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A DECISION ANALYSIS GUIDELINE FOR UNDERGROUND BULK AIR HEAT EXCHANGER DESIGN SPECIFICATIONS

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IN THE FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

DEPARTMENT OF MINING ENGINEERING

UNIVERSITY OF PRETORIA

NOVEMBER 2013

I hereby declare that this Study is my own unaided work. It is being submitted for the degree M.Eng (Mining Engineering) at the University of Pretoria, Pretoria. It has not been submitted before for any degree or examination in any other University. This document represents my own opinion and interpretation of information received from the mine or people on the mine.

______________________________________ (signature on copy of final document)
MARLE HOOMAN

Dated this _29th day of November 2013_

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ABSTRACT

A DECISION ANALYSIS GUIDELINE FOR UNDERGROUND BULK AIR HEAT EXCHANGER DESIGN SPECIFICATION

MARLE HOOMAN

UP Supervisor: Prof RCW Webber-Youngman, University of Pretoria.

Supervisors: Dr JJ du Plessis, University of Pretoria.

Mr W Marx, Managing Director, BBE Consulting.

Department: Mining Engineering

University: University of Pretoria

Degree: M.Eng (Mining Engineering)

This study investigated different underground bulk air heat exchanger (>100 m^3/s) design criteria. It was found that no single document exist covering these heat exchangers and therefore the need was identified to generate a guideline with decision analyser steps to arrive at a technical specification. The study investigated the factors influencing the heat exchanger designs (spray chambers, towers and indirect-contact heat exchangers) and the technical requirements for each. The decision analysers can be used to generate optimised user-friendly fit-for-purpose bulk air heat exchanger (air cooler and heat rejection) designs. The study was tested against a constructed air cooler and heat rejection unit at a copper mine. It was concluded that the decision analysers were used successfully. It is recommended design engineers use these decision analysers to effectively design other heat exchangers.

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1 This dissertation report is based on a theoretical study of an underground direct contact bulk air heat exchangers and the application thereof at a mine. Permission to use the material is gratefully acknowledged. The opinions expressed are those of the author and do not necessarily represent the policy of the Mine.

2 Financial support and the provision of data during the course of the study are from BBE Consulting.

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    a. Prof RCW Webber-Youngman.

    b. Prof JJL du Plessis.

    c. Mr WM Marx.

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LIST OF SYMBOLS

ACP	Air Cooling Power (W/m^2)
BAC	Bulk Air Cooler
COM	Chamber of Mines
CSC	Condenser Spray Chamber
CoP	Code of Practice
°C	Degrees Centigrade
C	Heat Capacity (kJ/kg°C)
ρ	Density (kg/m^3)
d	Diameter (m)
α	Diffusivity (m^2/s)
μ	Dynamic viscosity (N.s/m^2)
DB	Dry-bulb
DMR	Department of Mineral Resources
DPM	Diesel Particulate Matter
FOM	Factor Of Merit
FULCO	Full Calendar Operations
H	Enthalpy (kJ/kg)
HTS	Heat Tolerance Screening
IARC	International Agency for Research on Cancer
kg/s	Mass flow rate – kilograms per second
kW	Kilo Watt
l/s	Litres per second
LHD	Load Haul Dump
LMTD	Log Mean Temperature Difference
m^3/s	Volumetric Flow Rate (m^3/s)
m	Meter
M_a	Mass flow of air
M_w	Mass flow of water
MEC	Mine Environmental Control
MHSA	Mine Health and Safety Act (Act 29 of 1996)
MW_R	Mega Watt (thermal refrigeration)
MW_E	Mega Watt (electrical)
Mr	Molecular Mass (g/mol)
η	Efficiency
NIOSH	National Institute for Occupations Safety and Health

N	Number of stages
NTU	Number of Transfer Units
OEL	Occupational Exposure Limit
OEL-Stel	Allowed short time exposure limit
Pr	Prandtl Number
q	Thermal Duty (kW)
R	Thermal Capacity Ratio
RAW	Return AirWay
Re	Reynold’s Number
ω	Rock Density (kg/m^3)
S	Entropy (kJ/kg)
SAIMM	South African Institute of Mining and Metallurgy
T	Temperature (°C)
k	Thermal Conductivity (W/m°C)
Θ	Time (s)
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
TWA	Time Weighted Average
UA	Overall Heat Transfer Coefficient
v	Velocity (m/s)
VRT	Virgin Rock Temperature
WB	Wet-bulb

CHAPTER 1

MOTIVATION FOR THIS STUDY

1. INTRODUCTION

Mining is practiced all over the world to extract minerals and materials from ore bodies accessed from surface or underground. The mined ore is then transported to processing plants where it is processed. Trading of the beneficiated products is the core business of all mining operations.

Mines extract ore from surface (open cast) or underground operations depending on the geology, type of ore body and mining methods utilised. Each mine has unique rock properties, mining methods, working depths, rock geothermal properties, and heat loads to name a few.

During mine planning of green (new) or brown (existing) field projects, environmental design criteria are set to ensure legal compliance as well as to ensure a healthy and safe working environment. When ventilation thermal design criteria is exceeded, in other words ventilation air alone cannot dissipate the mine heat load, refrigeration and associated cooling systems need to be introduced. A number of options are available to introduce mine cooling and some will be addressed in this study.

1.1 Mine Refrigeration General Information and Background

South African legislation stipulates that thermal environmental conditions in underground workings are controlled and that temperatures remain below 32.5 °C wet-bulb (WB) and 37.0 °C dry-bulb (DB) by the Department of Mineral Resources (DMR) (2002). The DMR (2002) further stipulates that in deep hot mines a Code of Practice (CoP) is required when wet-bulb temperatures exceed 25.0 °C and a Heat Tolerance Screening (HTS) programme when wet-bulb temperatures exceed 27.5 °C.

Mining companies generally have their own specific thermal design criteria to ensure they comply with legislation. Typical thermal criteria in working areas is 27.5 °C (WB) with a maximum reject temperature of 29.5 ˚C (WB). In most deep hard rock mines, as stated earlier, the design criteria cannot be satisfied with ventilation air only and refrigeration systems are required.

Refrigeration systems are widely used in South African gold and platinum mines to provide air cooling for underground operations (Burrows et al. 1989). The required refrigeration is generally dictated by depth for hard rock mines where Virgin Rock Temperatures (VRTs) and auto-compression, amongst other heat sources, play a major role (Bluhm & Biffi 2001). Refrigeration and the associated cooling installations at depth become essential to ensure legal requirements are maintained. Work done by Bluhm and Von Glehn (2010) indicates the relationship between mining depth and type of refrigeration and cooling system required (Figure 1.1a).

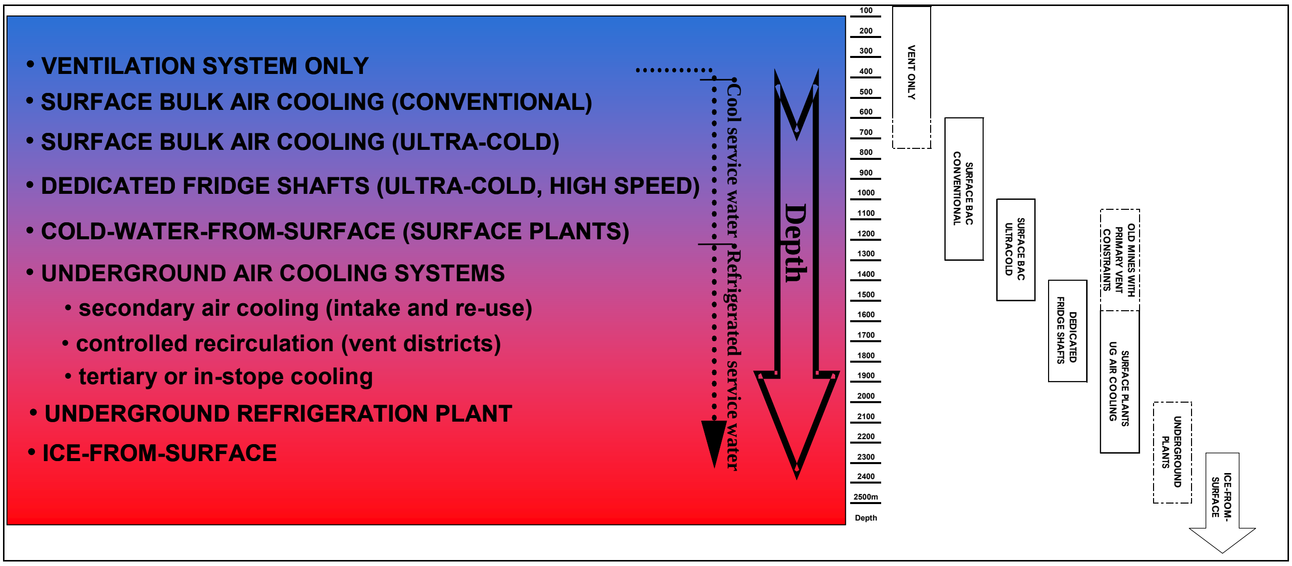

Figure 1.1a: Depth vs. Refrigeration System (Bluhm & Von Glehn 2010)

VRT is a function of a surface intersects temperature in °C and a geothermal gradient in °C/m (De Wet 2012). The VRTs for specific mines are calculated using the intersect temperature and geothermal gradient. The graph in Figure 1.1a is only a guide to determine which refrigeration option would be best suited, but many factors need consideration to make a system selection.

In addition to the depth of workings, the heat load of the mine is further impacted by the amount of rock broken. Research completed by Whillier (1982) illustrates the relationship between VRT and mining depth for South African gold mines and the expected heat load anticipated per ton of broken rock per month (Figure 1.1b). It is critical that accurate mine heat loads are determined including all heat sources such as geothermal heat, machine heat, auto-compression, etc. The calculated heat load determines the refrigeration capacity and the cooling installations required.

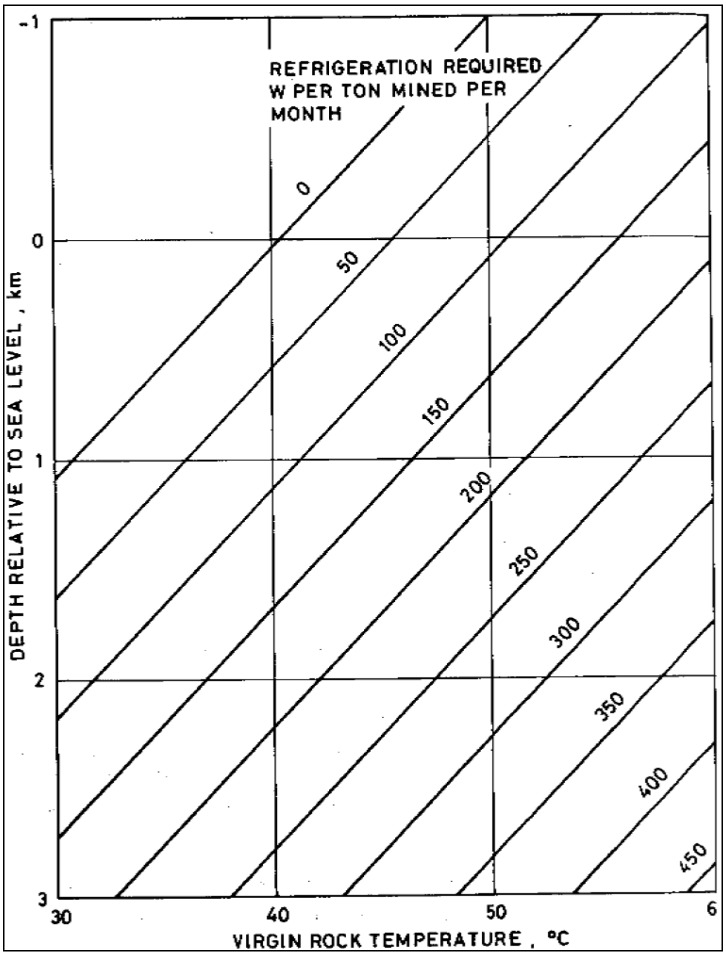

Figure 1.1b: Estimating Refrigeration Requirements (Whillier 1982)

Refrigeration requirements dictate the air cooling and heat rejection heat exchanger duties for surface or underground installations. Many of the design considerations of surface and underground cooling system installations are similar, but practically there are many differences. Due to the potential vast field of study in this regard, the study focuses on large underground heat exchangers, using only bulk air heat exchanger installations exceeding 100 m^3/s.

Bulk air heat exchangers in underground operations are either used to cool air when maximum reject temperatures are reached, or to cool water from underground refrigeration plants (heat rejection). These heat exchangers form part of two underground water refrigeration circuits, namely the ***evaporator*** circuit where chilled water is distributed to air coolers and the ***condenser*** circuit where heat is rejected to return air (Burrows et al. 1989) (Figure 1.1c).

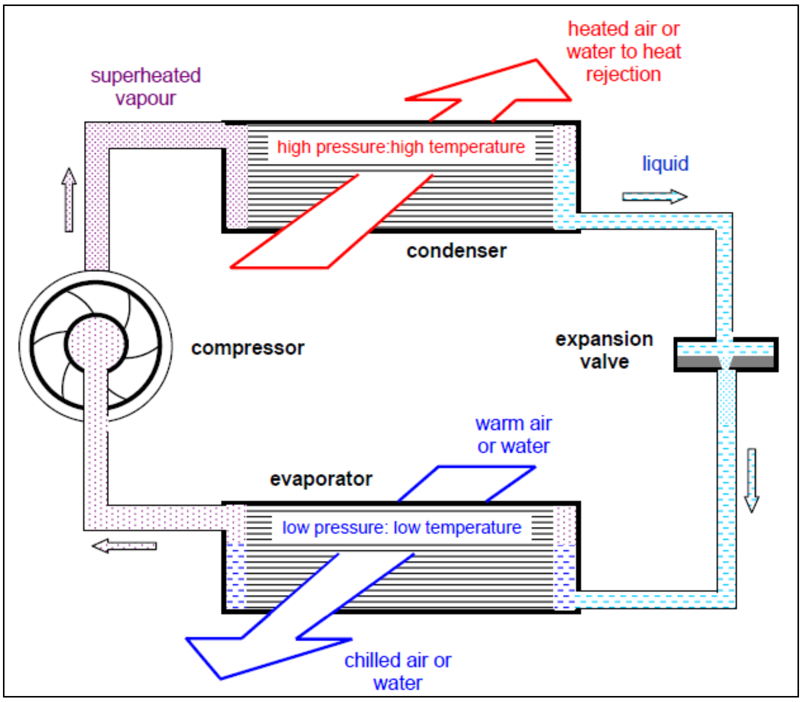

Figure 1.1c: Refrigeration Cycle Showing Evaporator and Condenser Circuits

Air cooling and heat rejection heat exchangers typically consist of three main types with very different design requirements and applications. Underground bulk air heat exchangers include direct-contact air-water horizontal spray chambers (Figure 1.1d), direct-contact air-water cooling towers (Figure 1.1e), or indirect-contact air-water banks of heat exchangers (Figure 1.1f).

Figure 1.1d: Horizontal Spray Chamber

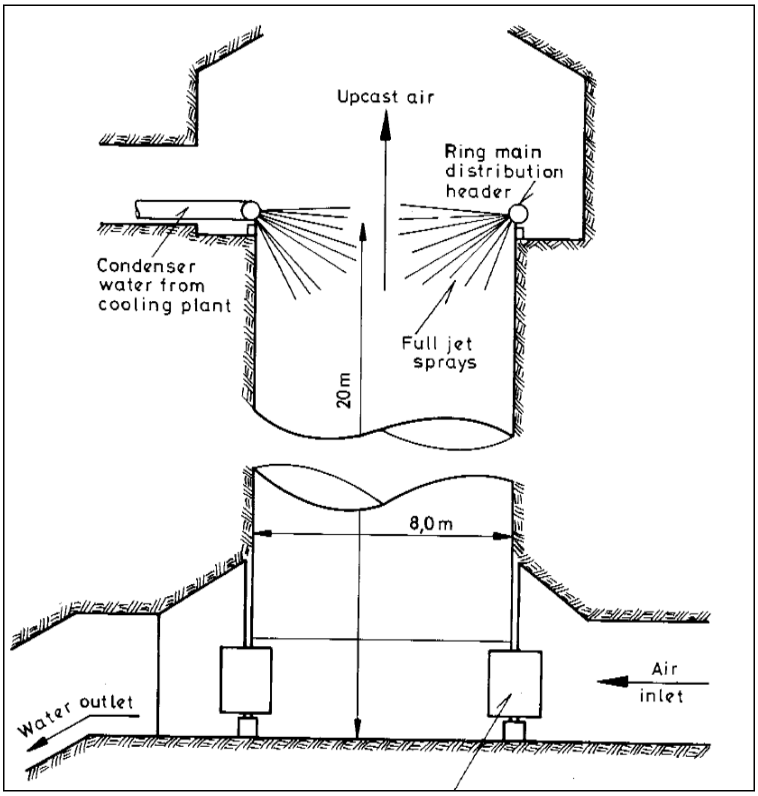

Figure 1.1e: Condenser Cooling Tower

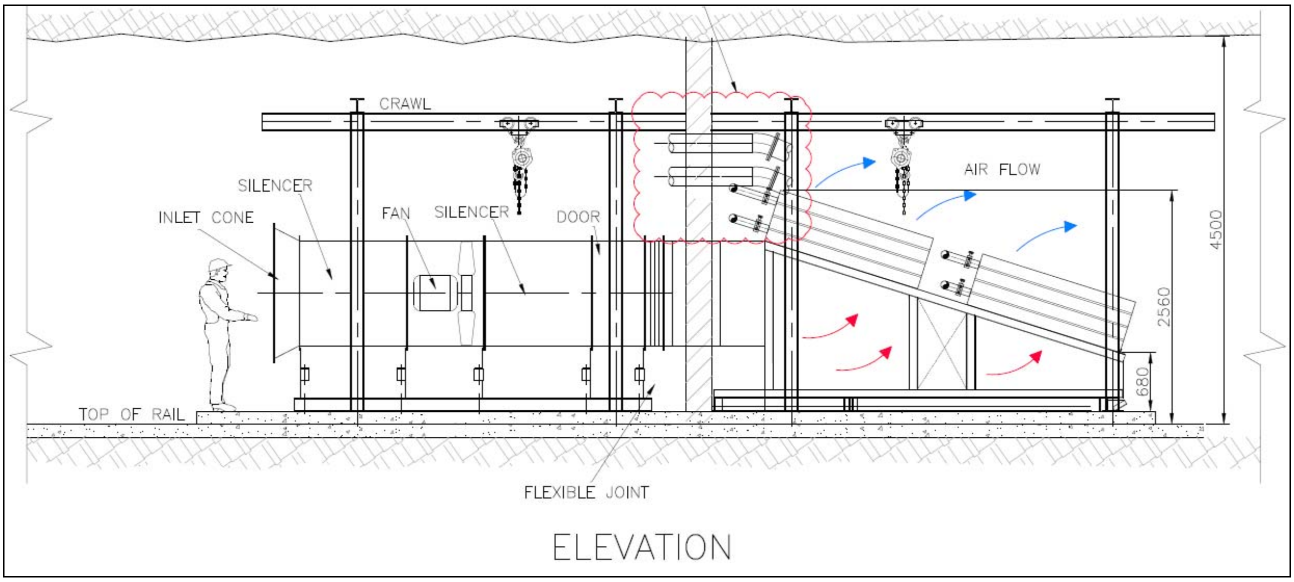

Figure 1.1f: Indirect-Contact Heat Exchanger Banks

1.2 Project Background

It often becomes evident that the design process lacks certain criteria at the onset when reviewing mine air cooling systems. Underground bulk air coolers (BACs) are required to cool to the ideal temperature, a parameter that needs careful consideration at the start of the design process as operational influences need to be considered. Important parameters to consider include, but are not limited to, personnel air temperature exposure, air quality requirements, location, excavation shape and size, air velocities, dust and diesel particulate loading, radiation, maintenance, surrounding activities, mine life, etc. The design criteria need to have a fine balance between different requirements to ensure an effective air cooling installation.

Many existing underground bulk air heat exchangers are inefficient. One of the main reasons is that the design process did not always consider all input parameters. These parameters include the physical thermal environmental conditions, size of the installation (excavation size), layout and pollutants to name a few. In some cases there is also poor understanding, by the designers, of how these heat exchangers work. Furthermore, not many heat exchanger design specialists exist in industry to assist less experienced designers.

Simulation software packages such as VUMA3D-network, Ventsim, etc. can assist the designers to solve aerodynamic and thermodynamic mass and energy balances. These software tools can assist the design engineer to evaluate the positional efficiency, design duty and overall effectiveness within the ventilation circuit. The simulation models provide accurate calculations of the actual working by including heat load components such as rock properties, ambient conditions, geothermal gradient, strike lengths, mean depth of workings, and other (Bluhm et al. 2001).

Once the heat exchanger thermal duty has been determined, a number of additional factors need to be assessed to determine an optimised design specification. These additional factors include aspects such as water quality, upstream mining activities (shot-creting, tramming and blasting), excavation constraints, presence of diesel equipment, maintenance schedules, mine life, etc.

The size of the heat exchangers depend on the required duty, thermal balance over the unit(s) and the ventilation air supplied to the workings. The balance is governed by design criteria such as air velocity, pollutant dilution requirements, cooling water temperatures achievable and practicality.

Underground heat exchangers are placed strategically underground to ensure effective cooling to different working areas. Heat rejection installations are typically installed where air returns from underground to surface. The selection of excavation positions for heat exchangers is done in conjunction with rock engineers to ensure structural constraints are met.

Mine engineering personnel are legally appointed and carry huge responsibility regarding mine safety, efficiency and cost of the operation. It is unreasonable to expect operational engineers to be experts in all areas of responsibility and hence the need was identified to develop a specification guide for one of the many aspects namely underground bulk air heat exchangers.

The intent of this study is not to guide the engineer to a ‘for-construction’ detailed design, but to enable a comprehensive fit-for-purpose design specification that can be issued to project/design engineers. A quick and easy to use guide in the form of decision trees/analysers was needed to minimise the time and effort mine engineers have to spend in developing design specifications. This guide of decision analysers (something not done before) envisaged will be complimented with a spreadsheet that calculates the required design specification with the assistance of a manual that will guide the design engineer with this specification generation process.

Engineers from mining companies therefore have to fully understand the design specifications when a mine air cooling system is designed, as it is likely to be part of their responsibilities. This objective of this study is to develop a user-friendly technical guide for engineers, specifically addressing underground bulk air cooling and heat rejection unit specifications as part of a mine air cooling system.

1.3 Problem Statement

To develop a guide consisting of decision analysers to assist mine operational engineers to easily prepare fit-for-purpose design specification(s) of underground bulk air heat exchangers, i.e. air coolers and heat rejection units.

1.4 Objectives

The objective of this study was to do extensive research on the requirements of underground heat exchanger designs and these are discussed in three Chapters:

i. Chapter 2 – the ***need*** for the study based on literature
ii. Chapter 3 – the many ***factors*** influencing the selection criteria for underground bulk air heat exchangers
iii. Chapter 4 – ***engineering and technical requirements*** to deal with these influencing factors.

Chapter 5 show ***quick and easy decision steps*** to assist mine operating engineers to compile ***design specifications*** for a specific heat exchanger type.

In Chapter 6 these decision factors are tested on an existing bulk air heat exchanger design.

Chapters 7, 8 and 9 complete this dissertation with conclusions, recommendations, and suggestions for further work.

1.5 Scope of the Study

This study focused on design specifications for optimal underground mine bulk air heat exchangers by researching all parameters and criteria impacting on performance of the cooling or heat rejection units. The scope has clear battery limits defined by considering the bulk air heat exchanger aerodynamically and thermodynamically as a control volume.

The work excluded factors influencing external inputs such as refrigeration plant selection and performance, primary ventilation circuit, secondary ventilation components, power supply, changes in mine heat load, external mining activities and detail input to pollutant sources. This study will assist the mine operation engineer during heat exchanger design specifications by providing a single document comprising of decision analysers.

1.6 Methodology

The study involved research of previous literature, text books, equipment supplier documentation, personal communications with mine operators, consultants and engineering specialists and the internet. Each of the influencing factors impacting on bulk air heat exchangers had to be fully understood.

The research of influencing factors was a theoretical study and evaluation of the input parameters required for an optimum design of bulk air heat exchangers. The factors that are typically included are shown in the Tables below.

Factor	**Brief description, Unit**
Thermal design criteria	Specified as per design, ºC
Mine heat load	Heat from sources, kW
Locations	Position of heat exchanger(s)
Excavations	Tunnel size required for heat exchanger, m^3
Air quality	As on mine
Air conditions	Inlet conditions at heat exchanger
Radiation	Personal exposure, mSv/annum
Dust	Silica dust, mg/m^3
Blasting fumes	As used at the mine
Diesel exhaust	Exhaust gasses from diesel machines
Water quality	As on mine
Water loading	Water loaded in every cubic meter, $l/s/m^3$
Rock mechanics	Rock engineering
Rock properties	Conductivity, density, specific heat
Life-of-mine	Duration that mine will operate, years
Maintenance	Scheduled maintenance
Surrounding activities	Blasting, installation, etc.
Constructability	Aspect impacting construction
Capital cost	Equipment cost, Rand
Operating cost	Energy consumption cost, Rand

Next the engineering and technical components of bulk air heat exchangers and their influence on each other and on the influencing factors had to be fully comprehended. Additional sources used, other than literature, included simulation software and mine specific operational data.

Engineering and technical requirements to deal with these factors were assessed, including:

Factor	**Brief description, Unit**
Types of heat exchangers	Open or closed circuit heat exchangers
Heat exchanger configuration	Cross/counter flow, multi-stage, etc.
Air-to-water ratio	Air to water flow rate ratios
Water temperatures	Inlet and outlet temperature, °C
Droplet sizes	Water droplets sizes at heat exchangers
Number of stages or cells	Stages of heat exchanger
Spray patterns	Pattern of water at open-circuit heat exchangers
Nozzle types	Type of spray nozzle
Type of fill	Type of fill at spray towers
Pump specifications	Water flow rate and pressure at pump
Construction materials	Equipment selection
Pipe materials	Steel, uPVC, HDPE, etc.
Sump sizes	Holding capacity of water
Mist eliminators	Water capture system
Blow-down ratios	Water drained to ensure good water quality

The decision analyser’s components were then developed to summarise and present the complex findings of the study in a comprehensive and simple manner, while maintaining cognisance of all interactions between influencing factors and bulk air heat exchanger technical components. This allows the engineer to prepare a comprehensive and informed technical specification to the manufacturer or designer.

The decision analysers included the following:

- Determine thermal design criteria of the mine
- Investigate the mine working depth and production method and profile
- Determine the air flow and water quantity and quality available for the heat exchangers, i.e. air cooler(s) and heat rejection unit(s)
- Establish whether surface or underground heat exchangers will be utilised
- Determine the heat load of the mine
- Verify ventilation surveys against software packages
- Determine the location(s) of these heat exchangers as well as their surrounding rock stability
- Determine the influencing factors on the type of heat exchanger to be specified.

Finally the guide was tested on an existing bulk air heat exchanger design to determine its relevance.

The guide can further assist engineers in understanding and analysis of other proposed designs.

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CHAPTER 2

LITERATURE RESEARCH

2. NEED FOR THE STUDY

South African gold and platinum mines have deep operations between 1 500 m and 3 500 m and encounters Virgin Rock Temperatures (VRTs) over 60 °C. These mining depths necessitate the consideration of underground heat exchangers. Rule of thumb developed in the FutureMine research program predicts that underground heat exchangers could be more beneficial than surface heat exchangers at depths from 1 500 m and/or VRTs exceeding 50 °C (MacKay & Butterworth 2002).

Heat exchangers discussed in this study are direct and indirect-contact water-air units using bulk air in underground applications. For air coolers, the chilled evaporator circuit water provides cooling of the air and for heat rejection units, the condenser water circuit cools hot condenser heat exchanger water.

The Literature Research was conducted over three Chapters and discusses first the need for bulk air heat exchangers underground (Chapter 2), second the factors influencing the design of such units (Chapter 3) and third the engineering and technical requirements pertaining to the factors influencing the overall performance of heat exchanger designs (Chapter 4).

2.1 Background

Chapter 1 indicated that heat exchangers are located on surface when mining depths extend up to 1 500 m (for most gold and platinum mines). These applications are generally easier to access, construct and maintain (MEC Workbook 2, 2008). Many mines have extended beyond 1 500 m and now require underground heat exchangers (MacKay, Bluhm & Van Rensburg 2010). These heat exchangers can be supplied with cold water from surface or underground refrigeration machines but energy requirements versus life-of-mine total owning cost need to be compared during project start-up. Most recent designs incorporate underground refrigeration machines as they ensure energy efficient designs, optimised positional efficiency and lowest total owning cost (Marx et al. 2010).

Underground heat exchangers have been selected for this study. They are mainly used for underground cooling and heat rejection as most underground mines. Most of these mines' shafts and shaft station temperatures are acceptable, but the access haulages and/or work places are very hot (Stanton 2004).

The refrigeration circuit for these heat exchangers will either include chilled water from surface or underground via refrigeration machines or from chilled water via underground ice melting dams supplied with ice from surface ice plants.

Many designs have been completed for surface heat exchangers which are mainly spray towers. Extensive research work has been completed over the past century on these systems and many have been constructed to test their operation, efficiency and reliability (Burrows et al. 1989; Bluhm 1983). Manufacturers have almost perfected the installation and operation of spray towers for surface heat exchangers.

Many spray towers have however been constructed underground for cooling and heat rejection, but these installations have challenges when it comes to excavation, access, installation and maintenance. Horizontal spray chambers and indirect-contact closed circuit heat exchangers are also installed underground for bulk air cooling and provide less complicated excavations, access, installation and maintenance. Work completed by Bluhm, Ramsden & Ferguson in 1984 indicated that these underground heat exchangers are relatively new installations but has been considered invariably since the 1980s for bulk air underground cooling installations.

