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UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

DEPARTMENT OF MINING ENGINEERING

HEATFLOW : AN INTERACTIVE COMPUTER PROGRAM FOR THE ANALYSIS OF HEAT PRODUCTION IN GOLD MINES

by

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A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, June 1986

DECLARATION BY CANDIDATE

I, Gilbert Chorosz, hereby declare that this dissertation is my own work and has not been submitted by me for a degree at any other University.



26th June, 1986.

ABSTRACT

The cooling of deep gold mines is costly and must therefore be planned carefully. To provide a precise assessment of underground air temperatures, a computer program, HEATFLOW, has been designed. HEATFLOW has a modular format, using independent algorithms for the prediction of heat and moisture transfer in shafts, tunnels, stopes, development ends, hoist chambers and fans. It also simulates the performance of air-coolers. HEATFLOW is a user-friendly program, running on IBM-PC compatible computers. It allows the user to enter complete mine networks (up to 320 elements) and provides two levels of simulation : 'simple', for global and rapid calculations, and 'complex', for improved accuracy and detail in input data and results. The network is schematically displayed on the screen and data are input interactively, using predefined forms on the screen. A generic mine representing the average 'deep' gold mine has been simulated, providing satisfactory answers (within 10% of actual data).

ACKNOWLEDGEMENTS

This dissertation arises from work carried out as part of the research programme of the Research Organization of the Chamber of Mines of South Africa.

I would like to express my thanks and to acknowledge the help of the Director and staff of the Environmental Engineering Laboratory of the Chamber of Mines, particularly to Steven Bluhm and Frank von Glehn.

In addition, I would like to thank Professor H. Phillips and Professor A.M. Starfield of the University of the Witwatersrand, for undertaking the supervision of this work.

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NOMENCLATURE

a	: radius (m)
α	: thermal diffusivity (m^2/s)
ASH	: apparent specific humidity (kg/kg)
B	: Biot number = $h.a/k$ (*dimensionless*)
β	: angle (*rad.*)
c	: thermal capacity of rock (J/kg.K)
CF	: correction factor (dimensionless)
C_{water}	: thermal capacity of water (J/kg.K)
Δ	: variation
D	: diameter (m)
DB	: dry-bulb temperature (^oC)
DFA	: *daily face* advance (m/day)
e	: partial pressure of water in the air (kPa)
E	: moisture transfer coefficient ($kg/m^2.s.Pa$)
E:M	: enthalpy over moisture ratio (kJ/g)
E_w	: water efficiency (dimensionless)
e_{sat}	: saturation pressure (kPa)
f	: wetness *factor* (*dimensionless*)
f_{eq}	: equi*valent wetness* factor (dimensionless)
F	: factor of merit (dimensionless)
Fl	: face length (m)
Fo	: Fourier number = $\alpha.t/a^2$ (dimensionless)
Fr	: roughness factor (dimensionless)
F(B,Fo)	: heat flow function *tabulated by* Jaeger and Chamalaun (*dimensionless*)
h	: film or surface heat transfer coefficient (W/m.K)
H	: enthalpy (kJ)
k	: thermal conductivity ($W/m^2.K$)
K	: radiative heat transfer coefficient from wet to dry rock surfaces ($W/m^2.K$)
K'	: radiative heat *transfer* coefficient from dry to wet rock *surfaces* ($W/m^2.K$)

L_w : latent heat of vaporization of water (J/kg)
Nu : Nusselt number (dimensionless)
P : barometric pressure (kPa)
Pdg : perimeter of the dip gully (m)
PERIM : perimeter (m)
Psg : perimeter of the strike gullies (m)
Pr : Prandtl number (dimensionless)
Q_{lat} : latent heat (kJ)
Q_{sens} : sensible heat (kJ)
Q_{tot} : total heat (kJ)
r : polar radius (m)
R : capacity ratio (dimensionless)
ρ : density of the rock (kg/m^3)
Re : Reynolds number (dimensionless)
Sw : stoping width (m)
t : time or age (s)
θ : polar angle (rad.)
t_{ai} : temperature of air at inlet (°C)
t_{surf} : temperature of the rock surface (°C)
t_{wi} : temperature of water at inlet (°C)
TW_{in} : temperature of the service water at stope inlet (°C)
t_{wo} : temperature of water at outlet (°C)
u : temperature (K)
v : temperature (K)
v_{dry} : average temperature of the dry rock surface (°C)
VRT : virgin rock temperature (°C)
v_s : rock surface temperature (°C)
v_{wet} : average temperature of the wet rock surface (°C)
WMF : water mass-flow (kg/s)
x : thickness of insulation (m)
X : distance from the dip gully to the face (m)
Xp : width of the production zone (m)

CHAPTER 1 : INTRODUCTION

South African mines are very deep : this results in a large heat load on the ventilation air. The deterioration of working conditions due to this is such that, at effective temperatures approaching 30 °C (the effective temperature takes into account the temperature, humidity and velocity of the air) productivity decreases quickly with temperature. Above 34 °C (Stew , 1982), the risk of heat stroke increases rapidly with temperature.

Heat loads mainly result from three elements:

(i) autocompression of ventilation air

(ii) heat from rock exposed to ventilation air

(iii) machinery.

Even with a limited geothermal gradient, virgin rock temperatures (VRT) are often in excess of 45 °C (Sheer et al., 1984) and can be up to 60 °C. Although ventilation air can be used to remove the consequent heat flow, at great depths this air loses all its cooling power as a result of autocompression. As an alternative, chilled water can be sent down the mine, to be used in air coolers or, directly, as service water, in stopes. Its effect is then to directly cool down the working place. Furthermore, the use of this water tends to increase the humidity of the air, which makes high temperatures less bearable.

Mine refrigeration processes, which are very costly, must be carefully planned. For this, a proper assessment of heat production in the mine is necessary.

1.1 Problem : the Current Approach

Bluhm et al. (1986) have reviewed all the existing models for th prediction of heat flow in deep mines and showed that the state-of-the-art provided, for given domains, acceptable, although not fully satisfactory, answers. However, the modelling of an entire mine remains difficult and this is normally limited to one shaft, airway or stope, of which a mine contains great numbers. The mine ventilation official will, rather than using these models one by one, refer to simple graphs of the type shown in Figure 1.1 (Hemp, 1982) for overall mine-wide heat load estimation. Using the depth, the VRT and a production figure, he will be able to compute the overall cooling requirements. This cooling will be applied according to conventional rules, but the whole process may be quite inefficient.

The optimum method of making models available for the study of heat load and cooling strategies is to provide them as computer programs; such a program, FRIDGE 5, is already available.

It was produced by the Chamber of Mines Research Organization (Van der Walt and Whillier, 1979) and allows the mine to be considered in its totality. The simulation requires from the user that he provides data such as cooling duty, power of machinery, stoping method or length of airways for each level. It uses a pre-defined lay-out which is the typical structure of a mine from the environmental point of view, and where a definite cooling strategy is assumed. Though the results provided by this program have generally shown satisfactory agreement with practical observations, this predefined cooling strategy eventually appeared as a major limitation.

Another limitation of FRIDGE 5 is its availability on main-frame computers only. It therefore restricts the use of such a

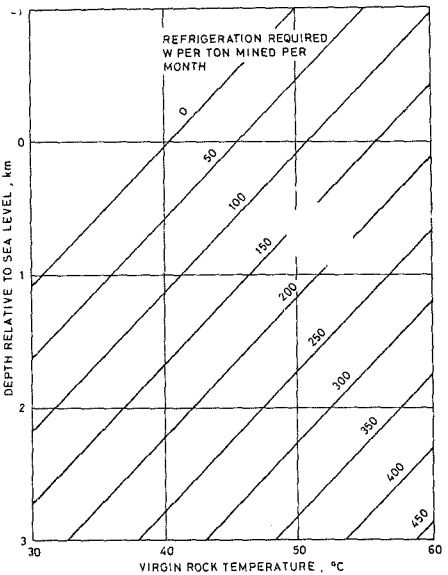


Figure 1.1 : Refrigeration requirements as a function of VRT

planning tool to the head-offices of the mining houses and it also makes the program less attractive, as access to main-frame computers requires a different degree of computing experience.

The problem posed by this type of approach is, therefore, that, while it makes recognized models available to the mine ventilation engineer, it often appears as too rigid for the study of particular cases.

The above limitation is probably even more important now that novel cooling strategies are being considered and introduced, and that ventilation officials consider the distribution of cooling throughout the mine as well as the optimum location of air coolers in greater detail.

1.2 Solution : the Micro-computer Approach

The need for a computer program with a flexible structure exists. This program must allow the user to enter not only general data for a mine, but its actual design, area by area and allow the possibility of studying details. The program, although possibly complex, must be easy to use. It should not, therefore, be developed for a main-frame computer.

Micro-computers have now reached the professional market, with appropriate increases in power, speed, size of memory and even hardware or software extensions. Because the requirements for memory of the proposed program are likely to be large, what could not be envisaged five years ago with a micro-computer is now possible. A micro-computer is now very similar, in terms of speed and memory, to a terminal connected to a main-frame computer, the main difference being the ease of use due to the fact that personal computers are designed for a single user.

Providing a simulation program on a micro-computer for studying heat flow problems will make it :

(i) widely available, as micro-computers are cheap and can be located on the mines

(ii) easily accessible to a user with little computer skill

(iii) efficient, as the result of each simulation is readily available, even in a printed form. No hardware has to be shared between a number of users. Neither is this ancilliary equipment at a remote location

(iv) more 'user-friendly', therefore allowing more simulations to be performed in a given time as the input is easier and the understanding of the results more straight-forward.

Because the program can be developed as a software package (a hand-book, the documentation, plus one or two diskettes on which the program is stored), it will allow easy upgrading. A modular approach in which separate routines or calculation modules are used independantly will also contribute to an easy production of improved versions. Each time better models are developed, they can, in the form of calculation modules, replace the older routines. Only one or two diskettes are required for the distribution of this new version, with no further computational work.

1.3 Objectives of the Work

From what has been mentioned earlier, the objectives are to provide a tool:

(i) for the study of the heat flow problem on the scale of an entire mine

(ii) with the possibility of a detailed study of heat loads in particular regions of the mine

(iii) capable of easy relocation, for use on mine sites

(iv) requiring little computer knowledge (and therefore very 'user-friendly')

(v) and which allows for extensive printed reports of results, in order to ensure the best possible communication.

This computer program, called HEATFLOW, has been written for an IBM-PC micro-computer. Most of the features detailed in this document have been implemented, with the exception of the second (complex) complexity level (see section 2.8). This does not apply to air coolers, for which the complex level has been implemented.

1.4 Lay-out of the Document

The remainder of this document is divided into five parts.

The first part (chapter 2) reviews all the requirements expressed in this introduction and shows their influence on the program's global structure. The second part (chapter 3) then analyses each of the models used for the simulation of heat and moisture transfer. The third part (chapter 4) details some particularly important features of the computer program which make it easy to use by mine ventilation engineers.

The fourth part (chapter 5) is concerned with the programming aspects of the development of the program on a micro-computer, namely the IBM-PC personal computer.

The fifth part (chapter 6) can be considered as a conclusion ; it shows how the program can be used in actual cases, how potential users regard it and what they would like to see

added. It also summarizes what enhancements should be made in order to make the system a more intelligent one, which could not only provide results, but solutions as well.

CHAPTER 2 : DESIGNING A TOOL TO MEET THE NEEDS OF THE MINING INDUSTRY

The program 'HEATFLOW' is a tool for use in the South African gold mining industry for planning purposes and research into new mine cooling strategies. Its prospective users are *therefore* mainly mine environmental control *officials. The* characteristics of *the potential user are a* good knowledge of the heat problem *in mines and* the required input but little or no *skill in computing*. The program must be designed to make as *much* use as possible of the user's skills, and to relieve him from the unnecessary worries generally linked to the use of computers.

It is very important to note that the user must be *conscious of* the limitations of the program. *This program is designed* to help engineers in their work *but cannot replace* the engineer. The user cannot *simply be an unskilled* operator since it is necessary *that the program* be used in an intelligent way. *Answers and* results provided are subject to discussion as the *models* used are only approximate. An intelligent method of using the program is to try to 'calibrate' it (against an existing mining situation) and to derive a systematic deviation between the results provided by the program and actual measured data. This deviation could then be used in order to *modify the* results of simulations of future projects.

It is also of paramount *importance* that the program be available *on each site*. Therefore, since only limited investments for *data-processing* equipment can be considered, a micro-computer would be the most suitable choice for this issue.

In this chapter, the global structure of the program is discussed. Some new terms are introduced and the method adopted to solve the problem is explained. Some *detail is also given* concerning the functional *organization of the program.*

2.1 Requirements

The requirements of the program, as a consequence of what has been suggested earlier, may be summarized as :

- a user friendly structure : no computer skill is required from the user
- a transportable program
- a standard computer
- the possibility of studying large mines or shaft systems in great detail
- compatibility with existing methods and habits in the field of heat flow problem solving
- the modularity at every level
- the accuracy of the results, achieved with the use of the latest models
- the possiblity of upgrading the models.

HEATFLOW is an attempt to meet these requirements on a micro-computer.

2.2 Network Structure

The major innovation of this program is the feature which allows the study of the heat problem in mines at both a global and a detailed scale. In order to comply with the global scale requirements, the program will adopt a representation of the mine which is similar to a mine ventilation network. In the following text a mine layout will often be referred to as a network.

As with a mine ventilation network, the heat flow network will contain nodes (numbered in the same way, as much as possible, as on mine ventilation plans). These nodes are linked together by branches (later referred to as 'boxes', as defined in section 2.3).

The main difference encountered when ventilation and heat flow networks are compared is that the latter have an orientation. The calculations of heat flow will be performed from the intakes towards the outlets. In the case of mine ventilation, a balance has to be found : therefore, no preference is given to an order of calculation and, as quantities and flow directions are computed, inlet and outlet cannot be differentiated before the calculation.

2.3 'Boxes' : the Branches of the Network

The branches of the network are the physical location of the heat and moisture transfer to and from the ventilation air. Unlike mine ventilation networks' branches, they may be of zero length. They will be referred to as boxes in the rest of this text. A box is simply an element of the heat flow network linking two nodes, where air is heated or cooled.

Eight types of boxes have been identified. Among them, some are similar to mine ventilation branches (tunnels, fans, etc...) and some differ (air-coolers, hoists, etc...). A box has, by definition, one inlet and one outlet only. A box is considered symmetrical : the inlet and outlet ends are not treated differently by the program. Therefore, in the case of a tunnel which contains a spot heat source, for instance, the user will not be prompted to give the distance from the intake to the spot heat source. In this case, the user will divide the tunnel into three boxes:

(i) first a tunnel section
(ii) then a spot heat source box
(iii) lastly another tunnel section.

2.4 Modularity

Modularity is a main feature of the program. Firstly, the mine considered for analysis is divided into modules (boxes) of different types. It is thus possible to study the heat problem in great detail, area by area. Different options for a cooling strategy can be analysed, by changing the location of the air-cooler boxes, for example.

Secondly, the user is presented with a main menu : each option of this menu allows the user to perform one or several tasks of a given type (create, edit, calculate, print, etc..., see section 2.9).

Lastly, the internal structure of the program is such that sub-routines are widely used. The aim of this structure is to allow for easy maintenance of the program : the routines can be changed as they are updated. The programming language used is PASCAL, which lends itself to this modularity aspect.

2.5 Data Input

Apart from global data (which will be treated under section 3.2.1), two kinds of input data are required from the user, once the plan of the network has been entered:

(i) data for nodes

(ii) data for boxes.

The mode of input selected for the program is such that both of these categories of data can be input at the same time, in 'forms' provided on the screen by the program. These forms contain three parts : one for the inlet node, one for the outlet node and one for the box itself. In the case where data relative to one node has already been entered during the creation of another box, this data can be left unmodified during the editing of the new box.

Only one system of units is available, namely the SI system. However, some consideration has been given to the practical usage in the mining industry. Ages and durations are given in years (not in seconds), face advance in m/month (not in m/s) and pressures in kPa (not in Pa).

Decimal numbers are entered with a point instead of the comma, as is normal with computer programs. The 'form' structure is such that a different form is available for each different type of box.

In case of an erroneous input (a negative value for a length, for instance, or a character where a number is expected), the program will emit a warning sound and the cursor will be positioned under the first occurence of an error. In the same fashion, the user cannot quit the creation phase for a given box until all necessary data (when not provided as a default) have been entered.

2.6 Windows

In order for the user to be able to keep track of the different items of information, they will have to be grouped by type. The screen is divided into 'windows', each containing a different type of information. For example, at data input level, three windows overlay the display of the network, which normally occupies the whole screen. These are:

(i) the inlet node data window

(ii) the box data window

(iii) the outlet node data window.

As soon as the display of these windows on the screen is no longer necessary, they are removed and the screen is returned to its initial state, showing the network only.

2.7 Help - Function

On-line explanations are provided for the user. At any stage of the input of data or of the selection of an option, this help facility can be called to the screen by simply pressing one key. This is one of the most important features concerning interactivity. It enables the program to be used by operators who have relatively little knowledge of computing. The practical aspects of the implementation of this function are discussed later (in sections 4.3 and 5.6). It must be stressed that this feature is convenient for the beginner, who can get help whenever it is needed, as well as for the expert, who will not be disturbed by unnecessary information on the screen.

2.8 Levels of Complexity

More than one level of complexity is required. This has two motivations:

(i) the user might have relatively little data available for the fi .t analysis of the mine

(ii) the models available sometimes use iterative calculations. These methods are time consuming and can be approximated by non recurrent methods with a lesser accuracy.

The two levels of complexity derived from this are:

(i) a first level, called 'simple level', where the requirement for data is limited. The calculations performed at that level avoid iterations as much as possible. The time needed to input data is short. The knowledge of the mine characteristics can be quite limited. The calculation time is the shortest possible and the algorithms might be less accurate. This level is likely to be used by someone who wants to perform a rather global and quick simulation of a mine, without having to provide too much detail. The user, at this level, is interested in average results which can give him 'an idea' of the situation. This level can be used for a complete mine calculation.

(ii) a second level, called 'complex level', where much more detail in the input of data is required. This level uses models which may include iterative procedures. It is more time-consuming as well as more accurate. This level is likely to be used by someone interested in precise temperatures and heat flow predictions, for strategy decisions, for instance. Instead of average conditions, precise results taking into account time variation might be needed. This level will probably be limited to the study of parts of a mine.

The level of complexity is not common to the program : a network can include boxes for which data have been input at a complex level (and where complex calculations are expected), as well as boxes at a simple level.

Two complexity levels are not always available. With a hoist, for instance, the input required is simple in any case and the

calculations do not require iterations : the complex and simple levels are thus the same.

On the other hand, in the case of air coolers, two levels of complexity are available. The first one does not require any technical knowledge of the air cooler and thus only the temperatures expected at the outlet are to be entered. The second one uses input such as the temperature of chilled water at inlet, the water flow rate and factor of merit of the installation.

2.9 Menu Structure : the Options

The program is controlled by the use of a menu (menu driven). There are eight options in the main menu and each option performs a given task :

(i) setting of defaults and global data
(ii) creation of a network
(iii) editing of a network
(iv) calculations
(v) disk storage
(vi) clearing memory to start a new network
(vii) printing data
(viii) quitting the program.

These options can be selected by pressing one or several keys in sequence. Once an option is selected, it may present the user with a secondary menu. For the printing option, for instance, the type of report needed will be selected from a menu.

2.10 Results

The results (mainly wet- and dry-bulb temperatures at the inlet and the outlet of each box, plus the heat generated in every box) are provided to the user in two ways.

