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A COMPUTER SIMULATION OF MINE AIR SHAFT THERMODYNAMICS

by

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A DISSERTATION

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ABSTRACT

Several earlier investigations have been conducted into various aspects of heat problems in underground mines. The application of general gas laws and thermodynamics in the approach of mine ventilation has been helpful in elucidating certain difficulties associated with the subject. By combining several of the techniques perfected by these researchers and applying Carrier's method of calculation for heat flow from exposed rock strata into a workable plan, a method was developed whereby it is possible to accurately and conveniently predict the quality of working environment at any point within a deep mine.

The findings of this study may be of great value to designers in selecting economic optimums of labor, air conditioning and air transmission costs. They may be of further use in predicting underground conditions of fogginess, etc., which can be remedied before the mining operations begin.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

The more lucrative, near surface ore deposits are gradually being exploited and consequently the mining of commercial minerals is extending deeper into the earth. As the operations penetrate greater depths, associated difficulties of economics, support and safety are amplified, sometimes to the verge of our technical capability. One of the most serious related problems confronting the mining engineer lies in predicting the atmospheric conditions that will be encountered, and particularly those that affect the comfort of miners. An extremely hot mine may be difficult or even impossible to operate from the standpoint of human endurance. Also, the natural tendency of heated air to flow without mechanical aid must be predetermined and integrated with the entire ventilation system in order to assure a positive flow control for normal operation and especially during emergencies.

The interdependent effects of time, depth, air autocompression, heat transferred by rock strata and mine water evaporation in conjunction with the seasonal and daily variations of intake air quality have yet to be evaluated in a satisfactory manner. The normally significant sources of mine heat have been identified and their respective contributions can be calculated for specific situations according to the principles of thermodynamics. Also, Carrier[1] has developed a method that relates the age of mine openings and the amount of heat flow from exposed rock strata. It is known, for example, that the rate of heat flow from exposed rock to air increases with depth and decreases with time. Also, it decreases with elevated intake air temperature. All of these phenomena are simultaneously influenced by the rate of mine water evaporation which is regulated by the quality of intake air, its resident time in the airway and the depth.

An accurate and useful determination of air properties at various key points in a mine ventilation circuit will involve the assignment of an initial intake air flow rate and quality, calculating the changes it will undergo in passing through an incremental length of airway of known conditions, adjusting its properties according to the thermodynamic changes invoked and repeating as before for new airway parameters of the next section. By such repetitive computations for all increments of an entire circuit, the air properties can be predicted for any point in the mine. Also, the entire procedure may be duplicated with appropriate adjustments to intake air quality to represent seasonal and daily changes and, furthermore, reduced strata heat flow, as a result of rock cooling, can be related to time in a similar manner. As a final goal, the thermodynamic properties of air can be ascertained for any point in the mine at any time during its operating life. However, because of the complicated, tedious and time-consuming procedure involved, this has never been accomplished for an actual mine to the best knowledge of this writer.

The purpose of this study is to alleviate the unfortunate situation described. As pointed out earlier, the pertinent thermodynamic principles are known and need only to be integrated into an accurate, workable method and the necessary computations reduced to a practical level. It is believed that both can be accomplished by appropriately assembling the known data and techniques into a suitable program for the 360/50 computer. The results are shown on the pages that follow.

II. LITERATURE REVIEW

A. Thermodynamics of Mine Air

1. Pertinent air properties

A clean atmosphere is a binary mixture of dry air and water vapor. On a volume basis, dry air contains 78.08 percent nitrogen, 20.95 percent oxygen and traces of approximately 15 other gases[2]. The molecular weight of dry air is 28.966 (Appendix B1) and its gas law constant R_a is 53.34 ft-lbf/lbm-R. Water vapor has a molecular weight of 18.016 and its R_v value is 85.76 ft-lbf/lbm-R. Being a mixture, air does not behave as would a pure gas but, within the atmospheric limits of an operating mine, its departure from the gas laws is considered negligible. Water vapor normally exerts a low pressure and exhibits nearly perfect gas behavior.

Air flowing in a mine is never perfectly dry, it is always associated with water vapor. Due to evaporation, and often condensation, the weight of water vapor and consequently that of the dry air in a pound of atmosphere will change. It is therefore convenient when dealing with moist air to regard one pound of dry air as the fundamental unit and the flow is then considered as $(1+w)$ pounds of moist air, where w is specific humidity, the water vapor content in pounds associated with one pound of dry air.

The following equation of state expresses the relationship between pressure, volume and temperature:

$$P\,v = R\,T \qquad (1)$$

where P = absolute pressure, lbf/sq ft.

v = specific volume, cu ft/lbm.

T = absolute temperature, ^{o}R.

R = gas law constant, ft-lbf/lbm-R.

This expression is correct for every gas of a mixture each having its own values of P and R. Esbroeck[3] suggested that the values of gas constants R are related to molecular weights M as

$$R\,M = 1545.4$$

For mine air in coal mines composed of dry air (a), water vapor (v), and methane gas or commonly known as firedamp (d),

$$R_a M_a = R_v M_v = R_d M_d = 1545.4 \qquad (2)$$

and the R value for the mixture is related as

$$G\,R_m = G_a\,R_a + G_v\,R_v + G_d\,R_d$$

and

$$G = G_a + G_v + G_d$$

where G is the total weight and G_a, G_v and G_d are partial weights of dry air, vapor and firedamp, respectively.

For specific humidity w, which is the weight of water vapor interspersed in each pound of dry air, the perfect gas equation may be applied as

$$w = \frac{\text{lb of water vapor}}{\text{lb of dry air}}$$

$$w = \frac{p_v\ V/\ R_v\ T}{p_a\ V/\ R_a\ T} = \frac{p_v\ /\ R_v}{(P - p_v)\ R_a}$$

$$w = 0.622\ \frac{p_v}{P - p_v} \tag{3}$$

from which

$$p_v = \frac{w\ P}{0.622 + w} \tag{4}$$

where P is the barometric pressure and p_v and p_a are respectively the partial pressures of vapor and dry air at temperature T. Since

$$P = p_a + p_v$$

then

$$p_a = P - \frac{w\ P}{0.622 + w} = \frac{P}{1 + 1.607\ w} \tag{5}$$

2. Principles of psychrometry

A convenient relationship exists between vapor pressures, dry-bulb temperature, wet-bulb temperature and dew-point temperature. The temperatures may be measured directly with appropriate instruments. Then, by reference to steam tables[4], psychrometric tables or charts[5,6,7], all of the pertinent properties of moist air may be ascertained. Regnault[8], in 1853, formulated an equation relating vapor pressure and dry- and wet-bulb temperatures in which

$$p_v = p_{s,tw} - A\,P\,(t_d - t_w) \tag{6}$$

where p_v = water vapor pressure, in.Hg.
$p_{s,tw}$ = saturated water vapor pressure at t_w, in.Hg.
P = barometric pressure, in.Hg.
t_d = dry-bulb temperature, °F.
t_w = wet-bulb temperature, °F.
A = psychrometric constant.

The value of A given by Regnault was 3.53×10^{-4} but has been modified by Barenburg[8] to 3.613×10^{-4}.

Air is usually deficient in water vapor and, therefore, its vapor pressure is lower than the maximum corresponding to the temperature of the mixture. The ratio of such vapor pressure to the vapor pressure of the mixture when saturated at the same temperature is termed the relative humidity ϕ, that is

$$\phi = 100 \frac{p_v}{p_s} \qquad (7)$$

The relationship between specific humidity w and relative humidity ϕ can be found by substituting the value of p_v of equation (7) into equation (3)

$$w = \frac{0.622 \phi p_s}{100 P - \phi p_s} \qquad (8)$$

This equation was used to plot various curves of relative humidity[6].

At any temperature, air and its moisture has a certain enthalpy. Enthalpy of moist air H, in Btu/lbm of dry air, is the sum of the enthalpies of dry air H_a and water vapor H_v, or

$$H = H_a + H_v$$

and

$$H = C_{pa} t_d + w (1061 + C_{pv} t_d) \qquad (9)$$

Specific heat of dry air C_{pa} and of water vapor C_{pv} vary slightly with temperature as stated by Carrier[5] in the expressions

$$C_{pa} = 0.24112 + 0.000009 t$$

and

$$C_{pv} = 0.44230 + 0.00018\ t$$

However, for all mining calculations the values of $C_{pa} = 0.24$ and $C_{pv} = 0.44$ Btu/lbm-°R are sufficiently accurate and will therefore be used. By using the principle of mass fraction in a mixture, the specific heat of moist air can be found as follows:

$$C_{pm} = \frac{C_{pa} + C_{pv}\ w}{1 + w} \qquad (10a)$$

and

$$C_{vm} = \frac{C_{va} + C_{vv}\ w}{1 + w} \qquad (10b)$$

The thermodynamic aspect of airflow in mines will deal with the bulk of energy quantities. It involves the effects of changes of volume, temperature, pressure, humidity, and other parameters of the air as it flows underground. It is very useful in solving the problems of mechanical and natural ventilation in mines. The general energy equation for the flow of air of uniform composition and state between two points, from station 1 to station 2, may be stated as follows:

$$J\left[(H_1 - H_2) + Q_{in} - Q_{out}\right] = \frac{U_2^{\ 2} - U_1^{\ 2}}{2\ g} + Z_2 - Z_1 - W_f$$

or

$$J \left((H_1 - H_2) + Q_{in} - Q_{out} \right) = \int_2^1 v \, dP - F_{1-2} \qquad (11)$$

where H_1 and H_2 = enthalpies at stations 1 and 2, Btu/lbm.

Q_{in} and Q_{out} = heat added or lost by 1 lbm of air.

U_1 and U_2 = air velocities, ft/sec.

Z_1 and Z_2 = heights of stations above datum, ft.

W_f = work done on the air by fans, ft-lbf/lbm.

J = Joule's equivalent of 778.26 ft-lbf/Btu.

v = specific volume, cuft/lbm.

P = absolute static pressure, lbf/sqft.

F_{1-2} = work done against friction, ft-lbf/lbm.

g = acceleration due to gravity, ft/sec^2.

The above equation refers to the flow of one pound of dry air. For (1+w) pound of moist air, considering that the change of kinetic energy is negligible and with no fans in the airway, equation (11) is modified into

$$(H_1 - H_2) + Q_{in} - Q_{out} = \frac{(Z_2 - Z_1)(1 + w)}{J} \qquad (12)$$

By considering the air flow process in the shafts as adiabatic due to auto-compression in downcast and expansion in upcast, then

$$\int_1^2 v \, dP = J (H_2 - H_1) = (Z_1 - Z_2)(1 + w) \qquad (13)$$

For the perfect gas relation,

$$J\ (H_2 - H_1) = J\ C_{pm}\ (T_2 - T_1) \tag{14}$$

and thus

$$J\ C_{pm}\ (T_2 - T_1) = (Z_1 - Z_2)\ (1 + w) \tag{15}$$

Equation (15) is used to find the final temperature of air flowing in a shaft of known depth, if the original state of air is known. For example, the temperature rise of air, having 0.00756 lb of water vapor per lb of dry air, for 1000 ft of depth will be:

$$T_2 - T_1 = \frac{(Z_1 - Z_2)\ (1 + w)}{J\ .\ C_{pm}} = \frac{1000\ (1 + 0.00756)}{778.28 \text{ X } 0.2415}$$

$$= 5.36\ {}^{o}F.$$

B. Sources of Mine Heat

The main sources of heat underground which will contribute to increasing mine air temperature are:

1. Auto-compression of the air.
2. Heat released by the rock strata.
3. Heat caused by blasting.
4. Heat caused by machinery, men, lighting and oxidation of rock, coal or timber.
5. Heat caused by friction of the air current.

The temperature increase caused by auto-compression and that issuing from strata are the major sources which contribute about 80 percent of all heat transferred to mine air[9]. Some is also contributed by rock movement[10] although its relative amount is very incidental.

1. Temperature increase by air auto-compression

When air flows down a shaft into a mine, it is compressed at the rate of about 1 in.Hg per 900 ft of descent. The air is heated in the same way as if it were compressed in a compressor. If the shaft is dry, the temperature of the air will increase at the rate of about 5.5 °F per 1000 ft of descent. If it is wet, the evaporation of moisture will modify the temperature-depth gradient as shown by equation (15). When no heat transfer takes place between the air and shaft, evaporation produces a fall in temperature.