This study provides a comprehensive summary of different heat exchangers from many resources. It further provides the mine ventilation and refrigeration design engineer with a user-friendly guideline for underground bulk air heat exchanger designs. All aspects pertaining to the design will be in a single document to save the user time in finding solutions for the specific application. This document will be a technical specification that can be used to complete ‘for-construction’ designs.

2.2 Guideline Motivation

Many influencing factors and technical parameters must be included in the design process. Design engineers have two major options when they approach this process. The first include using previous designs already implemented at their mine or the second is to find resources like hardcopy or softcopy handbooks or journals to assist in the design process.

The disadvantage of this process is that previous designs are not optimised or fit-for-purpose for the specific application. Existing designs do not take all influencing factors into account impacting on the overall efficiency of the heat exchanger. Many resources exist with each discussing technical items contributing to the design process but no single document exists summarising all design factors.

A lot of research has been completed on each of these heat exchangers (spray towers, horizontal spray chambers and indirect-contact heat exchangers) by different researchers on general process descriptions (McPherson 2007), spray tower technical requirements (Burrows et al. 1989; Stroh 1982; 'Energy Efficiency Guide for Industry in Asia' 2006), spray chamber technical requirements (Bluhm 1983; McPherson 2007; Burrows et al. 1989) and indirect-contact heat exchanger technical requirements ('Hendy coils' 2008).

A shortcoming of all the work done by these researchers is that each design has been completed in isolation and only focuses on a specific topic. The advantage of this guideline is that it takes the design engineer through all the technical requirements for each of these heat exchangers. In addition the guideline is complimented with practical recommendations from experienced specialists in the field and it includes environmental factors that will impact on the design of the heat exchangers which has never been included in study material.

During underground mine designs, problems are identified and amongst those the need for cooling is identified especially for deep hot mines. This project deals will underground mines that do require cooling and provides completed research guidelines to assist the design engineer in selecting the best design technical specification for the specific application.

As mentioned above, not many engineers on mines have heat exchanger specification experience and makes life difficult for new engineers. Many of the heat exchangers discussed in section 2.1 have been extensively researched and proto types built. The aim of this study is to provide design steps that will assist the design engineer with optimised technical specification(s).

2.3 Energy Efficient Cooling System Design

Work completed by (Du Plessis et al. 2013) indicated that energy efficient designs are imperative with increasing electrical costs. This work further indicated that energy consumption impact on carbon usage and need to be managed as penalties (carbon tax) are imminent.

For underground cooling systems many refrigeration options are available to achieve cooling. Some of the options include underground refrigeration machines, ice from surface, etc. (Bluhm & Von Glehn 2010). These will not be discussed in this document but each option needs to be considered when this design is started as they will impact the overall power consumed.

Underground cooling systems are generally more capital intensive than surface installations due to the refrigeration machine vessels. The absorbed power utilised over a certain life-of-mine is more generally more energy efficient because the refrigeration plant and heat exchangers are located near one another thus optimising on positional efficiency. This generally leads to viable total owning cost making this option favourable (Marx et al. 2010).

The location of the heat exchangers (coolers and heat rejection units) relative to the refrigeration system also impact on the power consumed. Installing these heat exchangers on different levels or in remote places far from the refrigeration system will result in increased pumping costs as the friction in the pipes is high (Meyer n.d.). This should be avoided where possible.

Equipment selected for the design of the heat exchangers needs careful consideration as pumps specifically may have high pressure drops over the unit thus increasing the absorbed power. Some equipment even has poor material properties that may lead to frequent maintenance schedules. The selected equipment needs to include insulation on chilled water pipes, energy efficient motor for the fans and pumps, best fill type, best nozzle type, best refrigeration machine, etc.

Design constraints will impact on the energy consumption of a mine and is an important part of the design process to consider. A result of poor designs is that the safety and health of personnel will be compromised and cannot be tolerated at mines as the mine are legally responsible to the health and safety of employers and employees.

2.4 Design Challenges

During this study it was found that no specific design specification guide was available or published. This explains the existence of poor heat exchanger designs and/or poor heat exchanger performance. Discussions with various ventilation and cooling engineers on mines indicated that many shortcomings were experienced during the design and commissioning phases for bulk air heat exchangers. Some of the shortcomings from discussions with ventilation and cooling engineers of heat exchanger designs are listed below:

- Incorrect ambient design conditions used. “This BAC was constructed and has never been used” (Conversation with Palabora Mining Company engineer on 2 April 2010).
- Use of mine specific standard design templates and not adjusting heat exchanger designs for fit-for-purpose applications (Conversation with Gold Fields Kloof mine engineer on 15 March 2013).

- Vertical tower packing design constructed in poor air conditions requiring regular maintenance that is costly (Conversation with Savuka mine engineer on 13 July 2012).
- Vertical tower configurations designed poorly leading to costly operating costs and poor efficiency of the unit (Conversation with BBE engineer on 9 January 2013).
- Vertical tower fill types incorrectly selected (Conversation with Hamon on 26 May 2011).
- Indirect-contact heat exchanger utilised requiring frequent maintenance. Congested tube-fin heat exchangers lead to poor efficiency of these units (Mackay & Butterworth 2002).
- Indirect contact heat exchanger banks incorrectly designed at incorrect ambient conditions leading to poor efficiency (Conversation with BBE engineer on 21 August 2012).
- Spray chambers constructed in small existing haulages with inefficient length for efficient heat transfer (Conversation with Savuka mine engineer on 4 September 2012).
- Air velocities over direct and indirect-contact heat exchangers were designed incorrectly leading to water carry over thus wasting water leading to poor efficiency of the heat exchanger (Conversation with BBE engineer on 22 February 2012).
- Poor understanding of theoretical principles relating to heat exchanger designs and a shortage of heat exchanger design specialists internationally (Conversation with International Specialist on 3 April 2013).
- And many more.

It is obvious that maintenance and operational demands require many different skills and capabilities. Engineers have to deal with many parameters, such as electrical distribution systems, water distribution and de-watering systems, refrigeration and ventilation systems, conveyances including hoists, conveyors and vehicles, etc. to affect an optimised design.

2.5 Mine Responsibility and Legal Obligation

In South Africa, The Mine Health and Safety Act, Act 29 of 1996 (MHSA 2002), defines that occupational hygiene means the anticipation, recognition, evaluation and control of conditions that may cause illness or adverse health effects to persons (MEC Workbook 5, 2008). Employers internationally are responsible to ensure health and safety of employees and themselves at all times. Legal requirements for other countries need be identified by the design engineer and applied to this study to ensure health and safety of personnel.

This study specifically focused on mitigating the risk of heat stress amongst workers although this is only one of the many health and safety factors to consider during the mine ventilation and cooling design. It is for this reason that thermal design criteria are critically important on mines.

A recent study from Karsten and Mackay (2012) shows that heat stress amongst workers impact on productivity and accident frequency when workplace wet-bulb (WB) temperatures are not maintained within 27.5 and 29.0 °C (Figure 2.1a). Schutte, Franz & Broom (2000) confirmed that a person's ability to concentrate and spatial perception decreases when temperature above 28.0 °C (WB) is experienced.

Brake (2000) further elaborated saying that heat stress and ultimately heat stroke leading to fatalities can be encountered in hot working areas and impacts on worker health and safety, productivity and morale (Figure 2.5a).

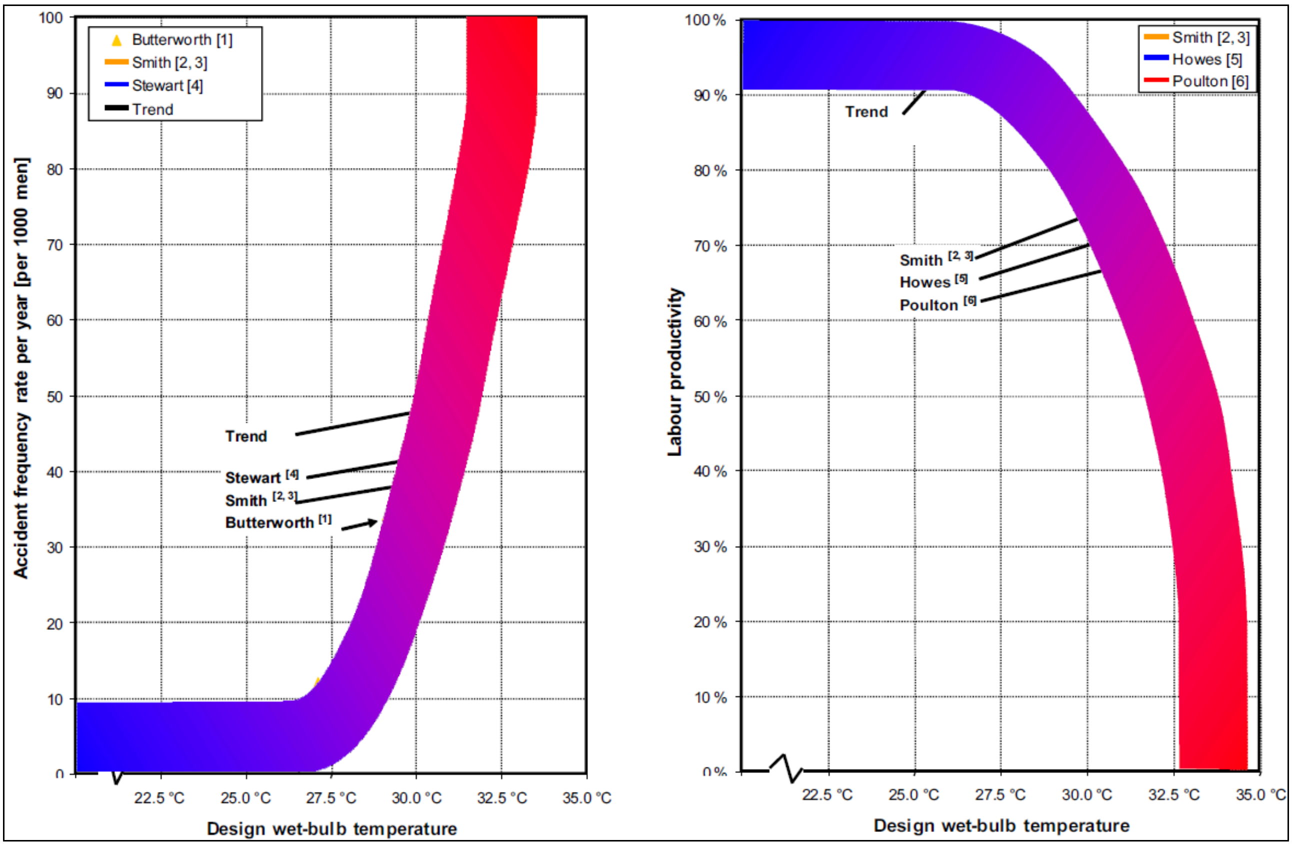

Figure 2.5a: Accident Rate and Productivity Compared to Wet-bulb Temperature (Karsten & Mackay 2012)

Karsten and Mackay (2012) further established a relationship between refrigeration and human inefficiency cost with wet-bulb temperature (Figure 2.5b). This relationship shows that with increased surrounding wet-bulb temperatures the accident frequency rate increases and personnel productivity reduces. It is therefore imperative that wet-bulb temperature remain below approximately 28.5 °C as these factors will reduce the overall revenue incurred.

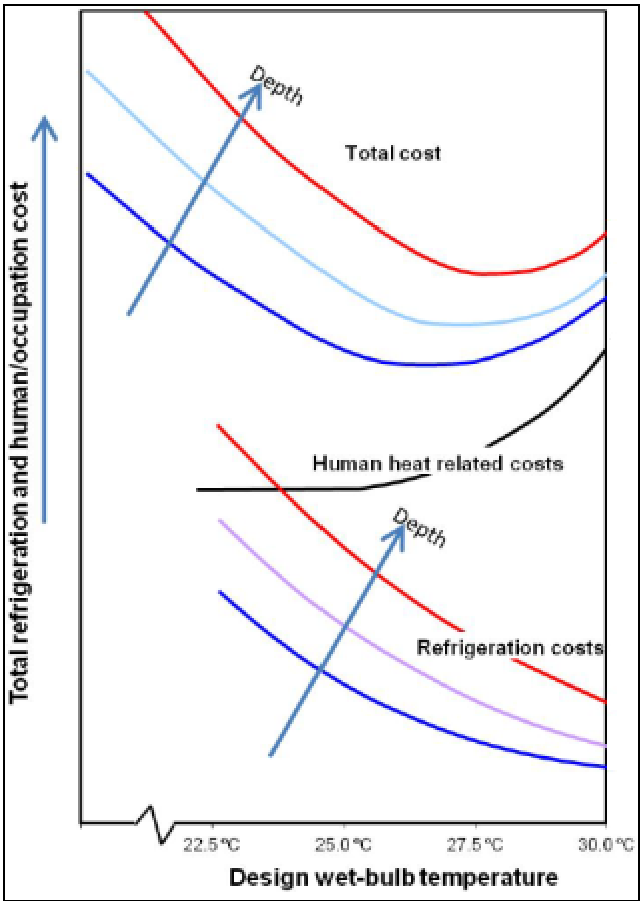

Figure 2.5b: Cost Impact on Workplace Wet-bulb Temperatures

Figure 2.5b emphasises the need for controlled environmental conditions as mentioned above. If these conditions are not maintained, a penalty will definitely be the result. The legally appointed staff member carries the responsibility towards the safety and health of employees on the mine. It is therefore important to identify, evaluate and mitigate the risk of exposure with controls. The need was therefore identified for an easy and quick guide assisting design engineers in determining technical specifications for underground heat exchangers.

2.6 Summary

Many heat exchangers' (spray towers, horizontal spray chambers and indirect contact heat exchangers) technical design specifications have been researched in the past, but no single document exists summarising important design selection guidelines. This study will provide design steps in the following chapters that guide the design engineer selecting the optimised and fit-for-purpose heat exchanger technical specification. These design steps includes environmental factors influencing the heat exchanger design.

One of the key objectives is to shorten the time spent to develop a design specification as a summary of the factors pertaining to the selection criteria is provided in this study. Technical and engineering requirements for heat exchangers will also be obtained from the decision analysis guideline, thus ensuring that more efficient heat exchangers are designed, constructed and operated.

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CHAPTER 3

FACTORS INFLUENCING SELECTION CRITERIA FOR BULK AIR HEAT EXCHANGERS

3. FACTORS INFLUENCING SELECTION CRITERIA FOR BULK AIR HEAT EXCHANGERS

This study investigated the design of direct and indirect-contact water-air heat exchangers using bulk air. In the evaporator circuit, chilled water is used to cool air that is supplied to working areas. In the condenser circuit hot water from the condenser heat exchanger is cooled with used warm air from the working places (Figure 3).

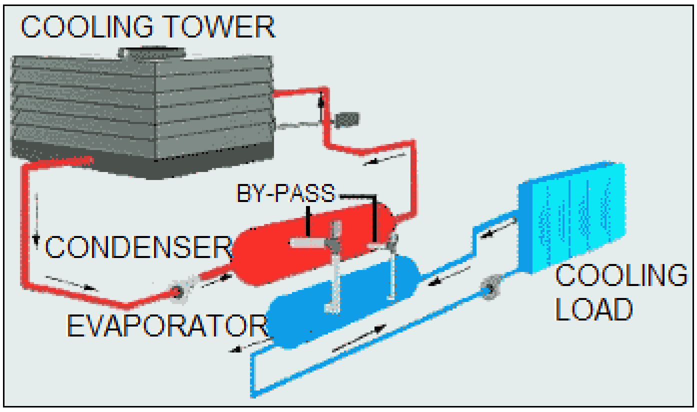

Figure 3: Evaporator and Condenser Water Circuits

In order to understand heat exchanger designs, a Literature Research was conducted and is discussed over three Chapters. The first chapter (Chapter 2) discussed the need for bulk air heat exchangers underground, the second chapter (Chapter 3) discusses the factors influencing the design of such units and third chapter (Chapter 4) discusses the engineering and technical requirements related to the factors of heat exchanger designs.

This Chapter discusses factors influencing the design of bulk air heat exchangers.

3.1 Thermal Design Criteria

As specified in Chapter 1, the mine thermal criteria must be determined. This will determine which heat stress management process will be followed as specified in the regulations of the Mine Health and Safety Act (MHSA Act 29 of 1996) Section 22.9(2)(b) (MHSA 2002).

The following heat stress management options are available:

- Heat Stress Code of Practice (at a wet-bulb temperature of >25.0°C); and
- Heat Stress Management Program (at a wet-bulb temperature of >27.5°C).

Heat stress management programs are set when the CoP option or HTS thermal criteria is exceeded. These must be comprehensively addressed in the CoP for an Occupational Health Programme (Occupational Hygiene and Medical Surveillance) on Thermal Stress as required by the DMR (2001, 2002).

Heat stress in a mine can only be mitigated by either using ventilation air or water as heat transfer medium. It is therefore important to optimise the air quantity in the mine first as it will determine the required size of haulages (or tunnels).

The amount of air distributed in the mine will have a certain cooling power keeping the temperature within the required thermal criteria. The cooling power depends on five climatic and two physiological factors that also need to be included in the heat load calculation; the main determinants in mines are the wet-bulb temperature and the air velocity, usually about 0.5 m/s in production crosscuts (Howes & Clarke 2007).

Climatic factors include respiratory, radiant, convective, evaporative and conductive heat transfer. Physiological factors include metabolic energy production and mechanical work done (Burrows et al. 1989). The wet-bulb temperatures that correspond to air cooling powers of 175 W/m^2, 140 W/m^2 and 115 W/m^2 are approximately 27.5°C, 30.5°C and 32.5°C respectively (Figure 3.1; Kielblok & Schutte 1998) based on a person wearing light clothing (Webber et al. 2003).

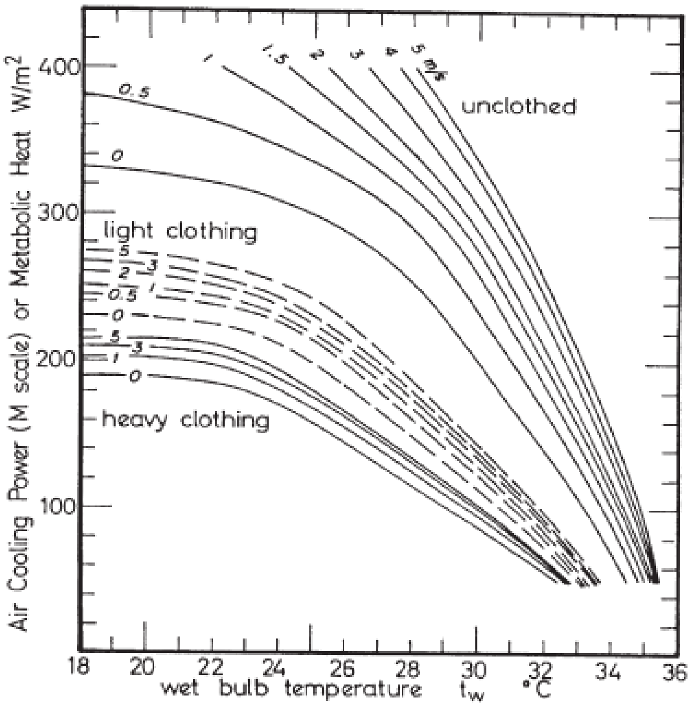

Figure 3.1: Air Cooling Power (Kielblok & Schutte 1998)

Certain underground locations will not be cooled sufficiently with ventilation air only and requires the addition of cooled air that can be distributed to working areas. Air is generally cooled in bulk air heat exchangers utilising chilled water from evaporator heat exchangers. To balance the heat transfer from a refrigeration machine, the heat of the machine is rejected in a condenser heat exchanger. Both the BAC and heat rejection units are discussed as part of this study.

3.2 Mine Working Depth and Surface or Underground Heat Exchangers

Chapters 1 and 2 indicated that VRT is a function of the geothermal gradient and depth below surface. The deeper the mine operations become, the higher the VRT gets as indicated in Figure 1.1a (Karsten and Mackay 2012). Chapter 2 further stated that a rule of thumb suggests that when the VRT reaches approximately 50 °C at depths from 800 m below surface, surface cooling is no longer efficient for platinum mines. This suggestion is dependent on the type of ore-body and mining method utilised and need to be adjusted for various mines. In these instances underground cooling is considered best practice. .

3.3 Heat Load

The required cooling for underground mining operations can only be determined if the overall mine heat load is known. To determine the overall mine heat load the contributions from all the mine heat sources must be taken into account (Burrows et al. 1989). Most of the components are listed below but each mining company needs to apply and modify their operations to this list.

Auto-compression of downcast ventilation air creates an increase in air temperature as a result of conversion of potential energy to enthalpy as it loses elevation. This results in a significant heat load on the intake ventilation.

This load will depend on the depth to which the air travels as enthalpy increases by 9.79 kJ/kg for every 1 000 m of depth. Similar to air water that flows down the mine shaft in a pipe will undergo the same enthalpy effect as air. This enthalpy increase can be summarized as a temperature increase of 2.34 ˚C for every 1 000 m of depth (Burrows et al. 1989).

The above is important to determine the heat added to the air going down the shaft and to which temperatures employees will be exposed when reaching shaft bottom. To mitigate high temperatures at shaft bottom surface cooling is generally employed. It is further important to determine the temperature gain of water going down the shaft.

Surrounding rock creates a heat load on the intake system by conduction heat transfer from the hot virgin rock interior to the rock surface and into the excavations (Bluhm et al. 1989). This heat component increases with depth as both VRT and the extent of exposed rock surface area grows. This heat load also depends on the strike length, excavation age and newly mined rock surfaces transmit heat rapidly initially but this slows as the rock cools. How to calculate this is shown in Equation 3.3a (Burrows et al. 1989).

$$q = k\,(T_r - T_{db})/\sqrt{\pi\,\alpha\,\theta} \qquad [3.3a]$$

T_r : Virgin rock temperature (°C)

T_{db} : Dry – bulb air temperature (°C)

k : Thermal conductivity (W/m°C)

α : $k/\omega C\,(m^2/s)$

ω : Rock density (kg/m^3)

C : Heat capacity (J/kg°C)

Θ : Time (s)

Broken rock creates a heat load because it enters the underground environment at a warm temperature and ultimately gets cooled to the ambient underground temperature by the time it leaves the mine. This heat component also increases with depth and the resultant higher VRT. How to calculate this is shown in Equation 3.3b (Van der Vyver et al. 2011).

$$q = m_r C_p (T_r - T_{wb}) \qquad [3.3b]$$

T_r : Virgin rock temperature (°C)

T_{wb} : Wet – bulb air temperature (°C)

m_r : Massflow of rock (kg/s)

C_p : Heat capacity of rock (J/kg°C)

In some mines broken mined out rock needs to be replaced by backfill to ensure that the hanging wall doesn't have a fall of ground. Research work completed by NIOSH (Williams et al., 2001) showed that backfill don't have a significant impact on the surrounding temperatures and can therefore be discarded.

Diesel vehicles can be a significant heat source depending on the size and usage of diesel fleet. Diesel engines are only about 30% efficient and a large percentage of the fuel combusted converts directly to heat.

Electrical vehicles are more efficient and they contribute less heat and are often considered for deep mines below 3 000 m (Rawlins 2006). To accurately determine the heat load, the rated power of a Load Haul Dump scoop (LHD) is multiplied by the load and the operating time (Hooman 2011). This will enable accurate heat load calculations by the engineer.

Criteria for diesel equipment listed in Table 3.3 will be used to determine the air quantity required to effectively dilute diesel exhaust emissions.

Table 3.3: Diesel Exhaust Dilution Criteria

Air requirement per kilowatt	0.06 $m^3/s/kW$ rated at point-of-use
Diesel heat load – LHD (production crosscut)	60% load for 90% of the time
Diesel heat load – Utility vehicles	50% load for 55% of the time

Notes (‘Trackless Mining’ 2010) (Belle 2007)

1. The figure 0.06 $m^3/s/kW$ is to dilute exhaust gas and does not take into account dilution of diesel particulates, see note 2 below.
2. Engine specifications assumed EU-Type III or higher, diesel sulphur content assumed <50 ppm, after exhaust treatment (Catalytic Converter and Diesel Particular Filter) to reduce total carbon emissions.

Fissure water

If there are large quantities of fissure water then this can be a significant source of heat (Burrows et al. 1989). The temperature of the fissure is normally similar to the corresponding local VRT and can be calculated from Equation 3.3c.

$$q = m_w C(T_R - T_{wb}) \qquad [3.3c]$$

T_R : Virgin rock temperature (°C)
T_{wb} : Wet – bulb air temperature (°C)
m_w : Water flow rate (kg / s)
C : Water heat capacity (kJ / kg°C)

Auxiliary devices include effects of machinery, people, explosives, oxidation of materials and strata movement.

Machinery as heat source is all equipment using electricity as power source that is not converted into useful energy which includes fans, hoists, lights, locomotives, motors, winches, pumps, rock drills and others.

Auxiliary fans do not do any useful thermodynamic work and all electrical energy entering a fan motor is converted into heat energy. The magnitude of this component depends on the method used for secondary ventilation control and the number of operational fans. In general, this heat load is not depth-dependent.

Hoists transport rock from the underground workings to surface. Electrical energy supplied to the hoist motors is converted to potential energy with the remainder liberated as heat which may be motor losses, friction in the shaft and the winding rope system (Burrows et al. 1989).

Lights and winches are powered by electrical energy and all this energy is dissipated as heat.

Locomotives are used in tracked haulages and operate at small gradients having virtually no impact on potential energy. All electrical energy manifests itself as heat energy.

Motors and pumps operate with electrical energy that is converted to mechanical energy and lost mechanical energy is dissipated as heat energy. For pumps the pumping efficiency will increase the enthalpy of the water.

Rock drills convert all mechanical input power provided by compressed air into heat.

Person's metabolic heat production rate varies but contributes as estimated:

At rest	90 to 115 W
Light work	200 W
Moderate work rate	275 W
Hard work rate (intermittent)	470 W

Explosives' heat is mainly removed by ventilation air during the re-entry period but some studies have shown that the heat is transferred to the broken rock. The heat capacity of the explosive used on a mine needs to be taken into account.

Oxidation of materials is mainly by sources like timber but has shown that heat involved is negligible.

Strata movement is an indication that the potential energy of the overlying rock is being reduced for a specific mining method which increases the temperature of the rock surface where it is moving. The heat from the rock is generally negligible.

Relationship between heat and work

Work carried out by Professor Wyndham (1967) at the Chamber of Mines during the 1960s, recognized the deteriorating effect of heat on mine labour efficiency. In addition, the harsh occupational environment found underground in terms of light, noise, dust, and cramped surrounds, is a recipe for low morale and motivation (Hermanus 2007).

Of all these exposures, heat has the biggest single effect on motivation and performance (Stanton 2004). Heat stress and heat stroke is excessive environmental heat loads that may cause incidents or accidents (Brake 2001 & Le Roux 1975). These need to be identified promptly as legal requirement stated in Chapter 1 and 2 may be exceeded. Identifying all heat sources will enable the engineer to determine how much cooling is required that cannot be removed by ventilation air only (Howes 2007).

3.4 Duty Verification by Software Program

After the ventilation engineer has determined the thermal design criteria, the duty can be determined theoretically and verified using computer software packages (VUMA3D-network, Ventsim or equivalent) that include air and thermal solutions. Duty is determined by subtracting cooling power of the air and water from the heat load of the air, water and auxiliary devices.

When the calculated duty is positive, air cooling is required to reduce the air temperature to acceptable environmental conditions, or else no cooling is required.

It is important to note that the overall cooling requirements are taken from various locations. Some isolated areas can be efficiently cooled by only increasing the ventilation air while other areas requires cooling that cannot be cooled with ventilation air only but with regional coolers depending on the cooling requirement. The latter will be considered in this project and the decision process followed for each unit.

3.5 Excavation Size and Location

During the design phase the ventilation engineer needs to identify possible existing or new locations for the heat exchanger for both air cooler(s) and heat rejection unit(s). Larger excavations will ensure improved heat transfer as the reaction time is prolonged. The size of the heat exchanger is determined by both the air velocity through the unit and factor of merit or efficiency of the unit.

Chapter 4 investigates the optimal design velocities for different types of heat exchangers that will determine the minimum cross sectional area required for the heat exchanger.

3.6 Inlet Conditions and Water Loading

The number of locations where heat exchangers will be positioned must be determined so that cooling and heat rejection can be distributed accordingly when water-to-refrigerant underground refrigeration machines are installed. Inlet air conditions will determine the duty of heat exchangers and the quantity of air through the length of the unit.

BAC heat exchanger duty is determined by the temperature difference between the water and air (Burrows et al. 1989). The outlet air temperature will always be higher than the inlet water temperature. Similarly the outlet water temperature will not exceed the inlet air temperature (MEC Workbook 2, 2008).

According to Hendy Coils (2008) the humidity of the air will also affect the total load to sensible load ratio. The humidity in the air will impact human sensation and needs to be considered where personnel will operate. In addition the humidity improves the heat exchanger’s capability to evaporate or condense water from the air system.

Specified inlet air should be as close as possible to normal running conditions and where systems are supplied with a mixture of fresh and return air; the mixed air temperature must be calculated using psychometric chart(s).

Heat exchanger duty is impacted by the water loading of the unit as the amount of water distributed to a heat exchanger needs to be compared and balanced with the open area of the heat exchanger where the air quantity will flow through. This balance between the heat exchanger duty, excavation size and water flow rate determines the length of the heat exchanger in order to achieve optimised heat transfer.

The duty of the heat exchanger is further impacted by the water and air quality and quantity and will be discussed in the following sections.

3.7 Air Quality and Conditions

Ambient air consists of a mixture of elemental gases of mainly oxygen and nitrogen and has a molecular mass of 28.97 g/mol (Perry & Green 1997). Industrial (surface and underground) applications are dependent on air properties that comprise of wet-bulb temperature, dry-bulb temperature, moisture content and enthalpy of the air at a specific pressure (Trott & Welch 2000). These properties can indicate to the ventilation engineer the conditions of the air in terms of heat addition, wetness rating and amount of water condensed or evaporated.

Air utilised underground are not ideal and can comprise of various pollutants including flammable gasses, dust, radiation and others. The existence of these will have a significant impact on the heat exchanger duty, excavation size and it will influence the maintenance frequency and water capacity (Whillier 1977).