Firstly, on the screen, the form attached to each box contains information concerning the results of the calculation. These are summarized in a side window, displayed with each box while the user browses through the network.

Secondly, on the printer (or in a file created on disk with the same format as the printer output), the results appear in what will be referred to as 'reports'. Obviously, more results will be available in a printed form. This includes the air psychrometric conditions (enthalpy, moisture content and sigme-heat). Four types of reports are available:

(i) the network global data (tabular)

(ii) the network lay-out (map)

(iii) node data (tabular)

(iv) box data (tabular).

There will necessarily be a redundancy of the information contained in each of these reports. A detailed account of these types of report, concerned with the user's requirements, appears later in section 4.9 of this document.

2.11 *Reliability and User Input*

The reliability of the program depends on two elements:

(i) the accuracy of the data input by the user

(ii) the reliability of the models used.

In case the user feels the results provided by the program are incorrect, provision is made for him to express his disagreement. This will be done with the user entering the values he thinks to be correct as outlet temperatures for the boxes concerned. The program will use this information in two steps:

Firstly, it will use the values provided by the user as reliable data for a new set of calculations. This will make the program more accurate, as these temperatures will enable better conditions be computed in the following boxes.

Secondly, depending on the model and on known sources of error, it will give a list of the most sensitive data input by the user. This list will display the data according to their decreasing influence on the model.

For example, if the wet-bulb temperature at the outlet of a tunnel seems to be correct, but the dry-bulb temperature is incorrect, the top of the list for sensitive data will be the wetness factor.

An advanced feature could be included, which would allow the user to input correction factors for each model, once he has precisely established a possible constant deviation between the results of some of the routines (e.g. tunnels) and a wide set of actual data. However, the basic problem of obtaining accurate field data remains and the feature of 'calibrating' the results of the program is purely to provide the user with a means of feeling the results provided by the program are tied to those actually obtained or recorded for the mine.

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CHAPTER 3 : MODELS USED

3.1 Introduction

The main concern of this work is to produce a program which is useful to the industry and highly modular (as mentioned under section 2.4). This chapter describes the modules and the routines used for the calculations in these modules. In most cases, there are several mathematical models available for performing the calculation. The decision on which to use has not been based on a judgement of their relative merits but has adopted the ones commonly used at the Chamber of Mines Research Organization or has selected one for illustrative purposes. If, in the future, better models are developed, the whole program is structured so that they can easily be introduced.

The major sources of heat in a gold mine are :

(i) auto-compression of ventilation air

(ii) heat from rock and fissure water

(iii) heat from machinery

For a typical hot deep mine (VRT > 38 °C and mean rock breaking depth > 2000 m), these sources of heat represent (Sheer, 1986):

rock heat.....	53 %
auto-compression.....	33 %
machinery heat.....	9 %
fissure water, etc.....	5 %
	100 %

This is merely an example and it should be noted that the figure for fissure water could be much higher.

The auto-compression of air causes an increase in dry-bulb temperature of approximately 1 °C per 100 m of depth, in the absence of any evaporation.

The program contains several different routines which calculate heat flow and moisture evaporation rates due to the different sources listed above. Consequently (because, *for a given pressure, there is a* unique relationship between wet- and dry-bulb temperatures on one hand and enthalpy and moisture content on the other), temperatures at different points of the network can be computed. Each of the *routines is applied to the calculation of a given* type of box. Their basic function is, from the knowledge of the inlet conditions of a box (wet- and dry-bulb temperatures) and of the characteristics of the box (length of a tunnel, for instance), *to compute the outlet conditions.*

In order to perform the calculations for the eight *different* models of boxes, eight *routines are used.* They are reviewed in *sections* 3.5 to 3.12. The input data needed for these calculations are discussed under section 3.2.

3.2 Reducing the Problem to Figures

The main goal of the program is to assess the production of heat and the moisture evaporation in an area (generally a *shaft* system), or the *totality, of a mine.* But it must also be clear where this production of heat takes place. Therefore, the values for heat flow rate and moisture evaporation must be determined for each box.

The effect of this heat flow on the air conditions is then determined giving temperatures (wet- and dry-bulb) at the outlet of each box. These data are essential for computing *the heat* flow in the *following boxes,* in the sequence dictated by air flow direction.

Let us consider two cases : air, which is cooler in one case than in another, flows through the same airway (box). In the cooler case, more heat will flow, as the driving force (virgin rock temperature minus air temperature) is larger than in the warmer case. The heat flow, as well as the temperatures at the outlet, will depend on the temperatures at the inlet. The study of a network is not limited to the study of each of its boxes independently. It is also the study of the interaction between boxes. This interaction will influence economic decisions such as duty, location or number of air-coolers.

Therefore, the mine under study must first be divided into boxes arranged in a network. The question of the reduction of the heat problem to figures can then be seen as providing:

(i) data common to the network

(ii) data of a type common to all box types

(iii) data characteristic of a given type of box.

3.2.1 Global data

These are the data which are common to the whole network. Some of them will be used by several models. A list is given below :

(i) Virgin rock temperatures (VRT). The VRT throughout the mine will be computed as the VRT at surface (level 0m) plus the VRT gradient (°C/m) multiplied by the depth relative to surface (m). Therefore, the VRT at level 0m as well as the VRT (or geothermal) gradient are global data. It will be possible, in future versions of the program, to consider several zones (between horizontal levels) where VRT gradients differ. This refinement has not been

implemented here, because horizontal levels cannot always account for strata boundaries. Different types of rock in different strata generally explain variations in geothermal gradients and it is very difficult to input non-horizontal strata. Instead, in the present version, the possibility is given to the user to locally overwrite the values of VRT for the inlet and outlet nodes of each box. The calculations are then performed using these new values.

(ii) Barometric pressure at surface (level 0m). The user can choose to have a ventilation network calculation (using the Hardy Cross method) performed by a compatible program. In this case (see section 3.13 of this document), pressures and mass flow in each 'branch' of the network are computed. When no detailed ventilation network balancing computation is done, Equation 3.1 (Threlkeld, 1970) gives an approximation of the pressure at each level. This formula does not take into account pressure losses due to friction or pressure increases due to fans. It is only an approximation in the absence of more detailed data.

$$P = P(0m) \times (1+2,256.10^{-5} \times depth)^{5,256} \qquad 3.1$$

For obvious reasons, these values of pressure may not be consistent with the values of mass flow input by the user. Nevertheless, they will give more accuracy to the psychrometric calculations where pressure is required. If the user has more accurate data concerning this value for certain nodes, he can overwrite the value produced by the program.

(iii) Rock characteristics : conductivity, diffusivity and density. These three items are generally known by the environmental control officials and are relatively easy to measure. Rock conductivity is in W/m K (typical values 5 to 6 for quartzite), rock diffusivity in m^2/s (typical value $2,5.10^{-6}$ for quartzite) and rock density in kg/m^3 (typical value 2700 for quartzite).

In some cases, it might be necessary to define two zones of rock, each with different characteristics. The user will then have to specify to what area each box belongs, when inputting information at this level.

(iv) Overall water consumption and percentage of the total amount of chilled water used in stopes. These two measures have been chosen to account for chilled service water because of their common use by the ventilation officials and their immediate availability.

(v) Step length for tunnel and shaft calculations (m). This number is global to a network although it is used only for the above calculations. From experience, 100 m is a generally satisfactory value. However, this number can be selected to be as low as 10 m for special applications.

3.2.2 Data common to all types of boxes

For each box, the following set of data will have to be entered, irrespective of the type of box :

(i) mass flow of air (kg/s)
(ii) depth at inlet (m)
(iii) depth at outlet (m)

The depths are used for determining virgin rock temperatures (obtained using the VRT at level 0m and the geothermal gradient, see section 3.2.1) and pressures (according to Equation 3.1), which may however be overwritten.

3.2.3 Box characteristic data

The data characteristic of each type of box are related to:

(i) geometry and age (for example : length, area or age)

(ii) production (for example : face advance)

(iii) wetness and water (for example : flow of water or enthalpy/moisture ratio)

(iv) power consumption (for example : efficiency or rated power).

This data input requirement is discussed in detail for each box, in the following paragraphs. Once all these data have been given, the only remaining information required is the starting point data : the user must input the wet- and dry-bulb temperatures for the intake of the network. Normally, only one set of temperatures (the surface conditions) will have to be entered for all the intakes. These could also be provided to the user, as a default option, if he specifies the area and part of the year. Myers et al. (1984) have developed a model using a Fourier series (limited to 3 terms) in order to predict atmospheric temperatures in the mining regions. This model could be used here.

3.3 Order of Calculation

As mentioned in 3.1, the network is studied in a strict order and the calculations are carried out from the intake towards the outlet. The structure adopted to depict the network and to display it on the screen is such that all intake boxes are on the top line of the network chart. The program will therefore begin the calculation with the top line boxes. Once all the calculations for these top boxes have been completed, it will proceed to the calculations on the next line, all the boxes on this line being directly in the down-stream of the top line boxes. Thus, from the knowledge of the temperatures at the outlet of these top line boxes (as resulting from the calculations) the program will derive the temperatures at the inlet of all the second line boxes. This procedure will continue, line by line, until the calculations for the last boxes on the bottom line have been performed.

The temperatures at the inlet of a box are obtained from the temperatures at the outlet of all the boxes directly linked to the inlet of the box considered. These boxes all 'merge' at the inlet node of the new box. The air entering the new box is a mixture of all the air flows leaving the other boxes. In order to calculate the temperatures of this resulting mixed air flow, the total enthalpy of the air-vapour mixture and the mass of air and vapour are conserved.

From these two parameters and the knowledge of the pressure, both wet- and dry-bulb temperatures can be calculated.

When condensation occurs, the moisture content of the air is obviously not conserved and it will be equal to the value corresponding to saturation, for the given enthalpy per unit of mass.

The structure considered here obviously does not allow local recirculation of air. This feature is however possible but it must be accounted for by a special box (discussed in section 4.7)

3.4 Different Levels of Complexity

Although numerous algorithms of varying complexity and accuracy are available for a number of box types (stopes or tunnels, for instance), it was decided to make use of two complexity levels only. This decision was taken in order to avoid complicating the program more than is necessary, from both the user's point of view (input of data) and the programming side. The maximum possible size of the program is, in addition, a limiting factor which had to be taken into account. These two levels of complexity can be compared to the 'basic' and 'non-basic' approaches of Bluhm et al. (1986).

Some box types do not require two levels of complexity. These are the hoists and other heat sources. Each of the following sections dealing with mathematical models explains the difference between the complexity levels for each box type.

3.5 Shafts

3.5.1 Introduction

As mentioned earlier, the change in energy content of the air flow in shafts can be regarded as a major source of heat in deep South African gold mines. This is mainly due to the auto-compression of ventilation air, which, in reality, is not a true source of heat, but a conversion of energy which results in a change of condition of the air. The two main characteristics of shafts are :

(i) most shafts are circular, with uniform distribution of moisture around the perimeter

(ii) the auto-compression of air can be treated in the same manner as sensible heat. Therefore, this will result in nearly all the heat pick-up being sensible, not latent.

Because the auto-compression can be regarded as the major part of the heat loads in shafts, the determination of heat flow from the surrounding rock and moisture evaporation from wet surface does not need to be very accurate.

These characteristics make the study of heat and moisture pick-up in shafts easier than in airways, which are otherwise similar, although evaporation is important and determines the final moisture content and conditions of the air.

Only circular, concrete lined shafts will be treated here. Any other type of shaft can be computed using an equivalent diameter and additional factors such as wetness can be taken into account using an 'other heat source' box.

Four elements of heat and moisture pick-up must be considered for shafts :

(i) the auto-compression of air

(ii) the heat from the rock

(iii) the moisture pick-up from the wet surface of the rock.

(iv) the radiative heat exchanges between air and rock and between the different zones of the rock surface.

Auto-compression creates a change in the sensible heat content of the air flow. The value of this energy conversion per metre of depth and per kilogram of air is 9,79 J (Hemp, 1982).

The problem of predicting the heat flow from rock is made simple by the regular nature of the shaft surface. A shaft can be well modelled as a cylinder in an infinite solid. The edge effects are negligible because of the average length of the shaft. The flow of heat is then radial. All the models developed for the study of shafts use this approach, with various degrees of refinement in the consideration given to the heat transfer taking place at the rock surface.

The moisture pick-up can be evaluated, concurrently with the heat flow from rock, using a wetness factor, which accounts for the dampness of the rock surface.

Because of the regular distribution of moisture, the whole perimeter of a given cross section can be considered to be at the same temperature. The radiation of heat between rock surfaces is therefore non-existent.

The equation for calculating radiation from the rock to the air may be reduced to a function of the difference between the rock surface temperature and the dry-bulb temperature (Whillier, 1982). The linear driving force is thus similar to that for convective heat transfer and hence the radiation exchange is generally taken into account in association with the convective heat. The radiation transfer coefficient and the convection transfer coefficient are merged in a single heat transfer coefficient. The only unknown, here, is the rock surface temperature. Its determination is the subject of the next section.

Two levels of complexity will be considered for shafts. The first one, which has been implemented, uses, with as much care as possible taken for the heat transfer at the rock surface, the 'cylindrical cavity' model (Goch and Patterson, 1940). The second level will attempt to cater for the rock temperature history, using the same model. This will enable the study of diurnal and seasonal variations of the atmospheric conditions, as well as the effect of irregular cooling and ventilation.

3.5.2 Simple level

The input from the user is limited to :

(i) the diameter (m)

(ii) the age (years)

(iii) the wetness rating, defined as a measure of the wetness of the perimeter. The user can choose from :

- bone dry : no moisture
- fairly dry : possible moisture
- damp : moisture visible
- fairly wet : free standing/running water on parts of surface
- totally wet : running water over whole of surface

The wetness rating can be related to f, the wetness factor as defined by Starfield and Dickson (1967) according to the following rules :

- bone dry : f = 0,0
- fairly dry : f = 0,1
- damp : f = 0,3
- fairly wet : f = 0,6
- totally wet : f = 1,0

(iv) the length (m)

(v) the total power of a linear heat source (kW). This caters for the heat load due to warm water pumped in pipes, for instance.

The mathematical theory considers an infinite solid of thermal diffusivity α only bounded internally by a cylindrical cavity of infinite length and of radius a. The solid is initially at a uniform temperature, u_0. At a given reference time (t=0), the temperature of the bounding surface is reduced to u_1 and maintained at this value. The heat conduction in cylindrical coordinates, neglecting the flow of heat parallel to the axis of the cylinder, is given by:

$$\frac{\partial u}{\partial t} = \alpha \cdot \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \times \frac{\partial u}{\partial r} \right) \qquad 3.2$$

This equation is called the Diffusion equation.

The boundary conditions are:

$$\left.\begin{array}{l} \text{for } t=0 \text{ and } r>a,\ u=u_0 \\ \text{for } t>0 \text{ and } r=a,\ u=u_1 \end{array}\right\}$$

The above model is obviously only an approximation for the following reasons:

(i) the solid around the excavation is neither infinite nor bounded only by the excavation

(ii) the cylinder is not infinite; there will be edge effects

(iii) the temperature is not uniform initially, as it varies with atmospheric conditions (time variation) as well as with depth (spatial variations) : this weakens the

assumption of no heat flow parallel to the axis of the cylinder, but, for South African gold mines, where the geothermal gradient is relatively low (roughly 1 °C per hundred metres), this remains a good approximation

(iv) the temperature of the air, and therefore of the rock surface, is not constant after t=0.

No closed form algebraic solution exists for the above equation. However, solutions have been tabulated by Goch and Patterson (1940) as a function of the Fourier number, Fo. The Fourier number is given by $Fo = \alpha.t/a^2$ where t is the age of the shaft (s).

These solutions require the knowledge of the rock surface temperature, which is not available in practice. These solutions can only be used if one assumes an infinite film (or surface heat transfer) coefficient. This infers that the rock surface is at the same temperature as the air. This assumption is not verified practically.

To circumvent this limitation, Jaeger and Chamalaun (1966) as well as Starfield (1966, a) have generated numerical solutions which take into account the film coefficient. These tables give the heat flow per unit of area and unit of temperature (driving force) as a function of the Biot number (B) and the Fourier number (Fo). The Biot number is given by $B = h.a/k$, where h is the film coefficient ($W/m^2.K$) and k the thermal conductivity of rock (W/m.K).

These tables have since been interpolated by formulae which give a very close approximation. The equation used in HEATFLOW has a maximum deviation of one percent compared with the tables, if Fo is in the range 1 to 5400 and for B varying from 0,1 to infinity. Both these ranges are more than adequate for shafts

and airways (a Fourier number of 1, for a shaft 6 metres in diameter in quartzite, corresponds to an age of about 40 days).

These tables give a function $F(B,Fo)$ which can be used to determine the rock surface temperature :

$$T_{surf} = DB + (VRT-DB).F(B,Fo) \qquad 3.3$$

and the heat flow from the rock :

$$Q_{sens} = 2.\pi.k.(VRT-DB).B.F(B,Fo) \qquad 3.4$$

These tables, generated for a dry surface, can be used for a wet surface provided an equivalent air temperature and an equivalent heat transfer coefficient are computed (Starfield, 1966 b and Hemp, 1982). The mass transfer rate is proportional to the difference between the saturation pressure of water at the temperature of the wet rock surface and the vapour pressure in the ventilation air. The temperature of the wet rock surface is easily derived from the equivalent air temperature. If the wetness factor is f, the total heat flow into the ventilation air is:

$$Q_{tot} = Q_{sens} + f.Q_{lat}, \qquad 3.5$$

Q_{lat} being computed for a fully wet surface.

The calculation for a shaft is performed in the following order:

(i) the shaft is divided into sections, according to a step length entered by the user (global data).

(ii) over a section, the air is assumed to be at constant pressure and wet- and dry-bulb temperatures. This assumption, using the model presented previously,

allows the heat flow from the rock and the moisture pick-up to be computed.

(iii) the enthalpy as well as the moisture content of the air at the outlet of the section can be computed, by adding the total heat (including auto-compression and a possible linear heat source) and moisture pick-up to the corresponding values at the inlet of the section.

(iv) knowing the enthalpy and moisture content and the pressure at outlet of the section, the new air temperatures are calculated.

(v) these temperatures are used for the inlet of the next section, for which steps (ii) to (iv) are repeated.

Increasing the number of steps will obviously give better results, although, as a general rule, a step length of 100 m is satisfactory. For a 1000 m shaft, the deviation in the prediction of heat between a calculation using a step length of 100 m and one using 5 m was found to be less than 0,3 %. The outlet temperatures were the same (up to the second decimal place).

3.5.3 Surface heat transfer coefficient

The only question left for discussion is the choice of the surface heat transfer or film coefficient, which cannot be measured underground in a satisfactory manner. Thus, for example, the results obtained using a program by McPherson, as quoted by Vost (1982), are constantly different from those obtained with HEATFLOW. This deviation is due to differences in the equations used for the calculation of the film coefficients, which are much higher in McPherson's calculations (2,5 times, in

a characteristic example, where the velocity is 2,5 m/s, the airflow 24 m^3/s and the friction factor 0,01 kg/m^3).

The transfer of heat from the rock to the air stream is hindered by a boundary layer. A characteristic of the resistance of this layer to the flow of heat is the film coefficient, h (actually inversely proportional to the resistance). This coefficient depends on :

(i) the air velocity : when this value increases, the thickness of the boundary layers decreases, thus diminishing the resistance to the heat flow.

(ii) the roughness of the rock surface : an increased roughness will tend to break up the boundary layer, increase the effective area of heat transfer and locally increase air velocities.

For reasons of convenience, the radiative heat transfer coefficient is sometimes included, together with the convective film coefficient, in an overall heat transfer coefficient.