According to the reversible adiabatic compression process,

$$P\, v^{k} = \text{constant}$$

Since $P\, v = R\, T$ and considering stations 1 and 2 as shown by Fig. 1,

$$\frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^{k} = \left(\frac{T_2}{T_1}\right)^{\frac{k}{1-k}}$$

$$P_2 = P_1 \left(\frac{T_2}{T_1} \right)^{\frac{k}{k-1}} \qquad (16)$$

where k is the specific heat ratio $\frac{C_{pm}}{C_{vm}}$, in which C_{pm} has been defined as specific heat of air at constant pressure and C_{vm} is the specific heat of air at constant volume. Values of C_{vm} may be obtained from the relation

$$R = \left(C_{pm} - C_{vm} \right) J$$

Equation (16) is used in the computer program to find the barometric pressure along the shaft.

Cooling due to evaporation is usually not sufficient to counteract the heating by compression. Thus, the air arrives at the downcast bottom with an increased temperature and absolute pressure and a reduced volume. The reverse processes occur in the upcast shaft where expansion takes place and work is done by the air to cause cooling. Hinsley[11] described the processes of the airflow in a mine circuit very similar to that occurring in a heat engine. The air is compressed in the downcast shaft, is heated in the levels and working areas where it expands and, in the upcast shaft, it expands still further due to the lowering of pressure. An indicator diagram shown in Fig. 1 represents the path of a pressure-volume change. The area enclosed by the P-v diagram indicates the quantity of work

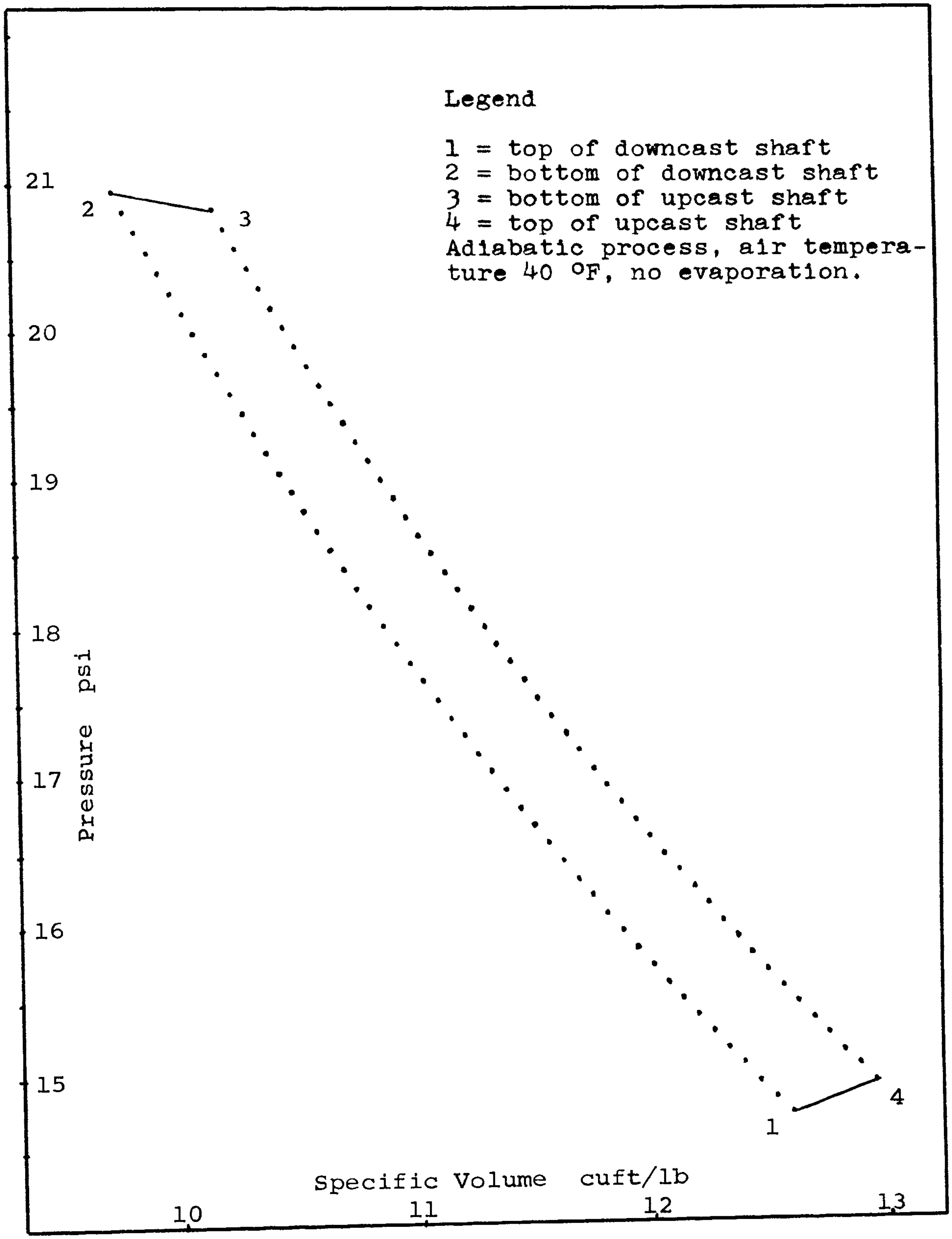


Fig. 1 Indicator Diagram

in ft-lbf done during the cycle.

2. Heat released by the rock strata

The temperature of rocks forming the crust of the earth increases with depth. The base point for calculating the temperature rise is normally taken at about 50 ft below surface where the rock temperature remains at mean surface temperature throughout the year. The chief concern is to find the geothermic gradient, that is, the average increase in depth for a rise of 1 °F. Where the rock formation consists of several layers, the geothermic gradient will usually differ for each layer. Studies made in various parts of the world have shown that their values vary from one area to another and, also, with different depths[12,13,14]. These variations are related[14] to:

a. Mountains or folded rock structures.
b. Movement of water in the strata.
c. Local changes in radioactivity.
d. Erosion of the area.
e. Effect of glaciation in the past.

Geothermic gradient of rock can be explained by considering homogeneous and isotropic rock. Using one dimensional heat transfer, the conduction of heat through rocks follows the Fourier equation for steady conditions as follows:

$$Q = - K_r A \frac{\Delta T}{\Delta Z}$$

where Q = rate of heat transfer by conduction, Btu/hr.

A = cross section normal to heat flow, sqft.

ΔT = change in temperature, ^{o}F.

ΔZ = change in depth, ft.

K_r = rock conductivity, Btu/hr-ft-^{o}F.

Assuming rock of constant thermal conductivity, the rate of heat transfer through a unit cross section is

$$Q = \frac{K_r}{Z} (T_z - T_o)$$

where T_z is the temperature of rock at depth Z and

T_o is the temperature of rock at the surface.

Also,

$$T_z = (Q + \frac{K_r}{Z} T_o) \frac{Z}{K_r}$$

and

$$T_z = T_o + \frac{Q\,Z}{K_r} \tag{17}$$

Thus, the temperature T_z at depth Z depends on the surface rock temperature T_o, the depth, the rate of heat flow and the thermal conductivity of the rocks.

The factors which influence heat flow from the exposed rock strata of underground mine openings are specific heat, thermal conductivity, thermal diffusivity of the rock surrounding the mine openings and the heat transfer coefficient between the opening walls and the ventilating air. Specific heat C_r for most rocks is of the order of 0.2 Btu/lbm-°F[15]. It varies slightly with temperature but, for this purpose, it may be regarded as being virtually constant for any given rock. Thermal diffusivity D, in sqft/hr, is related to the thermal conductivity and specific heat. Thus,

$$D = \frac{K_r}{\rho_r \; C_r} \tag{18}$$

where ρ_r = rock density, lbm/cuft.

Heat from the high temperature walls is transferred into all mining openings. However, its rate of inflow decreases as a cooled, insulating layer of rock is built up around the opening. A study of several mines, conducted by Carrier[1], produced a chart of heat flow versus time which permits an accurate determination of the rate at which heat flows after various periods of cooling. The method has been developed mathematically for smooth, circular openings of infinite length. Carrier's chart shows a relationship between time and conductivity factors where the time factor is expressed by D t, in which D is the thermal diffusivity of rock and t is the time in years. Conductivity factor is given as the ratio of rock conductance and rock conductivity, K/K_r where K represents the ability of rock to transmit heat expressed in Btu/sqft-hr-^{o}F. To use the chart, the radius equivalent R_e of the airway must first be calculated,

$$R_e = \frac{2\ A}{Pm\sqrt{2}} \tag{19}$$

where A = cross section of the shaft or airway, sqft.

Pm = perimeter of the airway, ft.

By a correlation-of-random-data method for curve-fitting, the general formula relating conductivity factor versus time factor as suggested by Carrier's chart was found to be

$$Y = (0.811)^{n-2}\ A\ X^{-\left((1.109)^{n-2}\ B\right)} \tag{20}$$

where Y = conductivity factor for radius of equivalent R_e = n.

X = time factor = D t.

D = thermal diffusivity of rock, as calculated by equation (18).

t = age of opening in years.

A = a constant = 0.0939034

B = a constant = 0.1956590

Rock conductance K is found by multiplication of Y by the rock conductivity K_r.

$$K = Y K_r \tag{21}$$

If the rock surfaces are wet, a combination of convective and radiative heat transfer and evaporation take place. The degree of wetness can be specified in terms of wetness fraction f, which varies from zero for a perfectly dry surface to unity for thoroughly wet surface[16]. The combination of sensible heat flow for rock strata and the latent heat due to evaporation of water can be stated as

$$J_w = Pm\ L \left(K (t_r - t_a) + f\ r'\ E (p_{s,tr} - p_v) \right) \tag{22}$$

where J_w = heat transmitted by rock surface, Btu/hr.

Pm = perimeter of airway, ft.

L = length of airway, ft.

K = rock conductance, Btu/sqft-hr-^oF.

t_r = rock surface temperature, ^oF.

t_a = air temperature, ^oF.

r' = latent heat of water evaporation, Btu/lbm.

E = coefficient of mass transfer, lbm/sqft-hr-inHg.

$p_{s,tr}$ = saturated vapor pressure at t_r, in.Hg.

p_v = partial pressure of vapor, in.Hg.

f = degree of wetness of rock surface.

The value of E can be computed by using the formula[17]:

$$E = \frac{h_c}{\rho_a\ C_{pm}\ R_v\ T} \tag{23}$$

in which ρ_a = density of mine air, lbm/cuft.

h_c = convective heat transfer coefficient, Btu/sqft-hr-°F

The convective heat transfer coefficient h_c is calculated by using Mc Adams' formula[17] which was based on experimental results for forced convection of turbulent flow. The formula was developed for smooth circular tubes:

$$h_c = 0.023\ \frac{K_a}{Dm} \left(\frac{G\ \ Dm}{u}\right)^{0.8} \left(\frac{u\ \ C_{pm}}{K_a}\right)^{0.4} \tag{24}$$

where K_a = thermal conductivity of air, Btu/ft-hr-°F.

u = dynamic viscosity of air, lbm/ft-hr.

C_{pm} = specific heat of air at constant pressure.

G = mass flow rate of air, lbm/sqft-hr.

Dm = diameter of airway, ft.

Considering the size of mine air shaft diameter, it can be assumed that air shafts have smooth walls and thus, equation (24) can be applied. However, for underground mine airways, equation (24) has to be multiplied by a roughness factor F, which was determined by Starfield[16] as 1.7. For airways with rectangular cross section, the value of Dm is replaced by De,

$$De = 4 \frac{\text{cross sectional area}}{\text{perimeter}}$$

The values of K_a and u can be found in Appendix B and the thermal properties of some rocks are given in Appendix C.

3. Heat from other sources

a. Heat from blasting

The heat caused by blasting can be very great, about 300,000 Btu/hr[10] or 3 Btu/hr per ton of monthly production in a metal mine. However, blasting is usually confined to a single hour on one shift a day or to a certain period of each shift. This great amount of heat combined with the large amount of steam released by the explosives may adversely affect the ventilation system by impairing the existing heat balance of the mine atmosphere. The amount of heat and other products of blasting can be calculated by knowing the chemical composition of the explosives used and the amount consumed for each blast.

b. Heat from machinery

The amount of heat given to the air as a result of the use of power operated machines underground depends on the type of power used and on the kind of work done by each machine. The usual power systems employed in mines are compressed air and electricity. Exhausting compressed air is usually cooler than the mine air thus it causes cooling. However, compressed air leaving a compressor at the surface is usually at an increased temperature compared with atmospheric air and when piped down a shaft there is usually a transfer of heat from the pipe line to the ventilating air. The heat lost by the compressed air in the shaft has been calculated from the approximate formula[9]:

$$Q_c = G_c \left(0.24 \ (t_1 - t_2) + 1061 \ (w_1 - w_2) + \frac{(Z_1 - Z_2)}{778.26} \right) \qquad (25)$$

where Q_c = loss of heat, Btu/min.