In some underground heat exchangers, specifically air coolers, air flowing from other working areas which are generally contaminated are re-used and reconditioned. Controlled recirculation of air from relatively large ventilation districts can increase the flow of primary ventilation underground (MacKay, Bluhm & Van Rensburg 2010).

The elemental properties of air and recirculation impacting on air will be investigated in this section.

3.7.1 Airborne Pollutants

All personnel exposed to airborne pollutants must be within the Occupational Exposure Limits (OELs) (DMR 2002) as specified in the Regulations of the Mine Health and Safety Act, Act number 29 of 1996 (MHSA 2002). Some of the commonly found gasses, Diesel Particulate Matter (DPM), flammable and explosive gasses and dust limits are shown in Table 3.7.1a. These will be discussed in the next few sections.

Table 3.7.1a: Airborne Pollutants

Description	**OEL**
Silica dust, crystalline	0.1 mg/m^3 Time Weighted Average (TWA)
Fibres	2 f/mL Time Weighted Average (TWA)
PNOC	inhalable 10 mg/m^3 and respirable 3 mg/m^3
Carbon Monoxide (CO)	30 ppm (TWA) and 100 ppm (OEL-Stel)
Carbon Dioxide (CO_2)	5 000 ppm (TWA) and 30 000 ppm (OEL-Stel)
Nitric oxide (NO)	25 ppm (TWA) and 35 ppm (OEL-Stel)
Nitrogen dioxide (NO_2)	3 ppm (TWA) and 5 ppm (OEL-Stel)
Sulphur dioxide (SO_2)	2 ppm (TWA) and 5 ppm (OEL-Stel)
Diesel Particulate Matter – Total carbon	160 µg/m^3 (Belle, 2007)
Diesel Particulate Matter – Elemental carbon	123 µg/m^3
Flammable gas	< 1.0%
Radiation	< 20 mSv/annum (personal exposure)

For all mining operations a Code of Practice (CoP) must exist for an occupational health programme on personal exposures to airborne pollutants (DMR 2002). This document must be prepared in compliance with DMR guideline16/3/2/4-A1 and implemented in terms of the MHSA and Regulations when the following hazard limits prevail (Table 3.7.1b).

Table 3.7.1b: Airborne pollutants OELs

Particulates	≥ 0.1 of the OEL
Gases	≥ 0.5 of the OEL

Investigating airborne pollutants will assist a mine to adhere to legislative requirements. These pollutants may end up in the general air that travels through the air cooler and should be monitored and managed (DMR 2002).

3.7.2 Flammable, Explosive and Toxic Gasses

Flammable gasses consist of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), ammonia (NH_3), nitrogen dioxide NO_2), and other hydro carbon gases. They might be present on mines and be released from fires, blasting, diesel vehicle exhaust gas, etc. and lethal to employees (MEC Workbook 4, 2008).

A CoP must be drawn up in compliance with the 'Guideline for the Compilation of a Mandatory Code of Practice for The Prevention of Flammable Gas Explosions in Mines (Other than Coal Mines)'. A flammable gas regime must be implemented on all mines to monitor, track, control and where possible eliminate any gas that may be present at the mine ('ACGIH' 2000) (DMR 2002). The CoP must be adhered to and within airborne pollutant OELs listed in section 3.7.1.

Explosive gasses include ammonia (NH_3), CO, carbon disulphide (CS_2), CH_4, hydrogen sulphide (H_2S), etc. Most explosive and flammable gasses are also toxic and need to be limited as stipulated by the DMR.

3.7.3 Dust

The significance of investigating respirable dust underground is that this impacts on the environmental engineer due to possible health risks and claims from employees (Table 3.7.1a for OEL). Dust exposure can lead to chronic health risks for individuals which in turn can have legal impact on the mine (De Koker 2010). The only way that dust exposure can be reduced is by introducing engineering control measures (Kessel 2003). Studies on South African underground mines show that individual dust control measures can achieve reductions of between 25 to 50% of dust. These could include methods for minimising dust levels by reducing dust generation and methods for dilution, suppression, capture, and containment; this can partially be achieved in open circuit heat exchangers (discussed in Chapter 4).

3.7.4 Diesel Particulate Mater

In June 2012 the International Agency for Research on Cancer (IARC) classified diesel engine exhaust as carcinogenic to humans (Group 1) based on sufficient evidence that exposure is associated with an increased risk for lung cancer (Karsten & Mackay 2012). All designs where mechanised equipment is utilised should consider DPM (Table 3.7.1a for OEL). This study does not investigate these in depth.

3.7.5 Blasting Fumes

Blasting operations produce both toxic and nontoxic gaseous products that mainly include CO and the oxides of nitrogen (NOx) (Bakke et al. 2001). The quantity of toxic gasses produced by an explosive is affected by formulation, confinement, age of the explosive, and contamination of the explosive with water or drill cuttings, among others (Mainiero, Harris & Rowland 2000).

No detail on blasting fumes is discussed in this study but needs to be incorporated when re-used systems are incorporated in the primary ventilation and BAC system (Table 3.7.1a for OEL).

3.7.6 Radiation

Radiation emissions are mainly liberated during breaking of rock, materials handling, backfill and groundwater and the exposure remained below 20 mSv/annum for a working level month (Table 3.7.1a). Radon daughters and other offspring can be controlled by ventilation to ensure low concentrations and need to include short residence times of up to 15 minutes limiting the mine atmosphere to 20% exposure. General ventilation control delivers residence times of 20 minutes yielding 30% radon decay (Gherghel & De Souza 2008).

Ventilation where radon is present is generally in parallel with the overall ventilation system and when recirculation systems are considered the radon levels need to be carefully monitored, controlled and maintained (Table 3.7.1a for OEL).

3.7.7 Recirculation of Ventilation Air

Recirculating air underground reduces air quantity drawn from surface. Recirculated air can only be used in horizontal bulk air cooling spray chambers and some cooling towers but not in indirect-contact heat exchangers which requires self-cleaning systems. Adequate filtering of dusty recirculated air is vital in the control of dust concentrations in recirculated schemes (Booth-Jones et al. 1984). It is beneficial to integrate spray chambers with dust-scrubbing systems that will result in efficient air-conditioning units that can provide cleaning and thermal cooling but this will not be discussed in this study.

Respirable crystalline quartz (SiO_2) is a known hazardous component in South African underground mines with particle sizes from below 7 µm. Spray chambers are known to remove dust particles from 10 µm but atomized spray systems are required to remove smaller particles (Table 3.7.7, 'Industrial Ventilation' 1988).

Bulk air heat exchangers are part of four dust collector types and fall in the group of wet scrubbers according to the Industrial Ventilation Recommended Practice (1988). Commercially six types of wet scrubbers are generally available namely chambers or spray towers, packed towers, wet centrifugal collectors, wet dynamic precipitators, orifice type and venturi, and each of these operate with different functions.

The main function of a wet scrubber is one or more of the following (ASHRAE 1996):

- Maintains compliance of the process with the laws or regulations for air pollution.
- Reduces nuisance or physical damage from contaminants to individuals, equipment, products or adjacent properties.
- Prepares cleaned gases for processes.
- Reclaims usable materials, heat, or energy.
- Reduces fire, explosion, or other hazards.

Most wet scrubber's uses water as fluid to capture and separate particulate matter (dust, mist and fumes) from a gas stream. Wet scrubbers' measure of performance is based on the dust particle diameter, energy class, maximum dust loading, liquid and gas pressure loss, comparative energy requirement, superficial velocity, capacity limits and space requirements (Table 3.7.7).

For this study the first type of wet scrubber will be investigated in detail, chambers or spray towers. These two heat exchangers together with coil/car banks (multiple smaller heat exchangers) will be investigated so that the engineer can decide which is more practical for his/her mine installation. Table 3.7.7 shows that dust, fume and other particle sizes of 10 μm and bigger will be attracted with liquid pressure of up to 690 kPa; in general pressure up to 300 kPa is used for open circuit systems.

Table 3.7.7 Measure of Performance of Wet Scrubbers (ASHRAE 1996)

Type of Scrubber	**Particle Diameter (μm)**	**Max. Loading (g/m^3)**	**Collection Efficiency (%by mass)**	**Pressure Loss, Gas**	**Pressure Loss, Liquid (kPa)**	**Comparative Energy Requirement**	**Superficial Velocity* (m/s)**	**Capacity Limits (m^3/s)**	**Relative Space Required**
Chamber or Spray towers	>10	>2	70	25-250	140-690	5.0	0.5-1.0	47	Medium
Packed towers	>5	>0.2	90	125-2 500	35-210	4.0-34	0.5-1.0	24	Medium
Wet centrifugal collectors	>5	>2	90	500-2 000	140-690	12-26	10-20	47	Medium
Wet dynamic precipitators	>2	>2	95	Provides pressure	35-210	30-200	15-20	24	Small
Orifice type	>2	>0.2	90	500-1 500	None	9.0-21	15	24	Medium
Venturi	>0.1	>0.2	99	2 500-7500	35-210	30-300	60-210	47	Small

* Average velocity of gases flowing through the equipment’s collection region.

To assist in particle size calculations, Booth-Jones et al. (1984) and Burton et al. (1984) developed a dust concentration model within a recirculation system to determine the mixed dust concentration (Figure 3.7.7a and Equation 3.7.7a):

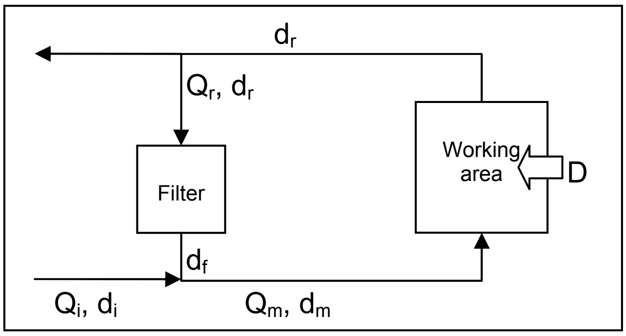

Figure 3.7.7a: Typical Recirculation System

$$d_m = \left(\left[d_i + \frac{D}{Q_i}\right] / \left[\frac{RE}{1-R} + 1\right]\right) - \frac{D}{Q_i}(1-R)$$

$$d_r = \left(\left[d_i + \frac{D}{Q_i}\right] / \left[\frac{RE}{1-R} + 1\right]\right)$$

$$R = \frac{Q_r}{Q_i + Q_r}$$

$$E = \frac{d_r - d_f}{d_r}$$

d_i : Intake air dust concentration (mg/m^3)
d_m : Mixed intake air dust concentration (mg/m^3)
d_r : Return air dust concentration (mg/m^3) [3.7.7a]
d_f : Recirculated air dust concentration (after filtration) (mg/m^3)
D : Dust generation in working area (mg/s)
E : Efficiency of filtering device (mg/s), $0 \le E \le 1$
R : Recirculation fraction, $0 \le R < 1$
Q_i : Intake airflow rate (m^3/s)
Q_r : Recirculated airflow rate (m^3/s)

There is however a critical efficiency, E_c, which will ensure that the mixed intake dust concentration will be maintained at a level equal or less than the intake dust concentration for all recirculation fractions [Equation 3.7.7b].

$$E_c = 1/\left[\frac{Q_i d_i}{D} + 1\right] \quad [3.7.7b]$$

Predicted dust concentrations have been determined by Booth-Jones et al. (1984) by using Equation 3.7.7a and shows that the return air dust concentration will always decrease as the recirculation fraction increases (Figure 3.7.7b).

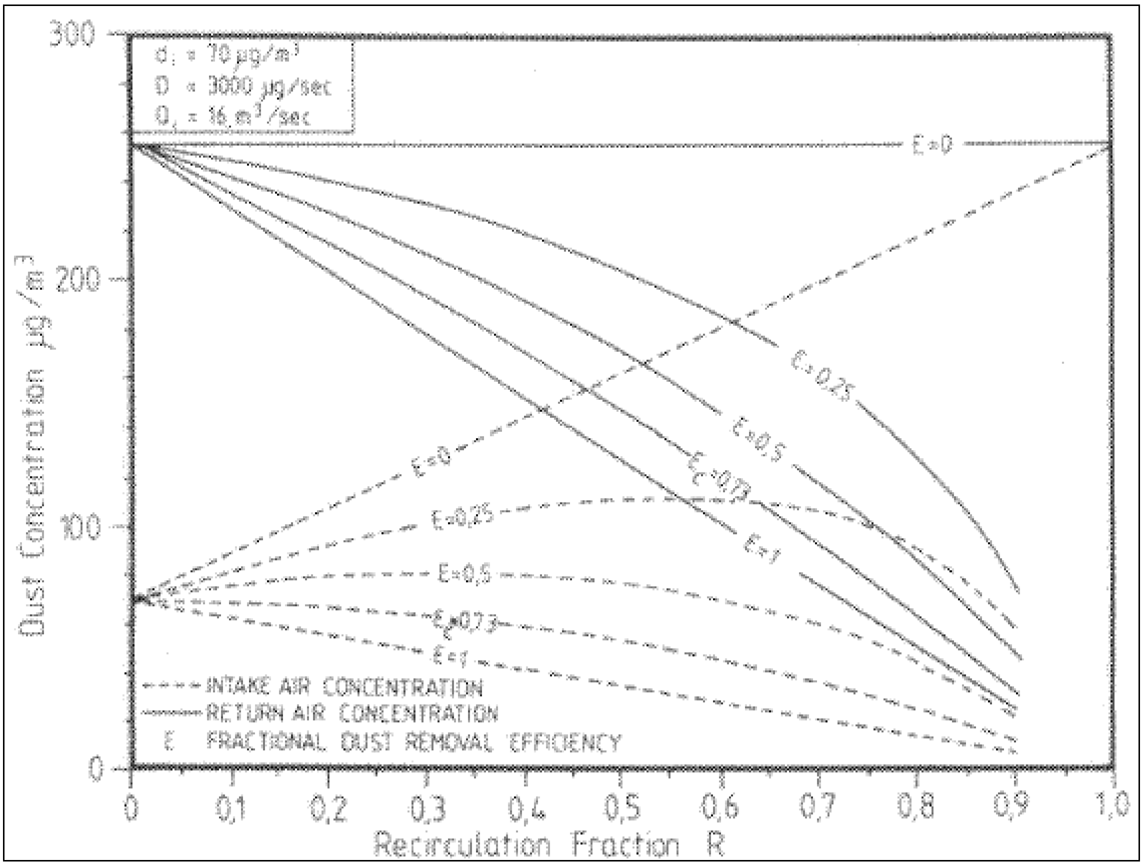

Figure 3.7.7b: Predicted Dust Concentration for Return and Mixed Airstreams

From Equations 3.7.7a and 3.7.7b and Figures 3.7.7a and 3.7.7b the dust concentration can be determined. After establishing the dust particle size, the type of air cooler and corresponding heat rejection facility can be determined. The following sections assist with this decision.

3.8 Water Quality

Water quality is determined by assessing three classes of attributes which include biological, chemical and physical according to ‘Exploring the Environment’ (2012). Biological attributes refer to number and type of organisms, chemical attributes to aesthetic qualities (smell, taste, etc.), and toxicity, and physical attributes to the path it flows. For this study the chemical impact of the water will mainly be considered as it will impact on the heat transfer process and physical components installed.

It is important that instrumentation is installed at the air sources and/or inlet position of the heat exchanger to determine the amount of flammable gases, airborne pollutants and dust in the heat exchanger.

Air entering the heat exchanger will react with water and the following may be experienced as listed below:

- NO_x and SO_2 from blasting, fires and/or vehicles in contact with water forms acid mine water (acid rain) which increases acidity (Cotton & Wilkinson 1976) that causes paint to peel and corrosion of steel in heat exchanger (Kadry 2008). This increased acidity will reduce pH levels and increase conductivity in the water. It can be treated by installing a conductivity meter to monitor the water by adding potable water to the system.
- CO and CO_2 from fires and diesel exhaust in water cause a weak acid that also contributes to water acidity levels.
- Dust build-up will cause the sump of these heat exchangers to fill up while more 'dirty' water is circulated through the unit that will block water flow through the unit thus causing inefficient heat transfer. An efficient monitoring system needs to be included in the design to ensure maintenance take place. Settled water needs to be treated to ensure corrosion is maintained.

Hardness is a characteristic of water caused by salts, calcium, magnesium and iron and must be limited to 150 mg/l (as $CaCO_3$) as precipitation of inorganic salts ($CaCO_3$) generates scale that can block pipes and nozzles (Himmelblau 1996).

Total Suspended Solids (TSS) is small particles of solid pollutants in a watery solution that contribute to turbidity while **Total Dissolved Solids (TDS)** are the total amount of dissolved organic or inorganic material, contained in water or wastes. Excessive dissolved solids make water unpleasant for drinking and unsuitable for industrial uses and needs to be limited to 3 000 mg/l (Perry & Chilton 1973).

Specific conductance is a measure of the ability of water to conduct an electrical current. It is expressed in micromhos per centimeter at 25 degrees Celsius ('Water Monitoring Analysis'). Specific conductance is related to the type and concentration of ions in solution and can be used for approximating the TDS concentration of the water. Commonly, the concentration of dissolved solids (in milligrams per liter) is about 65 percent of the specific conductance (in micromhos) ('Water Monitoring Analysis'). For this design TDS will be used as criteria to do water treatment.

3.9 Rock Mechanics

The location and size of the heat exchanger(s) will determine the impact on rock mechanics and needs to be addressed by the rock mechanic engineer (sizes of air coolers; towers, packed and unpacked spray chambers etc.).

3.10 Rock Properties

Underground working (stope) ventilation and cooling requirements are determined by the difference between the air and rock temperature being excavated (Bluhm & Biffi 2001). This increase is caused by the rock temperature that consists of certain properties that conduct heat. This calculation will be done with the heat load calculation.

Various models for different mine excavations and depth have been developed to calculate the Virgin Rock Temperature (VRT) which is influenced by the geothermal gradient and mining depth below surface as follows:

VRT (°C) = Surface rock temperature (°C) + (Geothermal gradient (°C/m) x Depth (m))

Table shows important rock properties that need to be known in order to determine the heat load from the rock on the surroundings (MEC Workbook 2, 2008). These can be used in software simulations and/or hand calculations to determine the heat load from the rock.

Table 3.10: Production Rock Properties

Description	**Unit**
Depth of mining	m
Surface rock temperature	°C
Geothermal gradient	°C/m
Density	kg/m^3
Thermal conductivity	W/m°C
Specific heat	J/kg°C
Thermal diffusivity	m^2/s

3.11 Surrounding Activities

Surrounding activities include all activities not listed above and may be development of a new section in a mine, construction of activities, etc. These are specific to mining companies and need to be taken into account by the designer when planning underground heat exchanger locations and surrounding air and water conditions.

3.12 Maintenance

Underground heat exchanger designs need to incorporate maintenance schedules and practicality of the heat exchangers. Maintenance schedules depend on available time for maintenance and quality of air and water used in these units. Generally air and/or water for air coolers are mainly clean but air and/or water for heat rejection units are of poor quality. In both cases the air and/or water quality needs to be maintained at proper levels indicated in section 3.7 and section 3.8.

Practical points to consider during the design process include the following, but are not limited to:

- Access to these units (roads and vehicle availability that relates to time associated with maintenance)
- Number of units
- Locations of these units (some will be in return airways)
- Safety of personnel during maintenance
- Working at heights and in dams
- Skills and training maintenance personnel
- Dam size and water capacity (generally 15 – 30 minutes capacity)

Only some points to consider are listed, but need to be elaborated on when heat exchanger designs are started.

3.13 Constructability Logistics

During the constructability phase of the study design engineers need to consider many aspects for successful construction. Some of these items are listed below however it is not limited to these points only:

- Availability of correct and checked excavation surveys
- Availability of correct and checked pegs and reference points including grade lines
- On-time order and delivery of equipment
- Sufficient budget for the installation and commissioning of the equipment
- Surface and underground fenced-off equipment storing space
- Contractor underground past installation experience and quality
- Shaft time availability
- Installation time availability (return airways are not always available to install heat rejection units in as blasting fumes need to be cleared)
- Regulatory requirements
- Quality inspection during installation
- Project management during construction
- Crane and hoist availability
- Training of contractors
- Electrical supply availability
- Availability of installation tools and equipment
- Location and accessibility of heat exchangers installations.

Before the designer can start with any technical and engineering requirements of bulk air heat exchangers, the above considerations should be addressed as these forms the base of any heat exchanger design process. Components discussed in this Chapter are not the only ones and other items need to be added pertaining to different mines.

The benefit of this Chapter however is that the designer has a comprehensive list of components to consider during the design process ensuring that no time is wasted on research during this design stage. Components listed here also promote the thinking process of the designer to ensure optimised heat exchanger(s) are designed.

3.14 Conclusion

This Chapter identified all factors that influence the selection criteria of bulk air heat exchanger technical specification. These factors will be used to guide the design engineer in simple steps that will be shown in Chapter 5.

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CHAPTER 4

ENGINEERING AND TECHNICAL REQUIREMENT FOR BULK AIR HEAT ECHANGERS

4. ENGINEERING AND TECHNICAL REQUIREMENTS FOR BULK AIR HEAT EXCHANGERS

A literature research covering the input to underground bulk air (>100 m^3/s) heat exchanger design specifications was conducted over three Chapters. As mentioned in Chapter 3, the heat exchangers consist of air cooling and heat rejection units. They are installed when ventilation air only cannot cool the air sufficiently to below the thermal criteria and when mining operations increase to beyond 1 500 m as indicated in Chapter 2's introduction.

When this design process is started the overall mine ventilation system needs to be considered and a balance obtained between the complex interaction of heat exchanger water systems and refrigeration machines. A systematic approach needs to be followed to find a balance between the ventilation and thermodynamic mass and energy balances (Karsten & MacKay 2012).

This Chapter investigates the types of heat exchangers and all identified technical requirements required to complete the heat exchanger technical specification.

4.1 Overview of Bulk Air Heat Exchanger Designs

Bulk air heat exchangers are dust collectors and fall in the group of wet scrubbers according to the 'Industrial Ventilation' (1988) as discussed in section 3.7.7. For this study spray chambers or towers together with closed-circuit indirect-contact heat exchangers (coil/car banks) will be investigated in detail that primarily remove thermal heat and larger dust particles (above 10 μm).

When selecting a type of heat exchanger, the following options are available:

- For bulk air cooling:
  - Spray chamber
  - Packed or unpacked tower
  - Indirect-contact coil banks
- For heat rejection:
  - Spray chamber
  - Packed or unpacked tower

It is further important to decide upfront whether fresh intake air only or used air (a mixture of re-used and fresh air) will be used.

When designing air coolers or heat rejection units, the design engineer has a certain amount of control over the air flow and water flow rates. The balance between air flow and water flow rates has different applications in the types of heat exchangers although the overall balance remains fairly constant for each.

When determining the heat exchanger duty from psychrometric charts (on surface and underground), the amount of water being condensed (air coolers) or evaporated (heat rejection) from the air will be calculated. When this design process is started, realistically air coolers should not overcool shafts colder than 8 °C WB (Ramsden, Butterworth & Johns 2002) or intake air to the working area to below 18 °C WB. Air cooler water and air flow rates should be balanced to ensure cooling duties are met and that excessive condensation does not reduce the cooler duty (Hendy Coils 2008).

The types of air coolers include indirect-contact coil banks, spray chambers or towers and are designed to provide cool air to the working face and its performance can be predicted for all operating conditions. Cooling is normally distributed via chilled water lines to provide any required combination of bulk air cooling (tower or spray chamber), face or stope air cooling (coils) and/or chilled service water.

The types of available heat rejection units include spray chambers or towers and are designed to remove heat from the condenser circuit in the refrigeration circuit and their performance can be predicted for all operating conditions.

4.2 Small versus Large Heat Exchangers

It is important to determine whether small or large heat exchangers will be used. Small heat exchangers are generally up to 2 MW (Hendy Coils 2008) while large heat exchangers are bigger than 2 MW. To achieve this, the ventilation engineer needs to determine what type of heat exchanger will be used. In industry most small heat exchangers operate at air flow quantities of 15 m^3/s or lower (Wood 2009). For this study large heat exchangers will be used and assume an air flow of 100 m^3/s or more.

4.3 Spray Chamber versus Spray Tower

A design engineer needs to understand the difference between a spray chamber (horizontal) and spray tower (vertical) as it will influence the final decision. The aerodynamics, thermodynamics, hydraulics, construction, maintenance, operation and capital for each is different.

For numerous reasons, Bluhm et al. (2001) describes the advantages the horizontal spray chamber format over the vertical spray tower format. It is important to consider the following recognized theoretical and practical points to assist the design engineer with decisions:

- Aerodynamics

  According to Bluhm et al. (2001), the aerodynamic features of a spray chamber are better than those of a vertical tower arrangement.
- Thermodynamics

  Bluhm et al. (2001) states that in horizontal spray chambers, cold water sprays are created and heat transfer occurs across the surface area provided by the water drops; high efficiency is achieved by re-spraying water in a second stage. In vertical towers, the cold water usually cascades through a wired screen to uniformly distribute the water sprayed (Whillier 1971). The design factor-of-merit of a typical vertical tower is 0.65 while a two-stage spray chamber is greater than 0.70. This results in vertical towers requiring a higher cold water flow rate (about 20%) to produce the same cold air condition as a horizontal spray chamber.
- Hydraulics

  The overall pump power of cooling towers compared to the horizontal spray chambers is similar.
- Pumping

  The vertical tower format will typically require a higher cold water flow and would use larger diameter piping and have pump power penalties.
- Construction

  The air flow rate determines the principal dimensions of the air cooler (in either configuration). The horizontal chamber requires a much lower construction height which makes them favourable during maintenance. The net result is that the civil cost of a horizontal chamber will be less than that of a vertical tower (horizontal arrangement needs a slightly larger ‘footprint’) as well as the construction and equipping period for the low horizontal formats.

- Operation and maintenance

  Horizontal spray chambers are simpler from an operational, control and maintenance perspective and blocking of nozzles is not a problem. In vertical packed towers it is important to maintain a uniform water (and air) distribution.
- Capital and power cost comparison

  Life-cycle cost comparisons shows that both capital and power cost savings are achieved when installing horizontal spray chambers (more than 50% saving). Spray towers are however still constructed as the initial capital expense may sometimes be less but if the total owning cost comparisons are completed this saving can be achieved.

4.4 Types of Bulk Air Heat Exchangers

The selection between spray chamber or spray tower has been discussed in section 4.3. Indirect-contact heat exchangers are mainly used when closed-circuit water pumping is required.

The types of heat exchangers are identified and summarised below. Each of the processes can be followed to determine the most suitable and efficient design although the final option depend on the design engineer.

4.4.1 Indirect-Contact Heat Exchanger Banks

Banks of cooling coils are indirect-contact heat exchangers as heat transfer takes place between a gas and fluid stream that don't come in direct contact (McPherson 2007). Copper tubular coils filled with water are usually located within an air duct. Air is cooled as it flows along the duct over the tubes in the evaporator circuit and heat is rejected directly into the return air.

The advantage of this heat exchanger is that the cooling is at point of operation which increases the positional efficiency. These heat exchangers however need to be installed in clean air away from dusty working areas otherwise tubes will cake up reducing the efficiency of the unit. Air to water tube coils are subject to caking by dust deposits in mine atmospheres and require regular cleaning and maintenance (McPherson 2007). Cleaning of these tubes may be facilitated by periodically cleaning with a high pressure water-jet.

For indirect-contact heat exchangers there are two established methods to determine the duty of these heat exchangers, namely the log-mean temperature difference (LMTD) method and the number of transfer units (NTU) method (Ramsden 1980).

The energy balance of an indirect-contact heat exchanger is shown in Equation 4.4.1a:

$$\begin{aligned} &q = m_w\ C_w\ \Delta t_w = m_a\ \Delta H_a + q_c \\ &m_{wi}\ C_w\ t_{wi} + m_{ai}\ H_{wi} = m_{wo}\ C_w\ t_{wo} + m_{ao}\ H_{wo} + m_a(r_i - r_0)C_w t_c \\ &m_w = \text{Mass flow of water (kg/s)} \\ &C_w = \text{Specific heat of water (4187 J/(kg °C))} \\ &\Delta t_w = \text{Rise in temperature of the water (°C)} \\ &m_a = \text{mass flow of air (kg/s)} \\ &\Delta H = \text{Fall in enthalpy of the air (J/kg)} \end{aligned} \qquad [4.4.1a]$$

Using the principle of Whillier (1977) for spray towers, Equation 4.4.1a reduces to Equation 4.4.1b:

$$\begin{aligned} &m_w\ C_w\ (t_{wo} - t_{wi}) = m_a\ (H_{wi} - H_{wo} - Y) \\ &Y = (r_i - r_0)C_w t_c \end{aligned} \qquad [4.4.1b]$$

Equation 4.4.1b can be rearranged and written as in Equation 4.4.1.c:

$$\begin{aligned} &m_w\ C_w\ (t_{wo} - t_{wi}) = m_a\ (S_{wi} - S_{wo} + X) \\ &X = C_w[r_i(t_{wbi} - t_c) - r_o(t_{wbo} - t_c)] \end{aligned} \qquad [4.4.1c]$$

Equations 4.4.1b and 4.4.1c are exact and are usually ignored as the error is relatively small. X and Y depend on the magnitude of condensate and the smallest of X and Y should be used when determining the duty of a coil (Ramsden 1980).

Ramsden (1980) has introduced a K-factor method for an indirect-contact heat exchanger (Equation 4.4.1c and Figure 4.4.1a). This method determines the cooling duty of a coil by multiplying by the temperature difference. K-factor charts can be obtained from manufacturers for specific coils. The water efficiency of a coil is a ratio of the actual energy added to the water to the maximum that can be added at a constant heat capacity. According to the second law of thermodynamics the outlet water temperature do not exceed the outlet air temperature.