Two approaches have been used in determining film coefficients. The first one derives from an empirical study of mine airways and the second one is an adaptation of a formula established for a turbulent flow in smooth pipes.

Empirical study of mine airways.

McPherson, as quoted by Vost (1981) uses, for his computer program called CLIMSIN, the following equation (Scott, 1958) :

$$h = 3540/3,6 \cdot \text{friction factor} \cdot \text{air velocity} \qquad 3.6$$

The friction factor is in kg/m^3 (typical value of 0,01 kg/m^3 for a mine airway) and the air velocity in m/s.

This value of h incorporates radiative effects, and therefore is an overall heat transfer coefficient.

Adaptation of the formule for smooth pipes.

McAdams (1954) gives a relation between the Nusselt, Reynolds and Prandtl numbers for a turbulent flow in a smooth pipe :

$$Nu = 0,023 \cdot (Re)^{0,8} \cdot (Pr)^{0,4} \qquad 3.7$$

where $Nu = h.D/k$.

By introducing Fr, a factor based on the roughness of the airway, the film coefficient is given by the equation :

$$h = 0,023 \cdot Fr \cdot k/D \cdot (Re)^{0,8} \cdot (Pr)^{0,4} \qquad 3.8$$

This equation is generally accepted. It does not include the radiative component. Fr is determined using a method described by Starfield and Dickson (1967) based on the use of a Moody diagram. For typical mine airways, Fr is equal to 1,7 (Starfield and Dickson, 1967 and Vost, 1973).

Vost (1973) performed in-situ measurements of film coefficients. He found a very satisfactory agreement between his experimental data and formula 3.8, with a value of Fr equal to 1,7. Danko and Cifka (1984) also conducted some underground measurements. Their results generally support equation 3.8 with a value of Fr equal to 1,7.

Formula 3.6 gives results notably higher than formula 3.8 (up to three times in typical cases). This will lead to large

deviations in the results provided by heat flow prediction models using either one or the other.

A knowledge of the radiative coefficient is also required.

This coefficient is defined by linearizing the Stefan-Bolzman radiation equation (Whillier, 1982). It is hence given as a function of the average temperature (to the cube power), the emissivities and the view factor.

Hemp (1985, a) makes use of a constant value of 6 $W/m^2.K$ and this is the value retained for HEATFLOW. It considers that the combined emissivity and view factor are close to unity. Vost (1973) makes use of a value of 0,16 for the emissivity of the moist air and thus uses a combined emissivity/view factor of well less than unity. This results in a radiative transfer coefficient value of about 1,0 $W/m^2.K$, which is considerably less than Hemp's value. The emissivity of moist air does not describe the emissivity of a surface but rather the radiation absorbing capability of the moist air. Bluhm (1981) considered typical air conditions and found, using a mean beam path length of 1,8 m, an emissivity of 0,2 (McAdams, 1954). Although this is not directly applicable to the geometry under consideration, it does support Vost's value.

It appears that some work must be done in resolving this issue. However, for HEATFLOW, use has been made of Hemp's work in its entirety.

A possible way of circumventing this problem is for the user to over-write the film coefficient. This could be catered for at the complex level.

3.5.4 Limitations of the simple level

These calculations are similar to those performed by one of the most widely used computer programs for the evaluation of heat flow in shafts (Gooch, 1971). The results are, therefore, consistent with those obtained using this program, especially considering that the major part of the change in condition of the air is due to auto-compression.

Compared with actual measured data (Oberholzer, 1986), the model used for shafts occasionally showed a slight disagreement in the moisture content at the outlet of the shaft : the difference between the dry- and wet-bulb temperatures is larger in the results of the calculations than it actually is, although the dry-bulb temperatures normally agree. This can be due to irregularities, not described by the model, such as :

(i) wet rock being hoisted out at the time the measurements were taken

(ii) wet rock waiting to be hoisted at the bottom of the shaft

(iii) the leaking of water and compressed air pipes.

In order to account for these particular cases, it is suggested that the outlet of the shaft is connected to the rest of the network using an 'other heat source' box (see section 3.10 of this document). This box can also possibly account for 'edge effects'. An 'other heat source' box can account for a dripping pipe in an adequate manner as it allows the moisture content, as well as the enthalpy of the ventilation air, to be increased in given quantities. For additional heat sources in the vicinity of shafts, a model for shaft pillar areas exists and is discussed in section 4.5.

Another limitation of the shaft model is the assumption that the shaft is always circular in cross-section. This will not be correct when the cross-section of the shaft is divided into sections (by a brattice wall, for instance). In the latter case, if the same shaft is used to exhaust air as well as for the intake, the additional heat flow will have to be accounted for using the 'linear heat load' item of data. This is a limitation, as this linear heat load will have to be estimated by the user, without the help of the program. It is also limiting because this type of heat flux is a counter-flow exchange.

3.5.5 Complex level

As mentioned earlier, the simple level for shafts is generally satisfactory. The only limitations, as described in the previous section, can easily be circumvented by an experienced user and their extent is small. Why implement a complex level, then? Because it might be useful to study the effect of atmospheric temperature variations on the temperature of the rock.

The temperature of the air flowing over the rock is not constant (for instance, due to diurnal variations). This changes the temperature of the rock surface and therefore affects the flow of heat. In order to model changes in the atmospheric temperatures, a sinusoidal representation can be used for both the diurnal and seasonal variations. The user will then be prompted for the type of variations he wants to study (diurnal or seasonal), the average wet- and dry-bulb temperatures and the amplitude of their variations. The frequencies are dictated by the type (diurnal or seasonal) of variation.

A similar approach could be used to assess the effect of switching the air coolers off and on, and to study the medium term consequences of these sudden temperature changes and the thermal storage effect of the surrounding rock. This complex level has not been implemented in the existing version of the program.

In order to compute the effects of a variation of air temperature in time, Duhamel's theorem will be used (Starfield, 1966, b). It gives the rock surface temperature response to a variation in air temperature, as an integral which can be conveniently calculated using discrete time steps.

A study conducted by Matthews (1986) using a program written by Mack and Starfield (1984) showed that diurnal variations are considerably damped out 2000 m down an intake shaft and that seasonal variations are simply delayed in time. It was therefore decided not to implement this level of complexity in the first version of the program, as:

(i) diurnal variations can be studied for the intake shaft only, using the program mentioned earlier

(ii) seasonal variations can be studied in a 'discrete' manner, in three representative cases : summer, equinox and winter. All intermediate cases can be interpolated.

The existing program for the simulation of these temperature variations is written in the same language as HEATFLOW and can be run on the same computer. The inclusion of this program in HEATFLOW would be an easy implementation at the complex level.

3.6 Tunnels

3.6.1 Introduction

In an average South African gold mine, there can be well over 100 km of tunnels, most of them located at levels with the highest virgin rock temperatures (Vost, 1982). For this reason, a major part of the heat pick up from the rock takes place in airways. The problem of heat flow in tunnels has been thoroughly investigated and, for relatively general cases, reasonable models exist. This problem is very similar to that of shafts, with two differences, with reference to the remarks concerning the shafts made in the previous section:

(i) auto-compression of air is not a major source of heat

(ii) the shape of airways is normally rectangular or square, with wetness occuring predominantly on the footwall.

The second point was a major consideration in choosing the model to be used in HEATFLOW.

The first point implies that the rock heat flow will be an important part of the total heat flow in tunnels (as opposed to shafts).

The second remark re-introduces the problem of the radiative heat exchange between rock surfaces, which could be ignored in the study of shafts. This heat will be transmitted by the hotter parts of the cross section (typically the dry parts) to the cooler parts. In any event, this heat is not exchanged between the rock and the air and, therefore, does not affect the temperature of the latter. But the effect of this radiation will be to modify the rock surface temperatures locally, thus

affecting the equations used in modeling the conduction of heat in the rock mass.

The models for the study of the heat problem in airways have been developed according to two different methods : an empirical and a theoretical approach.

3.6.2 Empirical approach

Although it is necessary for the verification of all models, the empirical approach has always proved to be, in practice, inefficient and in some cases even impossible. This is due to the particularly bad conditions found underground, which make measurements extremely inaccurate. Lambrechts (1967), though, published an empirical analysis of 320 mine airways, with different wet- and dry-bulb temperatures, virgin rock temperatures, air velocities, ages and perimeters. The wetness of the airway, an important parameter (as it was reported to cause up to a 40 % difference in wet-bulb temperature gradient), is not accounted for in a satisfactory manner (only a dry, damp or wet state was considered). In addition, the field data have been found to be very scattered, due, probably, to varying atmospheric conditions during the measurements. The reliability of these data is therefore questionable. The analysis highlights the impossibility to perform a scientific empirical study of the problem, as too many parameters influence the heat flow and they cannot be all accounted for by a simple empirical model.

3.6.3 Theoretical approach

A theoretical approach will therefore be essential, but must be verified for actual mining conditions. Two basic theoretical approaches have been used so far:

(i) the cylindrical cavity model, as discussed in section 3.5 for shafts, with adjustments for an uneven distribution of wetness

(ii) a rectangular tunnel model, where the heat flux from the rock is computed using finite differences.

Results using the former have been widely published, whereas the only paper based on the latter was published by Starfield and Dick[illegible]). These results were presented in the form of air[illegible], summarizing a data base built using an IBM 360 comp[illegible] perform the numerical analysis. They have been us[illegible] recently by Hemp (1985, a).

Vost (1982) reviewed the models for the prediction of air temperatures in circular tunnels available up to the early eighties. These methods result from the work of Starfield (the rapid method, 1969), Ramsden (1975) and McPherson (quoted by Vost, 1982). It shows that the two latter models are limited by the following assumptions:

(i) the flow of heat in the airway is one-dimensional

(ii) the radiation exchange between the wet and dry areas of a cross section can be ignored

(iii) an airway with a damp footwall (wetness factor of 0,2) is accounted for by a tunnel of which the footwall is perfectly dry, except for 20 % over which water is freely running.

One of the conclusions of Vost was that only Starfield's rapid method, an interpolation within the data base mentioned earlier, was theoretically sound enough, as it did not suffer from the above limitations and applied to square airways.

More recently, Bluhm et al.(1986), conducted a theoretical evaluation of the models existing for the prediction of atmospheric conditions in tunnels. They updated the work of Vost in the sense that they reviewed two recent models (Starfield and Bleloch's quasi-steady method (1983) and Hemp's simple approximate model (1985, a)). They did not draw any conclusion as to whether either of these two recent, more theoretically involved, models was preferable.

3.6.4 The quasi-steady method

Starfield and Bleloch solve the Diffusion equation (given in section 3.5.2) for a succession of steady-state situations for which $\partial u/\partial t \approx 0$. They also attempt to account for an uneven distribution of moisture on the perimeter of the tunnel in a appropriate way. The shape of the airway is not seen as a problem and therefore, they use a cylindrical model. In order to account for square airways with this model, they use an equivalent size determined on an equal cross-sectional area principle.

The method considers a section of a circular airway of which only the lower portion is damp. This portion subtends an angle $2.\beta$ at the center of the circle and its wetness factor is f. The model can be divided into two parts. Firstly, if the tunnel is assumed to be perfectly dry ($\beta \approx 0$), it solves the problem of the Laplace equation (the Diffusion equation, where $\partial u/\partial t = 0$) taking into account the variation of the rock temperature with time. The second step introduces the wetness (β not equal to 0). The polar coordinates are used (r, θ). Two equations express the heat flux at the rock surface. These are, for the dry portion of the surface ($\theta > \beta$) :

$$k.(\partial v/\partial r)_{r=a} = h.(v_s - DB) + K.(v_s - v_{wet}) \qquad 3.9$$

and for the wet portion ($\theta < \beta$):

$$k.(\partial v/\partial r)_{r=a} = h.(v_s - DB) + K'.(v_s - v_{dry}) + f.L_w.E.(e_{sat}(v_s) - e) \qquad 3.10$$

A step function (valued 0 when $\theta > \beta$ and 1 when $\theta < \beta$) is then introduced, in order to merge both equations into one. This step function is approximated by a Fourier series and this allows to solve the Laplace equation rather elegantly, using a Fourier series. The solutions (rock surface temperatures) are therefore given as a Fourier series.

3.6.5 Limitations and advantages of the quasi-steady method

In their paper, the authors mention that the iterations performed in order to find the rock surface temperatures can be stopped when the new temperature differs from the old one by less than half a degree. With eight terms in the Fourier series, the program needs 10 seconds to compute one cross section on an IBM PC computer. For a tunnel of 2000 m, with a step length of 100 m, this would lead to computing times acceptable only at a complex level.

The major problem posed by the quasi-steady approach remains the shape of the airway which is computed, as it does not solve the question of an equivalence between a rectangular and a circular airway. This masks an important aspect of the problem, as Bottomley and Bluhm (1985), using the work of Wiles and Grave (1954), showed that this is acceptable only when the footwall is totally dry. Hemp (1985, a) has shown the difficulties underlying the estimation of an equivalent radius.

Another limitation of the method is that it can only be used with a satisfactory degree of accuracy for tunnels older than six months. This will be particularly inconvenient for the simulation of any recently developed airway (see section 3.8). This also underscores the inadequacy of the method for the simulation of varying air temperatures. These limitations should nevertheless not mask the definite advantages of the method. It could be modified to cater for:

(i) the insulation of the airway on only part of its perimeter (Bottomley, 1985)

(ii) a non-isotropic nature of the rock around the tunnel

These advantages could be used at a complex level. The quasi-steady method remains the most elegant approach to the problem of heat flow in mine tunnels as it handles wetness very well.

3.6.6 Hemp's method

Hemp's goal (1985, a) was to try to use the circular airway approximation in order to compute heat-flow into non-circular tunnels. He therefore investigated the possible existence of an equivalent radius and of an equivalent wetness. His conclusions were that no such concepts could be introduced in a simple manner. He highlighted the lack of satisfactory models for the computation of tunnels. Nevertheless, the model introduced by Hemp is not afflicted by too many limitations (none of those quoted in section 3.6.3).

After performing a set of comparisons with Starfield and Dickson's 1967 data-base, Hemp concluded that there was no elegant way to fit the model to the data base and that the

equivalent parameters could be used only in association with correction factors. This is disappointing, but nevertheless leads to a quick model, which provides good agreement with the limited set of values available in the data base.

The results of the study show that a suitable equivalent radius does not exist, but that:

(i) for the calculation of the Fourier number, the radius should be computed on an equal cross-sectional area basis

(ii) for the Reynolds and Biot numbers and for fluid mechanics calculations, an equal hydraulic diameter should be used (the hydraulic diameter is equal to 4 times the area divided by the perimeter)

The study also shows that an equivalent wetness, given as $f_{eq} = 0,16.f^2 + 0,2.f$, applied uniformly around the circular perimeter is suitable for an accurate comparison. With these equivalent parameters, two correction coefficients must be used together with the circular airway model :

(i) the heat flow must be multiplied by 1,17

(ii) the moisture evaporation rate must be divided by 1+0,92.f

3.6.7 Limitations and advantages of Hemp's method

The main limitation of this model is that it is based too closely on a data base which does not cover a universal range of mining conditions. In addition, all the results in the data base have been lost and the research using these data will have an accuracy limited to that of taking repeat measures from the

simplified and small diagrams presented by Starfield and Dickson. This accuracy has been evaluated to 6 % by Bottomley and Bluhm (1985) and to 2 % by Hemp (1985, b), who justified this low error by the use of repeat measures with a vernier caliper. In any case, the error due to the method used to compute the data base (finite differences) can be estimated to 5 % (Bottomley and Bluhm, 1985). This is due to the limitations imposed by the relatively low power of the computers which were available in 1967, this allowing a limited number of nodes to be taken into account by the calculation.

Another limitation is that it is a "curve fit" and therefore lacks theoretical backing, although it uses the 'cylindrical cavity' model, thus allowing an accurate extrapolation of Starfield and Dickson's data base to be performed.

But it also has major advantages as it uses the only realistic modeling of South African gold mines tunnels : a square cross-section, with a wet footwall. It also is a very quick method, perfectly acceptable for a simple level. Its other major advantage is that it lends itself to the study of very young airways.

3.6.8 Simple level

Whatever the model, it will be imperfect, due to the difficulty in accounting for all the different parameters required to describe the heat and moisture flow problem in a tunnel. Therefore, the simplest model, which is not inconsistent with other existing models and available experimental data, will be suitable.

The method used at this level is therefore Hemp's, which is quick and allows square airways, possibly very young, to be accounted for correctly.

The practical calculations divide the tunnel into a number of steps (as derived from the step length, in metre, given by the user). For a step or section, the F(Fo,B) function is calculated using the same method as in section 3.5.2. The air temperatures (wet- and dry-bulb) at the inlet of the section are known from the previous step. The heat flow and moisture evaporation rate are calculated using 'equivalent' sizes and wetness factors, equivalent air temperatures and film coefficients (see section 3.5.2) and the correction factors as above. From those values, enthalpy and moisture content at outlet of the section are known, from which wet- and dry-bulb temperatures are derived. The heat flow into the next section can thus be calculated and so on until the end of the tunnel is reached. Auto-compression and any linear heat load in the tunnel are added to the enthalpy at each step.

In order to simulate the insulation of an airway on its entire perimeter, the film coefficient of the uninsulated airway (h) is replaced by h' given as : $h' = 1/(1/h + x/k)$, where x is the thickness of the insulation (in metre) and k the conductivity of the given insulation material.

The data required from the user are the length (m), the cross-sectional area (m^2), the perimeter (m), the wetness rating of the footwall only (see section 3.5.2) and a possible linear heat load (kW).

3.6.9 Complex level

At a complex level (not implemented in the existing version of the program), a more detailed modeling of special cases will have to be performed. These will concern :

(i) the non-homogeneity of the rock around the tunnel

(ii) the variation of air temperatures due to diurnal, or more importantly seasonal variations of atmospheric conditions, or irregularities in the operating conditions of air-coolers or fans

(iii) the insulation of the airway, possibly on only a part of its perimeter.

These special cases can be divided into two classes :

(i) the first one concerns relatively shallow mines, where the influence of surface temperature variations can be very important and where cooling and ventilation, for economical reasons, might be irregular.

(ii) the second one concerns deep mines : for those cases, the user might want to study the effect of insulating the airways, possibly on only a part of their perimeter and will need to input more detail concerning the effect of non-homogeneous rock surroundings.

For the first class, the model used at the complex level must take into account rapid temperature changes. This model will use Duhamel's theorem (see section 3.5) and will thus upgrade Hemp's method, as used in the simple level.

For the second class, a model which takes into account a non-isotropic distribution of rock and/or insulation around the tunnel perimeter will be necessary. The only model available at a present stage which enables these situations to be studied is the quasi-steady method.

In order to provide an answer to these different situations, it will therefore be necessary to introduce two different models for the complex level, when it is implemented.

3.6.10 Conclusions

As pointed out by Bottomley and Bluhm (1985), it is important to note that any model for an airway only approximates an actual situation, as a 3 m x 3 m airway will rarely have these characteristics for its whole length and its wetness will be assessed using only very subjective methods. One must also remember that the problem is complicated by, for instance, compressed air and water pipes, channels of water on the footwall or adjacent excavations. Bottomley and Bluhm state, in the same paper, that a finite element analysis will allow one to perform accurate modelling of the problem of heat and moisture in tunnels. One could also consider using finite differences.

The following steps could therefore be taken, in order to provide better answers for the prediction of heat flow in tunnels:

(i) conduct extensive underground experiments to gather enough information to test the available models

(ii) build another data base, similar to Starfield and Dickson's one, using finite differences or finite elements

(iii) determine, using (ii), possible equivalent radii and wetness factors (with correction coefficients) as an improvement of Hemp's model. The work will obviously include a lot of curve fitting or interpolation within the data-base mentioned in (ii), and the solution will therefore be limited by this aspect.