G_c = weight of compressed air flowing, lbm/min.

t_1 = temperature of compressed air at top of shaft, ranging between 200 and 250 °F.

t_2 = temperature of compressed air at bottom of shaft, ranging between 65 and 100 °F.

w_1 = moisture content in the pipe at top of shaft.

w_2 = moisture content in the pipe at bottom of shaft.

Z_1 and Z_2 are the heights above some datum of the top and bottom of the shaft, respectively, ft.

For practical computations, the value of 1061 $(w_1 - w_2)$ is relatively small and, therefore, negligible.

For electrical machines used underground, the amount of heat given to the air can be computed on the basis of one horse power being equivalent to 42.72 Btu/hr[10].

c. Heat from human metabolism

The chemical changes that take place in the human body produce heat. A miner working at his full normal capacity may produce heat at the average rate of 1100 Btu per hour[10]. Thus, assuming there are 300 miners underground working at an average rate, the heat output will be about 330,000 Btu/hr. Taking the volume of air flowing through the mine at 300,000 cuft/min., the temperature rise due to the human metabolism would be about 1 °F.

d. Heat from frictional losses

Frictional losses in the air stream are from two causes, those due to viscous drag in the thin laminar layer at solid boundaries and those due to turbulence. The heat caused by friction of air against the walls of the airways may be considered negligible. The air is heated by friction but the friction causes a drop in pressure and thus promotes an expansion of the air. The cooling by this expansion very nearly balances the heat produced by friction.

4. Evaporation of water

The dynamic equilibrium corresponding to the evaporation of water into air counterbalanced by the flow of heat from the air into the water is the basis of wet-bulb thermometry, a method used to determine the humidity of air. There is a saturated air film on the surface of water. This air film is at the same temperature as the water with which it is in contact. The transfer of heat and water vapor between the main air stream and the liquid water takes place through this saturated air film. Carrier[5] stated that the increase in heat of vaporization is equal to the decrease in the sensible heat of the air stream from which the heat is extracted, that is,

latent heat absorbed = sensible heat lost

or

$$r' (w' - w_o) = (C_{pa} + C_{pv} w_o) (t - t') \tag{26}$$

where r' = latent heat of vaporization at the resultant temperature t', Btu/lbm.

w' = final weight of vapor per unit weight of dry air, lbm/lbm dry air.

w_o = initial weight of vapor per unit weight of dry air, lbm/lbm dry air.

t' = final temperature.

t = initial temperature.

C_{pa} and C_{pv} are specific heats of dry air and of the vapor respectively.

There is a continuous change in water vapor content of mine air along the ventilation circuit due to water evaporation. If there is no heat transfer between the air and the walls of mine openings, the evaporation produces a fall in temperature of the air. The temperature of equilibrium t' may be found by

$$t' = t - \frac{r' (w' - w_o)}{C_{pa} + C_{pv} w_o} \qquad (27)$$

The rate of evaporation of water is given by Eckert[18] as

$$w_v = \frac{h_c}{C_p' R_v T} (p_{s,td} - p_v) \qquad (28)$$

where w_v = evaporation rate, lbm/sqft-hr.

$p_{s,td}$ = saturated vapor pressure at t_d, lbf/sqft.

p_v = partial pressure of vapor, lbf/sqft.

R_v = gas constant for vapor, equal to 85.76.

T = temperature in Rankine.

h_c = heat transfer coefficient, equation (24).

C_p' = specific heat of air per unit volume at constant pressure, equal to C_{pm} times the density of air, Btu/cuft-°F.

C. Effects of Mine Heat

As mine air moves deeper into the bowels of the earth, it absorbs heat and moisture from various sources until its condition becomes humanly unbearable and the control of its flow difficult. Also the rock temperature increases at a rate of 0.5 to 3.3 °F per 100 ft of depth. Assuming a gradient of 1 °F per 100 ft, a mine that is

10,000 ft deep will suffer a rock temperature of 100 °F plus the mean annual surface temperature. This could be on the order of approximately 160 °F.

1. Effects upon miners

The productivity of an underground miner is related directly to his working environment. His body functions much the same as that of a machine. He takes on fuel in the form of food which his metabolism converts into energy for doing work. But unlike a machine, his system is only about 20 percent efficient. That is, for each unit of work performed, his body system must dispel about 4 equivalent units of heat. The rejected heat must be absorbed by the surrounding environment or, otherwise, the work rate will decrease (or cease) to prevent a heat buildup in the miner's body which eventually could cause prostration.

The approximate endurance capabilities of industrial workers are shown in Appendix A. A work efficiency versus comfort diagram is shown wherein comfort is represented by effective temperature, an interdependent combination of temperature, humidity and air velocity. An effective temperature chart depicting these relationships is also shown. To employ the diagrams, one needs to predetermine the wet- and dry-bulb temperatures and air velocity. From these, the effective temperature may be obtained to ascertain the percent work efficiency that may be expected. Of course, incoming air is being cooled and dehumidified mechanically to promote a more productive working environment. However, it is not presently possible to accurately predict the amount of conditioning required. Instead, air conditioners of several thousand tons capacity are selected on the basis of empirical rules. Very often, extensive later modifications entail considerable additional expense.

Because the air conditioning demands will change daily, seasonally and with time as the mine rock cools, an accurate prediction of air quality during successive stages of its operating life would be of great value. Such data would show the cooling load extremes and a practical mean by which a single unit could be selected.

2. Effects upon natural ventilation

Most ventilation systems in underground mines are a combination of mechanically and naturally induced flow whether or not the natural aspect was ever considered in the initial design. A few air conditioned mines possess natural air pressures of such magnitude as to entirely eliminate the need for mechanical prime movers. Should the natural flow phenomenon be overlooked in an air circuit layout, future control of the system could prove difficult. For example, the writer has repeatedly observed a complete reversal in flow direction after a routine blast. Toxic fumes were routed into the mine instead of to the upcast shaft. Even more serious occurrences have been recorded during fires and other emergencies.

Natural ventilation is produced essentially by a thermodynamic process in which heat is converted into work. Thermal energy added to the system is converted into a pressure head capable of producing airflow. Warm humid air rises to displace cooler, drier air. Contaminating, low density gases will enhance the effect. The actual flow tendency within a mine is dependent upon the relative conditions of incoming and outgoing air. Also, a sudden influx of cold or hot air may disrupt a delicately pressure balanced air circuit on a specific mining level.

One of the methods for calculating the natural ventilation pressure h_n is by density. This involves the consideration of two stationary vertical columns of air, which constitute the downcast and upcast as in Fig. 2, and treating the system as a standard manometer. Where the surface levels of the shaft collars are not the same, the upper common level of the columns will be the level of the higher shaft collar. The lower level of the two columns is the deepest point reached by the air current.

Assuming that the air is at rest so that the full weight of air in each shaft is acting on its respective base, B is the absolute atmospheric pressure in lbf/sqft at the upper level joining the tops of the air columns and L the height of columns in ft., the natural ventilation

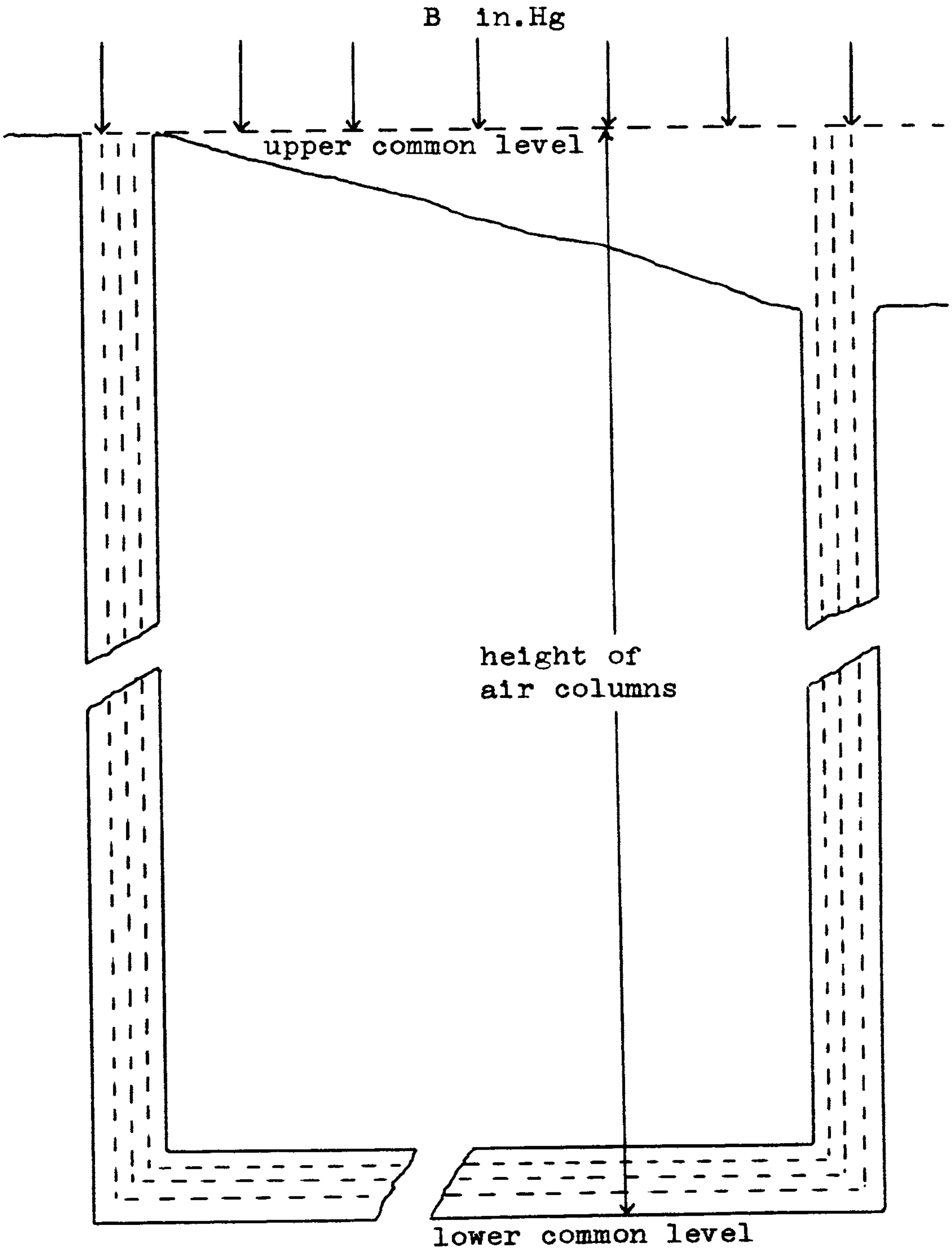


Fig. 2 Closed Circuit
of Natural Ventilation

pressure of the system can be calculated by

$$h_n = (B + L\ W_d) - (B + L\ W_u)$$

$$= L\ (W_d - W_u) \tag{29}$$

where h_n = natural ventilation pressure, lbf/sqft.

W_d = mean density of air in downcast shaft, and

W_u = mean density of air in upcast shaft, lbm/cuft.

As can be appreciated, the mean air densities are difficult to predict. However, it is known that the density of air along the shaft changes according to the following[7]:

$$W = \frac{1.3258\ (P - 0.3777\ p_v)}{t_d + 459.69} \tag{30}$$

where P and p_v are expressed in in.Hg. By basing the calculations on incremental sections along the shaft, the air densities of each section of the shaft can be computed. Then by averaging the densities in each column, the values of W_d and W_u can be found.

III. DISCUSSION OF PROBLEM

Several investigations[1,7,8,16,19] have been conducted into various phases of the problem and each has contributed in some degree toward formulating the procedures that follow. By accepting standardized techniques of these earlier researchers, combining them with some of the gas laws and thermodynamics into a workable plan and then modifying the whole for computer programming, the writer was able to attain the goals outlined earlier.

A. Method of Computation

In attacking the problem, it was first assumed that:

1. The rock is homogeneous and isotropic.
2. The shaft is circular in cross section (can be modified).
3. The air temperature is uniform in each cross section.
4. Intake air quality does not fluctuate during a computation.
5. The shaft walls are wet and underground airways have a wetness fraction of 0.6 (can be modified).
6. The effects of enthalpy change in each section increment of shaft and airways are instantaneous.
7. Mine air behaves as a perfect gas. The use of the existing formulas discussed in the literature review for the computer simulation was based on this assumption.
8. Air flows in mine ventilation circuit as a turbulent flow.