The water side is shown in Equation 4.4.1d:

$$\eta_w = \frac{t_{wo} - t_{wi}}{t_{wbi} - t_{wi}}$$

$$q = m_w C_w \eta_w (t_{wbi} - t_w)$$

$$q = K(t_{wbi} - t_w)$$

t_{wi} : Water temperature in (°C) [4.4.1d]

t_{wo} : Water temperature out (°C)

t_{wbi} : Air temperature in (°C)

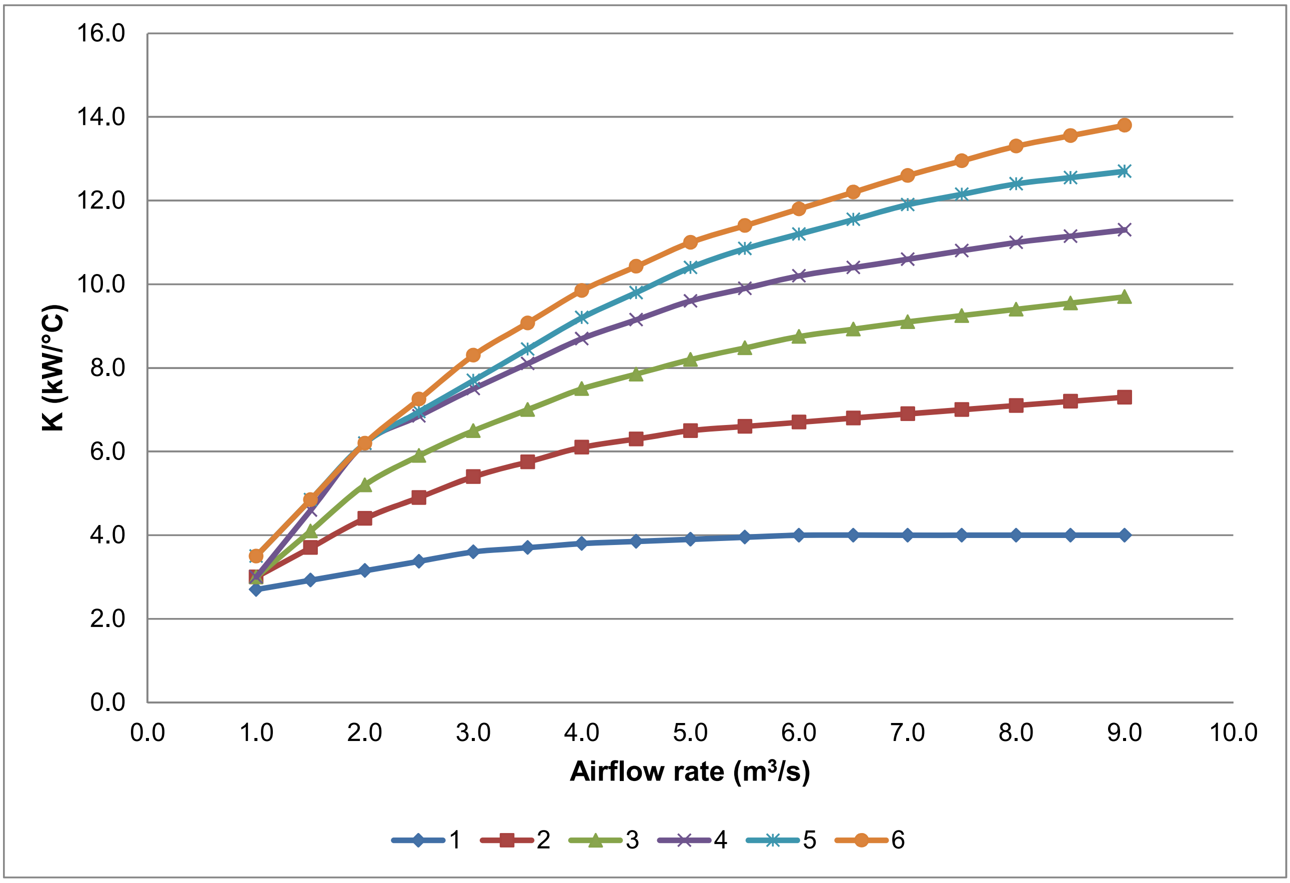

Figure 4.4.1a: Variation in K Factor with Air and Water Flow Rates

The **LMTD-method** for determining the duty of a cooling coil is as shown in Equation 4.4.1e (Incropera & De Witt 2002):

$$q = UA\ \mathrm{LMTD}$$

$$\mathrm{LMTD} = \Delta t_1 - \Delta t_2 \,/(2.303 \log \frac{\Delta t_1}{\Delta t_2})$$

$$\Delta t_1 = t_{ao} - t_{wi} \qquad [4.4.1e]$$

$$\Delta t_2 = t_{ai} - t_{wo}$$

UA : Overall heat transfer

The UA product is usually a measure of the effectiveness of an indirect-contact heat exchanger and can be calculated as shown in Equation 4.4.1f.

$$\frac{1}{UA} = \frac{1}{h_i A_i} + \frac{1}{h_o A_o}$$

$$h_i = 0.023 \frac{k}{d} Re^{0.8} Pr^{0.4} \quad (\mathrm{W/(m^2\ {}^\circ C)})$$

for a single tube :

$$h_o = 0.24 \frac{k_a}{d} Re^{0.6} \ (\mathrm{W/(m^2\ {}^\circ C)})$$

and for a bank of staggered tubes :

$$h_o = 0.29 \frac{k_a}{d} Re^{0.6} \ (\mathrm{W/(m^2\ {}^\circ C)})$$

$k =$ thermal conductivity of fluid (W/(m°C))
$d =$ internal diameter of tube (m)
$Re =$ Reynolds number $= \rho v d/\mu$ (dimensionless)
$\rho =$ fluid density (kg/m^3)
$v =$ fluid velocity (m/s)
$\mu =$ dynamic viscosity (Ns/m^2)
$Pr =$ Prandtl number $= C_w \mu/k$ (dimensionless, may be taken as 0.7 for air)
$C_w =$ Specific heat of water at constant pressure (J/(kg°C)) [4.4.1f]

The **Number of Transfer Units (NTU)-method** can also be used to determine the duty of coils and is calculated as shown below (Incropera & De Witt 2002). Similarly the duty can be predicted by using Equation 4.4.1a as shown above but this equation needs to be re-written as shown in Equation 4.4.1g (Ramsden 1980) (Kays & London 1964).

$$q = m_w\ C_w\ \Delta t_w$$
$$q = m_a\ \Delta H_a = m_a\ C_a(t_{wbi} - t_{wbo}) = Q_a \rho C_a(t_{wbi} - t_{wbo}) = Q_a CA(t_{wbi} - t_{wbo})$$

Q_a : Air volume flow rate (m^3/s)
ρ : Air density (kg/m^3)
C_a : Air heat capacity ($J/kg°C$)
CA : Air heat capacity ($J/m^3°C$)
C_w : Water heat capacity ($J/m^3°C$) [4.4.1g]
S_a : Air entropy ($J/kg°C$)
m_w : Water mass flow rate (kg/s)
m_a : Air mass flow rate (kg/s)

$$C_w = m_w H_w\ (W/°C)$$
$$C_a = m_a \frac{\Delta S_a}{\Delta t_{wb}} (W/°C) = m_a\ C_a = Q_a \rho C_a = Q_a CA$$

The performance and effectiveness of direct-contact heat exchanger for the NTU-method is expressed as the capacity-rate ratio (Z) and number of transfer units (NTU). Z is similar to R for spray chambers or towers.

$$Z = \frac{C_{min}}{C_{max}}$$
$$NTU = \frac{UA\ \text{of clean coil}\ (W/°C)}{C_{min}\ (W/°C)}$$

UA : Overall heat transfer ($W/°C$) (From Equation 4.4.1f) [4.4.1h]
C_{min} : Minimum of C_w and C_a (From Equation 4.4.1g)
C_{max} : Maximum of C_w and C_a (From Equation 4.4.1g)

For counter flow heat exchangers, Figure 4.4.1b can be used to determine the effectiveness of a heat exchanger in term of the thermal capacity, Z or C (Cabezas-Gomez et al. 2006). Similar figures need to be requested from coil suppliers for different heat exchanger arrangements.

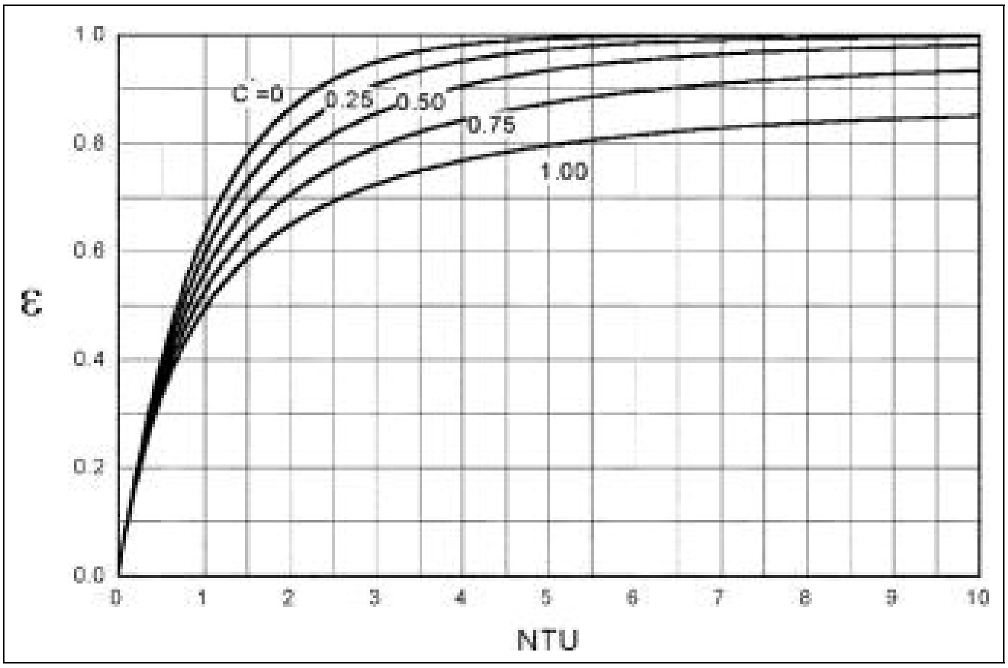

Figure 4.4.1b: Effectiveness vs NTU for Counter Flow Heat Exchangers

Two types of indirect-contact heat exchangers exist that include tube-fin type and plate-fin type; the latter not practical for underground operations as it requires more maintenance and becomes expensive. It is important to place these units in fresh intake airways to reduce maintenance cost. Tube-fin indirect-contact heat exchangers can be used for high pressure systems up to 30 MPa and for in-stope cooling (Burrows et al. 1989).

The size of a coil is mainly determined by the air flow volume. Face air velocities should remain between 1.5 and 2.6 m/s to ensure energy efficient designs (Hendy Coils 2008). A height to length ratio can be used as 2:1 during design but it is recommended that height be restricted to 750 – 900 mm to ensure trouble-free manufacturing.

Water velocity within the tubes should be between 0.3 and 1.5 m/s to ensure turbulent flow, reasonable efficiency and to avoid erosion problems according to Hendy Coils (2008). Water pressure drop is a result of water velocities and don't need to be a concern to the engineer.

The UA of a clean coil are usually between 10 and 25 kW/°C depending on the design of the heat exchanger and the configuration of fluid flow. Significant reductions in UA values indicate the need for cleaning or replacement of the tubes (McPherson 2007). Generally water temperatures are between 6 and 13 °C and the water pressure drop restricted to 30 – 40 kPa to ensure coil performance is a maximum.

It is advised that a maximum of 20 transfer units is used. When calculations give more than 20, another option like open circuit systems can be considered.

4.4.2 Spray Tower

When towers are used to cool air they are called **spray towers** and when towers are used to reject heat from a system they are called **cooling towers;** both are usually open circuit systems. Towers in general are classed as mechanical or natural draught towers with the first mainly used on surface and underground (Burrows et al. 1989). Mechanical towers use fans to force air through the tower and drift system and typically operate at full speed (Perry & Green 1997). In mines however, these units are installed in RAWs and the main fans ensure flow through these units.

Underground tower's uses wired screen to increase contact time and improve total area of contact between the air and water which improves the heat transfer of the unit. Generally packed towers are found in industry and are recommended as tower of choice.

Spray towers are designed to cool air and are part of the evaporator circuit of a refrigeration system (vapour compression circuit). In the tower chilled descending water is sprayed into a vertical tower and warm air ascends through the water droplets in a counter flow arrangement (Figure 4.4.2 with the exception that the cold and hot streams are opposite). The air flow usually enters at a wet-bulb temperature that is higher than the water temperature and will transfer heat from the air to the water by a combination of convection (sensible heat) and evaporation (latent heat), (McPherson 2007).

Cooling towers are designed to cool water from the condenser heat exchangers of a refrigeration plant by spraying hot water down a vertical tower while cool air ascends through the tower in a counter flow arrangement (Figure 4.4.2). In this system the water is never cooled below the inlet air temperature and heat is transferred from the water to the air by a combination of convection and condensation.

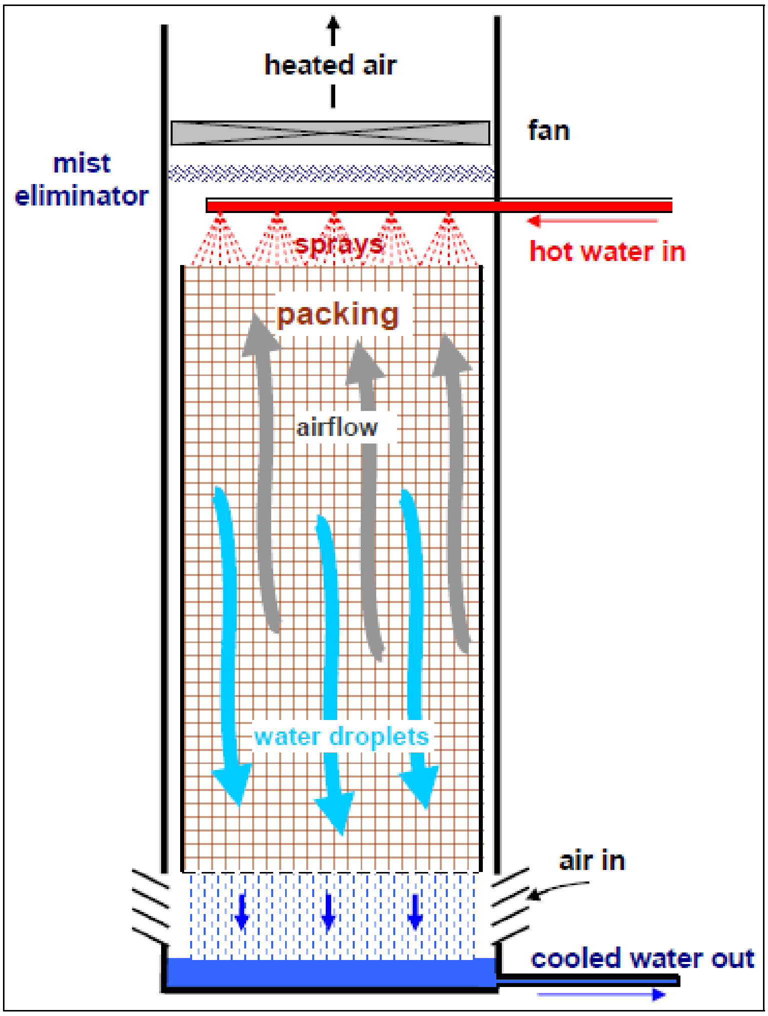

Figure 4.4.2: Counter Flow Cooling Tower (McPherson 2007)

Cooling tower and spray cooler designs are very different, but the following is similar:

- Water mass flow rate
- Inlet water temperature
- Air mass flow rate
- Psychrometric condition of inlet air
- Duration and relationship of contact between the air and the water droplets (influenced by relative velocity between air and water droplets, and the size and concentration of water droplets).

Today cooling towers are mainly used on surface and underground to reject heat. Condenser spray chambers (CSC) are also employed for this purpose and are mainly preferred as condenser water generally are of poor quality. When cooling is required in working areas, indirect-contact coil banks or horizontal spray chambers are used.

Air velocities through packed cooling towers are generally up to 3 m/s due to fill pack constraints but up to 7 m/s in unpacked cooling towers. Water flow rates in pipes are generally up to 2.5 m/s and steel flanged pipes are mainly used in South Africa. Towers typically cool condenser water by 7 to 9 °C and the water to air ratio are generally between 0.5 and 2.5 (Burrows et al. 1989).

Burrows et al. (1989) further states that heat rejection can vary between 20 and 100 kW per m^3/s of air depending on which condensing temperature is required. McPherson (2007) states that cooling towers used for mine air conditioning are typically 10 to 20 m in height and some 3 to 8 m in diameter, depending upon the rate at which heat is to be exchanged. Heat loads may be as high as 30 MW.

The Factor of Merit of towers needs to be determined (section 4.5) and are generally between 0.5 and 0.6 for **unpacked towers** with high water loading and 0.6 and 0.7 for low water loading. The Factor of Merit for **packed towers** range between 0.55 and 0.65 for high water loading and between 0.65 and 0.75 for low water loading. Water loadings should not be greater than 16 liters per second per square meter of cross sectional area (Stroh 1982). The FOM is calculated with Equations 4.5d to 4.5e and will determine the water loading of the tower (Table 4.4.2).

According to McPherson (2007) the materials used for packing may be treated fir or redwood timber, galvanized steel, metals with plastic coatings and injection molded PVC or polypropylene.

‘Energy Efficiency Guide for Industry in Asia’ (2006) states there are three types of fills:

- **Splash fills**. Splash fill media generates the required heat exchange area by splashing water over the fill media into smaller water droplets. The surface area of the water droplets is the surface area for heat exchange with the air.
- **Film fills**. In a film fill, water forms a thin film on either side of the fill sheets. The surface area of the fill sheets is the area for heat exchange with the surrounding air. Film fill can result in significant electricity savings due to fewer air and pumping head requirements.
- **Low-clog film fills**. Low-clog film fills with higher flute sizes were recently developed to handle high turbid waters. Low clog film fills are considered as the best choice for sea water in terms of power savings and performance compared to conventional splash type fills.

Different design values for various types of fill are shown in Table 4.4.2 ('Energy Efficiency Guide for Industry in Asia' 2006).

Table 4.4.2: Design Values of Different Types of Fill ('Energy Efficiency Guide for Industry in Asia' 2006)

	Splash fill	**Film fill**	**Low clog film fill**
Possible L/G ratio	1.1 – 1.5	1.5 – 2.0	1.4 – 1.8
Effective heat exchange area	30 – 45 m^2/m^3	150 m^2/m^3	85 - 100 m^2/m^3
Fill height required	5 – 10 m	1.2 – 1.5 m	1.5 – 1.8 m
Pumping head required	9 – 12 m	5 – 8 m	6 – 9 m
Quantity of air required	High	Lowest	Low

Concrete is used primarily for casings, structural reinforcements and water sumps or dams. Mist eliminator screens are placed within the tower to reduce water carry-over.

Evaporation in cooling towers may cause an increase in concentration of total dissolved solids and need to be maintained by water blow-down. The blow-down rate is determined by the water quality (Chapter 3) and is in the order of 1% of the circulation water rate (McPherson 2007).

The duty of a cooling tower can be determined as shown in Equation 4.4.2 (MEC Workbook 2, 2008):

$$\begin{aligned}
&q = M_w C_{pw} \Delta t_w = M_a \Delta S_a \\
&m_{wi}\, C_w\, t_{wi} + m_{ai}\, H_{wi} = m_{wo}\, C_w\, t_{wo} + m_{ao}\, H_{wo} + m_a (r_i - r_0) C_w t_c \\
&M_w \ \ : \text{Mass of water (kg/s)} \\
&C_w \ \ : \text{Water heat capacity (kJ/kg°C)} \qquad [4.4.2] \\
&\Delta t_w \ \ : \text{Water temperature difference} \\
&M_a \ \ : \text{Mass of air (kg/s)} \\
&\Delta S_a : \text{Air entropy difference (kJ/kg)}
\end{aligned}$$

4.4.3 Spray Chamber

Spray chambers can be used to cool air and reject heat from a system and operate in open circuit applications. Cooling occurs in BACs and heat rejection in **Condenser Spray Chambers** (CSCs). Spray chambers generally have horizontal spray arrangements and can consist of many stages (generally up to 3).

In BACs chilled water is supplied to the first stage so that the air meets the coldest water. Water is recirculated in the other stages to improve the thermal capacity of the cooler (Figure 4.4.3). In CSCs hot condenser water is cooled by spraying hot water into used warm air that removes heat. Cooled water is then pumped from the CSC sump to the condenser heat exchanger.

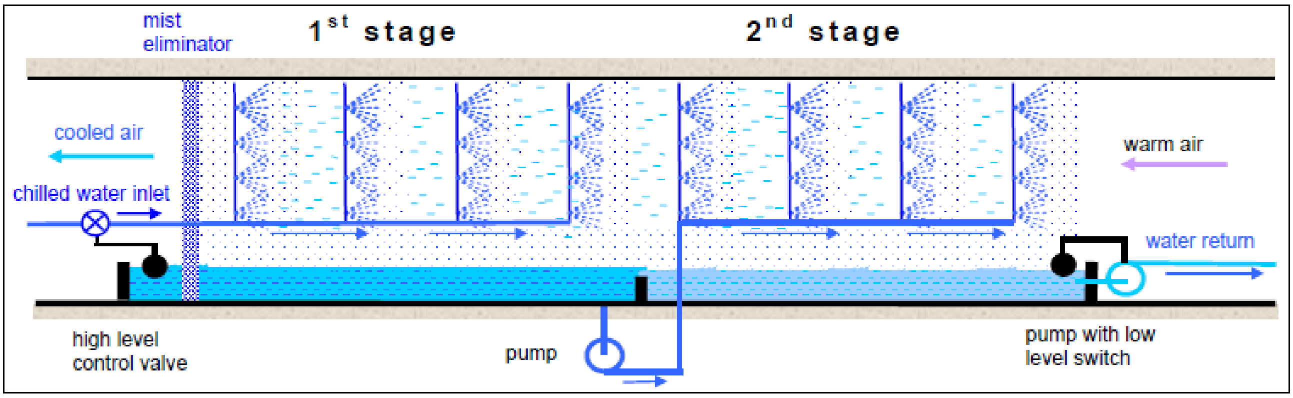

Figure 4.4.3: Two-stage Horizontal Spray Chamber

Water loading should lie within 2 to 5 liters/second for each square meter of cross sectional area (Bluhm 1983). In practice, droplet diameters of approximately 0.5 mm and water pressures in the range of 150 to 300 kPa give satisfactory results in horizontal spray chambers (Reuther 1987). These pressures can be achieved by nozzles that are usually flat vee-type nozzles at 65˚ angle. In spray systems, the water to air ratio in mines are generally between 0.3 and 0.6 l/m^3 (McPherson 2007).

Air velocities through spray chambers are generally up to 5 m/s with an absolute maximum at 7 m/s to ensure mist eliminator efficacy with minimal water carry-over (Burrows et al. 1989). Water flow rate in pipes are generally up to 2.5 m/s and up to 2 m/s in spray pipes and steel flanged pipes are mainly used in South Africa. Spray chambers typically cool condenser water by 7 to 9 ˚C and the water to air ratio are generally less than 1 with water efficiencies between 0.6 and 0.9 (Burrows et al. 1989). Efficiency of spray chambers are determined by the Factor of Merit (FOM).

The duty of a spray chamber can be determined as shown in Equation 4.4.3 (Burrows et al. 1989):

$$q = M_w C_{pw} \Delta t_w = M_a \Delta S_a$$

$$m_{wi} C_w t_{wi} + m_{ai} H_{wi} = m_{wo} C_w t_{wo} + m_{ao} H_{wo} + m_a (r_i - r_0) C_w t_c$$

M_w : Mass of water (kg / s)
C_{pw} : Water heat capacity (kJ / kg°C) [4.4.3]
Δt_w : Water temperature difference
M_a : Mass of air (kg / s)
ΔS_a : Air entropy difference (kJ / kg)

Mist eliminators are usually installed when high water carry-over is experienced and water needs to be captured for re-use. In the case that this is required, it is advised that air flow velocity be limited to 5 m/s. These units are generally only installed in cooling systems where mainly fresh air is used.

In BACs evaporation take place and this evaporated water needs to be pumped to the CSC where water is condensed. If this is not possible this water needs to be dumped in the mine water system so that it can be pumped to surface.

4.5 Factor of Merit and Positional Efficiency

The Factor of Merit (FOM) of indirect-contact, tower and spray chamber heat exchangers can be determined with the assistance of section 4.4 to determine the number of units, stages or cells. For indirect-contact heat exchangers the equivalent FOM is a measure of the UA-value which influences the thermal capacity ratio calculation. The FOM for indirect-contact and direct-contact heat exchangers can be determined as shown in Equations 4.5a to 4.5e (Burrows et al. 1989):

Condenser spray chambers or cooling towers (heat rejection):

Water efficiency :

$$\eta_w = \frac{t_{wi} - t_{wo}}{t_{wi} - t_{wbi}}$$

t_{wi} : Water temperature in (°C) [4.5a]
t_{wo} : Water temperature out (°C)
t_{wbi} : Air temperature in (°C)

Thermal capacity ratio :

$$R = \frac{m_w C_w}{m_a C'_a} \qquad [4.5b]$$

$$C'_a = (S_{wi} - S_{ai})/(t_{wi} - t_{ai})$$

BAC or spray tower air cooling water efficiency, thermal capacity ratio and Factor of Merit is shown in Equations 4.5c to 4.5e below:

Water efficiency :

$$\eta_w = \frac{t_{wo} - t_{wi}}{t_{wbi} - t_{wi}} \qquad [4.5c]$$

t_{wi} : Water temperature in (°C)

t_{wo} : Water temperature out (°C)

t_{wbi} : Air temperature in (°C)

Thermal capacity ratio :

$$R = \frac{m_w C_w}{m_a C'_a} \qquad [4.5d]$$

$$C'_a = (S_{ai} - S_{wi})/(t_{ai} - t_{wi})$$

Factor Of Merit :

$$\eta_w = (1 - e^{-N(1-R)})/(1 - Re^{-N(1-R)}) \qquad [4.5e]$$

$$N = \left(\frac{FOM}{1 - FOM}\right)\left(\frac{1}{R}\right)^{0.4}$$

The FOM determines how many stages will be present in the spray chamber (Table 4.5).

Table 4.5: Factor of Merit for Spray Towers and Horizontal Spray Chambers (Burrows et al. 1989)

Type of heat exchanger		**Typical FOM values**
Spray chamber, no packing	1 stage	0.40 – 0.55
	2 stages	0.58 – 0.67
	3 stages	0.67 – 0.75
Spray tower, with packing	High water loading	0.55 – 0.65
	Low water loading	0.65 – 0.75
Spray tower, no packing	High water loading	0.50 – 0.60
	Low water loading	0.60 – 0.70

Indirect-Contact Heat Exchangers (air cooling):

Equation 4.5c showed the calculation for the water efficiency of a bulk installation of indirect-contact coil. The thermal capacity ratio (Z) was calculated in Equation 4.5d and is similar to R for open circuit heat exchangers. The FOM for indirect-contact heat exchangers is calculated in Equation 4.5f below:

Factor Of Merit :

$$\eta_w = (1 - e^{-N(1-R)})/(1 - Re^{-N(1-R)}) \qquad [4.5f]$$

$$N = \left(\frac{FOM}{1 - FOM}\right)\left(\frac{1}{R}\right)^{0.4}$$

For each of these heat exchangers nomograms from suppliers or specialist engineers can be used to determine the FOMs graphically.

After the FOM calculation, the positional efficiency of the heat exchanger can be determined by taking the duty of the heat exchanger and dividing it by the duty dissipated by the refrigeration machine from the heat exchanger to the plant room as shown in Equation 4.5g.

Positional efficiency :

$$\eta_{pos} = \frac{\text{Heat Exchanger Duty}}{\text{Plant Duty}} * 100(\%) \qquad [4.5g]$$

Once the decision process reaches this point the type of heat exchanger needs to be verified to ensure that the correct unit is installed.

4.6 Water Reticulation System

The water reticulation system includes all components relating to the water system and consists of the following: pumps, valves, pipe material, pipe schedule, hydraulic gradient, system operating pressure, operating temperature, insulation, water velocity, sump sizes, water hammer, etc. Generally steel flanged pipes are installed underground as it is robust although uPVC pipes with couplings are widely used these days.

The process specifications need to be known before this section of work can be started. The water flow rate and heat exchanger location(s) need to be known for the evaporator and condenser circuits in order to calculate accurate pressure drops across the mechanical system. The selection of open or closed water circuit also needs to be known.

The pressure drop of a system consists of three main constituents namely pressure head, static head and velocity head. Velocity head includes all valves, fittings, strainers, refrigeration machine heat exchangers, etc. and generally has a velocity between 2 and 3 m/s, with 2.5 m/s the typical design value. Pressure head is frictional losses mainly on the inside wall of the pipeline. The static heat is the vertical difference between the heat exchangers and also needs to be included for accurate hydraulic gradient calculation of the total pressure drop over the length of the piping system.

The pressure drop of the system will then influence the pipe material, size and pressure rating. For closed-circuits the pipe schedule need to be high pressure in order for the piping to sustain water hammer in the event of a pipe burst, valve shut to pump stoppage. Open-circuit pipelines are usually low pressure pipes, below 2 MPa

Special consideration is required for the distance between adjacent pipe supports and where pipe direction changes to ensure the safety of personnel during emergency situations. In the event of emergencies, the mine de-watering system needs to be able to transport this water or stand-by facilities need to be in place.

The sump size is usually designed to cater for a minimum dam capacity of 15 minutes. The dam needs to be cleaned out regularly to ensure the water quality remains good as mentioned in section 3.8 as it will influence the maintenance frequency and water capacity (Whillier 1977). To keep good quality water the conductance levels need to be kept to 3 g/l and water need to be blown-down from the water circuit to ensure these acceptable levels. Make-up water will be required for all evaporated and blown-down water.

4.7 Conclusion

This Chapter identified all engineering and technical requirements that influence the selection criteria of bulk air heat exchanger technical specification(s). These engineering and technical requirements together with the factors identified in Chapter 3 will be used to generate simple steps to use during the heat exchanger selection criteria process. This selection criteria process will improve bulk air heat exchanger technical specification(s). These steps will be discussed in Chapter 5.