3.7 Stopes

Stopes, where new hot rock is continuously being exposed, are a major source of heat in deep mines. In addition, the use of service water (to allay dust, for instance) makes working conditions even less bearable, due to the humidity of the ventilation air. The workers' productivity is affected and they even risk heat stroke. The prediction of heat and moisture transfer in stopes thus plays an important part in any overall analysis.

3.7.1 Empirical approach

Only one example of an empirical approach leading to a model can be found in the literature. It is once again the work of Lambrechts (1959). This approach is once more very limited for the following reasons :

(i) the measurements taken were spot measurements, not a continuous monitoring of conditions. Therefore, the data obtained are not representative of average stope

conditions but of one moment in time in the stoping cycle.

(ii) the use of chilled service water had not been introduced in 1959. Therefore, it would not be possible to use this data for today's mining conditions.

(iii) the graphs produced are inaccurate for today's situation because of the huge change in the rate of production. For instance, the maximum face advance allowed for in this work was 4m/month. Today's average production rate is about 7 to 8 m/month.

(iv) the virgin rock temperatures were much lower than those experienced nowadays.

Present research work being carried out at the Chamber of Mines Research Organization is aimed at generating sound empirical data over a wide range of stoping conditions and over the entire mining cycle. This work involves the complete monitoring of numerous underground stopes (Alexander, 1986) and concerns parameters such as energy flows, temperatures at several locations, the flows of ventilation and compressed air and the flow of chilled service water, for instance.

Similarly, the final results of studies by Hemp (1984) could be used for the verification of theoretical models (stopes, together with tunnels and shafts).

3.7.2 Theoretical approach

For the reasons mentioned above (huge practical problems), only theoretical models have been used. The South African gold mining industry presently makes use of a number of different

models, all based on a similar philosophy, that of Starfield (1966, c). They all assume the stope to be of a regular nature (rectangular gullies, rectangular worked out areas, etc...), which might be a poor assumption but is essential in the production of a model.

The first and simplest model results from the work of Whillier and Ramsden (1975) and is based on a model developed by Starfield (1966). The input data required for using this method are : the stope width, the virgin rock temperature, the face advance and the stope span, plus, of course, some rock properties. The limitation of this simple model is that it is far too global to allow a precise description of the stope. For instance, it does not produce independent results for the worked-out areas and the face. It does not cater for the cooling effect of water, either.

The second model was devised by Van der Walt and Whillier (1979) and considers two areas of heat production : the stoped out areas and the production zone. This model requires the knowledge of additional data : the stope breaking (centares/month), the age of stoped out areas and the effective water cooling distance (this is the distance back from the face within which all the heat from the rock is removed by the service water). It is an improvement on the model above but remains limited because it still does not consider the stopes in enough detail and requires the knowledge of a parameter which is difficult to assess and cannot be measured directly : the effective cooling distance.

The third model results from the work of von Glehn and Bluhm (1986) and is a refinement of the above. It requires additional data for the gullies, as well as for the production zone. It can be adapted with a lot of flexibility to different stope lay-outs and computes separately the contribution of five

elements of the stope to the total heat flow. It shows a very satisfactory agreement with the experimental data available. As with the two models above, it nevertheless remains limited on several points :

(i) only overall heat transfer is considered, no differentiation being made between latent and sensible heat transfer

(ii) it considers the flow of heat at the face to be one-dimensional, therefore underestimating it.

(iii) it assumes that all the rock surfaces in the face area are wet during the total stoping cycle, which is far from being true.

(iv) it does not consider the extreme differences in the conditions prevailing during the stoping cycle, but assumes average conditions.

But, on the other hand, this model is detailed, simple and provides answers rapidly, as it is not iterative. It has therefore been selected for the simple level of HEATFLOW.

A modification to this model, based on work by von Glehn (1986), is presently being developed. It is an attempt to circumvent the limitations mentioned above as it models the stope face zone in a very precise manner (two-dimensional analysis of heat flow) and takes into account the variations of heat flow and moisture evaporation over the stoping cycle (the cycle is analysed and divided into major activities).

Because of the importance of the production of heat in stopes, a great degree of accuracy is required and, therefore, this model will probably be incorporated, when available, for the complex level.

3.7.3 Simple level

The model used divides the stope into five heat production zones:

(i) the gullies (strike and dip)
(ii) the ventilated worked out areas
(iii) the production zone (hangingwall and footwall)
(iv) the face and broken rock
(v) the other heat sources (mainly machinery).

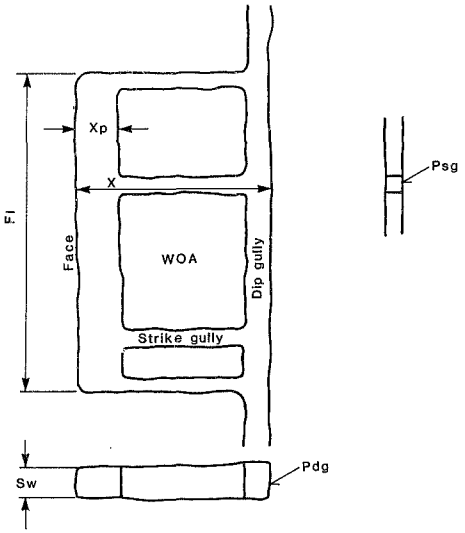
The amount of data required to go into such detail is obviously large, but the model remains simple in that a lot of defaults are provided. In case of a limited knowledge of the mine, these defaults will be reasonable guesses.

The data required are the geometrical details (see figure 3.1) :

(i) the stoping width (m) : this is the height of the production area
(ii) the face length (m)
(iii) the distance from the dip gully to the face (m)
(iv) the width of the production zone (m)
(v) the perimeter of the dip gully (m)
(vi) the perimeter of the strike gully (m)
(vii) the percentage of the stoped out areas that are back-filled
(viii) the number of strike gullies.

and the production information :

(i) the stope advance given in m/month but converted to m/s for the calculation,
(ii) the machine heat production (MJ/ton)



Fl : face length
Xp : width of the production zone
X : distance from the dip gully to the face
Sw : stoping width
Pdg : perimeter of the dip gully
Psg : perimeter of the strike gullies
WOA : worked out areas

Figure 3.1 : Stope geometrical data

(iii) the service water temperature at the inlet of the stope, TW_{in} (°C)

(iv) the quantity of service water used in tons per ton of broken rock.

The model uses the approximation of the semi-infinite solid (Hemp, 1982 and Holman, 1981) in order to account for the heat conduction to the worked out areas and the gullies. The heat transfer from the surface to air is described by the normal convective heat flow relationships which make use of a convective film coefficient. For the face area (including the footwall and hangingwall) and the broken rock, the rock surface is assumed to be at the wet-bulb temperature over the whole cycle (therefore, an infinite heat transfer coefficient is assumed). The heat from machinery is calculated using the machine heat (MJ/ton) and the rock production.

Two additional contributions are also accounted for : these are the cooling duty of the service water and the effect of the auto-compression or auto-decompression in inclined stopes. The duty (Alexander, 1986) is given by :

$$\text{duty} = WMF \cdot C_{water} \cdot (WB_{in} - TW_{in}) \qquad 3.11$$

By adding all the heat sources to the auto-compression term and by subtracting the cooling effect of the water, the increase in enthalpy for the air across the stope is obtained.

It should be noted that the film coefficients (see section 3.5.3) are difficult to assess with a satisfactory accuracy.

3.7.4 Moisture evaporation

This simple model calculates a value for the increase of enthalpy of the air flowing through the stope. But there is no

attempt made to model the change of moisture content of the air. This is due to the difficulty in describing the wetness of a stope. Instead, the value of the wet-bulb/dry-bulb gap of the air leaving the stope has to be specified. This is done from experience and as a general rule, would be in the range of 0 to 3 °C.

With a knowledge of the enthalpy and the difference between the wet- and dry-bulb temperatures, the actual values of the temperatures are then determined from standard psychrometric equations.

3.7.5 Complex level

At a complex level, as mentioned in section 3.7.1, more details will, in the future, be included in the model. These are the two-dimensional nature of the heat flow in the face area, the problem of the moisture evaporation and the time variations of the heat and moisture transfer, due to various stoping activities. This will include the cyclical use of chilled service water which affects the wetness of the rock greatly. The effect of the removal of broken rock will also be investigated.

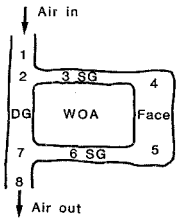
The stoping cycle will be broken down into four periods of different nature and length (re-entry, wetting-down, rock removal and drilling/blasting). The results (temperatures) will be given for average conditions as well as for each definite activity. In addition, the improved model will allow a better description of the flow patterns of the ventilation air and of the service water between the panels, in the stope. This improvement will allow the introduction of new technologies, such as transportable stope air coolers or back-filling, to be studied with great accuracy.

This level has not been implemented yet because the model is not fully developed and is still being verified by the Chamber of Mines Research Organization. One must not forget, however, that *even if this new model is very precise* in the description of the stope heat problem, it uses an ideal representation of the stope. The stope will in no case be regular and even at the complex level, serious deviations might occur, for this reason.

3.7.6 Modularity : stope as a sub-network

This section can be seen as introducing a possibly more complex level, which has not been implemented in the present version of HEATFLOW. The stope is a very modular box : it can be depicted as a dip gully from which strike gullies lead to the face. The stope can actually be seen as a smaller network made *up of boxes of different types* (Figure 3.2). A dip gully box in the centre has links to strike gully boxes which are linked together by the face and worked-out areas boxes. This allows one to consider the stope box as a sub-network : each time such a box is being edited, the user can 'zoom in' to get to the detailed level of the box.

For a better understanding of this future possibility, the reader might like to compare with the sub-network structure as reviewed in paragraph 4.7.



Is equivalent to:

DG : dip gully
SG : strike gully
WOA : worked out areas
FA : face

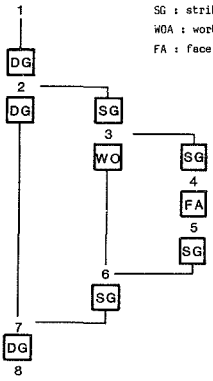


Figure 3.2 : Stope as a network

3.8 Development ends

3.8.1 Introduction

Development ends can be divided into two heat production areas:

(i) the face area, which includes 50 metres of tunnel back fro.. .he workings (Whillier and Ramsden, 1974)

(ii) the completed tunnel part, which is only slightly older than the final 50 metre section.

To ventilate these areas, the fresh air must be forced to the face or the used air exhausted through columns of ducts. Two types of development ends exist in South African gold mines. These can be represented in "boxes" as shown in figure 3.3 :

(i) single tunnel developments, where the air is forced to the face or exhausted using a column of ducts

(ii) twin developments, where one tunnel is used as an intake and the other as the outlet.

The problem is simpler in the case of twin developments where the situation can be regarded as an intake airway, the face area and an outlet airway. This approach is only valid if the interaction of both tunnels is neglected.

In the case of the single tunnel developments, the co-existence in the same tunnel of a flow of intake air and a flow of return air will lead to an interaction : leakage and heating of inlet air by return air. Iterations will be required for a proper assessment of air temperatures. In a simplified approach, a 'linear heat source' will account for these exchanges. Single tunnel developments are handled as the face area followed (or preceded, in case of forcing ventilation) by the tunnel section.

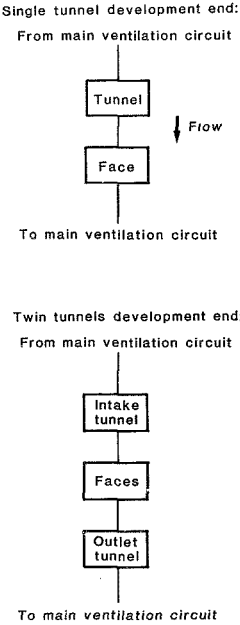


Figure 3.3 : Single and twin development ends

Two levels of complexity will, once again, eventually be available. But it must be remembered that the main limitation of both levels of calculation will be the determination of the production of heat at the face, for which a limited amount of experimental data is available. The models for this heat pick-up are *therefore quite coarse : generally, only educated* guesse; are made, taking into account production characteristics, the amount of explosives or of service water, *among other parameters.* In addition, special care has to be taken in the computation of the completed tunnel part, as it is very young.

3.8.2 Simple level

Depending whether it contains single or twin tunnels, the development end will be treated in a slightly different manner, as one or two airway sections will be computed. The algorithm described for calculating the heat flow into tunnels is used here.

At this level, the production of heat in the face area is given by equation 3.12, as quoted by *Whillier and Ramsden* (1974).

$$Q_{end} = DFA \cdot (VRT-WB) \times \left(\frac{PERIM}{12}\right)^{1,3} \times \left(\frac{k.\rho.c.}{13.10^6}\right)^{0,5} \quad (kW) \qquad 3.12$$

where DFA is the daily face advance, k the conductivity, ρ the density and c the thermal capacity of the rock. As for the stopes, *the problem of heat pick-up in the face area is* simplified in this model (see section 3.7.5, stopes), as Equation 3.12 assumes a one-dimensional heat flow.

The data required for the development end box at a simple level is therefore:

(i) tunnel characteristics : length (m), perimeter (m), cross-section area (m^2), linear heat source (kW), wetness factor

(ii) production particulars : DFA, the daily face advance.

From these parameters, an average age of the airway section is computed, considering the overall length of the development minus 50 metres of face, and the face advance. This is very approximative, but the crudeness of the model for the face heat production and the level (simple) do not motivate more detail.

3.8.3 Moisture evaporation

The other item of data required, similarly to the case of the stopes, is the difference between dry- and wet-bulb temperatures of the air leaving the face zone. The choice of this parameter to account for moisture pick-up can be motivated as for the stopes (section 3.7.4). The knowledge of the enthalpy increase across the face area gives the wet-bulb temperature of the return air. The dry-bulb is obtained by adding the temperature difference entered by the user.

3.8.4 Complex level

The complex level, when developed, will attempt to use the complex level for the airway part, a more precise model for the heat flow in the face area and, lastly, will try to account for the exchanges between the flows of air in and out of the developments, when applicable.

A detailed account of the first issue (the complex level for the airway part) was given in section 3.6.9. The only difference in the case of the development ends is the young age of the latter, especially in the section of the tunnel close to the face. This highlights the necessity to cater for ages less than six months, in the model for tunnels.

The complex model will perform a two dimensional analysis of heat and moisture pick-up in the face area in the same way as for stopes and to be consistent with the complexity used in the model for computing the tunnel section. The second major simplification of the simple model is that average conditions prevail over the development cycle : this can be circumvented as in the case of stopes, by dividing the development cycle into a number of activities, with specific durations, temperature and wetness conditions. The results will be given both as averages and for specific periods. This will allow, for instance, to cater for a more precise assessment of the effect of the removal of rock. A program by Mack and Starfield (1985), written in FORTRAN, performs this type of analysis for single development ends. It is under review at the Chamber of Mines Research Organization, which recently conducted an extensive monitoring of a developing tunnel and therefore has experimental data available, though they still need to be further analysed.

When this program is verified, it might be used for the complex level for development ends.

The last issue to discuss here is the problem of the interaction of intake and outlet air flows. In the case of twin developments, there is no such problem, as the inlet air does not come into 'contact' with the outlet air. Single tunnel developments, at a complex level, will pose this problem. Two new items of data will have to be entered :

(i) the extent of the leakage from the duct to the tunnel, or vice-versa (low, medium or high),

(ii) the quality of the insulation of the ducts (low, medium or high; Whillier and Thorpe, 1971).

These items of data will be used in iterative procedures which will compute a balance in the heat exchange. The problem of the radiative heat (between the rock and the column of ducts) will also have to be investigated. Work by Ouederni (1984) on this problem has lead to the writing of a program, in FORTRAN, called Climend. This program has not been designed for South African gold mines and, before it can be used at a complex level, it will need to be verified on a wide range of mining situations. But the details taken into account in this program are those required for the complex level.

3.9 Hoists

The routine for computing the heat flow in these boxes is the simplest one used in the program. It assumes that the hoist adds a quantity of heat (expressed as a fraction of the rated power of the machine) to the flow of air. Only sensible heat is increased, as the energy transfer does not raise the moisture content of the air.

The data needed to perform the calculation are therefore limited to three items:

(i) the rated power of the machine (kW)

(ii) the percentage of this power lost as heat to the air (%)

(iii) the percentage of utilization of the hoist (%).

This second item of data has typical values : it can thus be provided as a default for the whole network. It must be noted that the material hoisted gains potential energy and as a general rule, only 20 to 30 percent of the electrical power is lost as heat.

These data are used in the following fashion:

(i) the apparent specific humidity (in kg/kg) and the enthalpy per unit of mass of air (in kJ/kg) at the inlet are first calculated

(ii) the heat flow due to the machine (rated power x fraction lost as heat) is translated into an increase in enthalpy of the air, according to :

$$\Delta H = \frac{\text{Rated Power} \times \text{Percent as heat}}{\text{Mass Flow} \times 100} \qquad 3.13$$

(iii) The enthalpy per unit of mass at the outlet is the sum of the enthalpy at inlet and the enthalpy increase. The apparent specific humidity at the outlet is equal to its inlet value (dry transformation). With these items of data and the knowledge of outlet pressure, the outlet wet- and dry-bulb temperatures can easily be computed.

This type of calculation does not require a more complex mode. *Thus only one level of complexity is provided.*

The assumption that only sensible heat is produced in the case of a hoist chamber, is justifiable. In addition, if the air is too dry at the outlet of one of these boxes, it will tend to vaporize water in the following boxes, thus compensating the possible underestimation of moisture pick-up.

In case the user feels that moisture pick-up takes place, it is always possible for him to substitute for the 'hoist' box a box of the type 'other heat sources', in which the moisture pick-up is taken into account. In general cases, though, this is not necessary.

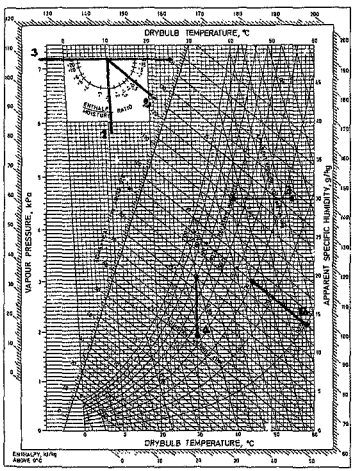
3.10 Other Spot Heat Sources

3.10.1 Introduction

One could assume that all spot heat sources are similar to a hoist or a winch end, therefore, that it is possible to describe them and assess their effect on the ventilation air using the above procedure. In fact, the limitation concerning moisture imposed on the latter model is not correct in the case of some spot heat sources. For instance, a pile of wet broken rock waiting to be hoisted at the bottom of a shaft can be considered as a spot heat source where moisture pick-up will be the major part of the transformation.

In order to describe the phenomenon fully, it is necessary to add to the data provided for hoists and winches, some information about the proportion of the total heat used in heating the air (sensible heat) and the proportion used in vaporizing the water (latent heat). The most convenient variable available for this purpose, is the Enthalpy-over-Moisture ratio (E:M), given in kJ/g. This parameter is widely used and accepted for most air-conditioning and psychrometric calculations. It has been chosen instead of a simple factor like the difference between dry-bulb and wet-bulb temperatures at the outlet (as for stopes and development ends) because it actually describes a path on the psychrometric charts. This ratio helps the user to visualize the transformation which is occurring, more than the guess-work using a temperature difference would do.