Consideration of the mine air circulation system was then divided into four convenient parts as shown in Fig. 3:

1. Definition of air quality on the surface.
2. Enthalpy change in the downcast shaft.
3. Enthalpy gain on the mining level.
4. Enthalpy change in the upcast shaft, with special note of the point at which condensation commences.

It was assumed that 200 miners were working on a mining level as schematically outlined in Fig. 4.

At the outset of the program, all necessary basic data were read into the computer. This included tables of saturated vapor pressures and latent heats of water vaporization, shaft dimensions, rate of air flow, rock properties, conditions and dimensions of the mine workings, age of openings, surface air conditions, etc. Having assigned wet- and dry-bulb temperatures and an appropriate barometric pressure to the surface intake air, all of the remaining pertinent thermodynamic properties of the atmosphere were computed by reference to input data and methods previously described in the review of literature.

The surface air, with its condition defined, was then assumed to pass the initial 5-foot increment of the shaft. Its enthalpy changes were computed according to the parameters previously assigned in input data. These changes involved the effects of:

1. Auto- compression.
2. Water evaporation.

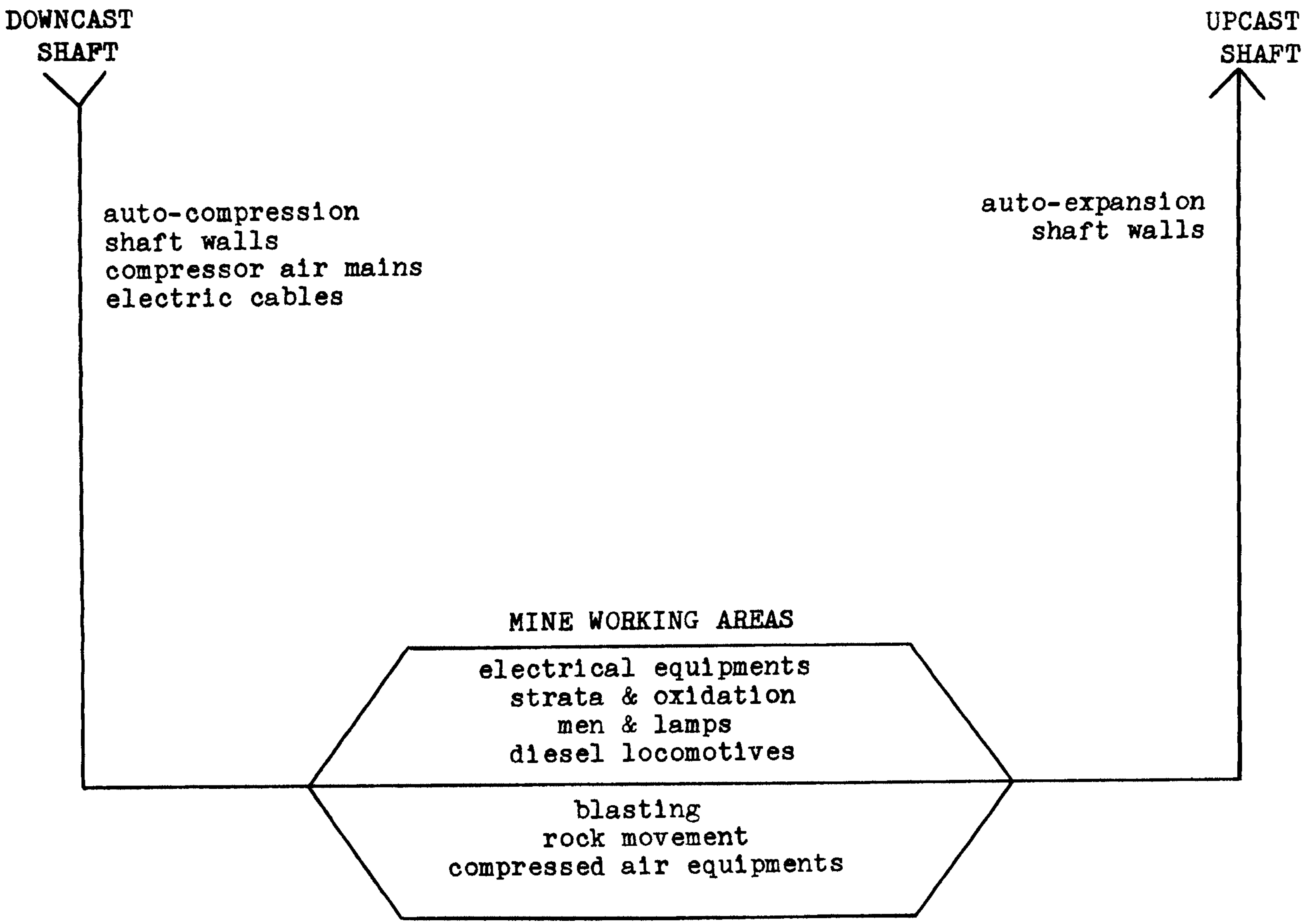


Fig. 3 Mine Circuit and Heat Sources Underground

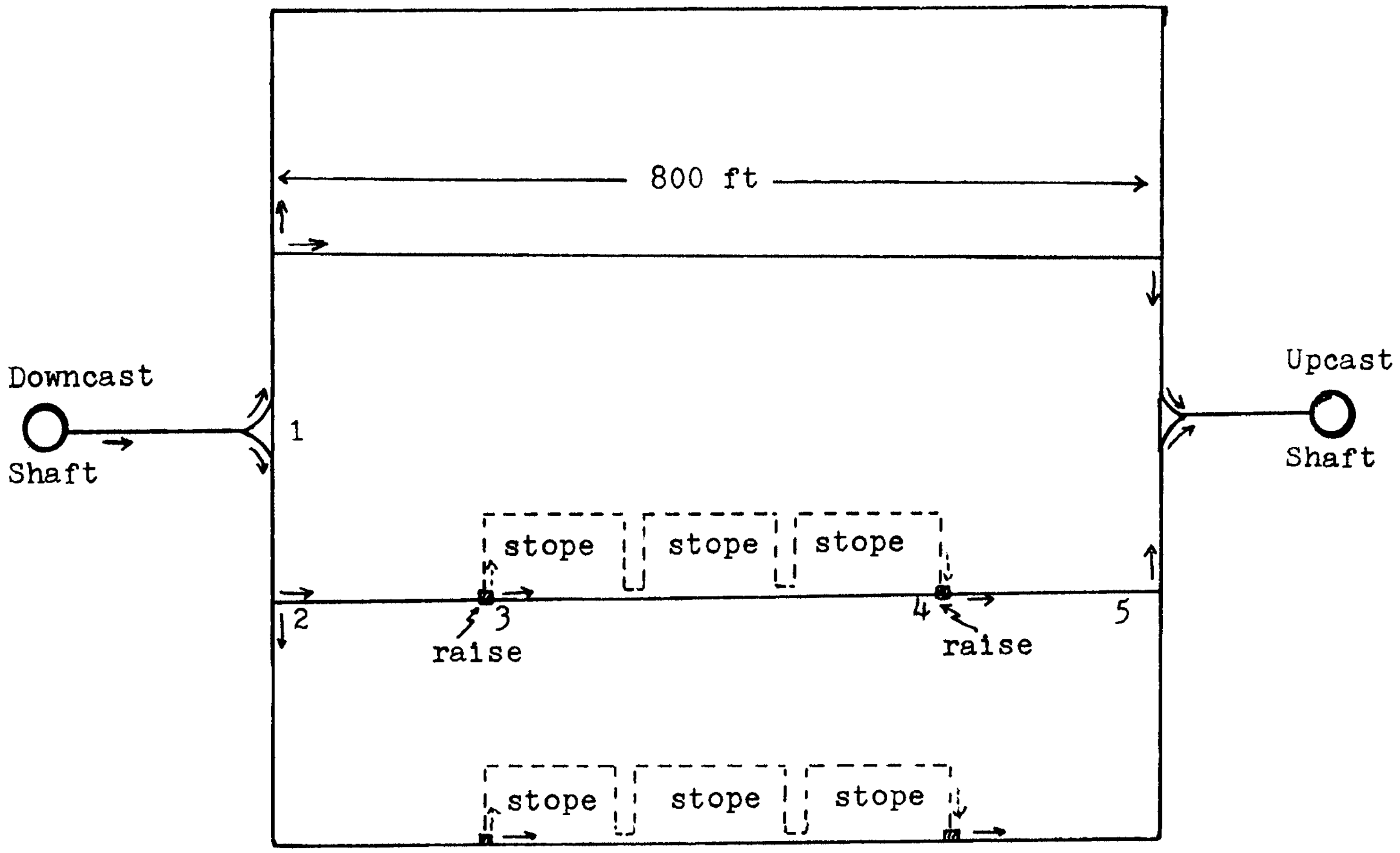


Fig. 4 Schematic of an Underground Working Plan

3. Heat from the exposed strata.
4. Compressed air lines.

Having the heat and water exchange determined, the air condition was redefined accordingly and passed through the next 5-foot segment of shaft where the process is duplicated for new shaft parameters in accord with the geothermic gradient. By repetitive computation, the entire depth of air column is treated in this manner to provide complete thermodynamic data at its base or at any desired increment along its length. At specified intervals the computer will print out the air conditions along the shaft.

The air is next moved through the working level where its enthalpy changes involve:

1. Heat from exposed rock.
2. Water evaporation.
3. Compressed air lines, machinery, workers, lights, etc.

Compressed air, in the working areas, has a cooling effect. For any complicated underground network, the amount of air flow through each airway can be found by using the Hardy-Cross method of ventilation network analysis[20]. Knowing the specific heat of the air, total sensible heat transferred to the air per unit time and the amount of air passing in the same time interval, the dry-bulb gradient of the air can be calculated. A new condition is assigned to the air at the base of the upcast shaft according to the heat and water exchanges undergone.

In the upcast shaft, the procedure duplicates that used in downcast but with proper consideration for a negative geothermic gradient and auto-expansion. Also, it was assumed that compressed air lines were not present. In addition to the usual data, the point at which condensation commences was ascertained. This is useful in combatting shaft water problems. The exhaust mine air in upcast shaft usually has higher temperatures compared to the surrounding walls, therefore, it can be expected that the age of opening has little effect on the amount of heat transmitted by rock strata.

Incremental densities of air in each of the shafts were averaged, converted to column base pressures and subtracted to produce a measure of the natural ventilation pressure existing in the mine. Fig. 5 shows the flow chart of the program and Appendices D-1, D-2 and D-3 list the computer input and output data.

B. Results

The results of this study are gratifying. As anticipated, air quality can be accurately and rapidly ascertained at any key point within a mine and natural ventilation pressures can be determined simultaneously as shown by the appended computer print-out and Tables 1, 2, 3 and 4.