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CHAPTER 5

DECISION ANALYSERS

5. DECISION ANALYSERS

Mine ventilation and cooling practices involve the use of direct and indirect-contact water-air spray heat exchangers for the rejection of heat from refrigeration plants and for the cooling of ventilation air according to Bluhm (1981). These are mainly found in deep mines or mines that have high VRTs and the design for each are different for all mining operations.

This Project investigated external factors and engineering requirements influencing the design of underground large bulk air heat exchangers. This Chapter was developed to use these factors and engineering requirements in the form of decision tree steps. These decision steps will assist with a quick and easy guide to compile technical specifications for optimised heat exchangers.

5.1 Step 1: Determine Thermal Design Criteria

The design process is started with the first decision analyser determining the thermal design criteria of the mine in Figure 5.1. The thermal design criteria form a basis for the mine to determine whether a Heat Stress Code of Practice (CoP) with wet-bulb temperatures exceeding 25.0 °C and/or Heat Stress Management Programme with wet-bulb temperatures exceeding 27.5 °C are required.

In addition ventilation and cooling requirements need to be determined so as to establish whether more air is available to cool the underground environment to below the thermal design criteria. If this is possible, then no underground heat exchanger is required. If no additional air is available, a heat exchanger is required and Step 2 needs to be followed.

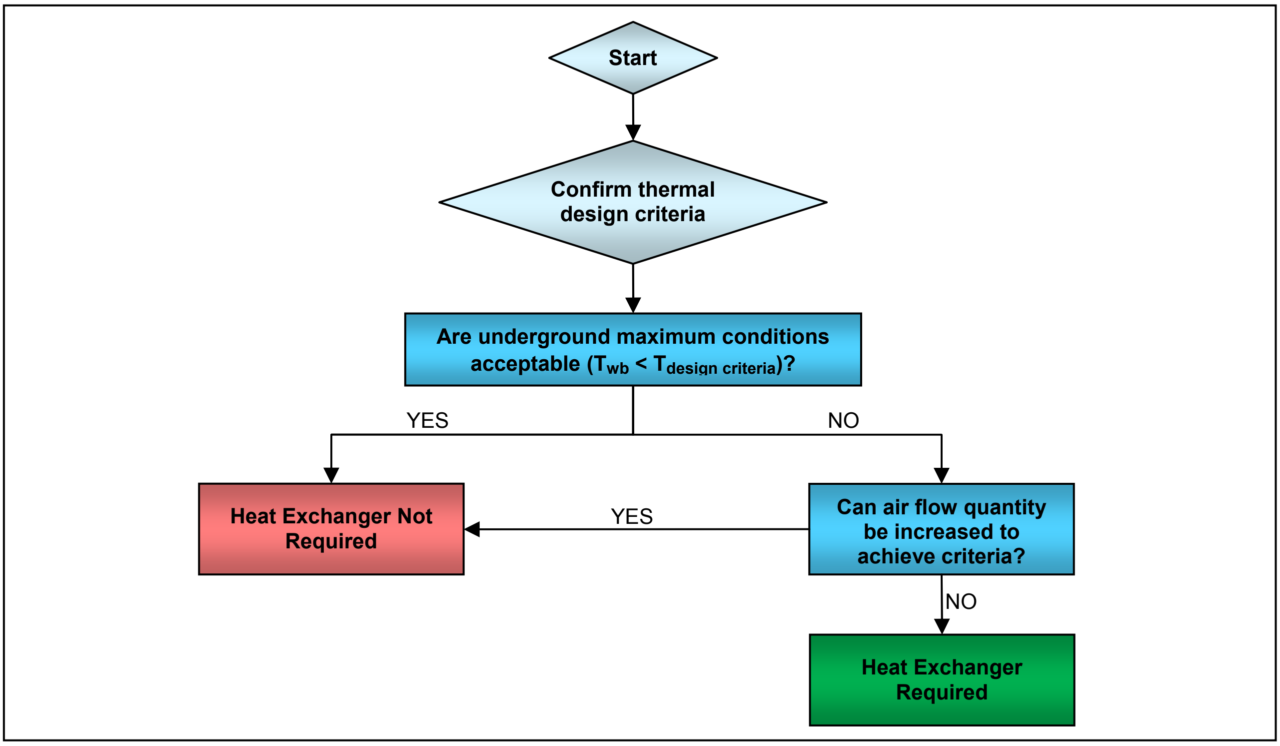

Figure 5.1: Thermal Design Criteria

5.2 Step 2: Surface Versus Underground Cooling

The second decision analyser as shown in Figure 5.2 determines whether surface and/or underground cooling is required. For this step the working depth of underground workings is required. A rule of thumb for platinum mines suggested (Chapter 3) that surface cooling is best utilised at critical depths from 800 m and VRTs from 50 °C. The designer needs to determine whether his/her applicable mine's VRT requires cooling at the particular mining depth. This decision will be different for the ore being mined, mining method utilised and distance from the shaft.

If the critical depth does not necessitate the need for an underground heat exchanger then other considerations like diesel vehicles, blasting conditions, and other activities need to be identified in this step. These considerations could motivate the need for an underground air cooler and subsequently heat rejection unit.

In the event that underground heat exchangers are required, it needs to be established whether bulk air is available for heat transfer. If this is true, continue to Step 3.

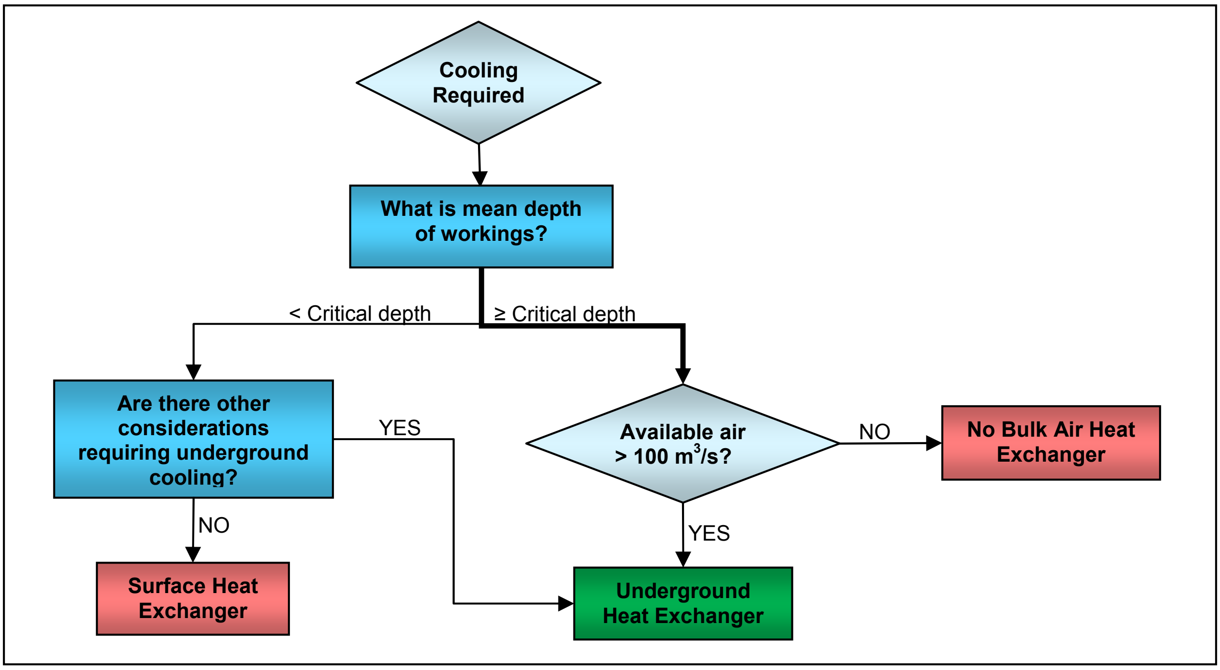

Figure 5.2: Surface vs Underground Bulk Air Heat Exchanger

5.3 Step 3: Determine Underground Heat Load and Confirm with Software Program

The third decision analyser determines the underground heat load in Figure 5.1c. Heat load components include auto-compression, rock heat, vehicles and other artificial sources. These items were discussed in Chapter 3 and it is important to ensure that all relevant heat loads are included.

Air carries a certain air cooling capacity (heat removal capacity) that cools the surroundings without being cooled (unless surface cooling is utilised). An additional cooling source on a mine is service water and both need to be determined. The energy balance will then determine the additional cooling required.

Air flow and thermodynamic software simulation models (VUMA3D-network or fully equivalent) includes air cooling capacity and determined heat loads that assists the design engineer with accurate heat exchanger calculations. These simulations will confirm heat exchanger requirements and Step 4 can start.

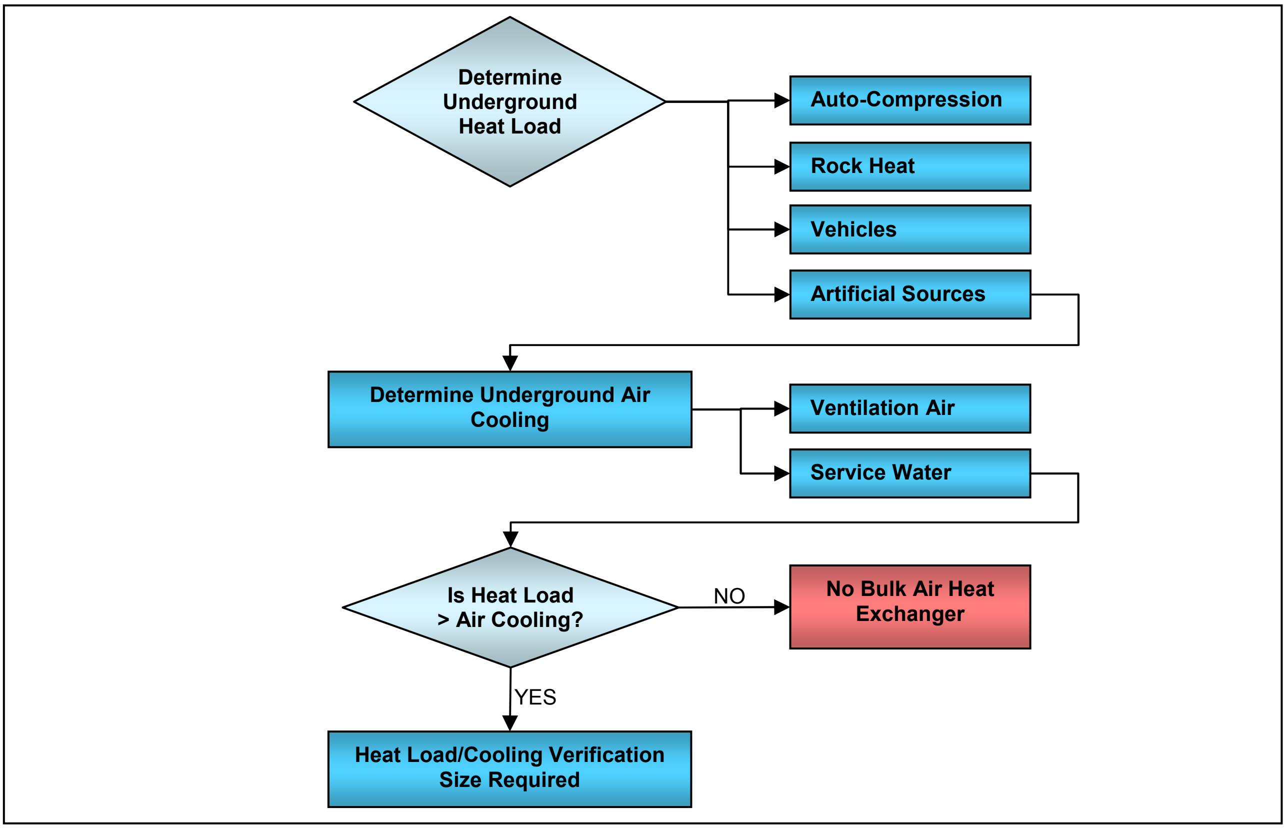

Figure 5.3: Underground Heat Load

5.4 Step 4: Excavation Size and Location

Confirmation of the heat load and cooling carrying capacity of the air ensures that design carried forward will be accurate. The first step in this section is to determine whether small or large duty heat exchangers will be used.

Small heat exchangers are referred to as heat exchangers with duties less than 2 MW and will not be discussed in this study. Large heat exchangers achieving air cooling and heat rejection have a wide selection of heat exchangers.

These heat exchangers can be divided into a number of units and the location for each need to be determined. These units are generally installed where thermal criteria is no longer archived. At the mine the number of these available locations needs to be determined in order to determine how many new excavations will be required. This is important to determine the most cost effective option to distribute smaller heat exchangers or less large heat exchangers in the available or new excavations (Figure 5.4). Large heat exchangers sometimes suffer from positional efficiency and in addition increase the system heat load.

Air coolers are generally placed adjacent to main intake airways and heat rejection units in/or adjacent to the main return airways. Once the number of heat exchangers and its locations are determined, proceed to Step 5.

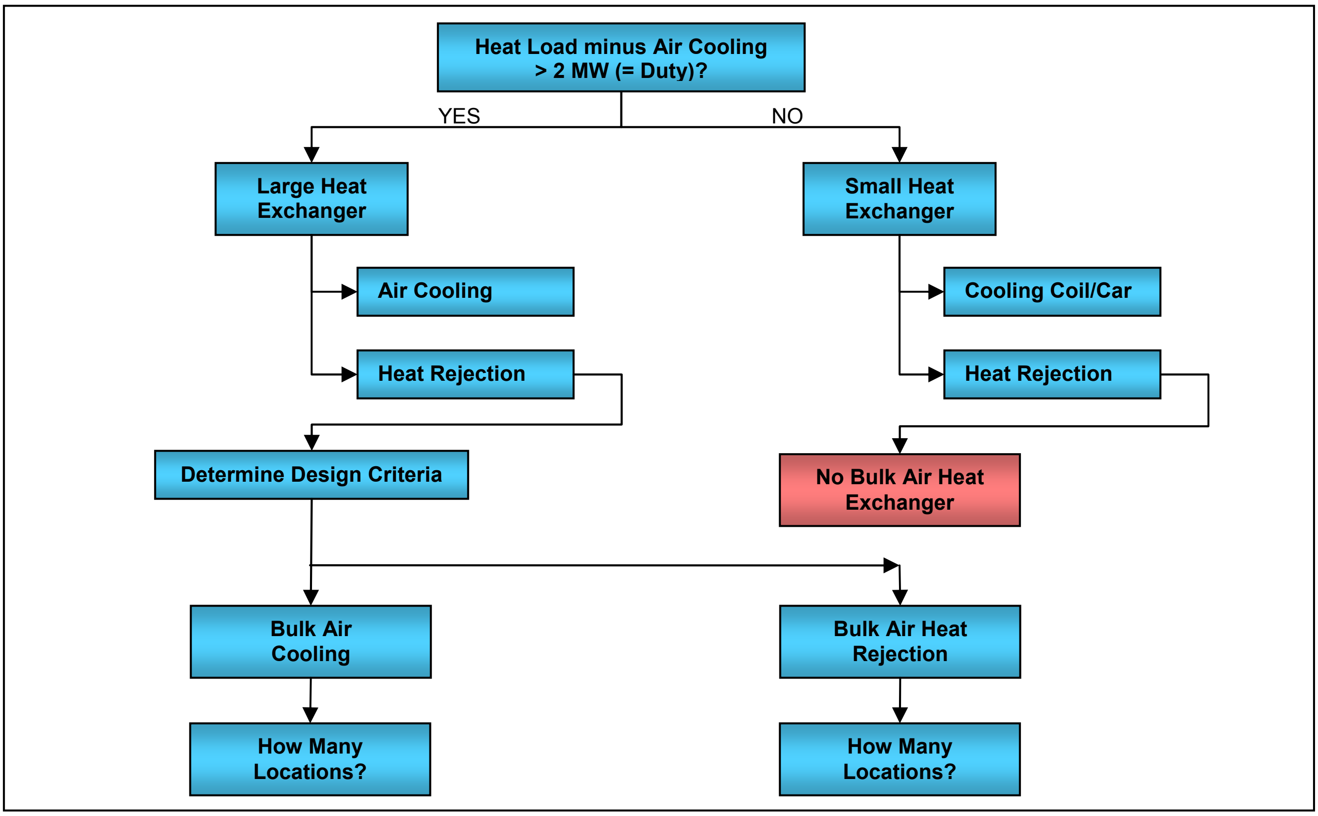

Figure 5.4: Heat Exchanger Locations

5.5 Step 5: Inlet Conditions and Water Loading

Once the number of locations to place air coolers and heat rejection units has been determined, the inlet conditions at each unit need to be confirmed. The inlet conditions will determine how much cooling or heat rejection can be achieved based on the thermal design criteria listed in section 3.1.

For air coolers the outlet air temperature needs to be within the minimum allowable air temperature to ensure safe and acceptable environmental conditions. For heat rejection units the maximum allowable water temperature that can return to the condenser heat exchanger need to be confirmed with suppliers. Figure 5.5 shows the input parameters of the air and water and depending on whether air coolers (on the left) or heat rejection units (on the right) are used, the design criteria need to be satisfied. When the design criteria are not met for these heat exchangers, the inlet air quantity needs be increased where possible.

The excavation size of the available or new heat rejection units need to be known in order for the designer to determine the correct water loading factor. For the air coolers and heat rejection units the water loading factor ranges between 0.5 and 1 (the lower the better) ('Horizontal spray-chambers for cooling ventilation air underground' 1983). The area of the available or new excavations will determine the required length of each unit. In this manner the amount of heat rejection units can be confirmed and correctly selected.

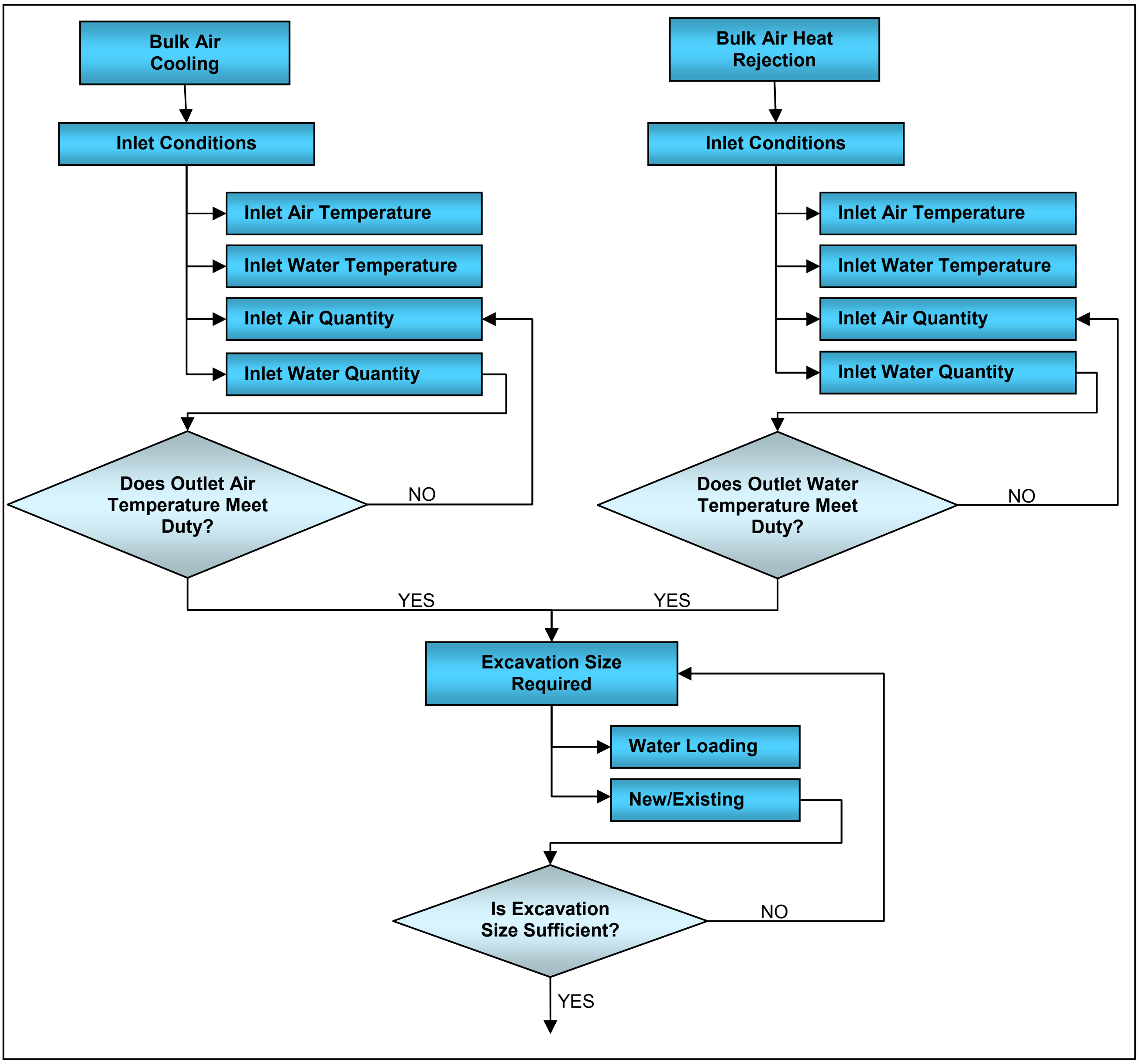

Figure 5.5: Inlet Conditions and Water Loading

5.6 Step 6: Environmental Conditions

Air and water quality are components to evaluate when designing heat exchangers. Both parameters will impact on the frequency of maintenance and inputs to these systems need to be known. Figure 5.6 lists items that need to be considered during the design process.

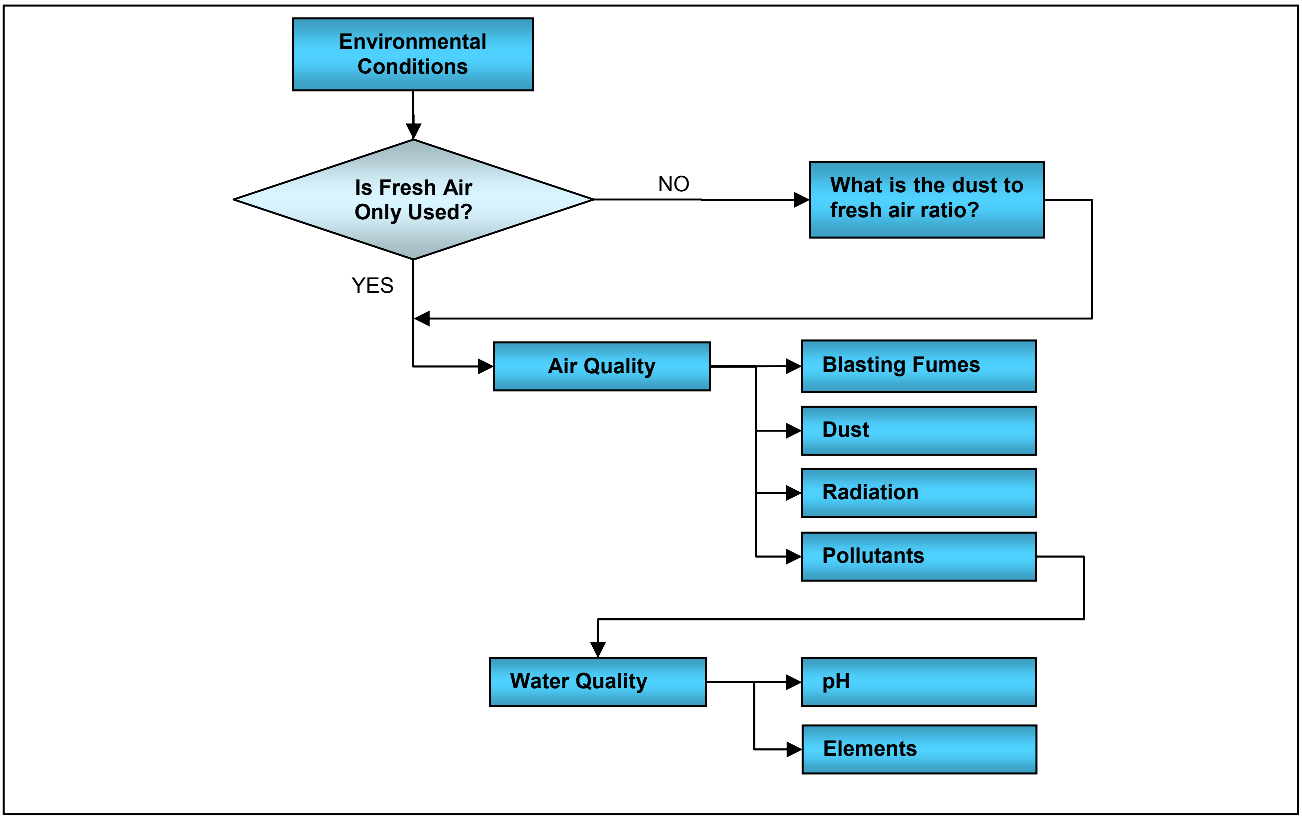

Figure 5.6: Environmental Conditions

During the design process the quality of the air that will be used needs to be investigated. In the event that fresh air is used, no problem should be anticipated. When air is re-used from certain working areas the quality of the air needs to be investigated in terms of blasting fumes, dust, radiation and other pollutant in order to accurately determine the factors influencing the heat exchanger design as listed in section 3.7. These factors will impact on technical requirements of the heat exchangers in terms of conductivity of the water, blow down rate, maintenance and cleaning frequency, make-up water rate, equipment selection, etc. (Chapter 4).

The quality of water needs to be identified as this will also impact on the technical requirements listed above. These requirements will be dependent on the pH of the water and the elemental composition in the water.

5.7 Step 7: Rock Mechanics and Surrounding Activities

The position of heat exchanger(s) is dependent on the stability of the ground and must be verified by a Rock Engineer. (Figure 5.7).

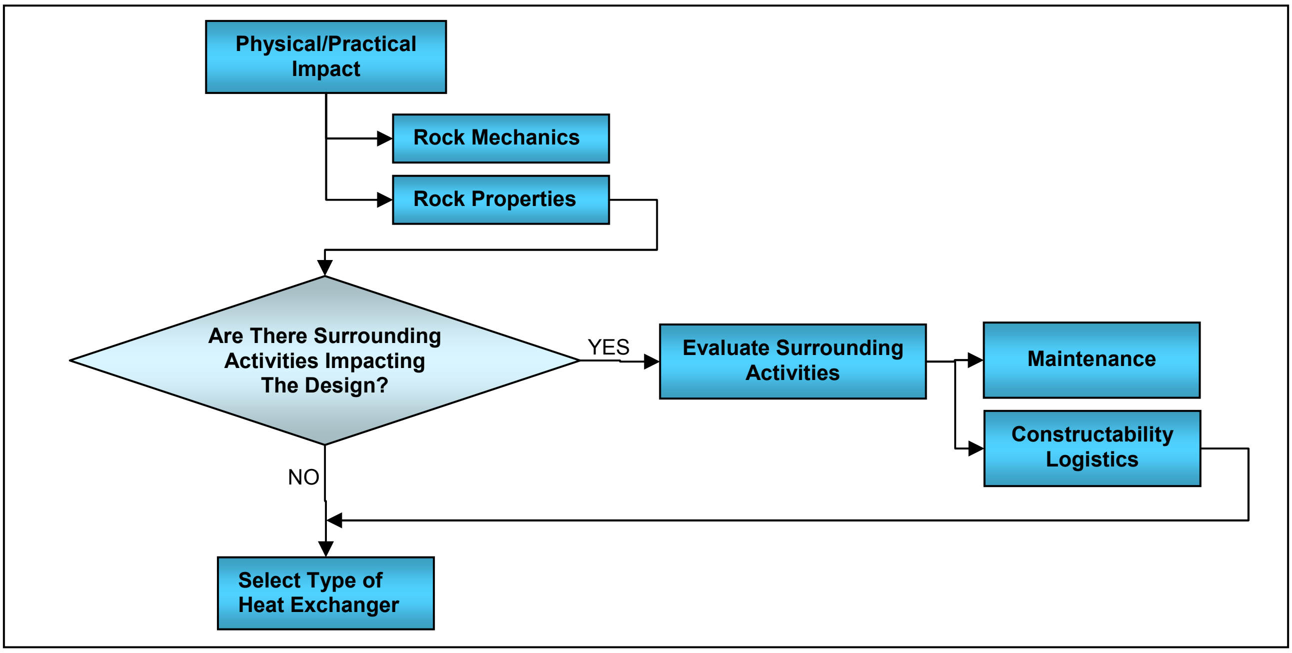

Figure 5.7: Rock Mechanics and Surrounding Activities

Surrounding activities include maintenance frequencies and need to be determined based on the quality of the air and water, type of equipment material and equipment life. In addition, constructability logistics include all activities involving installing the equipment from shaft time, crane installation to off-load equipment to actually commissioning the process system. A constructability manager is usually appointed for this purpose.

5.8 Step 8: Types of Bulk Air Heat Exchangers

In this step the type of heat exchanger will be determined. As mentioned in section 4.1 for air coolers, indirect-contact heat exchangers, spray towers and spray chambers are available to cool the air. Heat rejection can be achieved in spray towers and spray chambers. The type of heat exchanger can be selected with the assistance of section 4.3. Banks of indirect-contact heat exchangers will mainly be used in closed-circuit systems in clean air.

Section 4.4.1 established that for indirect-contact heat exchangers two design options exist, namely the log-mean temperature difference (LMTD) method and the number of transfer units (NTU) method. For direct-contact (open-circuit) heat exchangers, spray towers and spray chambers are possible options. Spray towers are classified under filled or unpacked units and the selection under each type is unique. Spray chambers design process together with spray towers and indirect-contact heat exchangers are discussed in a decision process is shown in Figure 5.8.