The use of this parameter is explained in Figure 3.4, an extract from Barenbrug (1974). In the upper left corner of the chart, a semi-circular diagram gives values of the enthalpy/moisture ratio. *Actually, this diagram gives the slope of the straight* line representing the transformation which occurs when the



(1) Enthalpy/moisture = 2,5 => constant dry-bulb

(2) Enthalpy/moisture = 0 => only moisture pick-up

(3) Enthalpy/moisture = ∞ => no moisture pick-up

Figure 3.4 : Enthalpy/moisture ratio

moisture pick-up and the enthalpy increase are in the given ratio. For instance, line 1 is a transformation where the Enthalpy/Moisture ratio is 2,5 kJ/g. This line is parallel to the line of constant dry-bulb temperature and, thus, there is no change in the dry-bulb temperature. Line 2 is a transformation where this ratio is 0 : there is no enthalpy increase and thus the wet-bulb is nearly constant. Line 3 has a ratio of infinite value and thus no moisture evaporation will take place and all heat transfer is sensible.

The only drawback of this ratio is that the units (kJ/g) are not S.I. It would perhaps be neater to use a factor such as the ratio of sensible heat over latent heat. But the habit in the mining ventilation community and the support of the Barenbrug Charts make the choice of E:M more relevant, as does the common use of this factor by environmental engineers (in air conditioning, for instance).

3.10.2 Calculations

The calculations are a little more involved than in the case of a purely 'dry' transformation.

The user is prompted for two items of data:

(i) the enthalpy-over-moisture ratio characteristic of the transformation of the air (kJ/g)

(ii) the heat change (kW) which will be converted to the enthalpy increase of the air if the previous ratio is not 0 or to the sensible heat increase of the air if the given ratio is 0.

Depending on the value of the enthalpy-over-moisture ratio, the calculations are performed as follows:

(i) Enthalpy/Moisture (E:M) not equal to 0 : the enthalpy increase (ΔH) is derived from the input data, and the moisture increase (in kg/kg) is simply $\Delta ASH = \Delta H/E:M$. The enthalpy of the air at the outlet, as well as its moisture content and therefore the wet- and dry-bulb temperatures, are easily computed.

(ii) Enthalpy/Moisture (E:M) = 0 : the enthalpy increase (ΔH) is also zero for the air. The sensible heat (Q_{Sens}) added to the air is derived from the input data and the total heat is : $\Delta H = Q_{Sens} + Q_{Lat}$. The latent heat ($Q_{Lat}$) is given by : $Q_{Lat} = L_w \cdot \Delta ASH$, where L_w, the latent heat of vaporization of water, is given by : $L_w = 2501 - 2{,}387 \cdot WB$ (kJ/kg)

It can be seen that the latent heat depends on the air wet-bulb temperature which is not known for the box. Once again an iterative process would be required to obtain a better accuracy. However, the influence of the wet-bulb temperature is very limited and this temperature is in a narrow range. Thus, an average temperature of 25 °C has been chosen, and if the wet-bulb temperatures remain in the range 15 to 35 °C, the error in L_w is less than 1 per cent, which is of no consequence when compared with the possible error made by the user when estimating the enthalpy-over-moisture ratio.

From this average value of L_w (2441 kJ/kg), ΔASH can be computed. Thus, the moisture content at the outlet as well as the enthalpy are known and this allows the calculation of the wet- and dry-bulb temperatures at the outlet.

3.11 Fans

3.11.1 Introduction

The solution for the fan box is intimately linked to the interfacing of the program with a ventilation network analysis tool (see section 3.13). In the latter, a fan is a branch with a characteristic curve which gives pressure loss as a function of the quantity which flows through the fan. From these two parameters, the power given to the air by the fan can be computed using :

$$\text{Power} = \text{Quantity} \times \text{Pressure increase} \qquad 3.14$$

The electrical power used by the fan is then given by :

$$\text{Electrical Power} = \frac{\text{Power}}{\text{Efficiency}} \qquad 3.15$$

The heat dissipated by the fan in the air is equal to the electrical power, and is purely sensible, as the moisture content does not increase due to the operation of a fan.

3.11.2 Data input

The fan operating conditions could be calculated using a ventilation network analysis program. Two levels of complexity in the input of data are thus required.

In the first level (the only one implemented at present), the user inputs the values of quantity and pressure loss characteristic of the operating point of the fan (it is assumed that he knows them from measurements or an external ventilation network calculation). In the second level (which could be introduced in the future), the fan curve (pressure loss versus quantity) is entered. If a simultaneous ventilation network

calculation is performed, mass flow is not required from the user, as the operating point is found by the program. If this calculation is not performed, the user will have to input the air mass flow.

Ten points on the fan curve are input. This gives an accurate representation of the fan, especially around the operating point, as it is possible to concentrate the points in this area (Chorosz and Deliac, 1985). Efficiency is also given as a function of quantity, using ten points.

3.12 Air Coolers

3.12.1 Introduction

Whatever their type, the effect of air coolers works on the same principle : their cooling duty is subtracted from the enthalpy of the inlet air and, as a general rule, the air is saturated at the outlet. This last assumption is motivated by the fact that the need for an air cooler occurs when the air temperature is too high : the refrigeration will typically cool the air to a temperature lower than the wet-bulb temperature at inlet. Only condensation can therefore take place.

Two levels of complexity have been made available.

3.12.2 Simple level

At the simple level, the calculation is performed on the basis of either the duty of the cooler or the temperatures at the outlet. The user can choose either option. If design duty is input, the enthalpy of the air at the outlet is calculated as the enthalpy at the inlet minus this duty. Then, saturated

conditions being assumed, the air temperatures at the outlet are easily calculated. If design temperatures at the outlet are chosen as input data, the duty is calculated as the difference between the enthalpy at the inlet and at the outlet (the duty is then positive). The resultant duty will help the user to choose the cooler which will provide the correct outlet temperature.

3.12.3 Complex level

The second (complex) level involves technical characteristics of the cooler :

(i) the water flow rate (ℓ/s)

(ii) the water temperature at the outlet (°C)

(iii) the factor of merit (non dimensional).

These items of data are used according to the work of Bluhm (1980), which is generally accepted by the South African gold mining industry.

First, R, the capacity-ratio, is calculated using thermal properties of the water and the air.

With the knowledge of the factor of merit (F), the water efficiency (E_w) is computed as:

$$E_w = (1 - e^{-N(1-R)}) / (1 - Re^{-N(1-R)}) \qquad 3.16$$

where $N = \left(\frac{F}{1-F}\right) \times \left(\frac{1}{R}\right)^{0,4}$

The temperature of the water at the outlet of the cooler, t_{wo}, is calculated using:

$$E_w = \frac{t_{wo} - t_{wi}}{t_{ai} - t_{wi}} \qquad 3.17$$

From this, the quantity of heat transferred from the air to the water is assessed. The absolute value of this quantity of heat is the duty of the air cooler, and the calculation is completed as for the simple level, when design duty is provided.

It should be noted here that cooling coils are also used in South African gold mines and that the theory governing their performance will have to be incorporated in the future.

3.13 Ventilation Network Calculations Interfacing

As explained in section 3.2.2, the user must input the mass flow of the air (kg/s) for each box, at the simple level. This item of data, in the case of a proposed mine lay-out, is obtained from a computer simulation of the network using a mine ventilation network analysis program (or from design requirements). It will be possible, in the future, to run such a program (VENTFLOW) together with HEATFLOW (Wernick, 1986). The possibility of interfacing both types of programs is reviewed in the following sections.

3.13.1 Data required

The data required to study a mine ventilation network are as follows:

(i) a map of the network
(ii) the nominal resistance factor of each 'passive' branch (a passive branch is an airway, shaft or stope, for instance, where no fan is installed and therefore where no pressure increase takes place),
(iii) the depth of each node
(iv) the characteristics and location of all the fans installed in the network.

(v) the temperature of the air in all parts of the network, in order to achieve a better accuracy for the calculation.

The latter allows the program to calculate precisely the density of the air, which combines with the nominal resistance factor (calculated for standard temperature and pressure conditions) to give an accurate resistance of the branch to the flow of air.

The set of the above data is a sub-set of the data input for the heat flow problem:

(i) The map of the network is given in a very similar way

(ii) The resistance factor :

- tunnels, shafts and stopes are plainly 'passive' branches. Their resistance factor is a function of geometrical dimensions and the friction factor. If he feels it is necessary to modify the resistance factor computed by the program, the user can overwrite it at the editing.

- hoists, other heat sources and air coolers are branches with a resistance factor equal to zero

- development ends are also branches with a resistance factor equal to zero as they are not part of the main ventilation network. A secondary fan is needed to force air from the ventilation circuit to the face and return it to the circuit at the same point, generally at a higher temperature.

- fan boxes are treated in the same way as fans.

(iii) the depth of each node is required in both ventilation and heat flow problems

(iv) the characteristics of the fans can be input at a complex level. Therefore, when a ventilation network calculation is performed, the complex level must be selected for all fan boxes.

3.13.2 Leakages

The only limitation encountered with this type of approach to the ventilation problem concerns leakages. These are generally treated differently from other passive branches in ventilation calculation programs (Deliac et al., 1985). The data required does not include the resistance, as it is normally computed from geometrical data which is not available in case of a leakage, or from the pressure loss and the quantity across the leakage : the pressure loss can be assessed only with great difficulty in the case of a leakage. Quantity across the leakage will be used as input data in what is generally called a 'fixed quantity' branch. The ventilation analysis program computes for all the fixed quantity branches, the resistance factor needed to ensure:

(i) a flow of air as fixed by the user

(ii) compatibility with the rest of the network.

For obvious reasons, there cannot be too many fixed quantity branches in the network (generally less than 7 per cent of the total number of branches) in order to reach a solution (Chorosz, 1984).

Leakage branches are branches for which little is known about their characteristics : this is not compatible with the definition of a box in the heat flow problem. Therefore,

leakages will not be accounted for in the same way as in a standard mine ventilation network analysis program, but as tunnels of known characteristics.

3.13.3 Interaction of the ventilation and heat flow prediction programs

The last item to be discussed concerns the accuracy of both the ventilation and heat flow calculations. As previously mentioned, the knowledge of the air temperature in all parts of the network gives better solutions for the ventilation problem. This knowledge results from a heat flow calculation. There will therefore be an iterative process involved :

(Step 1) with previously correct or guessed temperatures, a ventilation calculation is performed. This gives values for pressures and mass flows in the whole network.

(Step 2) with the knowledge of these mass flows and pressures, the heat flow problem can be solved : this produces a better estimate of the temperatures at each point of the network

(Step 3) with these new temperatures, a new ventilation calculation is performed : better estimates of quantities and pressures are thus obtained, in order to proceed with step 2 again.

This iterative process stops when the maximum temperature correction is less than a fixed limit.

3.14 Limitations of the Models

3.14.1 Accuracy of input data

The most important limitation is not imposed by the models but is linked to the accuracy of the input data.

In the case of a planned mine, the data are only a guess as to what future mining operations will be. Very often, an accurate idea of what the mine will look like is not even available. In the case of an existing mine, data such as wetness are assessed on a rule-of-thumb basis and measured data are bound to be inaccurate (a mine is not the best type of laboratory).

Therefore, as the accuracy of the results will not be any better than the accuracy of input data, a lot of attention must be given to the collection of data. The program, in order to diminish the risk of inaccuracy, must be used for different cases (different lay-outs and different data). A measure of the accuracy of the solution is obtained only if it is backed by numerous simulations, enabling sensitivity studies to be done.

3.14.2 Accumulation of error

Among other limitations of the program, the network structure and order of calculation tend to lead to a poorer precision. From one box to the following one, any error in the temperatures is transmitted and increased. This phenomenon, though, is limited by the following facts:

(i) some models lend themselves to self-correction : if the air entering an airway is too cold (due to a previous error), the heat flow will be larger than it would have been with correct values of the temperatures. Thus, the error on temperatures will be smaller at the outlet of the given tunnel than at the inlet.

(ii) the 'error-counter' is set back to zero in two cases encountered quite often : firstly, when an air-cooler is reached, with design outlet temperatures as input data, and, secondly, when disagreement is expressed by the user concerning the results. The program then uses 'correct' values of the temperatures to proceed with the following calculations.

3.14.3 Wetness

Another limitation of the program is the rather extensive knowledge it requires from the user concerning wetness. Wetness being generally given as a non dimensional value varying between 0 (bone-dry) and 1 (running water), no other method than rule-of-thumb is given for its assessment. Generally, in tunnels, only the footwall is considered to be wet. This can include an open drain, which of course, is fully wet. Under the same restriction comes the evaluation of the enthalpy/moisture ratio. The user will find examples concerning these items of data in the 'help-pages' of the program.

In addition, for stopes and development ends at the simple level, the difference between dry- and wet-bulb temperatures at the outlet is requested from the user as input data. This is due to the present non-availablity of models which, from an accurate description of wetness in the face area, could give an assessment of the latent part of the heat pick-up.

3.14.4 Water reticulation

Finally, the present version of the program does not consider the interaction of two networks, namely:

(i) the ventilation air network

(ii) the water reticulation network.

The most sensitive element in this interaction is the heat exchange between open drains and the intake air, which can be approximately catered for as a linear heat source. However, the air and water generally come into contact in counter-flow, which does not simplify the problem. Another heat exchange takes place between the chilled water pipes and the ventilation air. This is an important element in the determination of the location of air coolers.

CHAPTER 4 : DESIGN CHARACTERISTICS : AN INTELLIGENT SYSTEM

When a new tool becomes available, new methods must be developed in order to allow it to be used with the *maximum efficiency*. HEATFLOW not only provides accurate calculation routines, but also introduces a method and a framework for studying a mine in *terms of heat flow*. The new method must be easy to use by the mining engineer. All aspects of this ease of use and efficiency are reviewed in this chapter.

4.1 Provision of Defaults

The program includes an option called 'defaults'. This option has two functions:

(i) input of global data (see section 3.2.1)

(ii) input of default data.

The difference between *global* and *default data is small* but it has important consequences in the program.

4.1.1 *Global data*

Global data, firstly, are data given to be valid for the whole network. For instance, the name of the project or the virgin rock temperature at surface level are global data : they are given once for the entire network. A list of these data is given in section 3.2.1.

4.1.2 Default data

Default data are not directly used by the program, except in order to make the input of data simpler. For instance, the perimeter of airways is an item of default data : though it is

given for the whole network, it can be overwritten by the user *when required*. At the time of creation of a tunnel box, for instance, the item called 'perimeter' will already have been initialized to its default value, before the user starts inputing data for the box. It is possible for him to keep this value or to reject it by replacing it with the correct figure.

This feature proved very useful in the case of shafts, for instance : a shaft must be divided into many boxes in order to allow for the removal of airflow at each level. All the sections of the shaft will have a certain number of common characteristics : diameter and wetness factor, for instance. The length of the section is normally not constant from one section to the next : it is therefore not a default.

The items of data which have been selected as being default data are listed for each box type :

(i) Tunnels and shafts : age (years), cross-sectional area (m^2) and perimeter (m) or diameter (m), wetness factor (non dimensional) and linear heat load (kW)

(ii) Development ends : cross-sectional area, wetness factor, perimeter, advance (m/month) and difference between dry- and wet-bulb temperatures at the outlet (°C)

(iii) Stopes : distance from the dip gully to the face (m), width of the production zone (m), advance (m/month), stoping width (m), perimeters of dip and strike gullies (m), temperature of the service water at inlet (°C), machine heat (MJ/ton) and difference between dry- and wet-bulb temperatures at the outlet

(iv) Air coolers : wet- and dry-bulb outlet (°C), water temperature at the inlet, water flow rate (ℓ/s) and factor of merit (non dimensional)

(v) Hoists : percentage of the rated power lost as heat in air

(vi) Fans : efficiency.

4.1.3 Program specifications

In addition to the above parameters, a certain number of program specifications can be set in this option. These are:

(i) the type of screen used (text or graphics)

(ii) the emitting of a warning sound where a mistake is made (yes or no)

(iii) the possibility of over-writing virgin rock temperatures (yes or no)

(iv) the level of expertise of the user (novice or expert)

(v) the automatic saving of data during creation and editing a new network (yes or no)

(vi) the checking (fool-proof) function (yes or no) : this option is particularly convenient for the expert user who knows the program well enough to avoid major mistakes and who does not want to be prompted for confirmation when he selects 'quit', for example

(vii) the possibility of over-writing wet- and dry-bulb temperatures resulting from a calculation when more accurate data are available (yes or no).

The previous set of parameters and option choices allows both experienced and novice users to tailor the program to suit their particular needs.

4.2 Network Display

The basic aid to the input of data, as well as to the reporting of results, is a map of the network which is partially displayed on the screen. In order not to restrict this program to a graphics screen (an optional device on micro-computers), extended ASCII characters are used to produce a semi-graphic display of the network. The boxes are pictured as small frames, containing a code related to their type (Figure 4.1).

They are ordered on the screen according to the following convention : the direction of air flow is from top to bottom. All the mine intakes are on the top line. The user is given the opportunity of setting the horizontal coordinate of the boxes only. This choice allows him to reduce the number of intersections between box connections. It also enables him to isolate parts of the mine (e.g. a given level) for clarity.

A typical network is depicted on the screen, as in Figure 4.2.

With the 'arrow keys' (located on the right part of the key-board), the user can move the screen over the network, to display parts which were previously concealed. The network can thus have an unlimited span in both directions of the plan. The screen is used in the same way as a microscope, to show parts of the network only. The arrow keys are similar to the adjustment knobs used to move the slide under the objective of the microscope.

The network is always displayed on the screen. With this lay-out, the problem of heat flow becomes extremely visual, as the influence of boxes on each other can be seen as a spatial relationship.

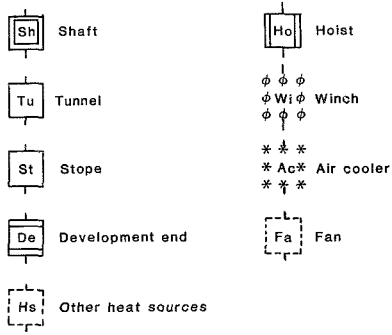


Figure 4.1 : Box types

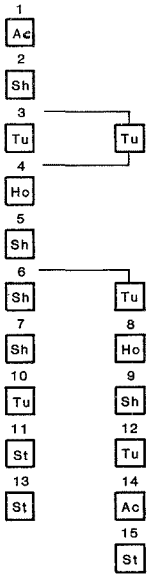


Figure 4.2 : Network

4.3 Help Function

One of the basic prerequisites of interectivity is that, wherever the user finds himself in HEATFLOW, he should be able to get help from the program. This feature exists in HEATFLOW and is called the 'Help' function. Whenever key '?' or key 'F1' is pressed, the execution pauses and a screenfull of text is displayed : this will be referred to as the help-page. The program contains 99 help-pages, in the form of a help-book.

Each help-page is assigned to one or several precise locations in the program. For instance, if the user is inputing data for a new tunnel and the cursor is positioned at 'wetness factor', the help-page which would be displayed when pressing '?' or 'F1' must explain how to enter this item of data, what kind of wetness factor is considered (from among the numerous definitions) and give typical values.

4.4 Side Psychrometric Calculations (PSYDE)

Whenever key 'F7' is pressed, execution is paused and a window appears on the left side of the screen. This window is used for psychrometric calculations, as a hand-held calculator, aside from the computer. It however allows only psychrometric calculations to be performed. It uses standard psychrometric routines.