Knowing the depth of mine, required air velocity, rock properties and range of surface air quality, the underground environmental conditions can readily be predicted. Also, because of the ease and rapidity of calculation, any

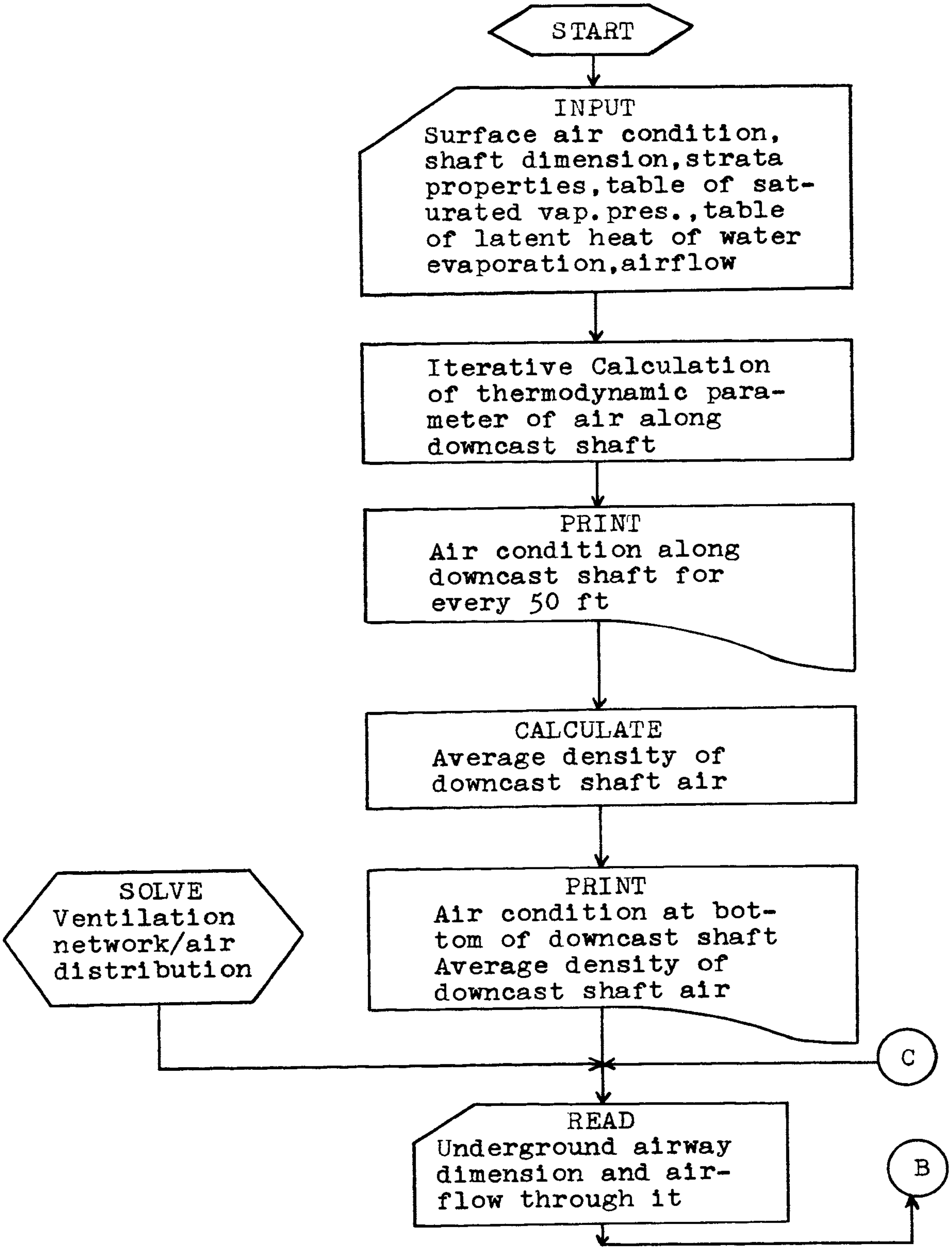


Fig. 5 Computer Flow Chart

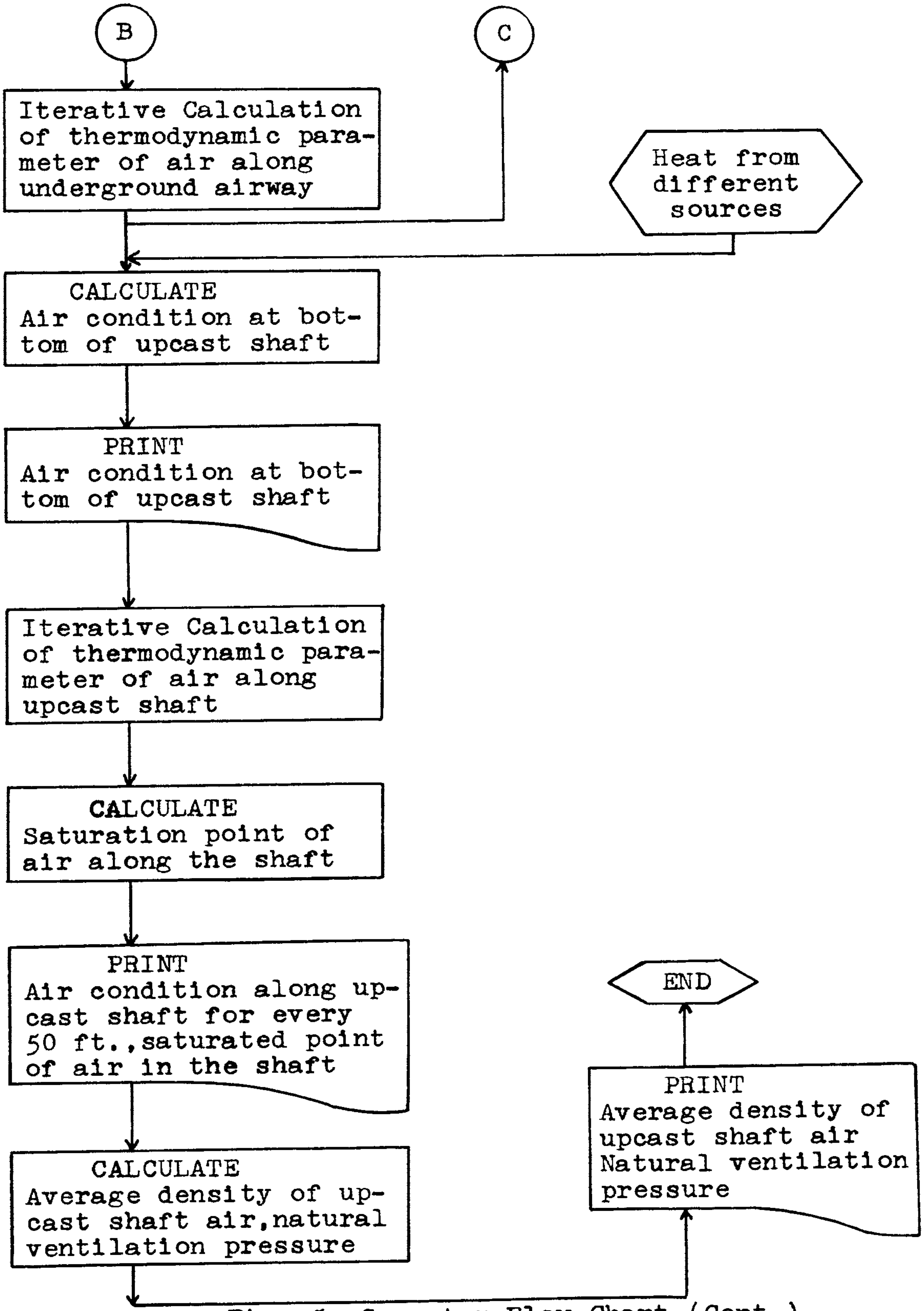


Fig. 5 Computer Flow Chart (Cont.)

number of determinations may be made to represent the situation that will exist during any period during the life of the mining operation. This should simplify the tedious task of air conditioner selection and flow system design.

Several computations were conducted to test the environmental response to various input air conditions. The resulting data compared very favorably to solutions derived mathematically and graphically for similar conditions. In addition, the mine atmospheric parameters varied in accordance with the laws of thermodynamics throughout the air course. Some of these displayed significant trends which may justify further discussion.

The rise in dry-bulb temperature with increasing depth is practically linear as shown in Tables 1 and 2 and Fig. 6. It would appear that because of increasing rock temperature with depth, the dry-bulb gradient would also increase. However, in examining equation (22), it can be seen that there is an increase in enthalpy gain as suspected but there is also an increase in sensible heat conversion to latent heat in evaporating more water. This is further substantiated by Table 4 wherein the more saturated incoming air displays a larger (very slightly) dry-bulb gradient.

Higher incoming air and rock temperatures appear to

TABLE 1. EFFECTS OF AIR VELOCITY ON AIR CONDITION ALONG DOWNCAST SHAFT *)

Dry-bulb = 50 °F Wet-bulb = 48 °F

Depth ft	Pressure inHg	Temperature Drybulb °F	 Wetbulb °F	Wetbulb Grad. °F/100ft	Density lb/cuft	Moist.Cont. lb/lb dry	Enthalpy Btu/lb	Rel.Humid. percent
			airflow 500000 cfm					
Surface	29.92	50.00	48.00	-	0.077325	0.0066089	19.16	86.83
1000	31.04	55.40	51.69	0.369	0.079363	0.0070024	20.96	77.32
2000	32.19	60.76	55.67	0.399	0.081422	0.0075766	22.82	72.37
3000	33.37	66.13	59.89	0.422	0.083503	0.0083972	25.02	68.80
4000	34.58	71.49	64.29	0.440	0.085607	0.0094388	27.47	66.55
			airflow 400000 cfm					
Surface	29.92	50.00	48.00	-	0.077325	0.0066089	19.16	86.83
1000	31.04	55.41	51.73	0.372	0.079362	0.0069929	20.89	78.16
2000	32.19	60.77	55.74	0.402	0.081421	0.0076127	22.87	72.71
3000	33.37	66.14	60.00	0.426	0.083501	0.0084587	25.09	69.29
4000	34.58	71.50	64.43	0.444	0.085603	0.0095289	27.57	67.18
			airflow 300000 cfm					
Surface	29.92	50.00	48.00	-	0.077325	0.0066089	19.16	86.83
1000	31.04	55.43	51.77	0.375	0.079361	0.0070132	20.92	78.38
2000	32.19	60.79	55.84	0.407	0.081418	0.0076608	22.92	73.16
3000	33.37	66.15	60.14	0.431	0.083497	0.0085398	25.19	69.95
4000	34.58	71.52	64.63	0.449	0.085598	0.0096473	27.70	68.00

*) shaft diameter: 24 ft.

TABLE 2. EFFECTS OF AIR VELOCITY ON AIR CONDITION ALONG DOWNCAST SHAFT *)

Dry-bulb = 75 °F Wet-bulb = 60 °F

Depth	Pressure	Temperature		Wetbulb Grad.	Density	Moist.Cont.	Enthalpy	Rel.Humid.
ft	inHg	Drybulb °F	Wetbulb °F	°F/100ft	lb/cuft	lb/lb dry	Btu/lb	percent
airflow 500000 cfm								
Surface	29.92	75.00	60.00	-	0.073668	0.0075606	26.27	41.08
1000	30.99	80.40	66.63	0.661	0.075415	0.0102883	30.58	48.26
2000	32.08	85.77	72.76	0.612	0.077187	0.0130822	34.96	53.20
3000	33.21	91.14	78.55	0.579	0.078981	0.0160134	39.51	56.62
4000	34.37	96.53	84.13	0.557	0.080796	0.0191450	44.29	59.04
airflow 400000 cfm								
Surface	29.92	75.00	60.00	-	0.073668	0.0075606	26.27	41.08
1000	30.99	80.41	66.79	0.676	0.075410	0.0103983	30.70	48.77
2000	32.08	85.78	73.01	0.621	0.077178	0.0132808	35.18	53.99
3000	33.21	91.16	78.87	0.585	0.078969	0.0162872	39.81	57.56
4000	34.37	96.54	84.48	0.561	0.080782	0.0194864	44.67	60.06
airflow 300000 cfm								
Surface	29.92	75.00	60.00	-	0.073668	0.0075606	26.27	41.08
1000	30.99	80.43	67.01	0.697	0.075404	0.0105459	30.87	49.45
2000	32.08	85.80	73.35	0.633	0.077167	0.0135441	35.47	55.03
3000	33.21	91.17	79.28	0.592	0.078954	0.0166465	40.21	58.80
4000	34.37	96.56	84.94	0.566	0.080763	0.0199310	45.17	61.38

*) shaft diameter: 24 ft.