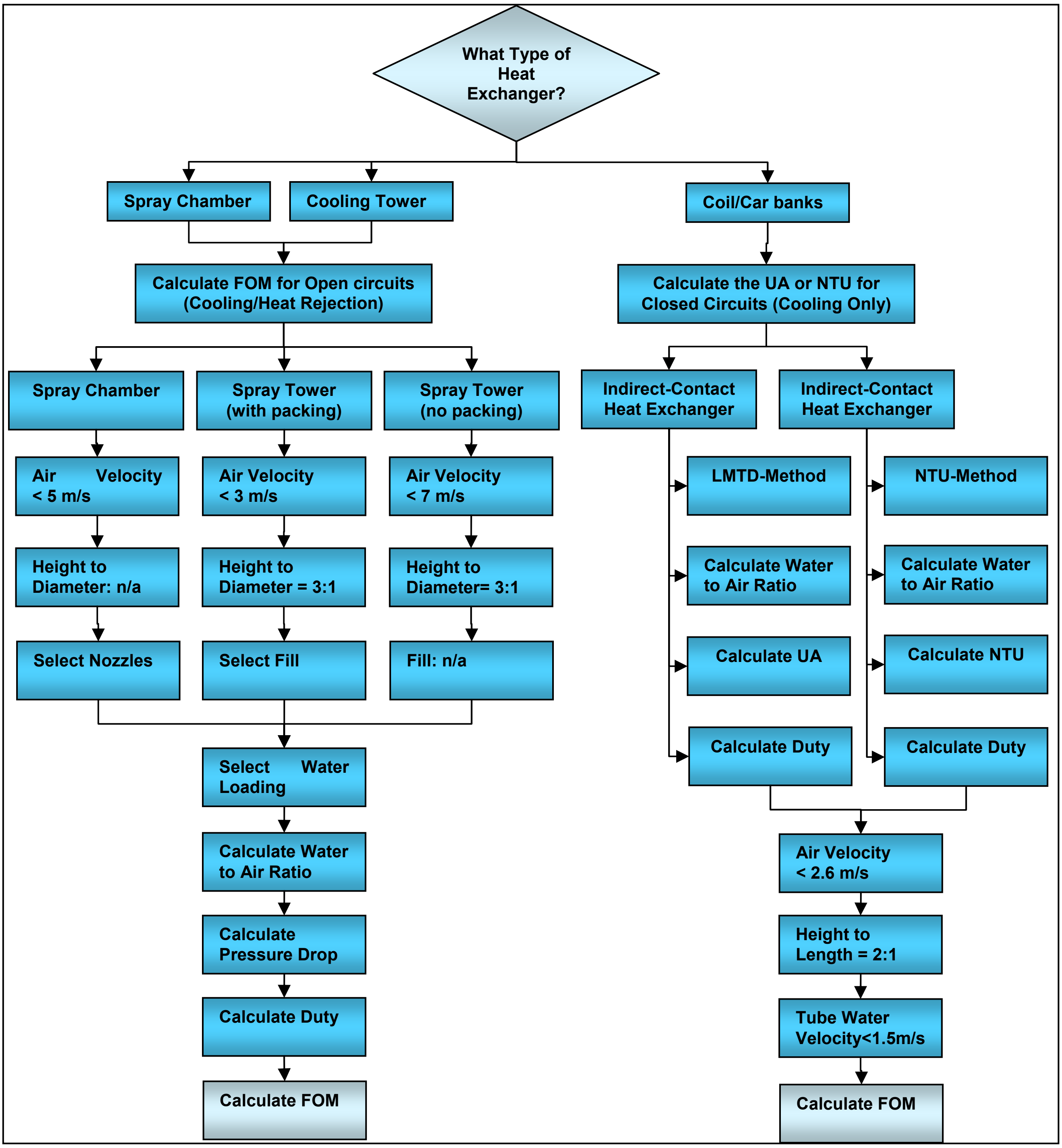

Figure 5.8: Type of Heat Exchangers

5.9 Step 9: Factor of Merit and Positional Efficiency

The Factor of Merit (FOM) and positional efficiency is one of the major contributors to the final heat exchanger type selection (Figure 5.9). As mentioned in sections 4.3 to 4.5, indirect-contact heat exchangers, spray towers and spray chamber heat exchangers can be selected for heat rejection and cooling.

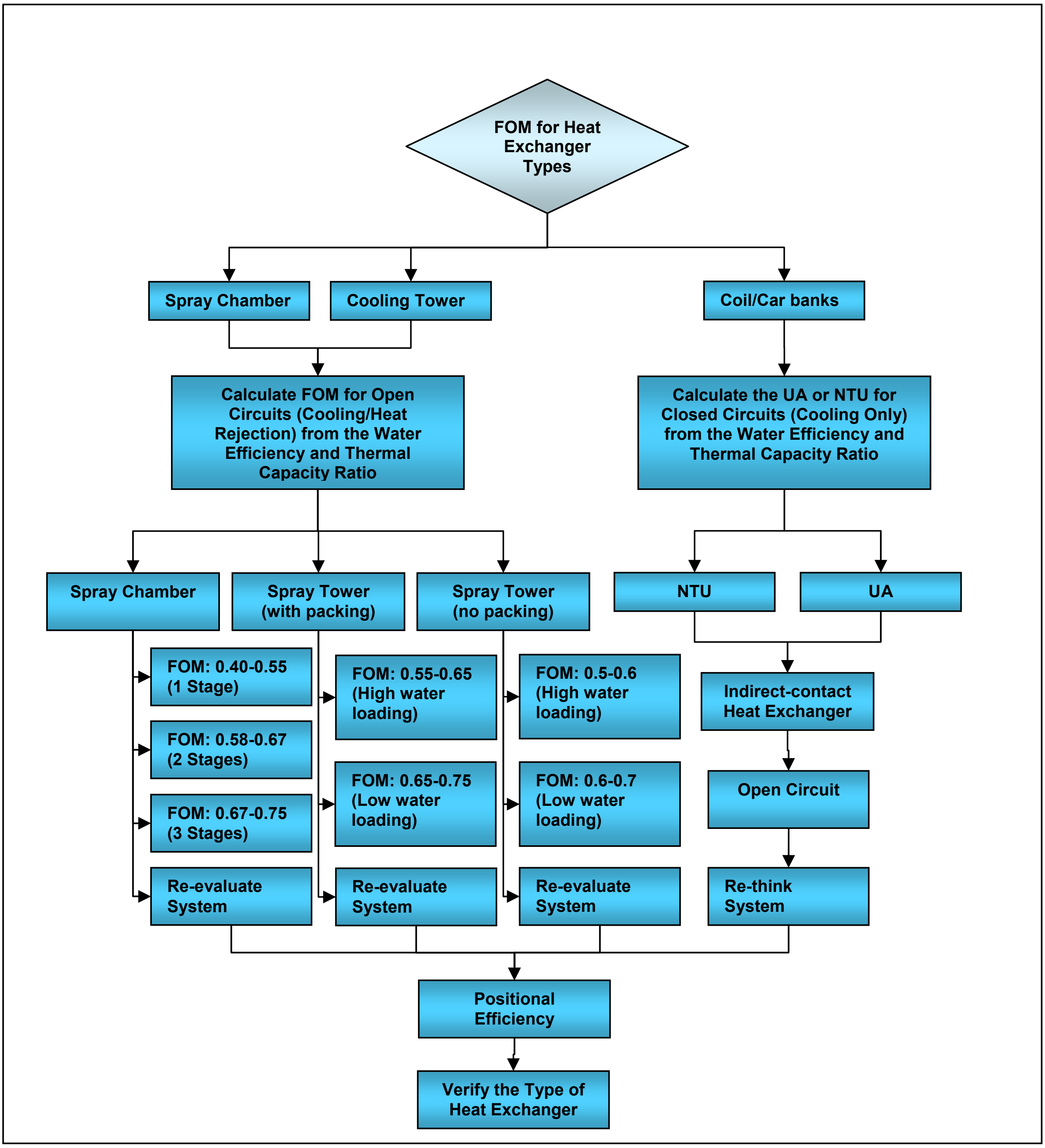

Figure 5.9: FOM of Heat Exchangers

The number of units, stages and/or cells will give an indication of the size of the excavation required to install the heat exchanger in. After this process, the heat exchanger type, location(s), quantities, air distribution, water distribution, etc. need to be verified to ensure that the correct unit will be installed. A number of other constraints are discussed below that might impact on the previously identified selection criteria.

5.10 Step 10: Water Reticulation System

The last step is the design of the water circuits between the refrigeration machine and heat exchangers. These routes need to be away from vehicles and other hazardous equipment and conditions. The hydraulic design process for closed-circuit and open-circuit heat exchangers are shown in Figure 5.10.

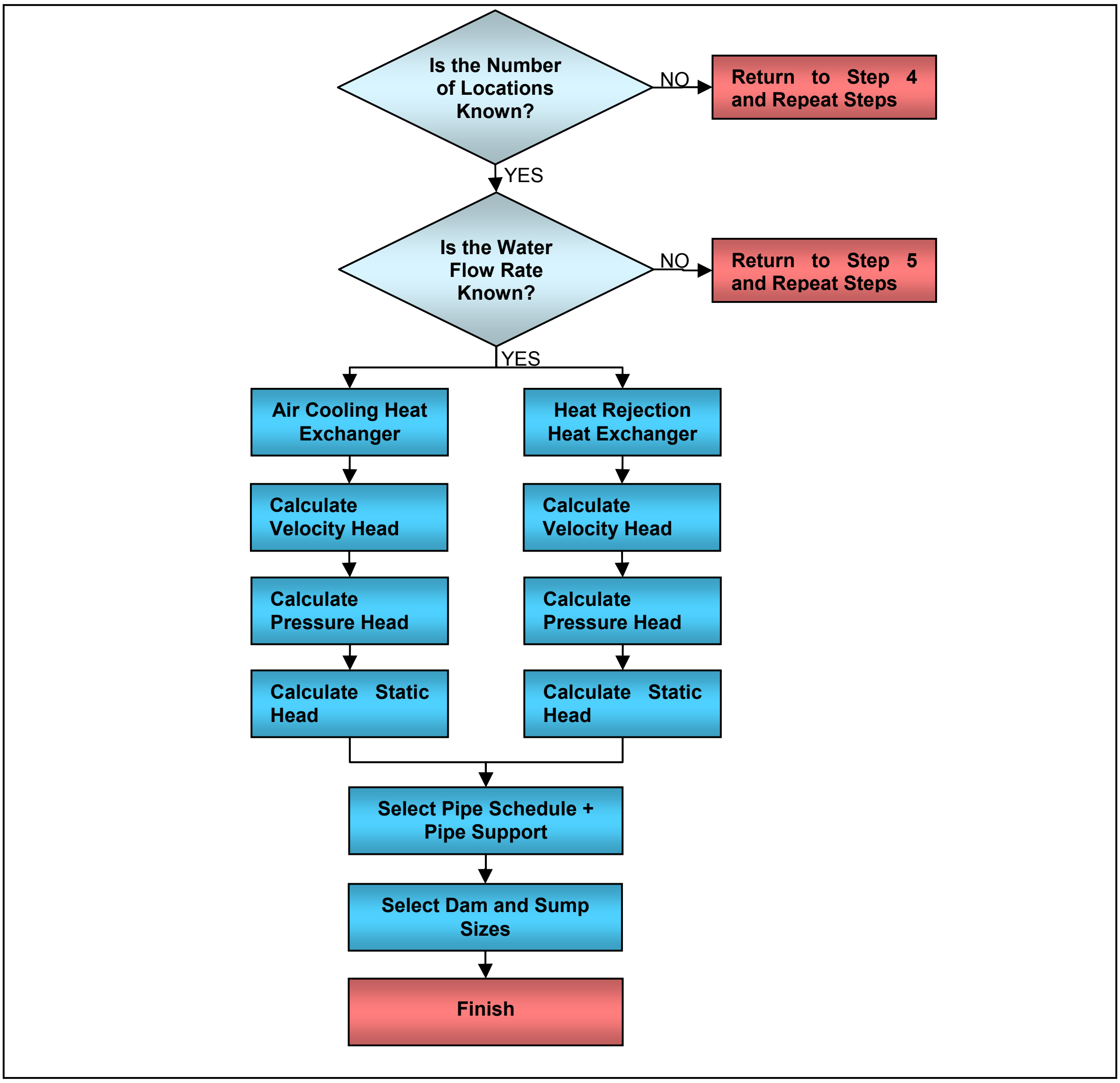

Figure 5.10: Water reticulation system Design

5.11 Conclusion

This Chapter provided a step-by-step guide of all items contributing to underground bulk air heat exchanger technical specifications. This guide was generated from environmental factors (including thermal design criteria, heat loads, excavation requirements, environmental conditions, rock mechanics) and engineering and technical requirements (including types of heat exchangers, factor of merit, hydraulics) that were described in detail in Chapters 3 and 4.

The step-by-step guide makes it possible to design a quick and easy fit-for-purpose underground heat exchanger technical specification. This specification can be sent to manufacturers and construction companies to design optimised ‘for-construction’ heat exchangers.

These steps will be applied to a case study in Chapter 6. The design process of an underground air cooler and heat rejection unit will be tested against this step-by-step guideline to determine whether the designs were optimised.

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Bluhm, SJ, 1981, *Heat transfer characteristics of direct-contact crossflow spray chambers*, MSc Dissertation, University of Witwatersrand.

‘Horizontal spray-chambers for cooling ventilation air underground’ 1983, *Chamber of mines research organisation.*

CHAPTER 6

CASE STUDY

6. CASE STUDY

An existing mine was used as a case study to apply and test the applicability of the decision analyses process developed during this study. This was done by comparing the actual technical specifications of a newly constructed underground BAC system with the guidelines produced using the decision analyses process. This study focused on underground refrigeration plants and large heat exchangers; hence a similar case study was chosen to test the decision analyses process.

The selected case study for this Project is an application in a hard rock mine in South Africa (hereafter 'The Mine'). Chapter 2 motivated that this study is required to assist mine operational engineers to improve bulk air heat exchanger specifications before the design and construction phases are commenced. Operational and site specific factors impacting heat exchanger design was described in Chapter 3 followed by technical requirements in Chapter 4. A step-by-step decision/guideline process was developed in Chapter 5 to assist operational engineers to specify optimized underground heat exchangers. Chapter 5 guideline process and design principles and recommendations from Chapters 3 and 4 were applied to test the decision analyses process against an existing design.

6.1 Mine Background

The Mine currently operates an underground block-cave operation, producing approximately 12 million tons ore per year on a FULCO (full calendar operations) basis. The Mine supplies most of South Africa's copper requirements and exports the remainder. Copper is domestically used for cast rods and internationally for cathodes. Small amounts of by-products like zirconium, magnetite, nickel sulphate, gold, silver and platinum are also produced.

Block cave operations generally have five levels per production block, namely Undercut Level (preparation of the caving process), Production Level (ore extraction from draw-points and delivery to ore passes), Conveying Level (transport from ore passes to main shaft by belt conveyor, rail or truck) and intake and return ventilation levels (Von Glehn et al. 2006).

Rock from the loading crosscuts on Production Level is tipped into crushers that service three to five crosscuts. Crushers are mainly installed underground to reduce the rock size handled by conveyor belts (used in this mine). Conveyor belts transport the crushed rock to the shaft from where it is hoisted to surface.

Existing Cooling and Ventilation Infrastructure

Cooling for The Mine's current mining operations are achieved from a surface refrigeration system and surface BAC. Air is circulated through The Mine by a main fan station situated on top of a dedicated Ventilation Shaft.

Intake air is cooled on surface, flows down the intake shaft system (Services and Production Shaft) and then to the intake side of the block cave operation. Some of this air is used to ventilate workshops, crushers and other services. A portion of the air is re-cooled in the new underground BAC. The design of this BAC was tested against the decision analyser steps. The bulk of the air drawn through The Mine flows through the block cave operation to a return air system and out of The Mine via the main fan station.

A bulk air CSC unit is installed in one of the return airways that reject the heat from the condenser heat exchangers situated in the underground plant room. This CSC will also be tested against the decision analysers.

A step-by-step process will be followed in the next few sections testing the theoretical principles summarised in the decision analysers (Chapter 5). This process will indicate whether the new underground BAC and condenser heat exchanger were specified optimally before design and construction took place.

6.2 Step 1 and 2: Thermal Design Criteria and Surface versus Underground Cooling

As described in Chapter 1, the ventilation engineer applies a mining-group or mine-specific workplace thermal criteria to determine at which time additional cooling is required. Predictions during mine design and actual ventilation surveys during mine operation generally determine the amount of air cooling required to meet thermal criteria. It is at this stage that cooling requirements are confirmed and that a cooling and heat rejection system specification process is applied.

Figure 6.2a starts the decision steps by requesting the thermal criteria of The Mine. Based on this criterion the temperature at the working areas can be determined calculation and/or simulation modelling. If the temperatures are too high the possibility of increasing the airflow in the area can be considered. If this does not suffice, a heat exchanger is required.

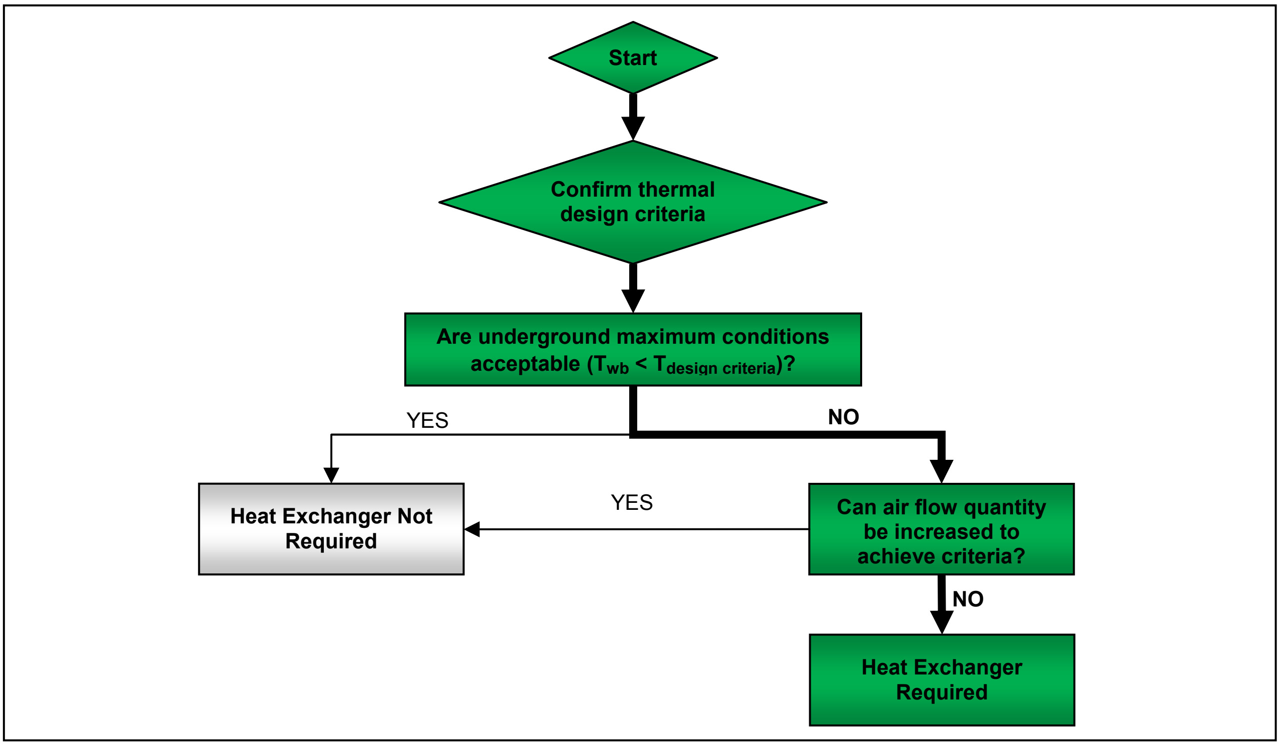

Figure 6.2a: Thermal Design Criteria

The first decision step (Figure 6.2a) determines whether cooling is required by investigating the design criteria of The Mine. Table 6.2a shows the results derived from The Mine to establish that a heat exchanger is required.

Table 6.2a: Step 1 – Thermal Design Criteria

Description	**Result**	**Remark(s)**
Thermal design criteria	Reject wet-bulb temperature below 27.5 °C	This is not achieved in the west of The Mine
Underground conditions	Above 27.5 °C (WB)	Not acceptable
Airflow quantity	Airflow at fans cannot be increased	Motor rated power is at its limit

Workplace temperatures exceeding 27.5 °C have been measured and a review of the ventilation system indicated that airflow velocities are already high and that the primary airflow quantity could not be increased hence the need for additional cooling. Additional air supply could have reduced the amount of cooling required.

At The Mine the station temperatures are just above 22 ˚C (WB) due to the surface BAC operation. It is therefore not practical to cool the air any more on surface. At the depth of the underground workings underground heat exchangers are generally considered (Figure 6.2b).

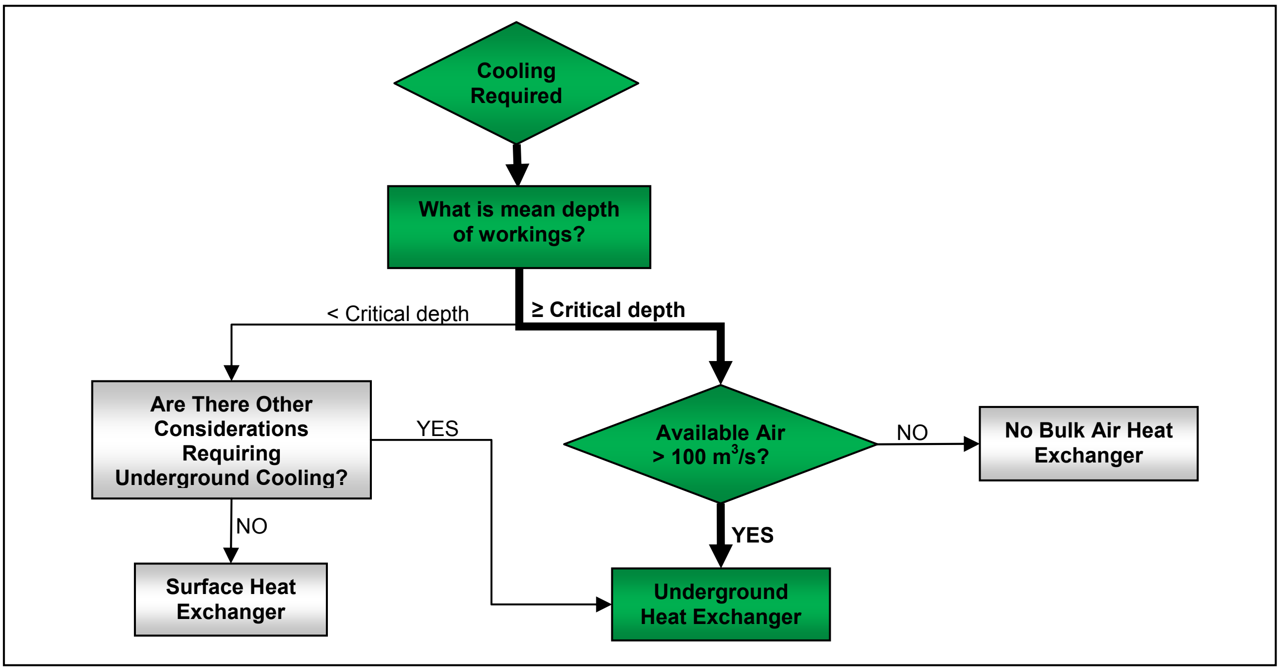

Figure 6.2b: Surface vs Underground Bulk Air Heat Exchanger

Now that cooling is required Table 6.2b shows the outcomes of The Mine to establish that an underground heat exchanger is required.

Table 6.2b: Step 2 – Surface vs Underground Heat Exchanger

Description	**Result**	**Remark(s)**
Critical depth	Mine is at the critical depth	Depth below 1000m and VRT above 55 °C.
Airflow	Airflow at working area is more than 100 m^3/s	Possible

Concluding these Steps, at this working depth the underground workplace conditions exceeded the thermal design criteria and considering alternatives the decision analyses process indicated that underground re-cooling would be the best solution. The Mine's decision to design and construct a new underground BAC and CSC is thus confirmed by the guideline.

6.3 Step 3: Underground Heat Load and Air Cooling Capacity

In Step 3 the decision analyses process is applied to specify underground bulk air cooling or heat rejection strategies. Figure 6.2b established that underground bulk air cooling is required due to mainly two aspects:

1. The surface BAC is delivering optimal conditions at the shaft stations,
2. There is enough (>100 m^3/s) airflow available. As a consequence a bulk air underground heat rejection unit will be required.

Next the underground heat load has to be determined as accurately as possible so the required cooling for underground mining operations can be determined. Contributions from all The Mine's heat sources must be taken into account as shown in Figure 6.3. The results are shown in Table 6.3 and detailed calculations can be viewed in Appendix A.

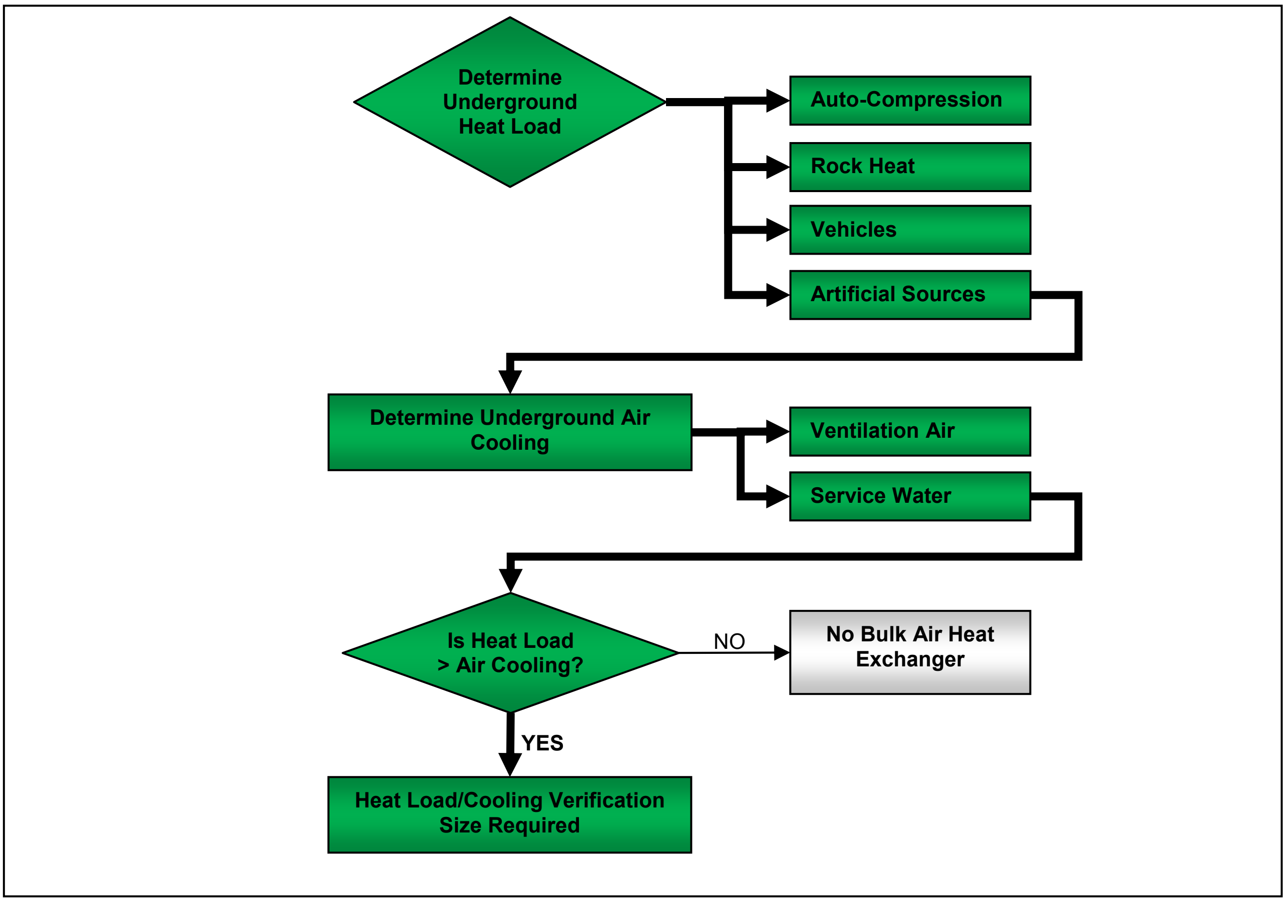

Figure 6.3: Underground Heat Load

Table 6.3: Summary of Heat Loads and Cooling Required

Description	Results	Remarks
Auto-compression	8 627 kW	Appendix A
General rock	591 kW	Appendix A
Production rock	651 kW	Appendix A
Broken rock	8 523 kW	Appendix A
Vehicles	4 056 kW	Appendix A
Services water	4 409 kW	Appendix A
Fissure water	2 204 kW	Appendix A
Auxiliary equipment	1 150 kW	Appendix A
TOTAL HEAT LOAD	**30 211 kW**	
Underground air cooling	27 200 kW	Service water and air cooling power
ADDITIONAL COOLING	**3 000 kW**	Underground cooling
Verification	VUMA3D-network	Any other software package can be used

Heat load predictions, using simulation software were calibrated for the existing mine as these parameters could be verified with thermal conditions. Manual calculation of the heat loads is difficult and tedious, and modern simulation software is used these days to calculate the heat loads. In this case VUMA3D-network was used to determine the heat load and associated cooling requirement.

In summary, the total heat load minus the natural air cooling power of the air amounts to about 30 200 kW (Table 6.3). About 27 200 kW of this heat is dissipated by the cooling power of the ventilation air and the surface BAC, the remaining 3 000 kW has to be removed by the underground BAC. The design specification by The Mine of 3000 kW has thus been confirmed as correct.

6.4 Step 4: Excavation Size and Location

This step investigates the available options for air cooler and/or heat rejection units as shown in Figure 6.4. A large bulk air cooling and heat rejection heat exchangers were installed.