4.4.1 *Input data and results*

In the PSYDE window, the user is prompted to input data according to the following rules:

(i) the pressure must be provided

(ii) in addition, two of the following parameters must be provided :

- wet-bulb temperature	(°C)
- dry-bulb temperature	(°C)
- enthalpy	(kJ/kg)
- Sigma heat	(kJ/kg)
- relative humidity	(%)
- Apparent specific humidity	(g/kg)

The calculator then provides the four missing items plus the following list:

- density of mixture	(kg/m^3)
- density of air	(kg/m^3)
- dew point	(°C)
- saturation pressure	(kPa)
- vapour pressure	(kPa)

For obvious reasons, all combinations of the above input parameters do not lead to an acceptable result. For instance, wet-bulb temperature and sigma-heat are too closely related to be used together. These two parameters are represented by parallel lines on the psychrometric charts : it is therefore impossible to find their intersection. The same can be said of wet-bulb temperature and enthalpy (nearly parallel representative lines) and enthalpy and sigma-heat. With the exception of these cases, all other combinations lead to very good results.

4.4.2 An example

An example is given below and illustrated by Figure 4.3.

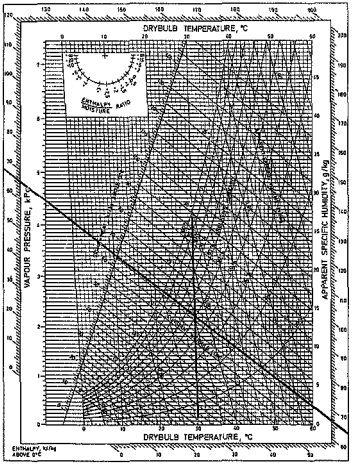


Figure 4.3 : Example of the use of the psychrometric routine, PSYDE.

The data input by the user are:

(i) pressure : 100 kPa

(ii) dry-bulb temperature : 30 °C

(iii) enthalpy : 66 kJ/kg.

The intersection of the constant enthalpy and constant dry-bulb temperature lines on the psychrometric chart for 100 kPa gives the missing data.

The results provided by PSYDE are:

wet-bulb temperature	: 22,35 °C
sigma-heat	: 64,69 kJ/kg
moisture content (apparent)	: 14,03 g/kg
relative humidity	: 52,01 %
saturation pressure	: 4,24 kPa
vapour pressure	: 2,21 kPa
mixture density	: 1,14 kg/m^3
dry air density	: 1,15 kg/m^3
dew point	: 18,28 °C

4.5 Shaft Pillars

4.5.1 Introduction

Although they cannot all be considered as boxes, three modules are selectable, in addition to normal boxes, in the creation option. These are:

(i) shaft pillars

(ii) sub-networks

(iii) recirculation sub-networks.

Shaft pillars are reviewed in this section and the two other 'box' types in the following two sections. They offer a convenient way to input data not covered by the normal box types and their main function is to allow the user to isolate a part of the network in order to treat it in a slightly different manner.

The shaft station area appears as a maze of tunnels of different geometries and of spot heat sources (for example : transformers, small pumps, welding equipment and dust filtering fans). There will also normally be a number of locomotives operating near the station. It is therefore not a simple box since it contains elements such as 'tunnels' and 'other heat source'.

In order to account for shaft station areas, two approaches are possible : a complex one and a simple one.

4.5.2 Complex approach

This approach is not so much complex as detailed. It simply expects from the user that he carefully describes the structure of the shaft pillar network, using as many boxes as necessary.

This is a time consuming procedure but brings maximum accuracy to the calculation, provided all the input data are known with precision.

4.5.3 Simple approach

A simpler approach will only require from the user that he inputs :

(i) the total length of tunnels included in the shaft area

(ii) additional data, as for tunnels : it is then assumed that all tunnels in the shaft pillar area have the same cross-sectional area, the same age and the same perimeter.

(iii) the total heat load of the machinery in the shaft pillar area (kW)

(iv) the air massflow (kg/s)

The calculation then determines the heat flow from the tunnel sections, using the RAMSDEN (1975) equation :

$$Q_{tunnel} = 5,57\ (f + 0,255)\ .\ (VRT - DB)\ .\ CF \qquad 4.1$$

with a correction factor, CF, given by :

$$CF = (PERIM/12)^{0,437}\ .(AGE/3)^{-0,147}\ .(k/5,5)^{0,853} \qquad 4.2$$

Note : this equation makes use of an average film coefficient and, hence, no specific information is required on air velocities.

With this calculation of the heat flow from the tunnels and the input value of the machinery heat, the enthalpy of the air at the outlet of the shaft pillar area can be determined. In order to assess the outlet air conditions, an enthalpy-over-moisture ratio determined from a number of case studies is used (CULVERWELL, 1986). The user is therefore not called upon to specify this item of data.

4.6 Sub-networks

In order to bypass the limitations of the number of boxes per network imposed by the amount of memory available in the computer (which is directly dependent on the characteristics of the computer's processor), an additional box type has been introduced : the 'sub-network' box. Its function is to link the network it belongs to with another network, the sub-network, which is stored on disk. The only specific item of data memorized in the sub-network box is therefore the file name of the associated network. This sub-network is a network on its own : it can be edited and computed separately from the main network. Its dependence on the main network is that the inlet temperatures are normally a function of the other boxes in the main network. But this is no limitation, as the user might decide to input his own values for these temperatures.

At the main network scale, the sub-network is just another box. From inlet conditions, outlet temperatures are computed. This means that there is a limitation for the use of this feature : *if a group of boxes has been isolated as being a potential* sub-network, it must have one inlet and one outlet only.

While editing the main network, the user can 'zoom' in on the sub-network level : the relevant file is loaded from the disk into the computer memory. Once the data have been entered they are stored on the disk as a network. This procedure obviously expands the number of boxes that the program can process, as the space necessary for storing the additional data is used on disk (where space is virtually unlimited, when compared with computer memory).

During the calculation option, when the sub-network box is reached, the data already computed at the main level is stored on disk and the sub-network is loaded into memory and

calculated as a normal network, using as inlet conditions the values resulting from calculations at the main-network level. Once this interim calculation is finished, the result is returned and provides the outlet conditions of the sub-network box considered : the calculation can resume at the main-network level.

In order to limit the programming complexity of this feature, nested sub-networks are not allowed. This feature is very similar to what the programmers call 'overlay' or to the use of 'virtual memory' on computers.

4.7 Recirculation

A new trend has appeared in recent years in the South African gold mining industry which is controlled recirculation of ventilation air (Burton et al. 1984). Its principle is to re-introduce, after cooling, a portion of the air from the outlet of a working area into the intake system of the same working area. Recirculation creates the potential hazard that a fire would lead to noxious gazes being introduced into the intake system. All recirculation schemes therefore require a fire detection system which can stop recirculation as soon as a fire occurs.

The benefits are a reduction of auto-compression heat loads together with an increase of ventilation volumes without an associated increase in main fan power (among other practical advantages). In the program, recirculation is allowed in a box similar to the 'sub-network' box (discussed in section 4.6). The calculations are performed in this box as for any other sub-network, except that they are subject to an iterative process. In the 'recirculation' box, three items of data are stored :

(i) the file name under which the recirculation sub-network is stored

(ii) the percentage of the outlet air recirculated

(iii) the cooling duty applied to the portion of the air which is recirculated.

An iterative process is necessary as the temperatures at the inlet depend on the temperatures of the air at the outlet, to which a given amount of cooling is applied.

Once again, as was pointed out for the sub-networks, the recirculation area must be isolated and have only one inlet and one outlet.

4.8 Calculation Option Characteristics

As the calculations can sometimes become lengthy, three special features have been included.

4.8.1 Progress of the calculation

Of all the models used, only the tunnel, shaft and development end models are time consuming. This is due to the fact that they divide the box into sections, performing iterative calculations on each section. In order to keep the user aware of the progress of the calculation, the box being calculated (tunnel, shaft or development end) is highlighted. The length of tunnel already calculated is displayed in a small side window. It is thus possible to check that the program has not stopped (as something keeps moving on the screen) and how much of the network has already been computed.

4.8.2 Re-calculation

When a change is made to the structure of the network, or to the data input for a given box, the calculations start again from the level where this change has an influence. Therefore, if the duty of an air cooler just before a stope is changed, the calculations, in a new simulation, will be carried out from the air cooler, through the subsequent stopes and towards the outlet.

4.8.3 Stopping the calculation

If any key is pressed while the calculation is being preformed, this will cause the program to pause. The user will be prompted for a confirmation of the decision to stop. If the calculation is halted, all the data already computed are kept in memory. Using this facility, it will be possible to immediately assess the effect of a modification at the top of the network without having to compute it totally.

4.9 *Reports : Output of Results*

The printed output of data for reports is a very important function of this kind of scientific program. Once a simulation has been performed, reports are required for:

(i) a global account of the simulation

(ii) communication of the results

(iii) archive purposes.

In order to have a clear vision of the heat flow problem for the entire network, the user will need a printed report.

Four types of reports are provided. Examples are given in Appendices A1 to A4.

4.9.1 Global data report (Appendix A1)

This report is nothing more than a summary of input global data. It does not provide any sort of result. The lay-out is tabular.

4.9.2 Node data report (Appendix A2)

This report will give, for each node, in tabular form :

(i) the depth (m)

(ii) the virgin rock temperature (°C)

(iii) the pressure (kPa),

4.9.3 Map of the network (Appendices A3.1 and A3.2)

Producing a map of the network achieves two main goals:

Firstly, it gives, in a printed form, a plan of the network, which cannot be seen entirely on the computer screen (Appendix A3.1). Secondly, it provides some results and data for each box. The data are thus presented in a more legible form than in a tabular report.

4.9.4 Box data reports (Appendices A4.1 and A4.2)

There are two types of box data reports.

The first one is a simple list of all the boxes entered which gives input and result data for each box.

An example of such a report is given in Appendix A4.1.

The second one is a list, type by type, of all the boxes. It includes all the data listed earlier, but is more legible as the user knows in which category to find a certain box (Appendix A4.2).

4.9.5 Output device

An interesting feature of the program is the possibility to choose a printer type. It will, for instance, be possible to use extended ASCII characters, if required, to produce reports with a better appearance (continuous borders for frames) and to choose two formats of output (80 or 132 columns), in normal or compressed text mode.

But the output need not be directed to a printer. The report can be sent to a file on disk. The user will have to enter the file name. The file thus created can be modified using any editor, as it is an ASCII file. The user might need only part of the data for a print-out, may want to add some comments or may even include part of the report in a text file. As the output is produced in English, this feature will allow the translation of terms to any other language, if required. This will obviously serve with more benefit a computer-oriented user.

4.10 Automatic Saving

In order to prevent accidental loss of data (through power surge, for instance), an option can be selected which, at regular intervals, will save the data on disk. This is particularly important when a new network is being entered. This feature can be 'switched off' when only modifications, for the sake of trying different operating conditions, are made.

The intervals at which this saving is performed depend on the user, who can chose to link the automatic saving to the activity of new data input or to a time step. The data will then be automatically dumped to disk after 5 minutes or when 15 modifications to the data have been made.

CHAPTER 5 : P.C. IMPLEMENTATION

Prior to the writing of the program, a choice had to be made regarding which computer to use. In the past all programs had to be 'transportable' while they now must be designed for a standard machine. The reason for this is that, in order to produce a more 'user-friendly' program, one must use the special features of a machine or a system. In addition, better development tools might only be available for a given type of computer.

The other factors in the choice of a system are the needs and wishes of the potential users. When this project started, an unpublished study was made by the Environmental Engineering Laboratory of the Chamber of Mines in order to determine the most popular computer in the mining industry. The results showed that the most wide-spread computers were in the IBM-PC *personal computer family*. This machine has now become a standard in the micro-computer market. All the tools needed for developing the program are available under the MS-DOS operating system for the IBM-PC. The program is designed for use on IBM-PC, IBM-XT, IBM-AT or any machine fully compatible with them.

The only particular specification of the implementation is the use of a small device : the INTEL 8087 mathematics co-processor. It is a standard add-on (a socket is especially provided on the computer mother board) for this type of machine. Its function is to speed up (15 to 20 fold) the calculations involving floating point data. Although this device is not required to run the program, the extra cost (5 per cent or less of the price of the computer) is low enough to make its use advisable, as it does not otherwise affect the characteristics of the machine. The speed of the IBM-PC equipped with such a device is equivalent to that of a mini or main-frame computer in time-sharing mode.

5.1 Definition of Requirements

5.1.1 Introduction

The main practical requirement of the program is perhaps data storage. It must be possible to handle large networks. Therefore, at least 300 boxes must be accommodated. Besides, some models need a lot of input data (stopes, for instance). Twenty-five items of data per box is a minimum figure.

Calculations should be as fast as possible.

The program must display the network on the screen. A certain amount of graphical effect must therefore be provided, even if graphics, as such, are not required. In order to use the program efficiently, a printer is necessary.

5.1.2 Choice of a computer system

From these requirements, a standard (or minimum) configuration can be derived.

It consists of:

(i) an IBM-PC central unit (or IBM-XT or IBM-AT), with at least 256 K-bytes of main memory

(ii) any type of screen, including a plain monochrome text screen, a Hercules graphics combination or a colour-graphics screen

(iii) a printer, preferably the IBM standard PC printer, though any printer will do

(iv) optionally, an 8087 mathematics co-processor, for improved calculation speed and accuracy.

5.2 Modularity

In order to be 'menu-driven', the program will have to be very *modular. Therefore, it will contain separate* routines grouped in options. A structured language is required to attain this goal.

This is also required as the program is thought of as relatively *fast changing. For example, in the foreseeable future, new* mathematical models will be available or new modes of input of data might be considered (for example a digitizer). The modular aspect of structured programming is, for the maintenance of such a program, of paramount importance.

5.3 Choice of a Programming Language

5.3.1 Introduction

Only three languages have been seriously considered for the writing of the program : BASIC, FORTRAN and PASCAL. Although this program presents aspects of Artificial Intelligence, the calculations form a major part. Specialized languages such as LISP or PROLOG have therefore been left aside. The same applies to ADA, for the above reasons and because of its limited development and availability so far.

Because the operating environment is MS-DOS, it was felt that C, dedicated to UNIX programming, was not to be considered. If exception is made of programming languages of a lesser importance (ALGOL, FORTH, MODULA 2, etc...) or dedicated to business applications (COBOL, PL-1), only three 'popular' languages are left : BASIC, FORTRAN and PASCAL.

It is important to choose from the popular languages, because efficient development tools exist for their support.

5.3.2 BASIC

BASIC, although it is primarily an interpreted language, can be compiled in an IBM-PC version. It is a very popular language at the moment, close to a standard for micro-computers. It provides numerous tools for the programmer : graphics, system input and output questions, excellent screen management and even structured programming with the use of sub-routine calls (on IBM-PC). It was not selected because the available versions of the compiler did not support the use of the speed-efficient 8087 mathematics co-processor and, in addition, it does not provide enough data storage possibilities.

5.3.3 FORTRAN

FORTRAN is the favoured language when it comes to scientific programs. It was one of the first languages to have been widely used on computers and it is still very popular for several reasons :

(i) the standard has been updated thoroughly twice (ANSI 66 and ANSI 77 in 1966 and 1977)

(ii) it is a concise language : its vocabulary is simple and easy to learn, and few lines contain a lot of information

(iii) it is very suitable for scientific applications because it contains many scientific functions and has a very logical lay-out.

On the IBM-PC, the compiler supports the 8087 mathematics co-processor : it is by far the fastest language available on this machine (with the exception of APL).

The limitations are the lack of structured programming facilities and of effective screen management. *This language* was not selected, mainly for the latter reason, which renders interactivity a difficult feature to include in a FORTRAN *program*.

5.3.4 PASCAL

PASCAL is a relatively new language. Its main features are its ability to process strings (and therefore ideas or choices), its structured aspect (of paramount importance for the maintenance of programs), and, on IBM-PC, the availability of screen management tools and support of the 8087 mathematics co-processor.

The limitations are average speed characteristics (running times twice as long as with FORTRAN) and the inherent lack of trust programmers show for every new language. *If has been felt that* PASCAL is merely a fashionable programming language and that it is likely to be dropped after five years, as has happened to FORTH, for instance. FORTRAN would, for this reason alone, be more preferable.

In the case of PASCAL, though, the standard now seems to be accepted. It has become the major language taught in universities which recognize its features as characteristics of today's and tomorrow's languages (ADA, a sort of super-set of PASCAL, enjoys a growing popularity for the same reasons).

In the case of this program, PASCAL has been selected as a development tool because it realizes a synthesis between BASIC (easy screen management) and FORTRAN (powerful calculations) in a structured programming environment.

From among all available PASCAL compilers for IBM-PC, TURBO-PASCAL, by BORLAND, was chosen. This was chosen in spite of the speed of the executable module since TURBO-PASCAL can only produce executable code which runs twice as slow as that obtained with other PASCAL compilers. The choice was motivated by the ease of use of the whole TURBO-PASCAL system: an editor, a compiler and a link editor, all integrated in one program. With this system, and taking into account a excellent compilation and link speed, (about 30 lines per second) the development time can be reduced enormously.

In addition, all necessary screen management routines are available and the compiler is becoming the standard PASCAL on IBM-PC.

5.4 *Internal Structure*

5.4.1 Menu

The internal structure of the program is entirely determined by the menu. Functionally, there are as many independent parts as menu options. A 'master' routine, the menu, calls each of these different options.

Some options are very short, for example 'Quit' or 'New', which first check that no fatal error is committed by the user before proceeding with his request.

The larger options make extensive use of sub-routine facilities. Some routines are included in a 'tool' section, in order for them to be used by several options. For instance, a routine called 'ReadForm' is called by both 'EDIT' and 'CREATE'. Another one, 'Help', is invoked by all the options.

Similarly, the calculation part starts with a 'psychrometric' section which contains intermediate routines (such as 'WB-from-Sigma') used by several models.

5.4.2 Overlays

This menu 'skeleton' also allows a particularly efficient use of computer memory through overlay. In its first version, the program contains more than 6 000 lines of instructions. This requires a storage size of at least twice the 64 K-bytes allocated to code. The separation into independent options is of great help for an efficient overlay management.

A very important condition for using overlay efficiently (i.e. without aggravating computation speed) is that two sections of a program used at the same time, or which call each other repetitively, should never be in the same overlay section. With the menu structure, different functions are well defined and separated, and, therefore, it will be possible to put the following in the same overlay section :

(i) the printout option

(ii) the disk storage option

(iii) the editing option

(iv) the calculation option.

Each of these options is totally independent of the others. When the user exits 'Printout', for instance, the memory space used by this option can be freed and assigned to 'Storage', as no part of 'printout' will be needed any longer.

5.5 Screens

The screen is used in a manner in which windows, forms and menu options share the display. In addition, certain functions such as the 'Help' facility, use the whole screen in some cases, for a temporary period only.

It was therefore necessary to write a routine which could allow an efficient management of the screen. This routine stores the data for up to four screens in memory. The prerequisites to writing such a routine are:

(i) that it must handle screens at a high speed (the user must not wait too long before seing another screen)

(ii) that it must work with any kind of display connected to the computer

The principle of the routine is that the display memory can be accessed from a PASCAL program using absolute addressing. An array of four screen pages is defined. Each screen page is a three-dimensional array of 25 lines by 80 columns by two bytes.

The two bytes are used for

(i) the ASCII code of the character on the screen on the nth line and in the mth column

(ii) the video status of this character.

The first page is the actual screen as displayed. Pages 2,3 and 4 are screen buffers. The program switches from one page to the other by simply assiging a buffer-array (from 2 to 4) to the first page-array.

For instance, if the user depresses the question-mark key, thus requesting a help-page, the program will:

(i) assign the present screen-array to a buffer page (e.g. page 2)

(ii) read the help-page from disk and display it on the screen.

When the user wants to exit the help-function, the program will simply assign the buffer page number 2 back to the screen page.

Because the program only handles starting addresses of arrays, instead of each of its elements, the refreshing of the screen is very fast.

