 294 | 301 | 306 | 311 |
| 31.0 | 170 | 183 | 195 | 206 | 216 | 225 | 233 | 240 | 244 | 248 | 252 | 255 | 259 | 262 | 264 | 267 | 269 | 272 | 274 | 278 | 282 | 285 | 288 | 291 | 298 | 303 | 308 |
| 31.1 | 167 | 180 | 192 | 203 | 212 | 221 | 230 | 237 | 242 | 246 | 249 | 253 | 256 | 259 | 262 | 264 | 267 | 269 | 271 | 275 | 279 | 282 | 285 | 288 | 295 | 300 | 305 |
| 31.2 | 164 | 177 | 189 | 199 | 209 | 217 | 226 | 233 | 239 | 243 | 247 | 250 | 253 | 256 | 259 | 262 | 264 | 266 | 268 | 273 | 276 | 280 | 283 | 285 | 292 | 297 | 301 |
| 31.3 | 161 | 174 | 185 | 196 | 205 | 214 | 222 | 229 | 236 | 241 | 244 | 248 | 251 | 254 | 256 | 259 | 261 | 264 | 266 | 270 | 273 | 277 | 280 | 282 | 289 | 294 | 298 |
| 31.4 | 158 | 171 | 182 | 192 | 201 | 210 | 218 | 225 | 232 | 238 | 242 | 245 | 248 | 251 | 254 | 256 | 259 | 261 | 263 | 267 | 270 | 274 | 277 | 280 | 286 | 291 | 295 |
| 31.5 | 155 | 167 | 179 | 189 | 198 | 206 | 214 | 221 | 228 | 234 | 239 | 242 | 245 | 248 | 251 | 253 | 256 | 258 | 260 | 264 | 268 | 271 | 274 | 277 | 283 | 288 | 292 |
| 31.6 | 152 | 164 | 175 | 185 | 194 | 202 | 210 | 217 | 224 | 230 | 236 | 240 | 243 | 246 | 248 | 251 | 253 | 255 | 257 | 261 | 265 | 268 | 271 | 274 | 280 | 285 | 289 |
| 31.7 | 149 | 161 | 172 | 181 | 190 | 198 | 206 | 213 | 219 | 225 | 231 | 237 | 240 | 243 | 245 | 248 | 250 | 252 | 254 | 258 | 262 | 265 | 268 | 271 | 276 | 281 | 286 |
| 31.8 | 146 | 158 | 168 | 178 | 187 | 194 | 202 | 209 | 215 | 221 | 227 | 232 | 237 | 240 | 243 | 245 | 247 | 250 | 252 | 255 | 259 | 262 | 265 | 268 | 273 | 278 | 283 |
| 31.9 | 143 | 155 | 165 | 174 | 183 | 191 | 198 | 204 | 211 | 217 | 222 | 227 | 232 | 237 | 240 | 242 | 245 | 247 | 249 | 253 | 256 | 259 | 262 | 265 | 270 | 275 | 279 |
| 32.0 | 140 | 152 | 162 | 171 | 179 | 187 | 194 | 200 | 206 | 212 | 218 | 223 | 228 | 232 | 237 | 240 | 242 | 244 | 246 | 250 | 253 | 256 | 259 | 261 | 267 | 272 | 276 |
| 32.1 | 137 | 148 | 158 | 167 | 175 | 183 | 190 | 196 | 202 | 208 | 213 | 218 | 223 | 228 | 232 | 236 | 239 | 241 | 243 | 247 | 250 | 253 | 256 | 258 | 264 | 269 | 273 |
| 32.2 | 134 | 145 | 155 | 163 | 171 | 179 | 186 | 192 | 198 | 203 | 209 | 214 | 218 | 223 | 227 | 231 | 235 | 239 | 240 | 244 | 247 | 250 | 253 | 255 | 261 | 266 | 270 |