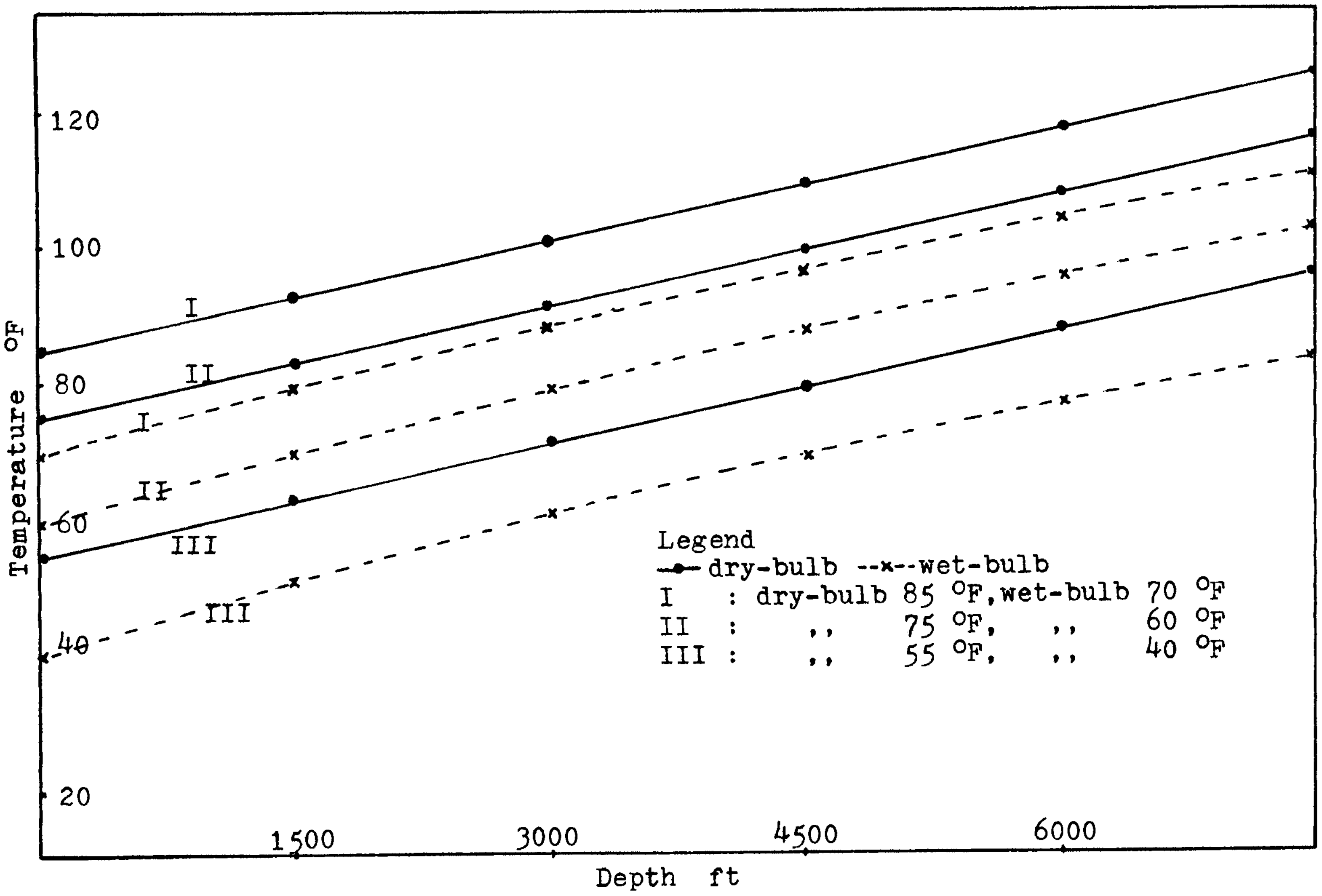


Fig. 6 Temperature Gradients vs Depth

have no practical effect upon the rate of increase.

Wet-bulb temperatures, when plotted against depth (Fig. 6), display a gradient that is minutely upward curving. However, the change in its depression below the dry-bulb will increase with depth for more saturated incoming air and decrease with drier intake. This in accord with equations (28) and (6) which show the rate of evaporation and the wet-bulb depression both being dependent upon the existing degree of saturation. Table 4 and Fig. 7 demonstrate the effect of relative humidity of air input on the dry-bulb and wet-bulb gradients. By varying the wet-bulb temperatures while maintaining the dry-bulb as constant, the effect of relative humidity of the incoming air on the dry-bulb and wet-bulb gradients can be seen. Dry air shows a steep wet-bulb gradient due to more water pick-up as suggested by equations (6) and (28) and thus reducing the wet-bulb depression significantly.

Natural vetilation pressure, N.V.P., results from a difference in air densities between the downcast and upcast shafts. As would be expected; cold, dry intake air will invariably result in a high pressure difference between the two columns. Hot, dry air entering the mine may result in a higher N.V.P. than cool, humid atmosphere since humidity reduces density in much the same manner as does increasing temperature. This is demonstrated in Table 3 and according to equation (30).

TABLE 3. EFFECT OF TEMPERATURE VARIATION OF AIR INPUT ON NATURAL VENTILATION PRESSURE *)

Air Input Temperature Drybulb °F	 Wetbulb °F	 Relative Humidity Percent	Natural Ventilation Pressure Inches Water
55.0	40.0	19.63	1.0531
55.0	45.0	44.09	1.0054
55.0	50.0	77.77	0.9527
75.0	53.0	19.09	1.5728
75.0	61.0	44.48	1.4801
75.0	68.0	70.23	1.3861
85.0	70.0	47.55	1.7807
65.0	58.0	65.89	1.1139 *)
65.0	58.0	65.89	1.1529 **)
65.0	46.0	17.12	1.2481

*) Age of working areas is 0.5 year

**) Age of working areas is 0.1 year

TABLE 4. EFFECTS OF RELATIVE HUMIDITY ON TEMPERATURE GRADIENTS *)

Depth ft	Drybulb °F	Wetbulb °F	Rel.Hum. %	Drybulb °F	Wetbulb °F	Rel.Hum. %
Surface	55.000	40.000	19.63	55.000	50.000	70.77
1000	60.398	47.134	33.47	60.402	54.322	67.54
2000	65.759	53.599	42.74	65.763	58.784	65.57
3000	71.121	59.612	49.01	71.127	63.365	64.41
4000	76.487	65.319	53.33	76.494	68.043	63.77
5000	81.858	70.812	56.35	81.865	72.791	63.47
6000	87.234	76.163	58.51	87.240	77.602	63.38
Surface	75.000	53.000	19.09	75.000	68.000	70.23
1000	80.397	61.860	33.47	80.407	72.342	67.96
2000	85.764	69.446	43.17	85.777	76.856	66.58
3000	91.137	76.228	49.79	91.152	81.504	65.77
4000	96.517	82.476	54.35	96.534	86.258	65.32
5000	101.911	88.369	57.55	101.926	91.095	65.12
6000	107.310	94.025	59.81	107.325	95.996	65.06

*) Geothermic gradient of rock strata: 0.75 °F/100 ft descent
Age of airway: 1.0 year, surface rock temperature: 65°F.

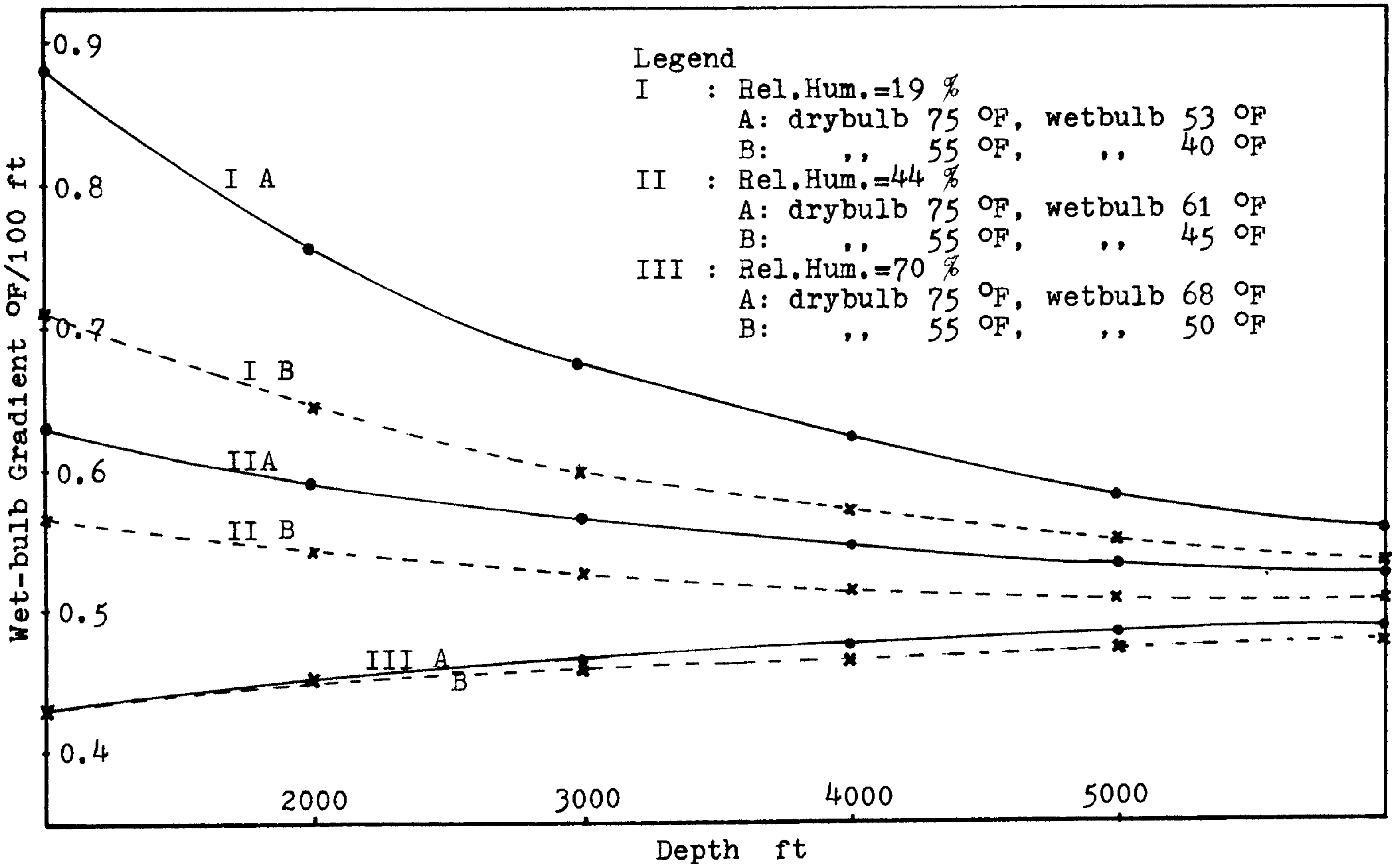


Fig. 7 Effects of Relative Humidities on Wet-bulb Gradients

As air passes through a mine shaft at an increased velocity, the rates of heat exchange and evaporation are increased. However, the enthalpy and wet-bulb gradients are lowered as shown in equation (9) and Fig. 8 respectively. That is, the amounts of heat and water absorbed per unit time are greater but the effects upon each pound of dry air decreased. This is because the larger air volume is less affected by the shaft conditions and, as a result, is more amenable to heat and water absorbtion. These behavior are in accord with equation (28).

Relative humidity, in its response to depth, is dependent to a major extent upon the conditions of input air. Cold, saturated intake atmosphere will cause a decreasing relative humidity as the air flows deeper. The reverse holds true for hot, dry air entering the mine. This situation is the same as described earlier for wet-bulb temperature. The two are interdependent and should therefore react in a similar manner.

In reviewing the above phenomena associated with the original purpose of this study, it appears that the designer of air conditioning and flow systems for deep mines may utilize these findings to great advantage. For example, they can be useful in seeking economic optimums between N.V.P. (which reduces the required mechanically induced pressure) and the air conditioning load (which affects N.V.P. and the rate of strata cooling) while main-