The second condition, compatibility with different screen systems, was more difficult to meet. The different screen cards and different screens available on IBM-PC use different addresses for the screen buffer.

As it is difficult to determine what kind of display is used from within a PASCAL program, and as several screens can be connected to the same machine, the user must, each time he starts the program, input what combination of display-card and screen is in use. The starting address of the screen buffer is set to be compatible with the indicated combination.

5.6 Help Function

Each time he presses key '?' or 'F1', the user is presented with a 'help' page. This page is part of a book organized in chapters.

5.6.1 The book

The help function can be compared with a book, including the support of an index. Each 'location' in the program, where input of information is required from the user, is assigned a page number.

The 'help-book' is stored as a file of records, each record being a page of the 'book'. It is therefore easy to retrieve the page sought for, using the SEEK and READ commands of PASCAL. The space needed by this help function is used on disk, which allows the size available for data storage to be increased.

5.6.2 The chapters

All the help pages are stored in chapters. An index (currently the four last pages of the 'help-book') is provided. The user can browse among pages using :

(i) PgDn (page down) and PgUp (page up) keys

(ii) the number of the requested page, directly

(iii) key END to go to the index.

The chapter organization is such, that the user can search for additional information related to the page he is looking at, by just using 'page-up' and 'page-down'. The first chapter explains the goals of the program, its 'philosophy' and some of the global information for its use. The second chapter explains the selection of defaults and global data. Another one comments on the input of data at creation of a box, depending on its type. In general terms, there is one chapter for each menu option.

The basic feature of this help-function is that it overlays the screen totally, providing access to the 'book'. When the user wishes to return to the program, he is taken back to exactly where he pressed the '?' key to get the information. He can then proceed to use the knowledge he gained from using 'Help'.

It must also be noted here that this help 'book' is separated from the program and can be 'edited' using a special editor. The editing allows easy updates or corrections to the book, as well as a possible translation into another language, even if the rest of the program is not translated.

For the same reason the user can potentially be provided with help files of different levels of complexity.

5.7 Graphics

No actual graphic capability of the computer or of the language is used, even though the visual aspect of the program is very important. To obtain a 'picture' of the network, *semi-graphical*, extended ASCII characters have been used. They allow horizontal and vertical continuous borders to be drawn in order to build boxes in a network environment.

The use of these characters allows the program to run on the very basic configuration of IBM-PC, with no graphics screen.

Networks are printed out on a standard printer. If the given printer can handle extended ASCII, these characters are used to provide a very neat output. If not, the output of the network is done using plain dashes and vertical bars. It does not look as neat as with continuous borders, but is a lot faster.

Because no graphics are used, output on any kind of printer is possible (even letter quality) and the time needed for printing

reports is reasonable (it can be up to 30 times slower in graphics mode).

No plotting of the network is possible at this stage.

5.8 Debugging

'Debugging' or finding mistakes in the program by testing the routines in different cases, can be performed very easily with HEATFLOW. The reason is that each calculation routine (where major errors can occur) can be tested *separately, on a simple* network comprising only one box using this calculation module.

The user can, under normal operating conditions, request a printout of intermediate calculations as they are carried out. These printed documents help the programmer in the development phase, as well as the user when disagreement arises between his values and results from a simulation.

5.9 Batch Routine : Auto-Loading

The user is required to *have very little computer knowledge.* Therefore, the program is provided on a diskette in an auto-loadable form. The user just has to insert the diskette in the computer drive and switch the machine on. The auto-executable routine (AUTOEXEC.BAT) contains all the necessary information to start the program. It resides on disk and is the first file executed by the system when it starts.

This is an important user-friendly feature of the program, as it means that the operator can use it without knowing anything about the operating system (DOS).

5.10 Limitations

The main limitations of the implementation concern the maximum size of networks and the relative lack of graphical facilities.

5.10.1 Size

As has been mentioned earlier (section 4.7), the problem of network size can *easily be circumvented using sub-networks*. The actual maximum size of a network with no sub-networks is 320 boxes. *If sub-networks* are used, this figure has virtually no limit other than the storage available on disk. In any case, 320 boxes are usually large enough to study a single shaft system, and can be sufficient for a whole mine.

5.10.2 Graphics

The second problem is not so much a hardware problem as the problem of defining a standard. With modern micro-computers, the use of special graphics work-stations (for example, TEKTRONIX), pen plotters or digitizers is widely spread. Two problems exist though. Firstly, the required hardware can be quite costly. Secondly, no actual standard has been defined in the field of external graphic devices *for micro-computers*.

The development of involved routines for one specific kind of configuration is out of the question. Also, in the case of mine networks, a satisfactory simple ventilation plan is already a symbolic representation of reality. It is the projection of the three-dimensional space on a plan, with particular care taken so that neither airways nor shafts overlay each other. Three-dimensional representation is both costly and memory consuming. A planar representation is already well accounted for by the 'network' structure used in this program.

In the foreseeable future, though, it may be planned to use a standard-to-be digitizer/pen-plotter combination in order to allow easier data input. The only element to change in the program will be the data input part, which is not a major part. The data structure will have to be altered, as well, in order to memorize a geometrical description of the network.

But, even if this can be planned, paper sizes of A3 (for digitizing as well as for plotting) will probably not be exceeded, for economical reasons. On an A3 sheet of paper, not more than 100 boxes (or branches) can be pictured with sufficient resolution.

CHAPTER 6 : RESULTS, DISCUSSION AND CONCLUSIONS

The objectives of this work were to give a global structure to a program, making sure it would be modular enough to be updated in the future. A practical tool has been developed, and, as every care has been taken in the selection of the calculation routines, it should be 'accurate' enough for mining conditions. In this chapter, a practical example of the utilization of the program is given and the accuracy of the solutions is discussed. This is followed by some concluding remarks.

6.1 An Example of the Use of HEATFLOW

Although the study of a real mine could have been presented here, it was felt that it would be too specific and may well not have been truly representative of every mine. Hence a generic mine has been set up. This mine summarizes the characteristics of South African 'deep' gold mines. These 'deep' gold mines are defined by Burton et al.(1986) as the 14 out of 41 mines which use 80 per cent of the installed refrigeration capacity, 60 per cent of the downcast air and produce 45 per cent of the total rock broken. This model of a mine was used by Burton et al. for the investigation of future refrigeration requirements as well as a possible increase of refrigeration to eliminate the need for acclimatization of workers.

The mine has been modeled on the basis of a weighted mean rock breaking depth which is the same as the overall mean rock breaking depth for these mines (1950 m with an associated VRT of 40 °C) and its yearly average stope wet-bulb exit temperature, 28,4 °C, which is the same as the overall average for 'deep' mines.

To simplify the structure of the mine, it is considered to be fully developed (only stoping activities take place), cooled using a conventional cooling strategy (surface and underground air coolers as well as chilled service water), has a typical length of intake airways per level and a typical machine power consumption. It is a relatively young mine (main shaft : 8 years, first level : 4 years and second level :1,5 years). In practice, one would expect such a mine to still be in its development stage.

6.1.1 Mine representation

The mine, as shown in Figure 6.1, consists of two production levels. A bulk cooler cools the air on surface, this air travels down the main shaft, then along a horizontal airway and down the sub-vertical shaft. The air is distributed between the two main production levels where it travels up the longwall faces toward the outlet.

The mine is represented by the network of Figure 6.2. Some box types, namely fans and development ends, are not used in this network.

The level of complexity used was the simple level, because of the nature of the input data (average representative values) and also because of the objectives of the exercise.

6.1.2 Data provided

The input data are given in Figure 6.1. The arrows indicate the direction of the air flow. Additional data typical of that for scattered stoping are as follows. Any form of stoping can be accommodated by the use of appropriate input data.

(i) stoping width = 1,5 m

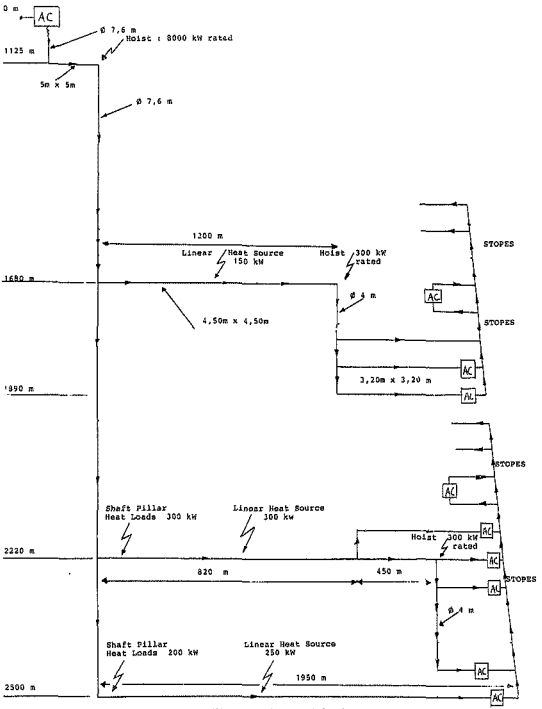


Figure 6.1 : model mine

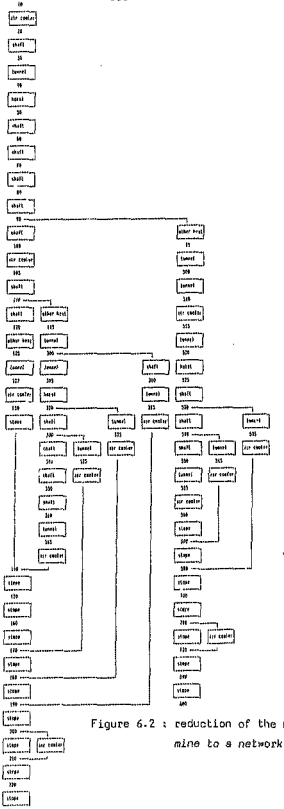


Figure 6.2 : reduction of the model mine to a network

(ii) distance from dip-gully to face = 100 m

(iii) width of the production zone = 6 m

(iv) perimeter of dip gully = 12 m

(v) perimeter of strike gullies = 8 m

(vi) water temperature at inlet = 15 °C

(vii) stope advance = 6 m/month

(viii) in-stope machine heat = 25 MJ/ton

(ix) one strike gully every 20 metres of face

(x) difference between dry- and wet bulb temperatures at the stope outlet = 1,5 °C.

In addition, 60 per cent of the average amount of service water consumed, namely one ton per ton of broken rock, is used in the stopes.

For airways and tunnels, the wetness factor is assumed to be 0,25.

The cooling strategy adopted, apart from bulk air cooling on surface and the use of chilled service water, was to place a cooler, if technically possible, in the production levels wherever the wet-bulb temperature would exceed 28 °C.

6.1.3 Results and deviation from average data

The correlation between the actual data and the calculated results is very satisfactory, as the agreement is better than 10 per cent. The details of the comparison are:

(i) actual data : 595 MW(R) for a total production of 4869 kton/month

(ii) calculated data : 10,8 MW(R) for a mine production of 83 kton/month.

The specific refrigeration requirements are 122 W/ton/month in the actual case as against 130 W/ton/month in the simulated.

The difference (less than 10 %) can be explained by:

(i) the fact that in this very simple and average example : the cooling strategies would vary for each of the 14 mines, as do the stope temperatures and specific refrigeration requirements for each mine.

(ii) calculation and modelling errors.

The program has been used to determine the cost of providing an average stope temperature 2,5 °C less than the actual one (28,4 °C). The result was 13,5 MW(R) for a production of 83 kton/month. This corresponds to an increase of about 25 % in the cost of refrigeration.

It is not suggested that this calculation has validated the program. The example, using an artificial mine lay-out, is purely for the purpose of demonstrating the capabilities and structure of the program.

6.1.4 Discussion : how does the program help?

As shown in the above exercise, it is possible to use the program to investigate ways of providing better working conditions and assess the cost of this improvement. It is also possible to use increased depths and virgin rock temperatures, in order to determine what the future needs, in terms of cooling power requirements, will be, as the rock breaking depth increases.

This is a simulation tool : it will therefore be very suitable for "what-if" type questions, for example, 'what if a new part of the mine enters a production phase?', or 'what if the bulk cooler, for a future project, is located underground?'. The use of this program to determine the answer to these questions has been demonstrated in this exercise.

6.2 Reactions and Comments from Users

The program has been tested preliminarily, mainly for its functional abilities and ease of use in the 'field'. This evaluation has been conducted by officials at the head offices of the mining houses as well as by environmental control officials from the mines. The reactions have been positive, as the need for such a planning tool definitely existed. The users were particularly attracted by the possibility of describing their heat flow problems in a very modular fashion. In addition, the user friendly aspect, enhanced by the use of a micro-computer, was a major subject of satisfaction The clarity and legibility of printed reports, especially the map of the network, was found to be a major aid in the interpretation of results.

Nevertheless, most people concerned with these field trials contributed a number of critical comments. A summary is listed below.

6.2.1 Accuracy

The accuracy was generally not a major problem. When the users disagreed with the results of a calculation, it was a systematic deviation over the whole network. They could therefore derive a constant deviation of the results for the simulation of a given mine, and take it into account as the 'calibration' factor for the progam.

6.2.2 Graphics

It was often felt that the program did not go far enough, as more graphics were required. This aspect has already been discussed and will be taken into account in future versions of the program.

6.2.3 Network representation

It is interesting to note that the new method (reducing the mine to a network of boxes), although it is complicated by certain aspects (location of boxes on the screen, for instance), has generally been well received.

6.2.4 Program errors

These 'field trials' brought to light a number of programming errors. They also highlighted the malfunctions and awkward aspects of some options.

6.2.5 Interactivity

Some comments were specifically directed towards improving the interactivity of the program : for example, they showed the necessity of including a routine to give a 'directory' of all the data files on disk, from within the program.

6.2.6 Output of results

Some of the potential users were concerned with the output of results : printout of a summary report including total production, total heat flow, cooling, etc... As a consequence, the printout of results is probably the part where the opinion of the users has been sought the most. The required types of reports have been determined from these comments.

6.3 Precautions of Use

As mentioned earlier, this tool cannot be used efficiently by an operator who has no knowledge of environmental control. Because of the inaccuracy in the input data, special care has to be taken in the interpretation of results.

Special attention must also be given to the selection of input data, as errors tend to accumulate from one box to another. To control excessive deviation, the *over-write facility* should be used as often as possible. The user should, in addition, try to 'calibrate' the program on an existing mine, for which both *input and 'result'* data are reliable. This will ensure successful use for planning purposes.

The experienced user will, in addition, test the sensitivity of the models to parameters which are not known with precision. He will therefore run the program not only with one set of data, but over a complete range. This remark applies especially to items such as the wetness factor and the enthalpy-*over-moisture* ratio, which can only be assessed by experts using rule-of-thumb methods.

6.4 Interfacing with Other Programs

Two issues need to be discussed here. They will be referred to as 'up-stream' interfacing (use of the output of a program for the input to HEATFLOW) and 'down-stream' interfacing (reversed roles).

6.4.1 'Up-stream' interfacing

The 'up-stream' interfacing has already been partly discussed. It concerns :

(i) the pre-processing of input data through a mine ventilation network analysis program

(i) the input of data using a device other than the keyboard or another data collection program

The mine ventilation calculation interfacing has been reviewed in section 3.13.

As for input of data, three types of methods can be considered for the future :

(i) using a spreadsheet (Lotus 1-2-3, for instance). The prerequisites would be to define a spreadsheet format (that is defining which cell is assigned to which item of data) and to write a conversion program to translate a spreadsheet file to a *HEATFLOW file.*

(ii) using a data base management tool (dBase II, for instance). Similar prerequisites as for a spreadsheet (define a format for the input to the data-base).

(iii) using a digitizer. The problems of standard discussed in section 5.10.2 can be circumvented by defining a standard ASCII input file. A conversion program would have to be written at the Chamber of Mines to translate this ASCII file to a HEATFLOW file. Each user, depending on his specific equipment, would have to write a simple program to transfer the data collected using the digitizer to the ASCII format. The main reason for using an intermediate ASCII file is that it does not depend on a given type of computer, or on a programming language. It can also be edited to remove obvious errors in the data. If this solution is adopted, each user will be able to make use of his specific equipment : for example, use an AO digitizer connected to the company main-frame to create the ASCII file (using FORTRAN,

perhaps), transfer the ASCII file down to a Personal Computer, connected as an intelligent terminal, and use the conversion program for the translation of this data file to the HEATFLOW format.

6.4.2 'Down-stream' interfacing

The 'down-stream' interfacing similarly concerns the use of a device other than the printer to display results and the post-processing of output data.

The different options for the modification of output data are:

(i) to convert the result file to a spreadsheet format. The prerequisites are the same as for the 'up-stream' use of a spreadsheet. The spreadsheet program will allow the user to present the results in a more elaborate manner, depending on his requirements.

(ii) to convert the result file to a data-base management program format. The prerequisites as well as the advantages of such a solution are similar to those given above.

(iii) to convert the result file to a format recognised by a standard graphics or statistics package. This can be done through the spreadsheet program. The user will then be able to take advantage of a plotter, for example.

(iv) to convert the result file to an ASCII format (as for the digitizing of input data). This will give access to the hardware available on a main-frame computer, for instance.

(v) to use a text processing package to edit, translate or include in another text file, the result files provided by the 'PRINT' option.

Most of the possibilities given above require the writing of special conversion tools. These tools could be included in future versions of the program. Standards for ASCII files, spreadsheet or data-base input formats must be defined at a global scale and not by each individual user.

6.5 Conclusion and Future Developments

6.5.1 Conclusion

The work summarized in this document has found its application in a computer program called HEATFLOW. This program has, so far, given satisfaction, and its structure appears to be flexible enough to be used by environmental control officials. The research work involved in the design of this program showed that :

(i) the results are satisfactory but there is a definite need for further research in order to produce better models for airways (finite elements to create a data-base for square airways) and development ends (better simulation of the face area)

(ii) the graphics should be improved

(iii) two levels of complexity are definitely useful for a universal use of the program

(iv) the modular approach is particularly suited to the description of heat flow problems in mines.

The following paragraphs give directions for a future research in the field of heat flow prediction in mines using computer programs.

6.5.2 Enhancements

In sections 3.14, 5.10 and 6.4 possible enhancements and modifications to the program were listed. Briefly, these concern : the problem of wetness, the interaction of water reticulation and ventilation networks, the use of graphics and the interfacing with other programs. All those modifications are part of a wider issue, namely to provide the Industry with a more powerful, more interactive and 'user-friendly' tool. Another important aspect of this issue is to make the program more 'intelligent'.

6.5.3 An expert system

The program should not only be able to provide results of calculations, but also help in their interpretation. It should answer questions such as :

(i) what are the best locations for stope coolers, in a given mine lay-out ?

(ii) what percentage of cooling through chilled service water is the most efficient, for a given mine ?

(iii) should the bulk cooler be located underground or on surface ?

In other words, the form of the program should ultimately be an expert system. The expertise would not only result from an 'expert-decision' data-base, but would in addition be based on the results of the calculations performed by the present program. The expertise would therefore be found in the

development and choice of the heat flow models as well as in an interpretation of the results. The present program would then be, to a certain extent, the 'calculation-expert' in a more complex program.

The program could help the user to determine the correct value of certain parameters. The film coefficient used in the calculations of shafts and airways, for instance, can be computed using several different models. This leads, sometimes, to very important deviations. The choice of the equation used in determining this coefficient should be left to the user. He would then be able to seek advice from the program, in order to make the decision which will give the best results, in a given situation.

The choice of a programming language such as PASCAL, which allows the user to manipulate text and ideas, is very important in that respect. Its capability of handling calculations and text as well as its modular structure, should facilitate the writing of an expert-system as a super-program using the present one as a routine.