| 32.3 | 131 | 142 | 151 | 160 | 168 | 175 | 181 | 188 | 193 | 199 | 204 | 209 | 213 | 218 | 222 | 226 | 230 | 233 | 237 | 241 | 244 | 247 | 250 | 252 | 258 | 262 | 267 |
| 32.4 | 129 | 139 | 148 | 156 | 164 | 171 | 177 | 183 | 189 | 194 | 199 | 204 | 209 | 213 | 217 | 221 | 225 | 228 | 232 | 238 | 241 | 244 | 247 | 249 | 255 | 259 | 263 |
| 32.5 | 125 | 135 | 144 | 153 | 160 | 167 | 173 | 179 | 185 | 190 | 195 | 199 | 204 | 208 | 212 | 216 | 219 | 223 | 226 | 233 | 238 | 241 | 244 | 246 | 252 | 256 | 260 |
| 32.6 | 122 | 132 | 141 | 149 | 156 | 163 | 169 | 175 | 180 | 185 | 190 | 195 | 199 | 203 | 207 | 211 | 214 | 218 | 221 | 227 | 233 | 238 | 241 | 243 | 248 | 253 | 257 |
| 32.7 | 119 | 129 | 137 | 145 | 152 | 159 | 165 | 170 | 176 | 181 | 186 | 190 | 194 | 198 | 202 | 205 | 209 | 212 | 216 | 222 | 227 | 232 | 237 | 240 | 245 | 250 | 253 |
| 32.8 | 116 | 125 | 134 | 141 | 148 | 155 | 161 | 166 | 171 | 176 | 181 | 185 | 189 | 193 | 197 | 200 | 204 | 207 | 210 | 216 | 221 | 227 | 231 | 236 | 242 | 246 | 250 |
| 32.9 | 113 | 122 | 130 | 138 | 144 | 151 | 156 | 162 | 167 | 172 | 176 | 180 | 184 | 188 | 192 | 195 | 198 | 202 | 205 | 210 | 216 | 221 | 225 | 230 | 246 | 243 | 247 |
| 33.0 | 110 | 119 | 127 | 134 | 140 | 147 | 152 | 157 | 162 | 167 | 171 | 175 | 179 | 183 | 187 | 190 | 193 | 196 | 199 | 205 | 210 | 215 | 219 | 224 | 233 | 240 | 243 |
| 33.1 | 106 | 115 | 123 | 130 | 137 | 142 | 148 | 153 | 158 | 162 | 167 | 171 | 174 | 178 | 181 | 185 | 188 | 191 | 194 | 199 | 204 | 209 | 213 | 218 | 227 | 235 | 240 |
| 33.2 | 103 | 112 | 119 | 126 | 133 | 138 | 144 | 149 | 153 | 158 | 162 | 166 | 169 | 173 | 176 | 179 | 182 | 185 | 188 | 193 | 198 | 203 | 207 | 211 | 221 | 229 | 236 |
| 33.3 | 100 | 108 | 116 | 123 | 129 | 134 | 139 | 144 | 149 | 153 | 157 | 161 | 164 | 168 | 171 | 174 | 177 | 180 | 183 | 188 | 193 | 197 | 201 | 205 | 214 | 222 | 229 |
| 33.4 | 97 | 105 | 112 | 119 | 125 | 130 | 135 | 140 | 144 | 148 | 152 | 156 | 159 | 163 | 166 | 169 | 172 | 174 | 177 | 182 | 187 | 191 | 195 | 199 | 208 | 215 | 222 |
| 33.5 | 94 | 102 | 109 | 115 | 121 | 126 | 131 | 135 | 140 | 144 | 147 | 151 | 154 | 157 | 161 | 163 | 166 | 169 | 171 | 176 | 181 | 185 | 189 | 193 | 201 | 208 | 215 |