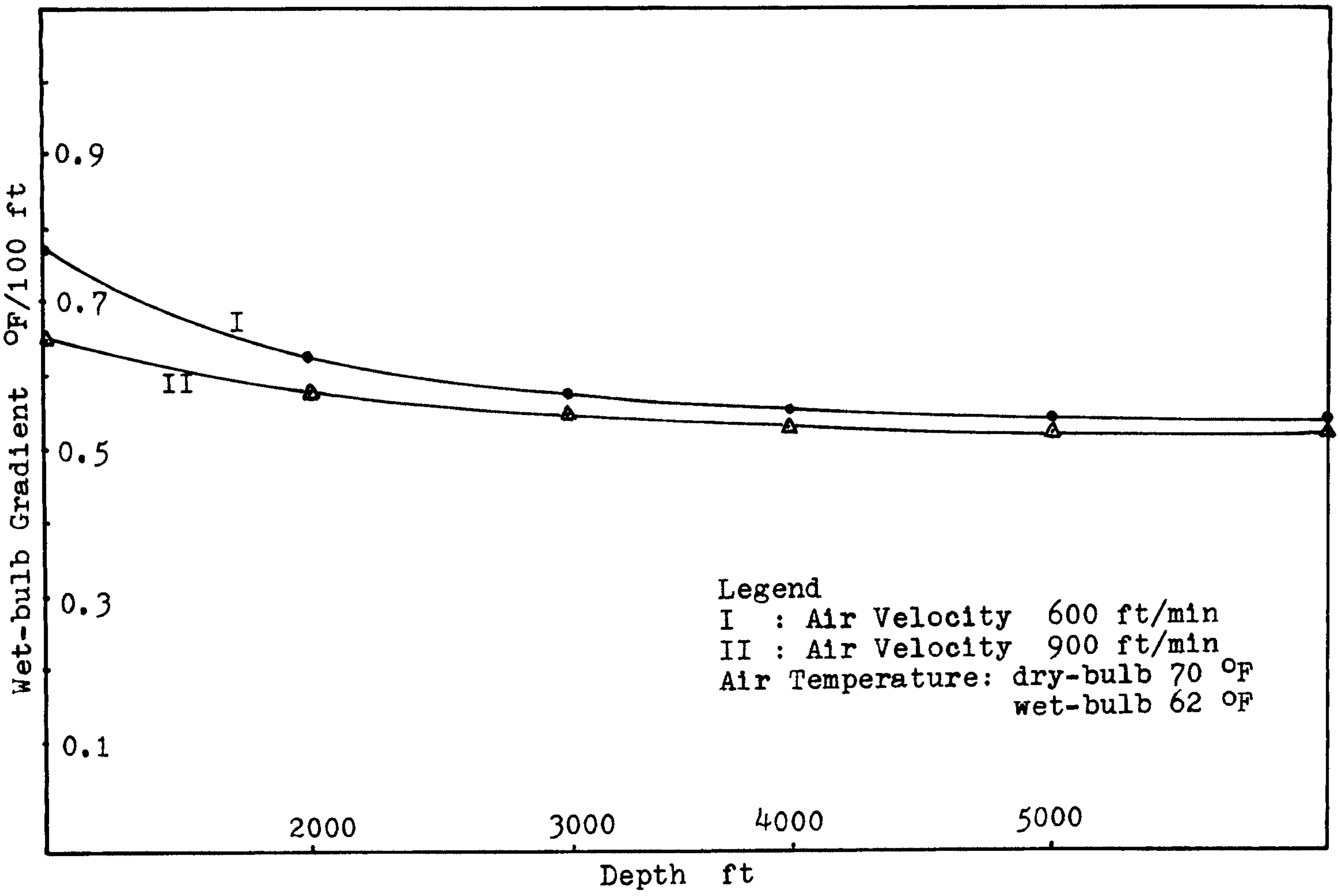


Fig. 8 Effects of Air Velocity and Depth on Wet-bulb Gradient

taining a suitable environment in the working areas.

The ideal cooling load must also be considered with respect to the age of the air course. Initially the strata will be hot and the mine air will require considerable conditioning whereas in time the rock will be cooled and the load reduced. An air conditioner selected to fit the original demands will be too large in the final stages. A smaller unit will cause an initial decrease in work efficiency but also a reduction in air treatment costs. This, coupled with the potential advantages of N.V.P., poses a problem in economics that has plagued the design engineer for decades.

Of lesser importance but still significant is the shaft size. Heretofore, this has been fixed at an optimum between installation and air transmission costs. Now, because of the ease in predicting its influence upon the rates of enthalpy gain and strata cooling, the shaft size is destined to play a more important role in mine system design. Other, indirect effects of environmental control, such as fogginess, spalling, etc., may also become involved but their predictions can be accomplished without difficulty.

A computer simulation of the many mine environmental situations that are possible for a given ore deposit can be utilized in predicting the various related expenses that will prevail for each. It seems, therefore, that it is now practical to balance the per ton (of ore mined) costs of labor, air conditioning and air circulation to an overall minimum.

The point where condensation commences in the upcast shaft will depend on intake air conditions and the conditions in the underground levels. The point was found by the same method of heat exchange computations used in the downcast shaft. It can be expected that the age factor of the upcast shaft does not have any effect in the computations due to the fact that the exhaust mine air has higher temperatures compared to the surrounding walls. This situation has been incorporated in the computer program. Fig. 10 shows the effect of air velocity on the point of saturation of air along the upcast shaft.

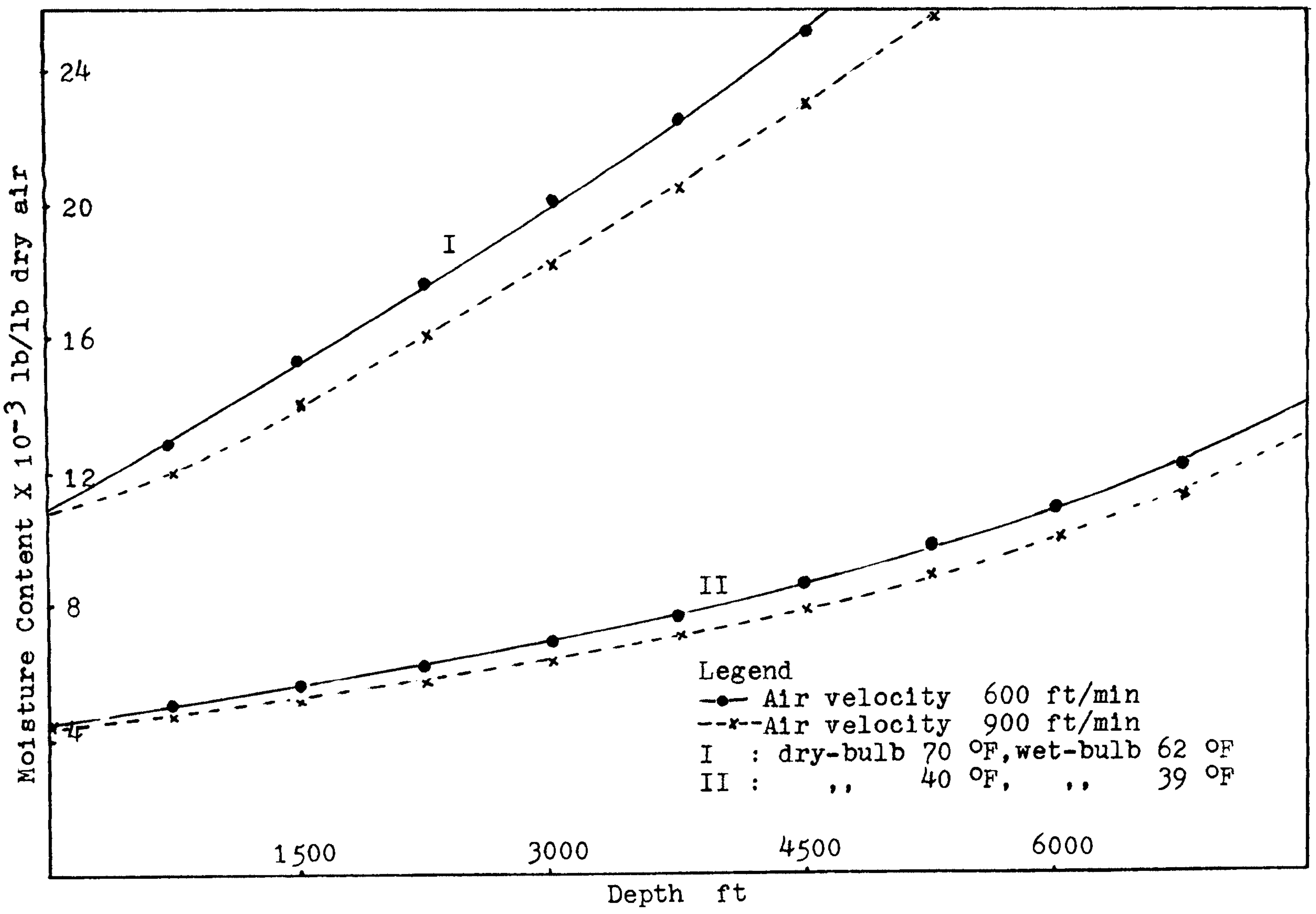


Fig. 9 Effect of Air Velocity on Moisture Content

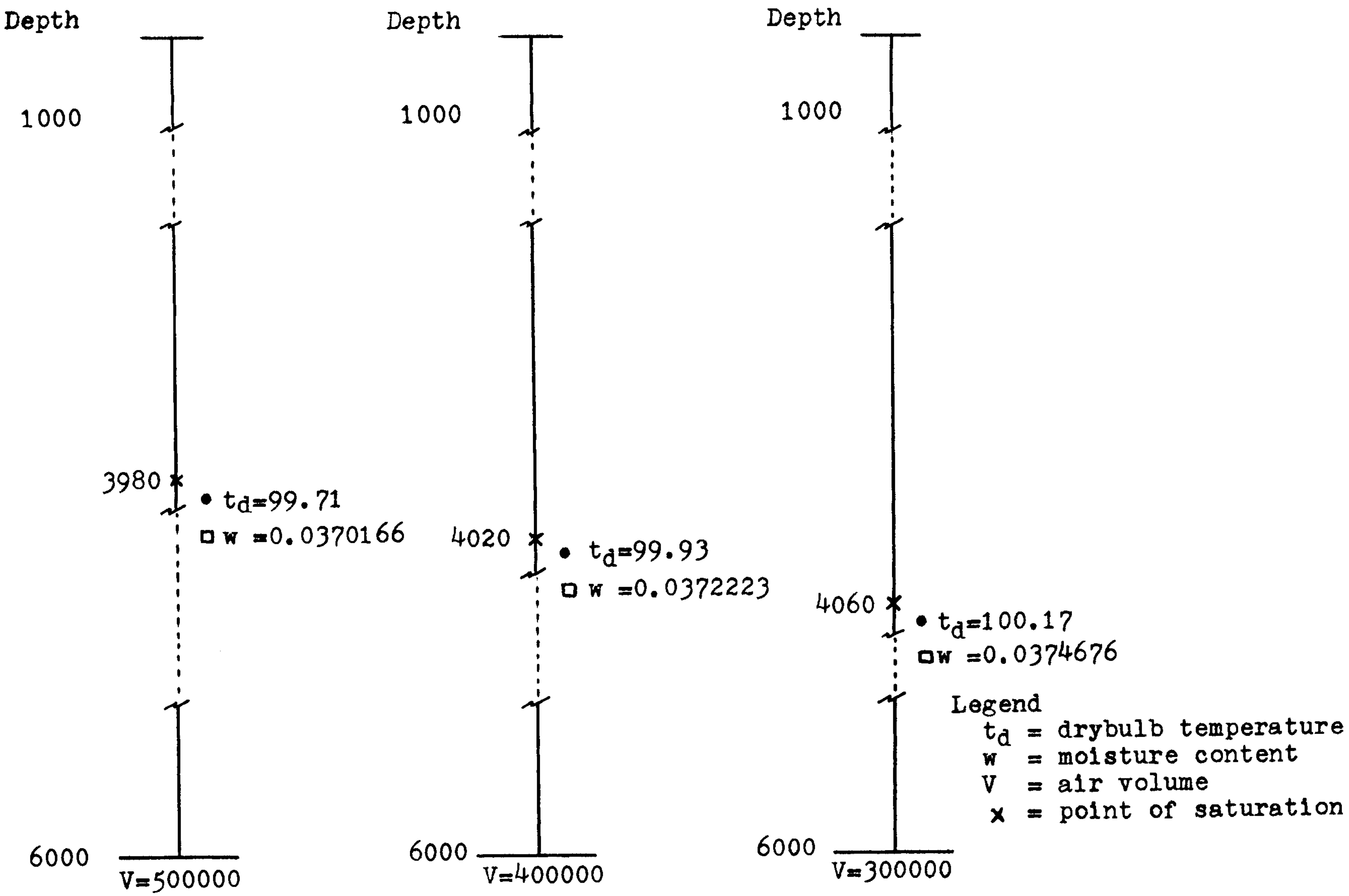


Fig. 10 Effect of Air Velocity on Point of Saturation of Air in Upcast Shaft

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

The procedures followed and the results obtained during the course of this study have already been discussed. However, a review of the findings indicates that the following conclusions may be drawn:

1. A computer simulation method has been developed whereby the quality of underground environment and the related N.V.P. may be accurately and conveniently predicted for any predefined combination of mine circumstances.
2. The effects of air input rate and quality and shaft size upon N.V.P. and air conditioning load may be determined by the same technique.
3. The above procedures can be of great assistance to designers in optimizing the per ton costs of labor, air conditioning and air circulation.
4. Underground conditions conducive to foginess, rock spalling, reverse air flow, etc., can be predicted and remedied during the early stages of design.