CHAPTER 7 : REFERENCES

ALEXANDER, N.A., BLUHM, S.J., MARCH, T.W., BOTTOMLEY, P. and VON GLEHN, F. (1986), 'The Measurements of Heat Loads in a Deep Level Stope in the Klerksdorp Gold Fields', Mine Vent '86, JOHANNESBURG : The Mine Ventilation Society of South Africa, May 1986.

BARENBRUG, A.W.T. (1974), '*Psychrometry* and Psychrometric Charts', 3rd ed., Johannesburg : Chamber of Mines of South Africa Research Organization, 1974.

BLUHM, S.J. (1980), 'Predicting Performances of Spray Chambers for Cooling Air', Journal of Heating, Air Conditioning and Refrigeration, November 1980, pp.27-39.

BLUHM, S.J. (1981), 'Heat Transfer Characteristics of Direct-contact Crossflow *Spray Chambers*', *M.Sc.* Dissertation, Johannesburg : University of the Witwatersrand, February 1981.

BLUHM, S.J., BOTTOMLEY, P. and VON GLEHN, F. (1986), 'Theoretical Evaluation of Heat Flow from Rock in South African Gold Mines. The State-of-the-art', IIF/IIR FRIGAIR '86, Pretoria 1986.

BOTTOMLEY, P. (1985), 'The Reduction of Heat Flow Due to the Insulation of Rock Surfaces in Mine Airways', *Proceedings of the* 2d. US Mine Ventilation Symphosium, University of Nevada, Reno, Rotterdam : Balkema, pp.457.464.

BOTTOMLEY, P. and BLUHM, S.J. (1985), 'A Contribution to the *paper* : "Air Temperature Increases in Airways" by R. Hemp', Journal of the Mine Ventilation Society of South Africa, April 1985, pp. 46-47.

BURTON, R.C., PLENDERLEITH, W., STEWART, J.M., PRETORIUS, B.C.B. and HOLDING, W. (1984), 'Recirculation of Air in the Ventilation and Cooling of Deep Gold Mines', Proceedings of the Third International Mine Ventilation Congress, Harrogate, 1984, pp. 291-299.

BURTON, R.C., KIELBLOCK, A.J., SHEER, T.J. and BLUHM, S.J. (1986), 'The Future Implications of Controlling the Thermal Environment in Deep Gold Mines', *Proceedings of the Conference* GOLD 100, Johannesburg, September 1986, to be published.

CHOROSZ, G. (1984), 'Simulation sur Micro-Ordinateur de l'*Incendie dans un Réseau* d'Aérage Minier', Final Undergraduate Year Thesis, ENSMP, Paris : Ecole des Mines de Paris.

CHOROSZ, G. and DELIAC, E. (1985), 'Exemples d'Application de la Micro-Informatique Professionelle à Différents Problèmes d'Aérage', Revue de l'Industrie Minérale, Supplément à Août-Septembre 1985, Vol. 67, pp. 309-315.

CULVERWELL, W.V. (1986), 'Heat Loads in Shaft Areas', Unpublished Report, Johannesburg : *Chamber of Mines of South* Africa Research Organization, April 1986.

DELIAC, E.P., CHOROSZ, G. and D'ALBRAND, N. (1985), 'Development *of Ventilation Software on Personal* Computers in France and the Application to the Simulation of Mine Fires', Proceedings of the 2d. US Mine Ventilation Symphosium, University of Nevada, Reno, Rotterdam : Balkema, pp.19-27.

GOCH, D.C. and PATTERSON, H.S (1940), 'The Heat Flow into Tunnels', Journal of the Chemical , Metallurgical and Mining Society of South Africa, Vol. 41, September 1940, pp. 117-128

GOOCH, C.D. (1971) 'A Computer Model for Estimating Air Temperature and Humidity in Downcast Shafts', Unpublished Report by the Chamber of Mines of South Africa Research Organization, November 1971.

HEMP, R. (1982) 'Sources of Heat in Mines' in 'Environmental Engineering in South African Mines', Johannesburg : Mine Ventilation Society of South Africa, 1982.

HEMP, R. (1985, a), 'Air Temperature Increases in Airways', Journal of the Mine Ventilation Society of South Africa, Vol. 38, No. 1 and 2, January and February 1985, pp.1-8 and 13-10.

HEMP, R. (1985, b), 'Author's Reply to Contribution by Messrs. P. Bottomley and S.J. Bluhm', Journal of the Mine Ventilation Society of South Africa, May 1985, p. 59.

HEMP, R., DEGLON, P. and CILLIERS, P.F. (1984), 'Heat Loads in a Longwall Stoping Section of a Deep Gold Mine', Proceedings of the Third International Mine Ventilation Congress, Harrogate, 1984.

HOLMAN, J.P. (1982), 'Heat Transfer', 5th ed., Tokyo : Mc Graw Hill.

JAEGER, J.C. and CHAMALAUN, T. (1966), 'Heat Flow in an Infinite Region Bounded Internally by a Circular Cylinder with Forced Convection at the Surface', Australian Journal of Physics, Vol. 19, 1966, pp. 475-488.

LAMBRECHTS, J. de V. (1959), 'An Empirical Study of Heat Flow in Stopes in South African Gold Mines', Journal of the South African Institute of Mining and Metallurgy, January 1959, pp.285-316.

LAMBRECHTS, J. de V. (1967), *'Prediction of Wet-Bulb Temperature Gradients in Mine Airways'*, Journal of the South African Institute of Mining and Metallurgy, June 1967, *pp.595-610.*

MACK, M.G. and STARFIELD, A.M. (1984), *'The Effect of Daily and* Seasonal Inlet Temperature Cycles on Air Temperatures in Shafts and Underground Airways', unpublished contract report by *Itasca* Consulting Group for the Chamber of Mines of South Africa Research Organization, November 1984.

MACK, M.G. and STARFIELD, A.M. (1985), 'A Computer Model of Heat and Moisture Transfer in a Developing Tunnel', unpublished contract report by Itasca Consulting Group for the Chamber of Mines of South Africa Research Organization, April 1985.

MATTHEWS, M.K. (1986), 'The Propagation of Diurnal and Seasonal Atmospheric Temperature Variations through Mine Shafts and Airways', unpublished report, Johannesburg : Chamber of Mines of South Africa Research Organization, 1986.

MYERS, C., BOTTOMLEY, P. and BLUHM, S. 'Prediction of Atmospheric Temperature Data For The Mining Areas of Carletonville, Klerksdorp and Welkom', unpublished report, Johannesburg : Chamber of Mines of South Africa Research Organization, September 1984.

OBERHOLZER, C. (1986), Personal Communication.

NUEDERNI, A. (1984), 'Prévision des Conditions Climatiques dans un *Traçage Profond*', Memoire de D.E.A., PARIS : Ecole des Mines de Paris, 1984.

RAMSDEN, R. (1975), 'Estimation of Heat Pick-up in Mine Airways', *unpublished report, Johannesburg* : Chamber of Mines of South Africa Research Organization, 1975.

SCOTT, D.R. (1958) 'The Cooling of Underground Galleries', Transactions of the Institution of Mining Engineers, U.K., vol. 118, pp. 356-372.

SHEER, T.J. (1986), Personal Communication.

SHEER, T.J., BURTON, R. and BLUHM, S.J. (1984), 'Recent Developments in the Cooling of Deep Mines', The South African Mechanical Engineer, Vol. 34, January 1984.

STARFIELD, A.M. (1966, a), 'Tables for the Flow of Heat into a Rock Tunnel with Different Surface Heat Transfer Coefficients', Journal of the South African Institute of Mining and Metallurgy, July 1966, pp. 692-694.

STARFIELD, A.M. (1966, b), 'The Computation of Temperature Increases in Wet and Dry Airways', Journal of the Mine Ventilation Society of South Africa, October 1966, Volume 19, pp. 157-168.

STARFIELD, A.M. (1966, c), 'Heat Flow into the Advancing Stope', Journal of the Mine Ventilation Society of South Africa, February 1966, Volume 19, pp. 13-24.

STARFIELD, A.M. (1969), 'A Rapid Method of Calculating Temperature Increases Along Mine Airways', Journal of the South African Institute of Mining and Metallurgy, vol. 69, 1969, pp. 77-83.

STARFIELD, A.M. and DICKSON, A.J. (1967), 'A Study of Heat Transfer and Moisture Pick-Up in Mine Airways'. Journal of the South African Institute of Mining and Metallurgy, Vol. 68, December 1967, pp. 211-234.

STARFIELD, A.M. and BLELOCH, A.L. (1983), 'A New Method for the Computation of Heat and Moisture Transfer in a Partially Wet Airway', Journal of the South African Institute of Mining and Metallurgy, December 1983, pp. 263-269.

STEWART, J. (1982), 'Fundamentals of Human Heat Stress' in 'Environmental Engineering in South African Mines', Johannesburg : Mine Ventilation Society of South Africa, 1982.

THRELKELD, J.L. (1970), 'Thermal Environmental Engineering', 2d. ed., New-York : Prentice Hall Inc., 1970.

VAN DER WALT, J. and WHILLIER, A. (1979), 'Heat Pick-up from the Rock in Gold Mines : the Water-Rock Thermal Balance and the Thermal Efficiency of Production', Journal of the Mine Ventilation Society of South Africa, Vol. 32, No. 7, 1979, pp.125-144.

VON GLEHN, F. (1986), 'A Study of Heat Exchange in Advancing Stopes', M.Sc. Thesis, University of the Witwatersrand, in preparation, Johannesburg, 1986.

VON GLEHN, F. and BLUHM, S.J. (1986), 'The Flow of Heat from Rock in an Advancing Stope', Proceedings of the conference GOLD 100, to be published in Johannesburg, September 1986.

VOST, K.R. (1973), 'In-situ Measurements of the Surface Heat Transfer Coefficient in Underground Airways', Journal of the South African Institute of Mining and Metallurgy, March 1973, pp. 269-272.

VOST, K.R. (1982), 'The Prediction of Air Temperatures in Intake Haulages in Mines'. Journal of the South African Institute of Mining and Metallurgy, November 1982, pp. 316-328.

WERNICK, B. (1986), 'VENTFLOW : User's Guide', *Report in* preparation, Chamber of Mines of South Africa Research Organization, 1986.

WHILLIER, A. (1982), 'Heat Transfer' in 'Environmental *Engineering in South African Mines*', Johannesburg : Mine Ventilation Society of South Africa, 1982.

WHILLIER, A. and RAMSDEN, R. (1975), 'Sources of Heat in Deep Mines and the Use of Mining Service Water for Cooling', Proceedings of the First International Mine Ventilation Congress, Johannesburg, 1975.

WHILLIER, A. and THORPE, S.A. (1971), 'Air Temperature Increases *in Development Ends*', Unpublished report, Chamber of Mines of South Africa Research Organization, 1971.

WILES, C.G. and GRAVE, D.F.H. 'Heat Flow Studies Using an Electrolytic Tank', Journal of the Chemical, Metallurgical and Mining Society of South Africa, Vol 55, December 1954.

APPENDIX A1 : GLOBAL INPUT DATA REPORT

Project :	
Mine :	*appendices*
Official :	B.C.
Date :	
Global input data	

VRT at surface (0 m)	:	19.0	°C
VRT gradient	:	0.0110	°C/m
Chilled water usage (tons/ton)	:	1.0	t/t
Percent of this water used in stopes	:	60	%
Pressure at surface (0 m)	:	83.5	kPa
Rock type 1 :			
- conductivity	:	6.0	W/m.°C
- diffusivity	:	2.5x10-6	m²/s
- density	:	2700.0	kg/m3
Rock type 2 :			
- conductivity	:	5.0	W/m.°C
- diffusivity	:	2.4x10-6	m²/s
- density	:	2670.0	kg/m3

APPENDIX A2 : NODE INPUT DATA REPORT

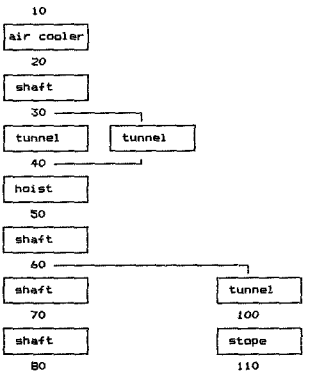
Project	:
Mine	: appendices
Official	: G.C.
Date	:
Nodes in use	

*	10,	depth :	0.00 m,	VRT :	19.0 °C	and pressure :	83.5	kPa
*	20,	depth :	0.00 m,	VRT :	19.0 °C	and pressure :	83.5	kPa
*	30,	depth :	2000.00 m,	VRT :	41.0 °C	and pressure :	105.3	kPa
*	40,	depth :	2000.00 m,	VRT :	41.0 °C	and pressure :	105.3	kPa
*	50,	depth :	2000.00 m,	VRT :	41.0 °C	and pressure :	105.3	kPa
*	60,	depth :	2100.00 m,	VRT :	42.1 °C	and pressure :	106.5	kPa
*	70,	depth :	2200.00 m,	VRT :	43.2 °C	and pressure :	107.7	kPa
*	80,	depth :	2300.00 m,	VRT :	44.3 °C	and pressure :	108.9	kPa
*	100,	depth :	2100.00 m,	VRT :	42.1 °C	and pressure :	106.5	kPa
*	110,	depth :	2070.00 m,	VRT :	41.8 °C	and pressure :	106.1	kPa

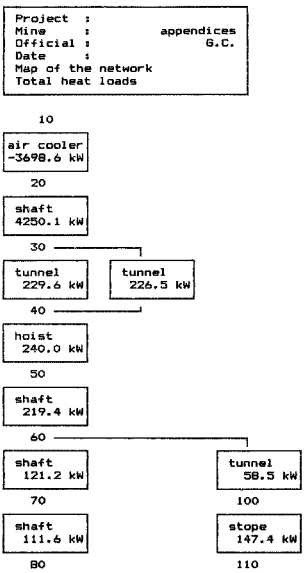
APPENDIX A3 : MAP OF THE NETWORK

A3.1 : Simple Map

Project :
Mine : *appendices*
Official : G.C.
Date :
Map of the network



A3.2 : One Item Only



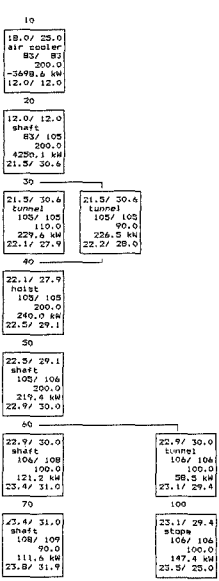
total heat generated : 5604.4
total cooling duty : 3698.6

A3.3 All data

```
Project  :
Mine     :                    appendices
Official :                          B.C.
Date     :

Map of the network

Wet/dry bulb temperatures in
Types
Pressures in and out
Air mass flows
Total heat load
Wet/dry bulb temperatures out
```



APPENDIX A4 : BOX DATA REPORTS

A4.1 : Tabular

Project	:
Mine	: appendices
Official	: G.C.
Date	:
Boxes and relevant data	

Box N° 1 air cooler : bulk cooler

Starting node	: 10 at a depth of	0.0 m
Ending node	: 20 at a depth of	0.0 m
Wet-bulb at inlet	:	18.00 °C
Dry-bulb at inlet	:	25.00 °C
Pressure at inlet	:	83.5 kPa
Vrt at inlet	:	19.00 °C
Air massflow in	:	200.00 kg/s
heat load	:	-3698.58 kW

Simple calculations.

duty (calculated)	:	3698.58 kW
wet-bulb at outlet	:	12.00 °C
dry-bulb at outlet	:	12.00 °C
Pressure at outlet	:	83.5 kPa
Vrt at outlet	:	19.00 °C

Box N° 2 shaft :

Starting node	: 20 at a depth of	0.0 m
Ending node	: 30 at a depth of	2000.0 m
Wet-bulb at inlet	:	12.00 °C
Dry-bulb at inlet	:	12.00 °C
Pressure at inlet	:	83.5 kPa
Vrt at inlet	:	19.00 °C
air massflow in	:	200.00 kg/s
heat load	:	4250.13 kW

Simple calculations.

wet-bulb at outlet	:	21.45 °C
dry-bulb at outlet	:	30.58 °C
Pressure at outlet	:	105.3 kPa
Vrt at outlet	:	41.00 °C
Diameter of cross section	:	7.00 m²
Length	:	2000.00 m
Wetness factor	:	0.10
Age	:	6.00 years

Box N° 3 tunnel :

Starting node : 30 at a depth of 2000.0 m
Ending node : 40 at a depth of 2000.0 m

Wet-bulb at inlet	:	21.45 °C
Dry-bulb at inlet	:	30.58 °C
Pressure at inlet	:	105.3 kPa
Vrt at inlet	:	41.00 °C
air massflow in	:	110.00 kg/s
heat load	:	229.64 kW

Simple calculations.

wet-bulb at outlet	:	22.07 °C
dry-bulb at outlet	:	27.86 °C
Pressure at outlet	:	105.3 kPa
Vrt at outlet	:	41.00 °C
Area of cross section	:	10.00 m²
Perimeter of cross section	:	12.65 m
Length	:	1200.00 m
Wetness factor	:	0.40
Age	:	6.00 years
Total linear power	:	0.00 kW

Box N° 5 hoist :

Starting node : 40 at a depth of 2000.0 m
Ending node : 50 at a depth of 2000.0 m

Wet-bulb at inlet	:	22.13 °C
Dry-bulb at inlet	:	27.93 °C
Pressure at inlet	:	105.3 kPa
Vrt at inlet	:	41.00 °C
air massflow in	:	200.00 kg/s
heat load	:	240.00 kW

Simple calculations.

wet-bulb at outlet	:	22.47 °C
dry-bulb at outlet	:	29.09 °C
Pressure at outlet	:	105.3 kPa
Vrt at outlet	:	41.00 °C
Power	:	1200.00 kW
Percent of power as heat	:	20.00 %

Box N° 9 stope :

Starting node : 100 at a depth of 2100.0 m
Ending node : 110 at a depth of 2070.0 m

Wet-bulb at inlet	:	23.06 °C
Dry-bulb at inlet	:	29.42 °C
Pressure at inlet	:	106.5 kPa
Vrt at inlet	:	42.10 °C
air massflow in	:	100.00 kg/s
heat load	:	147.36 kW

Simple calculations.

wet-bulb at outlet	:	23.47 °C
dry-bulb at outlet	:	24.97 °C
Pressure at outlet	:	106.1 kPa
Vrt at outlet	:	41.77 °C
Stoping width	:	1.50 m
Face length	:	100.00 m
distance dip gully to face	:	60.00 m
width of production zone	:	6.00 m
perimeter of dip gully	:	12.00 m
perimeter of strike gully	:	8.00 m
water temperature at inlet	:	15.00 °C
stope advance	:	6.00 m/month
machine heat	:	25.00 MJ/ton
number of strike gullies	:	1.00
(db - wb) at outlet	:	1.50 °C
percent of WOA backfilled	:	0.0 %

A4.2 By type

Project :
Mine : appendices
Official : B.C.
Date :
Box data by box type

Hoists :

In	Out	Depth in m	Depth out m	Temp in °C	Temp out °C	VRT in °C	VRT out °C	Pres in kPa	Pres out kPa	massFl. kg/s	Heat kW	Rated P. kW	% air %
40	50	2000.0	2000.0	22.1/27.9	22.5/29.1	41.0	41.0	105.3	105.3	290.0	240	12000	20.0

Author Chorosz Gilbert
Name of thesis Heatflow: An Interactive Computer Program For The Analysis Of Heat Production In Gold Mines. 1986

PUBLISHER:
University of the Witwatersrand, Johannesburg
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