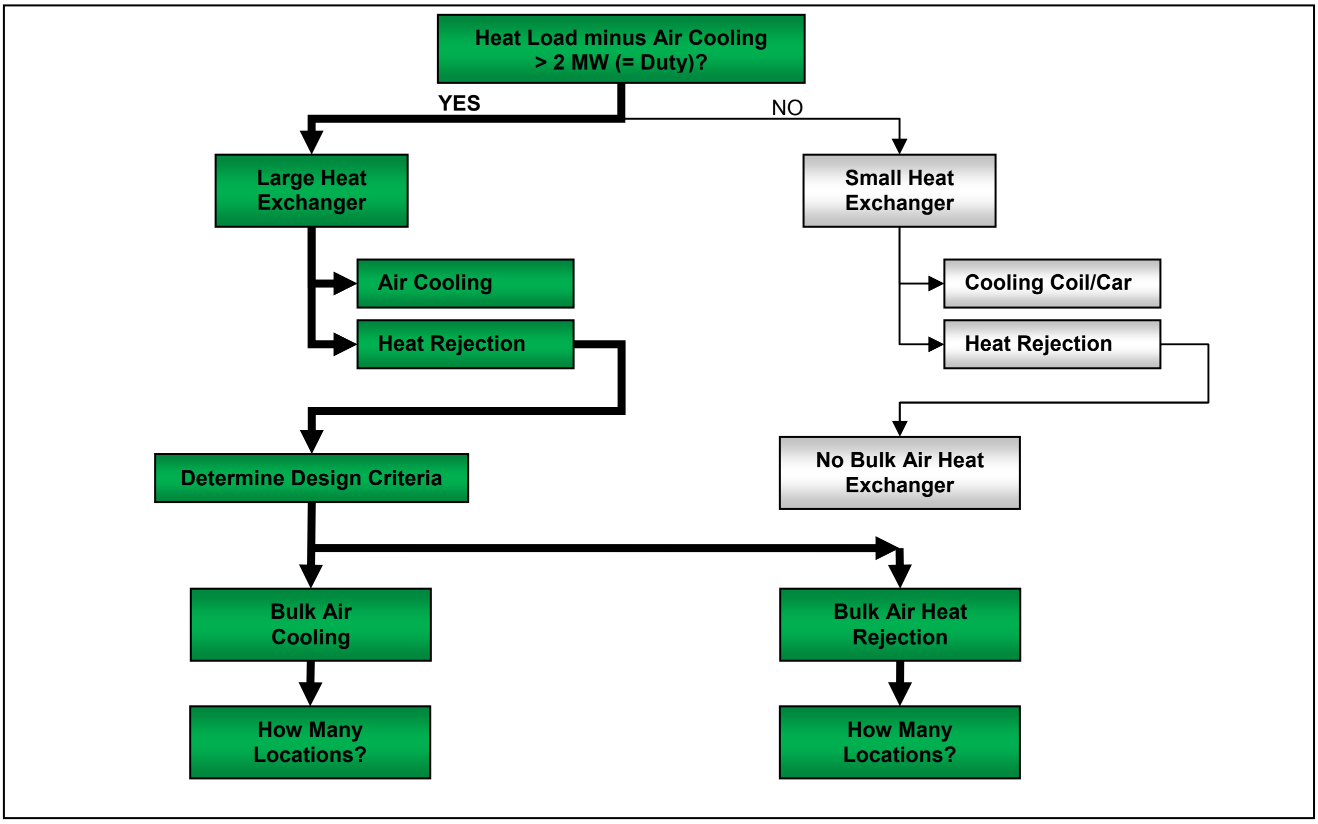

Figure 6.4: Heat Exchanger Locations

Table 6.4 shows the outcomes of The Mine to establish the underground heat exchanger locations.

Table 6.4: Step 4 – Heat Exchanger Locations

Description	**Results**	**Remark(s)**
Large heat exchanger	Airflow above 100 m^3/s for air cooler and heat rejection unit	No small heat exchangers (<2000 kW) will be used.
Thermal criteria	Using the air cooler provided adequate thermal conditions	Satisfied
Bulk air cooler	One location required	New excavation
Heat rejection units	One location required	Existing excavation

During the decision analyses process the operational engineer needs to establish whether available tunnel sizes are sufficient for the required heat transfer. The simulation model indicated that the 3 000 kW can be effectively applied in its current position to achieve the thermal design criteria. The decision process in Figure 6.4 is assumed to have been followed successfully.

6.5 Step 5: Inlet Conditions and Water Loading

Air inlet conditions to the heat exchanger will influence the specification. For air coolers the outlet air temperature needs to be within a minimum allowable air temperature of The Mine (typically >18 °C (WB)). Figures 6.5a and 6.5b show the process to consider water loading based on inlet conditions for the BAC and CSC respectively.

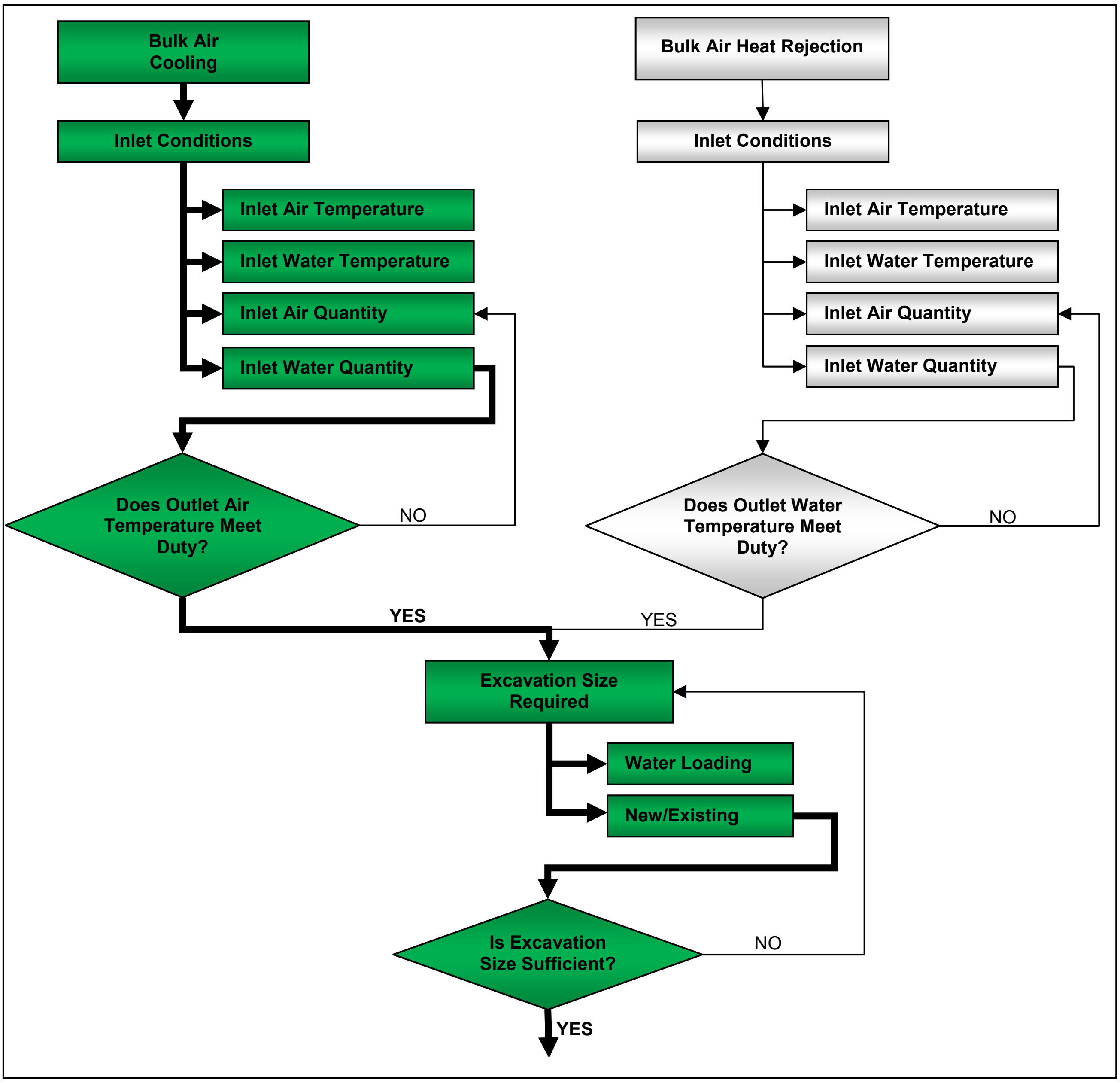

Figure 6.5a: BAC Inlet Conditions and Water Loading

Table 6.5a shows the application of Figure 6.5a for the air cooler. The data received to arrive at these results was obtained from measurements on The Mine.

Table 6.5a: Step 5 – Air Cooler Inlet Conditions and Water Loading

Description	**Results**	**Remark(s)**
Inlet conditions	Inlet air temperature: 23.9/32.3 °C (WB/DB) Inlet water temperature: 12 °C Inlet air quantity: 160 kg/s (each) Inlet water quantity: 40 l/s (each)	From available mine information and equipment suppliers
Outlet air temperature	Outlet air temperature: 21.0/21.0 °C (WB/DB)	Acceptable
Excavation size	5.5 m(H) X 5.5 m(W) X 25 m(L)	Acceptable
Water loading	0.5 l/m^3	Acceptable
New/existing excavation	New	Sufficient

The new underground BAC installation will be at one location in a tee configuration as shown in Figure 6.8b. The water side duty is calculated after which the outlet air temperature is calculated to ensure that it meets the thermal criteria of The Mine and minimum allowable air temperature. The size of the new BAC excavation is sufficient as the air velocity remains below 5 m/s and shows that the guideline in Figure 6.5a is satisfied.

Table 6.5b shows the application of Figure 6.5b for a heat rejection heat exchanger and the data shown was acquired from The Mine.

Table 6.5b: Step 5 – Heat Rejection Inlet Conditions and Water Loading

Description	**Results**	**Remark(s)**
Inlet conditions	Inlet air temperature: 30.2/35.5 °C (WB/DB) Inlet water temperature: 39.2 °C Inlet air quantity: 300 kg/s Inlet water quantity: 150 l/s	From available mine information and equipment suppliers
Outlet water temperature	Outlet water temperature: 35 °C	Acceptable
Excavation size	5.5 m(H) X 5.5 m(W) X 60 m(L)	Acceptable
Water loading	1.0 l/m^3	Acceptable
New/existing excavation	Existing	Sufficient

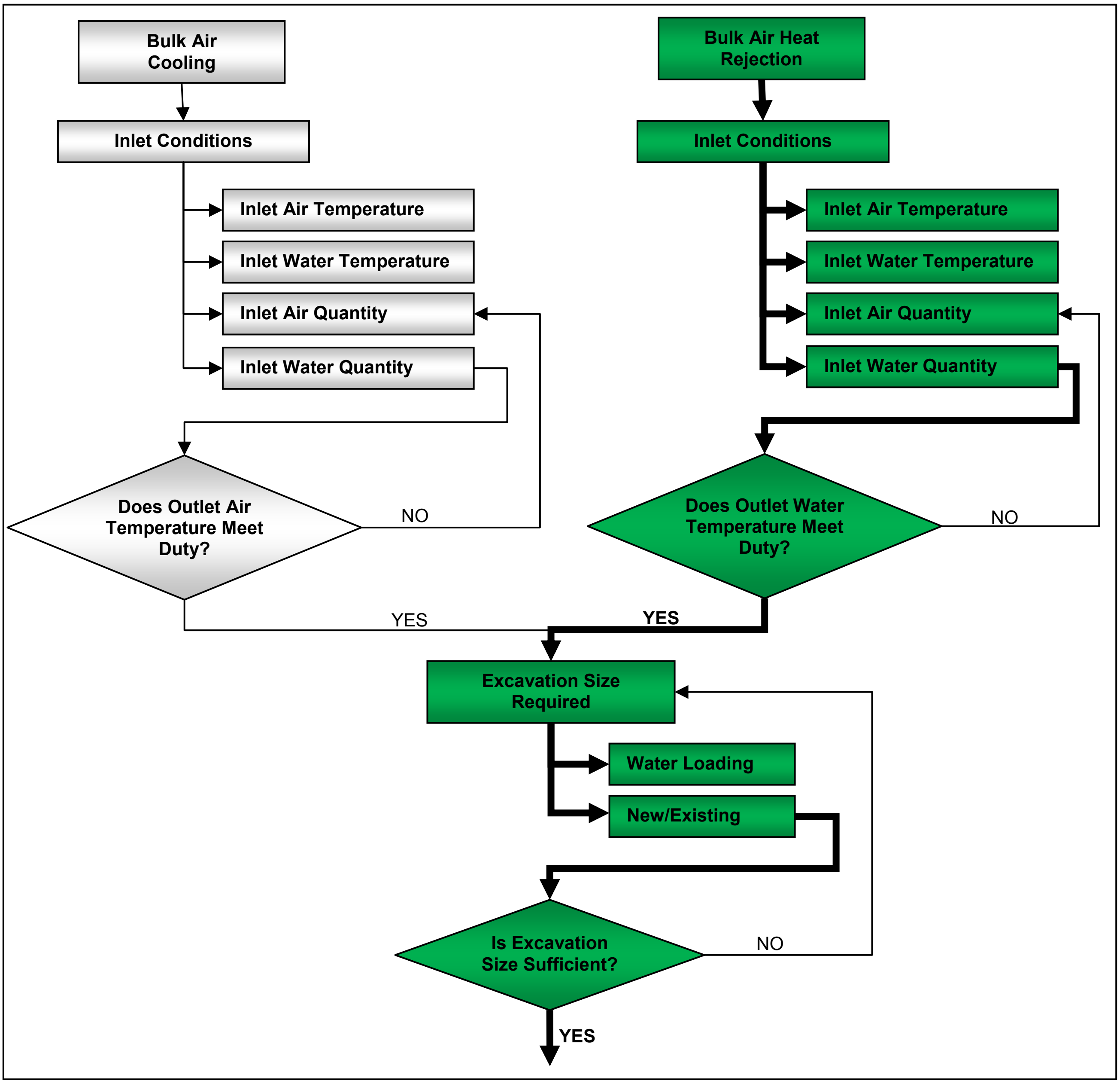

Figure 6.5b: CSC Inlet Conditions and Water Loading

The underground bulk air heat exchanger consists of one CSC as shown in Table 6.5b. The water side duty is calculated to determine the outlet water temperature of the unit to ensure that the refrigeration machine can achieve its duty and that the heat rejection can be effectively tolerated by the condenser heat exchanger. The size of the CSC excavation is adequate as the area and length available in the existing tunnel provides enough fall-out for water droplets.

Figures 6.5a and 6.5b show that the guidelines can be applied successfully to determine the inlet conditions and water loading of heat exchangers.

6.6 Step 6: Environmental Conditions

Underground environmental conditions include air and water quality impacting on heat exchanger designs, material selection and maintenance schedules. The sixth step shows the process to follow to ensure that all the relevant air quality conditions are catered for.

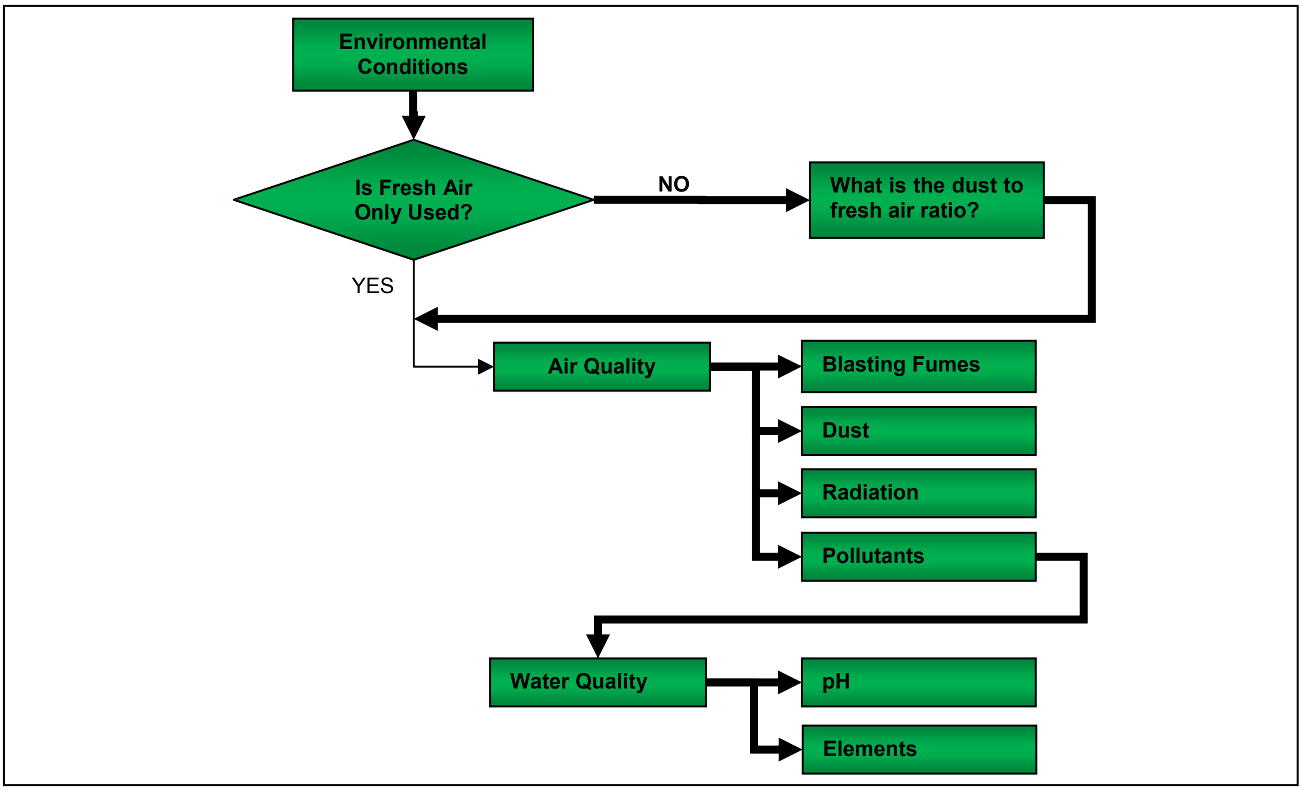

Figure 6.6: Environmental Conditions

Figure 6.6 shows that fresh air only will not be used in the heat exchangers. The re-use ventilation air calculations for the BAC can be viewed in Appendix B and the results are shown in Table 6.6. Air and water quality results obtained from The Mine can also be viewed in Appendix B and a summary of the results in Table 6.6.

Table 6.6: Step 6 – Environmental Conditions

Description	**Results forAir Cooler**	**Results for Heat Rejection**	**Remark(s)**
Fresh air only	Re-use air from conveyor belt and crushers	Return air	Appendix B
Dust to fresh air ratio	3.6 mg/m^3 :60 m^3/s	n/a	Appendix B
Blasting fumes	Negligible	Present	-
Dust	3.6 mg/m^3	Not available	Appendix B
Radiation	1.1 mSv/annum	Not available	Appendix B
Pollutants	Below Time Weighted Average (TWA)	Not available	Appendix B
pH	7.2	7.2	Appendix B
Elements	Below TWA	Not available	Appendix B

Applying the decision analyser shown in Figure 6.6 to information shown in Table 6.6 then proves that this decision step was successful.

6.7 Step 7: Rock Mechanics and Surrounding Activities

The new BACs are located in new excavations that had to be developed and the CSC is located in an available excavation. Rock mechanics properties play a vital role in the physical location of heat exchangers and the stability of the ground needs to be verified with Rock Engineers. The decision analyser in Figure 6.7 also shows that surrounding activities need to be investigated to ensure that construction personnel are safe at all times. These activities will also provide a good indication of the required maintenance schedules.

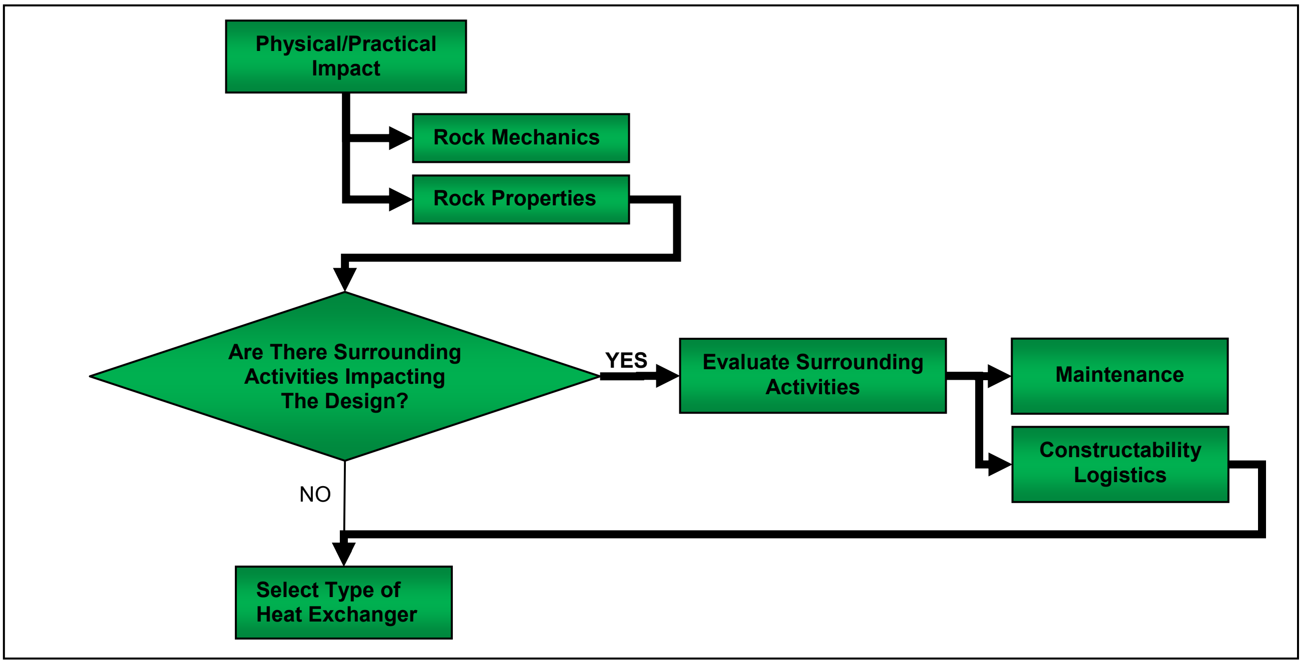

Figure 6.7: Rock Mechanics and Surrounding Activities

Table 6.7 shows the rock mechanic feedback and surrounding activities results received from The Mine to establish this decision analyser.

Table 6.7: Step 7 – Rock Mechanics and Surrounding Activities

Description	Results for Air Cooler	Results for Heat Rejection	Remark(s)
Rock mechanics	Sufficient	Sufficient	Verified with engineers
Rock properties	Sufficient	Sufficient	Verified with engineers
Surrounding activities	Blasting and pollutants	Blasting and pollutants	Dilution by ventilation
Maintenance	Water treatment	Water treatment	-
Constructability logistics	In fresh air	In return air, access limited	-
Verify type of heat exchanger	Verified	Verified	-

Table 6.6 shows data received from The Mine that indicates that both the new BAC and CSC will be installed in suitable excavations. The installation and maintenance of these heat exchangers will be in adequate environments. It can therefore be assumed that the decision analyser process has been satisfied.

6.8 Step 8: Types of Bulk Air Heat Exchangers

Large bulk air heat exchangers including spray chambers, towers and indirect-contact coil banks was considered for this study. For the air cooler indirect-contact heat exchangers were not possible as the overall total owning cost was more expensive due to high pressure pipes. Cooling towers were not possible as no vertical space is available between levels at The Mine. For the heat rejection unit a cooling tower was not possible as there is no access to the Ventilation Shafts. For the air cooler and heat rejection units, horizontal spray chambers will be used.

Technical requirements for both air cooler and heat rejection unit will be determined with the assistance of the decision analyser shown in Figure 6.8a. Figure 6.8b shows a layout of the air cooler spray chamber.

Table 6.8 shows the selected equipment and criteria used as stipulated in Figure 6.8a.

Table 6.8: Step 8 – Spray Chamber Heat Exchangers

Description	Result – Air Cooler	Result – Heat Rejection	Remark(s)
Air velocity	5 m/s	7 m/s	Acceptable
Height to Diameter	n/a	n/a	-
Nozzles	200 kPa	200 kPa	Standard selection
Water loading	0.5 l/m^3	1.0 l/m^3	Acceptable
Water to air ratio	0.3 l/m^3	0.4 l/m^3	Acceptable
Pressure drop	300 kPa	300 kPa	Acceptable
Duty	3 000 kW	4 500 kW	Acceptable
FOM	-	-	Section 6.9

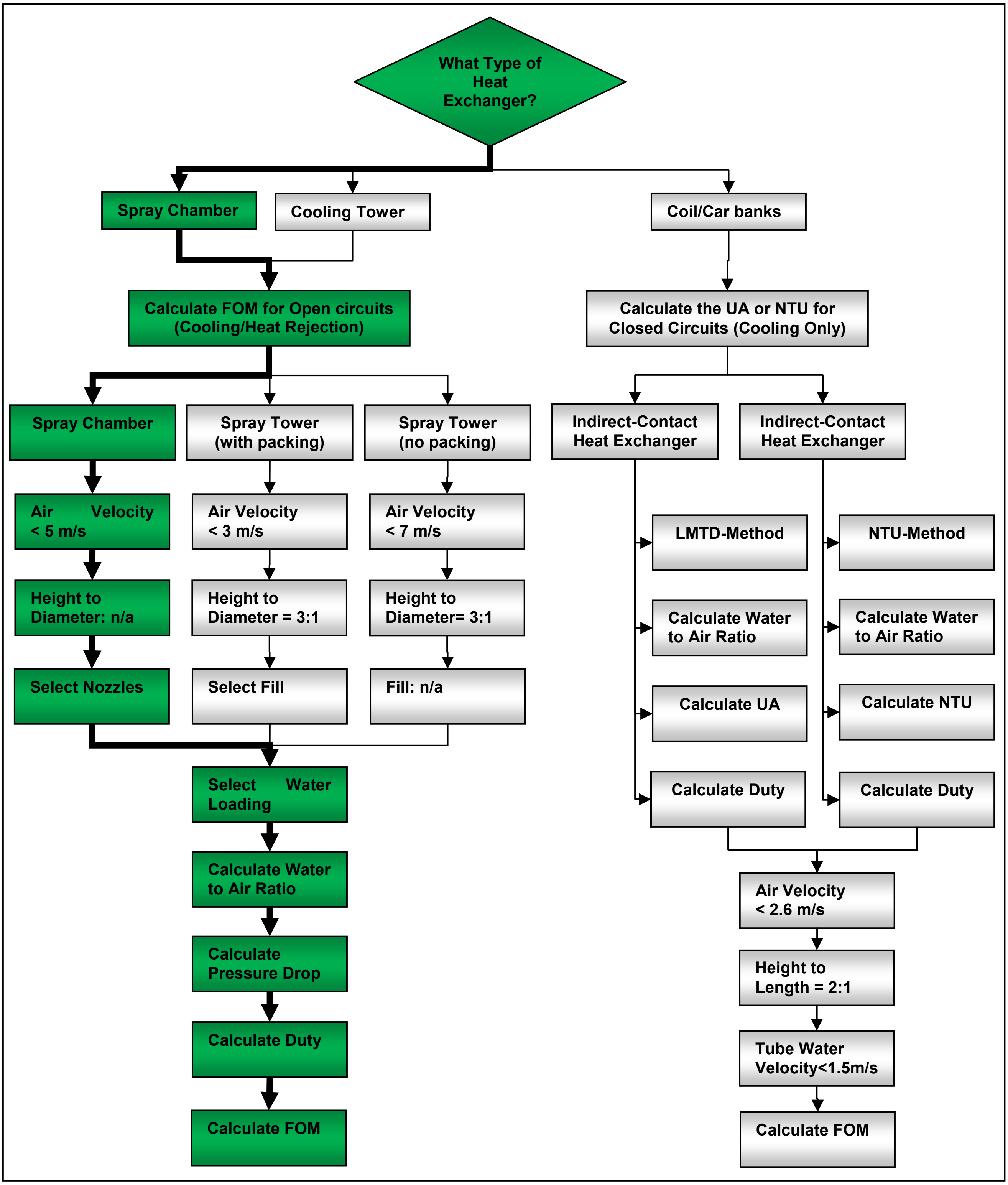

Figure 6.8a: Heat Exchanger

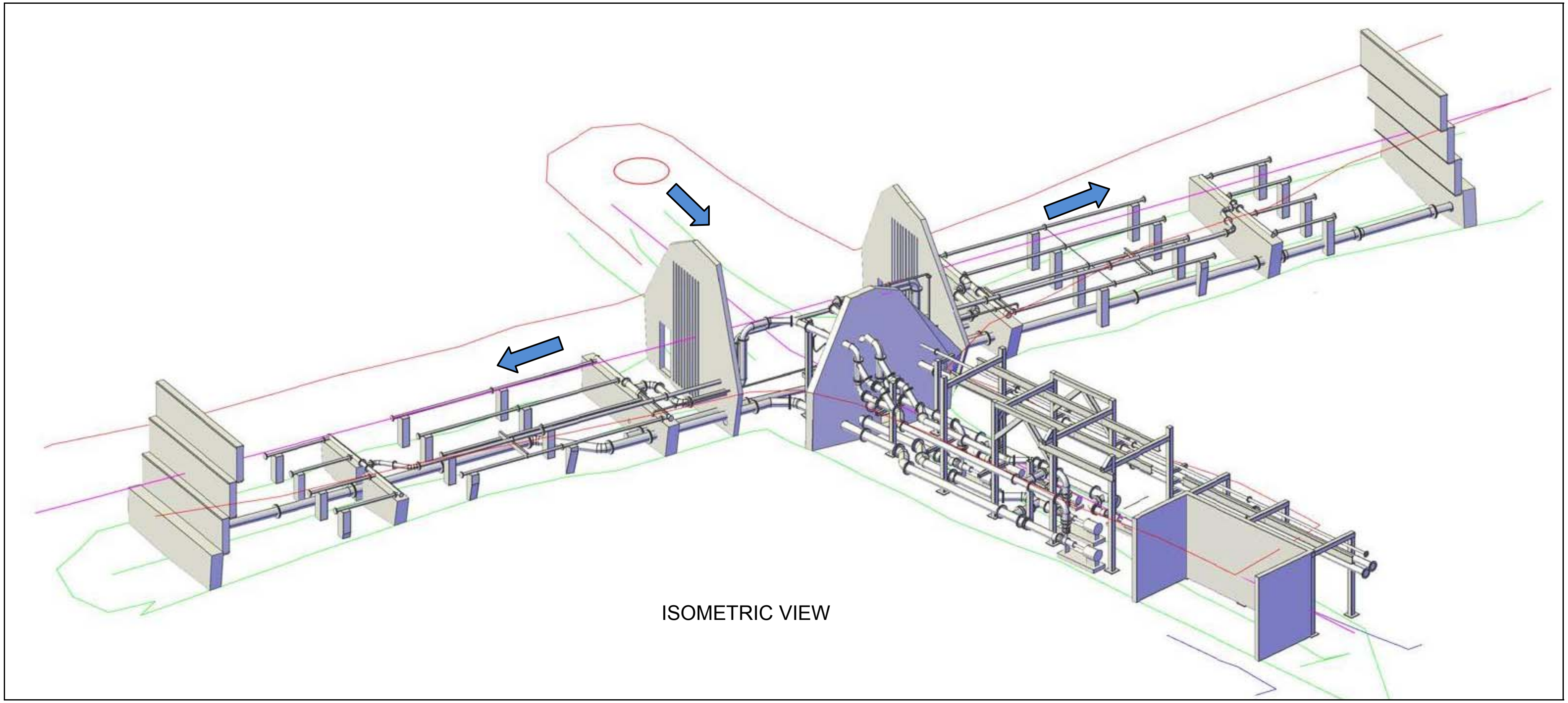

Figure 6.8b: Two-stage horizontal spray chamber

Table 6.8 and Figure 6.8b show that the decision analyser is satisfied.