| 33.6 | 91 | 98 | 105 | 111 | 117 | 122 | 126 | 131 | 135 | 139 | 142 | 146 | 149 | 152 | 155 | 158 | 161 | 163 | 166 | 171 | 175 | 179 | 183 | 186 | 195 | 202 | 208 |
| 33.7 | 87 | 95 | 101 | 107 | 113 | 117 | 122 | 126 | 130 | 134 | 138 | 141 | 144 | 147 | 150 | 153 | 155 | 158 | 160 | 165 | 169 | 173 | 177 | 180 | 188 | 195 | 201 |
| 33.8 | 84 | 91 | 98 | 103 | 108 | 113 | 118 | 122 | 126 | 129 | 133 | 136 | 139 | 142 | 145 | 147 | 150 | 152 | 155 | 159 | 163 | 167 | 170 | 174 | 181 | 188 | 194 |
| 33.9 | 81 | 88 | 94 | 99 | 104 | 109 | 113 | 117 | 121 | 124 | 128 | 131 | 134 | 137 | 139 | 142 | 144 | 147 | 149 | 153 | 157 | 161 | 164 | 167 | 175 | 181 | 187 |
| 34.0 | 78 | 84 | 90 | 95 | 100 | 105 | 109 | 113 | 116 | 120 | 123 | 126 | 129 | 131 | 134 | 136 | 139 | 141 | 143 | 147 | 151 | 155 | 158 | 161 | 168 | 174 | 180 |
| 34.1 | 74 | 81 | 86 | 91 | 96 | 100 | 104 | 108 | 112 | 115 | 118 | 121 | 123 | 126 | 129 | 131 | 133 | 135 | 137 | 141 | 145 | 148 | 152 | 155 | 161 | 167 | 173 |
| 34.2 | 71 | 77 | 83 | 88 | 92 | 96 | 100 | 103 | 107 | 110 | 113 | 116 | 118 | 121 | 123 | 125 | 128 | 130 | 132 | 135 | 139 | 142 | 145 | 148 | 155 | 160 | 166 |
| 34.3 | 68 | 74 | 79 | 84 | 88 | 92 | 95 | 99 | 102 | 105 | 108 | 110 | 113 | 115 | 118 | 120 | 122 | 124 | 126 | 130 | 133 | 136 | 139 | 142 | 148 | 153 | 158 |
| 34.4 | 64 | 70 | 75 | 80 | 84 | 87 | 91 | 94 | 97 | 100 | 103 | 105 | 108 | 110 | 112 | 114 | 116 | 118 | 120 | 124 | 127 | 130 | 133 | 135 | 141 | 146 | 151 |
| 34.5 | 61 | 67 | 71 | 76 | 79 | 83 | 86 | 90 | 92 | 95 | 98 | 100 | 102 | 105 | 107 | 109 | 111 | 112 | 114 | 118 | 121 | 123 | 126 | 129 | 134 | 139 | 144 |
| 34.6 | 58 | 63 | 67 | 72 | 75 | 79 | 82 | 85 | 88 | 90 | 93 | 95 | 97 | 99 | 101 | 103 | 105 | 107 | 108 | 112 | 114 | 117 | 120 | 122 | 128 | 132 | 137 |
| 34.7 | 54 | 59 | 64 | 67 | 71 | 74 | 77 | 80 | 83 | 85 | 88 | 90 | 92 | 94 | 96 | 98 | 99 | 101 | 102 | 105 | 108 | 111 | 113 | 116 | 121 | 125 | 129 |
| 34.8 | 51 | 56 | 60 | 63 | 67 | 70 | 73 | 75 | 79 | 80 | 82 | 84 | 86 | 88 | 90 | 92 | 93 | 95 | 97 | 99 | 102 | 104 | 107 | 109 | 114 | 118 | 122 |
| 34.9 | 48 | 52 | 56 | 59 | 63 | 65 | 68 | 71 | 73 | 75 | 77 | 79 | 81 | 83 | 85 | 86 | 88 | 89 | 91 | 93 | 96 | 98 | 100 | 102 | 107 | 111 | 115 |