6.9 Step 9: Factor of Merit and Positional Efficiency

In this step the Factor Of Merit (FOM) and positional efficiency are determined. The decision process in Figure 6.9 was used to calculate the FOM. The calculations are shown in Appendix C and a summary of the results are:

- BAC FOM = 0.6
- CSC FOM = 0.58

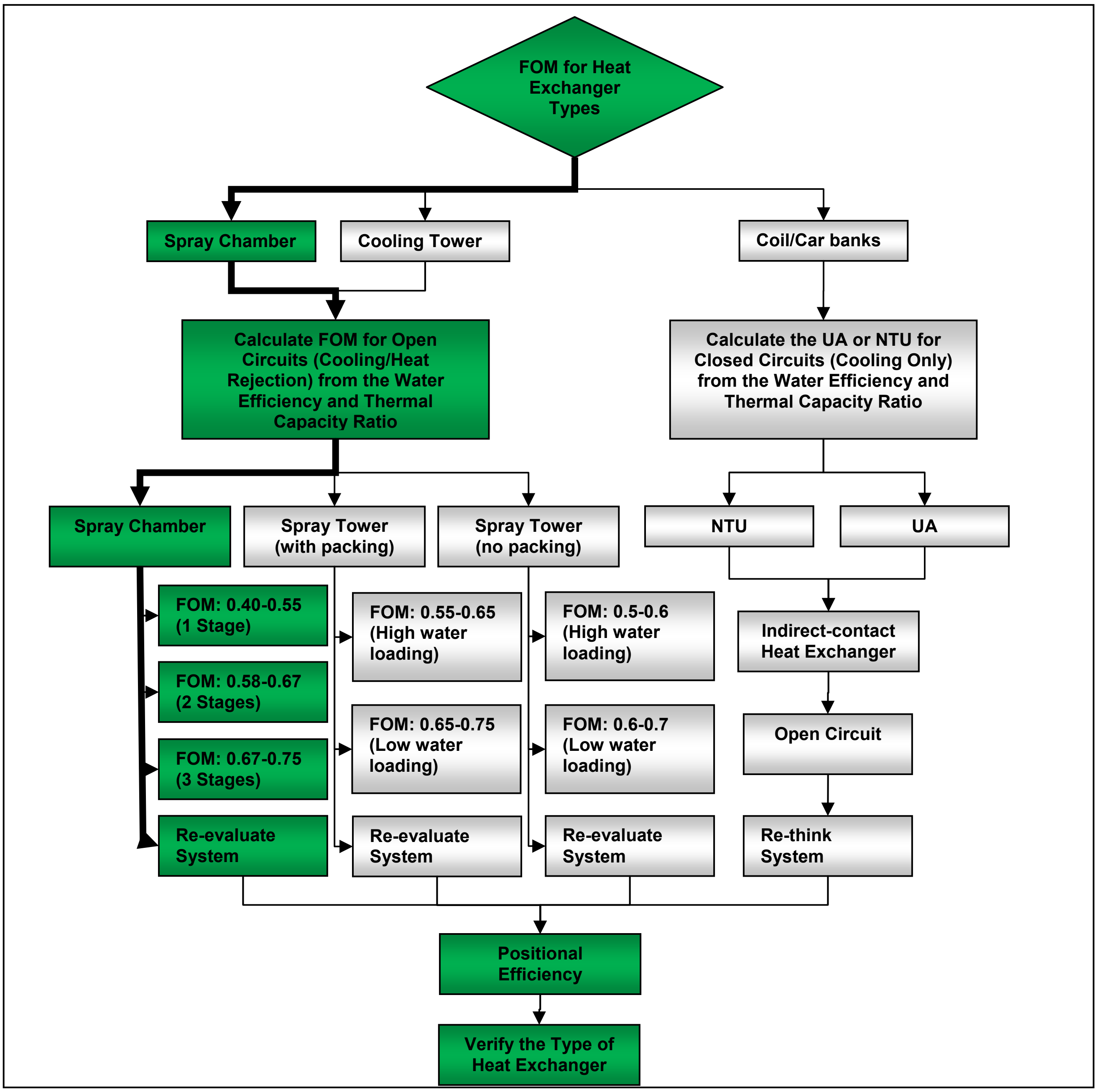

Figure 6.9: FOM of Heat Exchangers

The calculated FOMs compare well with the FOMs displayed in Figure 6.9. It can therefore be confirmed that the decision analyser was applied successfully.

6.10 Step 10: Water Reticulation System

Now that the number of heat exchanger locations and water flow rates to each are known, the water reticulation system for each can be determined as shown in Figure 6.10.

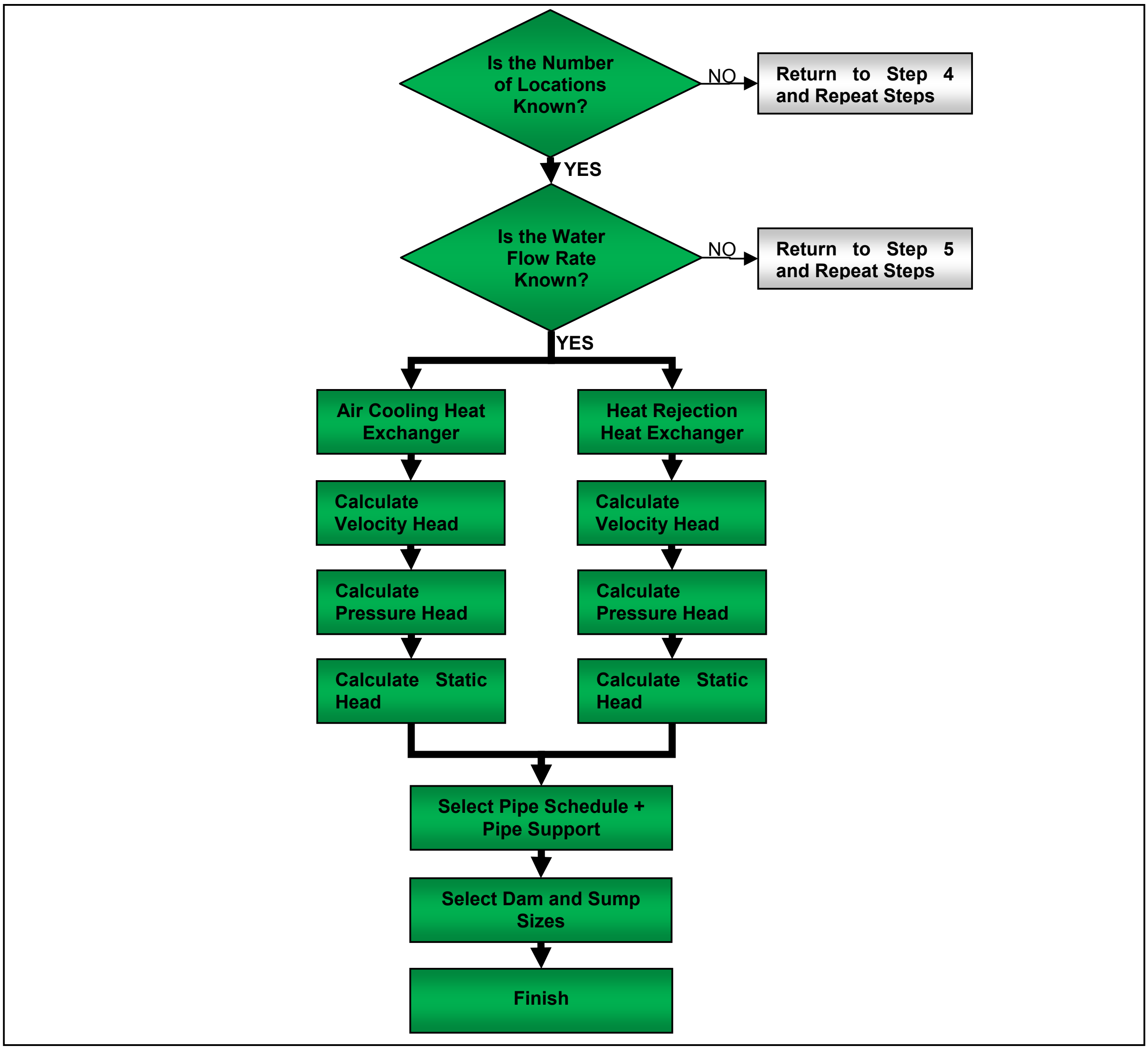

Figure 6.10: Water Reticulation System Design

Table 6.10 shows the results of The Mine to establish the water reticulation system design. The items listed in Figure 6.10 were calculated from information gathered from The Mine in terms of elevation differences and preferred equipment selection that contribute a certain pressure loss.

Table 6.10: Step 10 – Water Reticulation System

Description	**Results for Air Cooler**	**Results for Heat Rejection**	**Remark(s)**
Locations	Known	Known	Acceptable
Water flow rate	Known	Known	Acceptable
Velocity head	10 m	15 m	Calculated
Pressure head	10 m	4 m	Acceptable
Static head	10 m	0 m	Acceptable
Pipe schedule	Schedule 10	Schedule 10	Acceptable
Sump size	2 minutes	15 minutes	Acceptable

Figure 6.10 was therefore completed successfully with a summary of the results shown in Table 6.10.

6.11 Conclusion

In summary the comparison between an actual BAC and CSC design and construction and a specification from the decision analyses process has been very successful indicating the usefulness of the guideline process developed for this study. Again the overall aim was to facilitate operational engineers with a tool to quickly and easily specify fit-for-purpose heat exchangers to be designed and constructed by relevant design and construction parties.

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CHAPTER 7

CONCLUSION

7. CONCLUSION

This study takes a design engineer through the process of selection criteria that can be used to generate a technical specification for underground bulk air (>100 m^3/s) heat exchangers. These heat exchangers can either be air coolers where air is cooled or heat rejection units where hot condenser heat exchanger water is cooled.

The first objective of this study was to determine the need for the study (Chapter 2). It was found that many heat exchanger designs exist for direct-contact and indirect-contact water-to-air heat exchangers. It was however found that no single document exist summarising the selection criteria that would generate a technical specification. The criteria investigated in this study were used to generate optimised fit-for-purpose heat exchangers with the use of a quick step-by-step guideline of decision analysers.

The second objective of this decision guideline identified aspects that influenced the selection criteria for underground bulk air heat exchangers. The elements contributing to this design included identifying the thermal design criteria, the depth of the underground workings and to establish whether the airflow at a specific warm area in the mine could be increased. If this was not possible an underground heat exchanger was required. In addition, the overall heat load and cooling provided from the ventilation was also determined.

Thereafter the locations (new and/or old) of the heat exchangers were identified with the assistance of the rock engineers. The rock properties are important factors that influence the rock engineering design. This is to ensure that the excavation stand-up time is reliable.

The inlet conditions, water loading, surrounding activities and air and water quality of the heat exchangers were investigated as this will determine the required maintenance, schedules and efficiency of the heat exchanger(s). The information and formulas derived in Chapter 3 contributed successfully in achieving this objective.

The third objective investigated the engineering and technical requirements of direct-contact (spray towers and horizontal spray chambers) and indirect-contact (closed circuit coils) heat exchangers. The types of heat exchangers were studied in terms of size, number of units or stages, air and water velocities, thermal capacity ratios, water and air efficiencies, type of fill or nozzle, mist eliminators, factors of merit, positional efficiency, etc. Calculations for each criterion were listed in Chapter 4.

The fourth objective was to generate quick and easy decision steps in the form of flowchart diagrams for each of the factors impacting the design of heat exchangers and technical requirements identified. These decision analysers were compiled successfully in Chapter 5.

The fifth objective was to test the decision process against a case study that has been completed. Using the decision analyser flow charts assisted to prove the success of designs that were previously completed on a BAC chamber and condenser spray chamber. It was found that the design of the BAC was 60% efficient with a positional efficiency of 90%. The CSC was 58% efficient with a positional efficiency of 95%. These results were reliable as they could be confirmed with measured data as these heat exchangers exist on The Mine. More detail regarding the designs can be viewed in Chapter 6.

Finally, it can be concluded that this case study provided proof that the decision analysers can be used as a guideline when designing underground bulk air heat exchangers. The design process identified in this study can be used to optimally specify technical specifications of heat exchangers in order to be used by detail design engineers to generate 'for-construction' designs and drawings.

This study therefore met all objectives and will add value in the context of establishing design criteria for heat exchangers.

CHAPTER 8

RECOMMENDATIONS

8. RECOMMENDATIONS

This study enables ventilation and refrigeration design engineers with selection criteria to accurately design bulk air heat exchangers for cooling or heat rejection. It was concluded that the criteria selected and evaluated were successfully used to design underground BACs and heat rejection facilities.

It is therefore recommended that the findings from this study be implemented in any mining environment where heat exchange strategies need to be employed. It is further suggested that all designs completed and/or verified by the criteria set in this study are complimented with best practice and personal experience.

CHAPTER 9

SUGGESTIONS FOR FURTHER WORK

9. SUGGESTIONS FOR FURTHER WORK

Additional work that could be completed after this study includes the following:

1. This study can further be improved with the assistance of other engineers that use these decision analysers during their designs. These designs can be complimented with detail designs from experienced manufacturers or design consultants. Results from constructed heat exchangers can then be used to improve this study.
2. This study investigated underground bulk air direct and indirect-contact heat exchangers. These heat exchanger options (spray tower, spray chamber and cooling coils) can be expanded to other alternatives that include underground ice makers, desiccant coolers, evaporative coolers, etc. to provide cooling underground.
3. This study used water-to-air heat exchangers from The Mine. It is suggested that alternative heat exchanger possibilities such as scrubbing dust, gasses and particulates be investigated and summarized as a lot of research has been completed on this matter. This will improve the reliability, life and maintenance schedules of the currently proposed designs.
4. This study used mist eliminators for BACs to capture water particles. Alternative capturing devices that are more cost effective and easier to install should be studied and/o designed and built.
5. One of the heat exchangers investigated in this study was an air cooling tower which utilise wired screens to evenly distribute water and air for heat transfer. Alternative distributions systems for underground can be investigated with low pressure losses.

APPENDICES

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APPENDIX A

APPENDIX A - HEAT LOAD CALCULATIONS

Detailed calculations referred to Chapter 6 are summarised below.

Heat Load

Auto-compression of downcast ventilation creates an increase in air temperature as a result of conversion of potential energy to enthalpy as it loses elevation. At The Mine the current surface main fans operate at a total duty of 680 m^3/s at 1.9 kPa (surface density is 1.08 kg/m^3).

$$\begin{aligned}\text{Auto - compression heat load} &= m_a \frac{9.79}{1000\text{m}} \frac{\text{kJ}}{\text{kg}} \\ &= 680 \frac{\text{m}^3}{\text{s}} * 1.08 \frac{\text{kg}}{\text{m}^3} * 9.79 \frac{\text{kJ}}{\text{kg}} * \frac{1200\text{m}}{1000\text{m}} \qquad [\text{Aa}] \\ &= 8\,627 \text{ kW}\end{aligned}$$

Currently the only water supplied underground is for services. This heat load together with the fissure water heat load will be determined below.

Surrounding rock creates a heat load by conduction from the hot virgin rock interior to the rock surface. Rock properties were obtained from previous measured data completed. In this study core drill samples were taken and analysed for the type of rock and thermal readings were taken for a certain mass of rock.

From this work it was established that the VRT can be described by Equation Ab:

VRT (°C) = 26.3°C + (0.0186°C/m x depth (m)) [Ab]

Reference VRT for Lift I Production Level at approximately 1 200 m below surface is 49 °C.

Table Aa show the general rock properties used for the The Mine project that is not part of the ore body being extracted. Shaft and tunnel general rock mass properties were based on bulk rock type data.

Table Aa: General Rock Properties

Density	3 055 kg/m^3
Thermal conductivity	2.71 W/m°C
Specific heat	825 J/kg°C
Thermal diffusivity	1.08×10^{-6} m^2/s

Table Ab shows the production rock properties used for the The Mine project and are based on rock type data.

Table Ab: Production Rock Properties

Density	3 200 kg/m^3
Thermal conductivity	3.24 W/m°C
Specific heat	800 J/kg°C
Thermal diffusivity	1.08 x 10^{-6} m^2/s

Heat load contribution of general rock at The Mine and was determined with VUMA3D-network as 591 kW. This will only be included during the capital development phase and not here. Similarly for production rock is 5 400 kW.

.

Broken rock creates a heat load because it enters the underground environment at a warm temperature and ultimately gets cooled to the ambient underground temperature by the time it leaves The Mine. This heat load is calculated as shown in Equation Ac.

$$\begin{aligned} q &= m_r C_p (T_r - T_{wb}) \\ &= 380.5 * 800 * (49 - 21) \\ &= 8523\,\text{kW} \end{aligned} \qquad [\text{Ac}]$$

T_r : Virgin rock temperature (°C)
T_{wb} : Wet – bulb air temperature (°C)
m_r : Massflow of rock (kg/s)
C_p : Heat capacity of rock (J/kg°C)

Diesel vehicles are used at The Mine and contribute a significant heat load. Heat from diesel engines is a multiple of the engine rating due to the low efficiency of the diesel engine. For The Mine a heat load factor of 1.5 times the diesel rating applies, giving vehicle heat loads as shown in Equations Ad. Twelve LHDs (Sandvik LH514) will be used during steady state production.

LHD heat load is determined below:

$$\begin{aligned} \text{LHD heat load} &= 0.9 * 225 / 0.6 * 12 \\ &= 4056\,\text{kW} \end{aligned} \qquad [\text{Ad}]$$

Fissure and Service Water

If there are large quantities of fissure water then this can be a significant source of heat. At **The Mine** very little fissure water is generated.

Table Ac shows the water usage design criteria for the production -phase.

Table Ac: Water Design Criteria

Service water consumption	0.1 ton-water/ton-rock mined
Fissure water expectation	0.05 ton-water/ton-rock mined

Fissure water heat load (Equation Ae):

$$q = m_w C(T_R - T_{wb})$$

$$m_w = 0.05\frac{ton}{ton} * 32500\frac{ton}{day} * \frac{1day}{24hr} * \frac{1hr}{3600s} * \frac{1000kg}{1ton}$$

$$= 18.8\,kg/s$$

$$q = 18.8 * 4.186 * (49 - 21)$$

$$= 2204\,kW \qquad [Ae]$$

T_R : Virgin rock temperature (°C)

T_{wb} : Wet – bulb air temperature (°C)

m_w : Water flow rate (kg/s)

C : Water heat capacity (kJ/kg°C)

Auxiliary devices include effects of machinery, people, explosives, oxidation of materials and strata movement. At The Mine none of these are used or the rated power is negligible.

Machinery as heat source is all equipment using electricity as power source that is not converted into useful energy which includes fans, hoists, lights, locomotives, motors, winches, pumps, rockdrills and others.

At The Mine four auxiliary fans operate at the crushers producing an accumulated heat load of 150 kW. The other fans are the main fans which are not taken into consideration as they are situated in surface. The booster fans only operate in emergency scenarios and are not incorporated.

At The Mine the hoist motors are situated in the winder and the electrical power of the motor is converted into mechanical energy. The inefficiency of the motor is lost in the shaft due to friction and potential energy. The motors supply a total of 6.4 MW of power to the winders and are approximately 90% efficient with a heat load of 640 kW.

At The Mine 50 W lights are installed every 10 m and no winches are used as this is a mechanised mine.

No locomotives operate underground at The Mine.

Service and fissure water is pumped back to surface with high pressure pumps producing a total heat load of approximately 360 kW.

Rock drills are used for rock ‘hang-ups’ that blocks the natural breakage of the pipe like ore body; this heat load is negligible.

Person’s metabolic heat production rate varies but contributes as estimated:

At rest	90 to 115 W
Light work	200 W
Moderate work rate	275 W
Hard work rate (intermittent)	470 W

Personnel work is in air conditioned LHDs with a few workers in the vicinity. Heat load due to personnel will be in the region of 200 W every 500 m.

Explosives’s heat is mainly removed by ventilation air during the re-entry period but some studies have shown that the heat is transferred to the broken rock. At The Mine virtually no explosives are used and rock ‘hang-ups’ are generally removed with the use of secondary breaker machinery. The heat from these machines will not exceed the heat load from an LHD and is thus used.

Oxidation of materials is mainly by sources like timber but has shown that heat involved is negligible. No timber supports of back fill is used at The Mine.

Strata movement is an indication that the potential energy of the overlying rock is being reduced for a specific mining method which increases the temperature of the rock surface where it is moving. The heat from the rock is generally negligible.

In summary, the total heat load for the Mine amounts to **30 221 kW** as seen is the table below.

Description	**Heat Laod**
Auto-compression	8 627 kW
Production rock	5 651 kW
Broken rock	8 523 kW
Vehicles	4 056 kW
Fissure water	2 204 kW
Auxiliary equipment	1 150 kW
Total Heat Load	**30 211 kW**

APPENDIX B

APPENDIX B – ENVIRONMENTAL CONDITIONS

Re-Use Ventilation Air

Recirculating air underground facilitates constant air quantity drawn from surface. Adequate filtering of dusty recirculated air is vital in the control of dust concentrations in recirculated schemes.

At The Mine the return infrastructure and main fans are restricted and no or very little additional air can be added without major cost implications with infrastructure expansion(s). It is therefore that recirculated air needs to be investigated to assist with ventilation and cooling shortfalls. Air from the Belt Level and crushers can be recirculated and reconditioned for re-use in the required air cooler. Approximately 255 m^3/s (320 kg/s at 1.25 kg/m^3) can be re-used in the 3 MW BAC only and the air will comprise of large dust particles (>5 μm). All other coolers will be supplied with fresh air only.

To assist in dust concentration calculations, a dust concentration model within a recirculation system was used to determine the mixed dust concentration (Figure B).

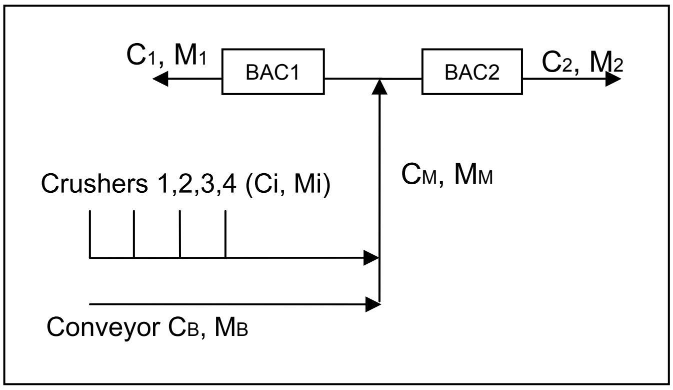

Figure B: Typical Recirculation System

Air will be re-used from the crushers and conveyor belt, and data received from The Mine from stationary measuring instruments indicated that on average 3.6 mg/m^3 of dust will be in the air at the conveyor belt and particle sizes above 8 μm. Similarly at the crushers (4 off), the measured average dust concentration at the bottom of the crushers are:

- Crusher No.1 = 5.4 mg/m^3
- Crusher No.2 = 2.2 mg/m^3
- Crusher No.3 = 1.8 mg/m^3
- Crusher No.4 = 2.4 mg/m^3

No fresh air will enter the BAC and the mixed dust concentration entering the BAC will be 3.1 mg/m^3 with a filtering efficiency of 61% as calculated in Equation B.

$$
\begin{aligned}
C_T &= \frac{C_1M_1 + C_2M_2 + C_3M_3 + C_4M_4 + C_bM_B}{M_T} \\
&= \frac{5.4(60) + 2.2(60) + 1.8(60) + 2.4(60) + 3.6(80)}{320} \\
&= 3.1 mg/m^3 \\
E &= \frac{C_M - C_1}{C_M} \\
&= \frac{3.1 - 1.2}{3.1} * 100 \\
&= 61\%
\end{aligned}
\qquad [B]
$$

Air Quality Mine Data

Description	**Mine Data**
Silica dust, crystalline (at crushers)	3.6 mg/m^3 Time Weighted Average (TWA)
PNOC	respirable 3 mg/m^3
Carbon Monoxide (CO)	25 ppm (TWA)
Carbon Dioxide (CO_2)	3 000 ppm (TWA)
Nitric oxide (NO)	15 ppm (TWA)
Nitrogen dioxide (NO_2)	1 ppm (TWA)
Sulphur dioxide (SO_2)	1.6 ppm (TWA)
Radiation	1.1 mSv/annum (personal exposure)

Water Quality Mine Data

SAMPLE INFORMATION								
Customer:		THE MINE						
Date sampled:		23 October 2012						
Sample ID:		Service Water						
Lab No.		147/10						
Sample ID		UG overflow						
PHYSICAL ANALYSIS								
pH @ 20°C	pH units	7.2						
Temperature	°C	25						
Conductivity @ 25°C	µS/cm	2285						
T.D.S (By Calculation) @ 25°C	mg/l	1600						
Suspended solids	mg/l	18						

CATIONS								
Total Hardness	mg/l $CaCO_3$	810.0						
Calcium Hardness	mg/l $CaCO_3$	190.0						
Magnesium Hardness	mg/l $CaCO_3$	620.0						
Soluble Iron	mg/l Fe	<0.02						
Total Iron	mg/l Fe	4.4						
Copper	mg/l Cu	0.3						
Soluble Zinc	mg/l Zn	<0.005						
Sodium	mg/l Na	250.0						
Potassium	mg/l K	120.0						
Magnesium	mg/l Mg	76.0						
Calcium	mg/l Ca	151.0						
ANIONS								
P-Alkalinity	mg/l$CaCO_3$	0.0						
Total Alkalinity	mg/l $CaCO_3$	52.0						
OH-Alkalinity	mg/l $CaCO_3$	0.0						
Chlorides	mg/l Cl	340.0						
Nitrite	mg/l NO_2	5.0						
Nitrate	mg/l NO_3	58.0						
Phosphates	mg/l PO_4	0.7						
Sulphate	mg/l SO_4	500.0						
Silica	mg/l SiO_2	10.8						
Nickel	mg/l Ni	<0.1						
Other								

APPENDIX C

APPENDIX C - FACTOR OF MERIT

The FOM of a spray tower and chamber can be determined as shown in the following equations and from nomograms:

Condenser spray chamber:

Water efficiency :

$$\eta_w = \frac{t_{wi} - t_{wo}}{t_{wi} - t_{wbi}} = \frac{42.2 - 35}{42.2 - 26.9} = 0.48 \qquad [Ca]$$

t_{wi} : Water temperature in (°C)

t_{wo} : Water temperature out (°C)

t_{wbi} : Air temperature in (°C)

Thermal capacity ratio :

$$R = \frac{m_w C_w}{m_a C'_a} = \frac{300 * 4.187}{265 * 0.087} = 54.5 \qquad [Cb]$$

$$C'_a = (S_{wi} - S_{ai})/(t_{wi} - t_{ai}) = \frac{4.187 - 2.86}{42.2 - 26.9} = 0.087$$

FOM = 0.58

Bulk air cooler:

Water efficiency :

$$\eta_w = \frac{t_{wo} - t_{wi}}{t_{wbi} - t_{wi}} = \frac{16 - 6.5}{24 - 6.5} = 0.54 \qquad [Cc]$$

t_{wi} : Water temperature in (°C)

t_{wo} : Water temperature out (°C)

t_{wbi} : Air temperature in (°C)

Thermal capacity ratio :

$$R = \frac{m_w C_w}{m_a C'_a} = \frac{40 * 4.187}{140 * 0.127} = 9.4 \qquad [Cd]$$

$$C'_a = (S_{ai} - S_{wi})/(t_{ai} - t_{wi}) = \frac{2.8 - 0.6}{23.8 - 6.5} = 0.127$$

FOM = 0.6

Factor of Merit and Positional Efficiency

The FOM and UA value for the coils, BACs and CSCs have been determined in Section 4.6.

The positional efficiency of the equipment is as listed below:

3.0 MW Re-Use BAC:	86%
4.5 MW CSCs	95%

Mist eliminators are usually installed when high water carry-over is experienced and water needs to be captured for re-use. In the case that this is required, it is advised that mist eliminator(s) be installed and that air flow velocity be limited to 5 m/s. These units are generally only installed in cooling systems.