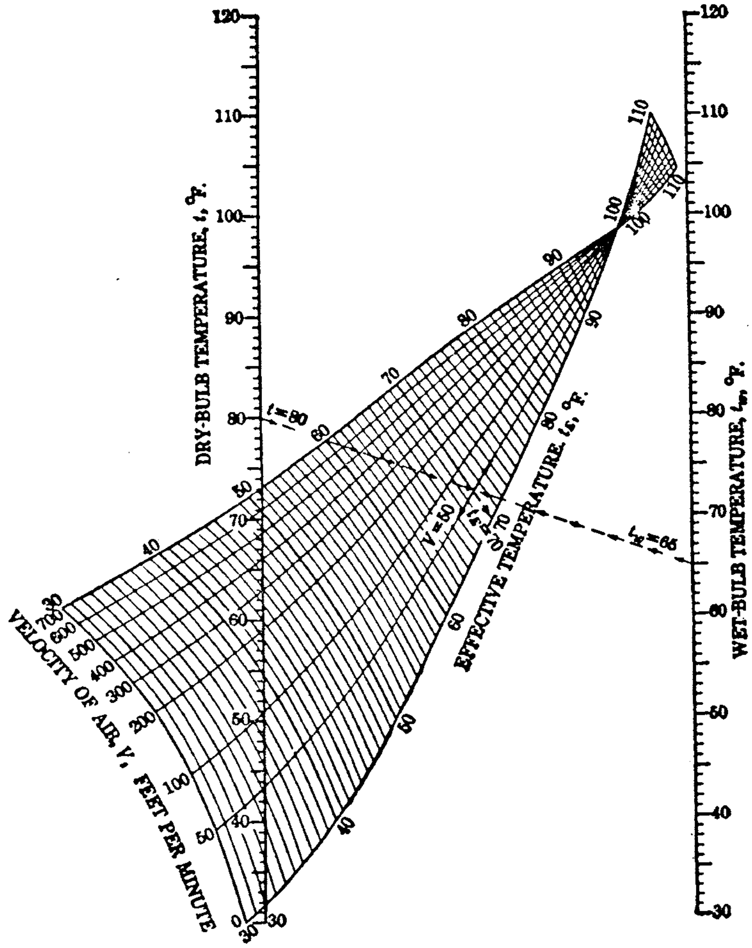
B. Recommendations

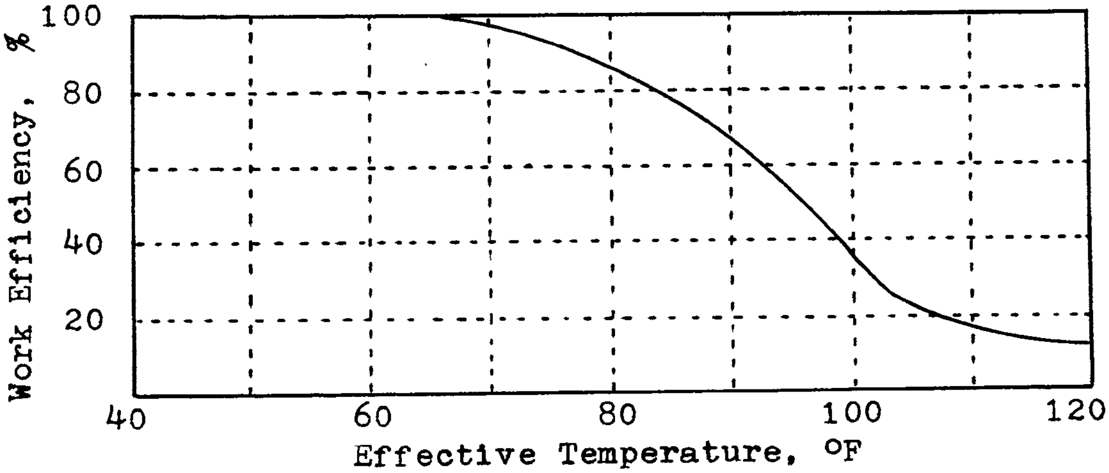
The method described has been developed in theory only. It should therefore be tested against existing mine conditions before its practicality can be accepted. The writer has spent some months in a deep mine with this very purpose in mind but due to circumstances beyond his control, the project had to be abandoned. Initiation of an alternate experiment was prevented by lack of time.

Should this investigation be continued, it will soon become apparent that the computer simulation program has been developed to permit simple modification to fit conditions that may exist in nearly any mine. However, the computer outputs will be no more accurate than the data supplied.

APPENDIX A

Effective Temperature Scale and the Effect of Effective Temperature on Work Efficiency





APPENDIX B

1. Composition of Dry Air

Substance	Molecular Weight	Mol-fraction Composition in Dry Air	Partial Molecular Wt. in Dry Air
Oxygen (O_2)	32.000	0.2095	6.704
Nitrogen (N_2)	28.016	0.7809	21.878
Argon (A)	39.944	0.0093	0.371
Carbon Dioxide (CO_2)	44.01	0.0003	0.013
		1.0000	28.966

Source: Reference (2)

2. Property Values of Dry Air

t °F	ρ lbm/cuft	C_p $\frac{\text{Btu}}{\text{lbm-°F}}$	ν sqft/sec	k $\frac{\text{Btu}}{\text{ft-hr-°F}}$	D sqft/hr	Pr
-58	0.0959	0.241	10.23×10^{-5}	0.0118	0.507	0.721
32	0.0783	0.240	14.77	0.0140	0.747	0.712
122	0.0662	0.240	19.89	0.0162	1.02	0.701

Source: Reference (18)

t = temperature
ρ = density
C_p = specific heat
ν = kinematic viscosity
k = conductivity
D = diffusifity
Pr = Prandtl number

APPENDIX C

1. Geothermic Gradient for Different Mining Districts

District	Temperature Rise °F/100 ft Mean
Anaconda Copper, Montana	3.33
Magma Copper, Arizona	1.67
Coal Mines, Great Britain	1.43
Kolar Gold, India	0.91
Rand Gold, South Africa	0.50
Mc. Intyre Gold, Canada	0.44

Source: Reference (8)

2. Conductivity and Density of Rocks

Rock Type	Conductivity $\frac{\text{Btu}}{\text{ft-hr-}^{\circ}\text{F}}$	Density lbm/cuft
Granite & Quartz Monzonite (Colorado)	2.71	165
Dolomite & Anhydrite	4.10	172
Quartzite	3.10	165
Limestone	2.10	163

Source: Clark, Jr., S.P. Handbook of Physical Constants

APPENDIX D

1. Input Data and Symbols for the Computer Program

DIAM or DIAMT = diameter of airways in feet.

AIRCFM or AERCFM = airflow in cubic feet per minute.

DEPTH = depth of shaft in feet.

STRAT1 and STRAT2 = bedding planes of different strata.

DTEMSF = drybulb temperature in °F.

WTEMSF = wetbulb temperature in °F.

SAPDCS = barometric pressure at surface of downcast shaft, in lbf/in^2.

SAPUCS = barometric pressure at surface of upcast shaft, in lbf/in^2.

SURPIN = barometric pressure, in inches Hg.

LAYERS = number of layers of rock strata.

SUROCK = annual mean temperature of rock at surface, in °F.

GRAD1, GRAD2 and GRAD3= geothermic gradient of strata.

CONDR1, CONDR2 etc. = rock thermal conductivity.

ROCDS1, ROCDS2 etc. = density of rock.

CPROCK = specific heat of rock.

TABLE(I), ETABLE(I) = table of latent heat of evaporation.

TABLE(I), BTABLE(I) = table of saturated vapor pressure.

KKEY, KEY = symbols for repetition of program.

CPAIR and CPVAP = specific heat of air and vapor.

APPENDIX D

2. Output of Computer Program*)

A	B	C	D	E	F	G	H	I	J	K	L
					DOWNCAST SHAFT						
0.	14.69	29.92	75.00	61.00	14.00	0.000	13.58	0.0736	0.008194	26.9	44.48
250.	14.83	30.18	76.38	62.34			13.50	0.0741	0.008836	28.0	46.20
500.	14.96	30.45	77.72	64.23			13.42	0.0745	0.009481	29.0	47.79
750.	15.08	30.72	79.06	65.79			13.34	0.0749	0.010131	30.1	49.24
1000.	15.22	30.99	80.40	67.33	13.07	0.631	13.26	0.0754	0.010785	31.1	50.55
1250.	15.35	31.26	81.75	68.84			13.19	0.0758	0.011445	32.2	51.75
1500.	15.49	31.53	83.09	70.33			13.11	0.0763	0.012113	33.2	52.85
1750.	15.62	31.81	84.43	71.80			13.03	0.0767	0.012788	34.3	53.84
2000.	15.76	32.08	85.77	73.25	12.52	0.592	12.96	0.0772	0.013473	35.4	54.75
2250.	15.89	32.36	87.12	74.69			12.88	0.0776	0.014167	36.5	55.58
2500.	16.03	32.64	88.46	76.11			12.81	0.0781	0.014873	37.6	56.34
2750.	16.17	32.92	89.80	77.51			12.74	0.0785	0.015591	38.7	57.04
3000.	16.31	33.21	91.15	78.91	12.24	0.565	12.66	0.0789	0.016321	39.8	57.68
3250.	16.45	33.50	92,49	80.29			12.59	0.0794	0.017065	41.0	58.27
3500.	16.59	33.78	93.84	81.66			12.52	0.0799	0.017824	42.2	58.81
3750.	16.74	34.07	95.18	83.03			12.45	0.0803	0.018598	43.4	59.31
4000.	16.88	34.37	96.53	84.38	12.15	0.547	12.38	0.0808	0.019389	44.6	59.76
4250.	17.02	34.66	97.88	85.73			12.31	0.0812	0.020196	45.8	60.19
4500.	17.17	34.96	99.22	87.07			12.24	0.0817	0.021022	47.0	60.58
4750.	17.32	35.26	100.57	88.40			12.17	0.0822	0.021866	48.3	60.94
5000.	17.46	35.56	101.92	89.73	12.19	0.535	12.10	0.0826	0.022729	49.6	61.28
5250.	17.61	35.86	103.27	91.06			12.04	0.0831	0.023613	50.9	61.59
5500.	17.76	36.16	104.62	92.38			11.97	0.0835	0.024518	52.2	61.88
5750.	17.91	36.47	105.97	93.69			11.90	0.0840	0.025445	53.6	62.16
6000.	18.06	36.78	107.32	95.01	12.31	0.527	11.84	0.0845	0.026395	55.0	62.40

AVERAGE DENSITY OF DOWNCAST AIR = 0.078957

APPENDIX D-2 (Cont.)

AIR CONDITIONS AT JUNCTION 1 DRYBULB= 107.37 WETBULB= 95.01
AIR CONDITIONS AT JUNCTION 4 DRYBULB= 107.66 WETBULB= 95.01
BOTTOM OF UPCAST SHAFT, DRYBULB= 110.60 WETBULB= 97.51

UPCAST SHAFT

A	C	D	I	J			
6000.	36.53	110.60	0.08330	0.0288628			
5760.	36.24	109.31	0.08272	0.0310272			
5520.	35.95	108.02	0.08217	0.0327793			
5280.	35.66	106.72	0.08163	0.0341676			
5040.	35.38	105.43	0.08111	0.0352358			
4800.	35.09	104.13	0.08061	0.0360232			
4560.	34.81	102.84	0.08011	0.0365651			
4320.	34.52	101.54	0.07963	0.0368929			
4080.	34.24	100.25	0.07916	0.0370347			
3980.	34.13	99.71	0.07897	0.0370166	*SATURATED*	VAP.PRES.=	1.9177
3840.	33.97	98.96	0.07872	0.0366087	*SATURATED*	VAP.PRES.=	1.8887
3600.	33.69	97.66	0.07829	0.0358743	*SATURATED*	VAP.PRES.=	1.8378
3300.	33.35	96.05	0.07776	0.0349063	*SATURATED*	VAP.PRES.=	1.7727
3000.	33.01	94.44	0.07724	0.0338980	*SATURATED*	VAP.PRES.=	1.7066
2700.	32.67	92.82	0.07672	0.0328627	*SATURATED*	VAP.PRES.=	1.6401
2400.	32.34	91.21	0.07620	0.0318121	*SATURATED*	VAP.PRES.=	1.5740
2100.	32.01	89.60	0.07569	0.0307551	*SATURATED*	VAP.PRES.=	1.5085
1800.	31.68	87.99	0.07517	0.0296988	*SATURATED*	VAP.PRES.=	1.4441
1500.	31.35	86.38	0.07466	0.0286497	*SATURATED*	VAP.PRES.=	1.3810
1200.	31.03	84.77	0.07413	0.0281360	*SATURATED*	VAP.PRES.=	1.3428
900.	30.71	83.16	0.07360	0.0276021	*SATURATED*	VAP.PRES.=	1.3047
600.	30.39	81.55	0.07308	0.0269914	*SATURATED*	VAP.PRES.=	1.2638
300.	30.07	79.94	0.072565	0.0263210	*SATURATED*	VAP.PRES.=	1.2208
0.	29.76	78.33	0.07205	0.0256051	*SATURATED*	VAP.PRES.=	1.1765

APPENDIX D-2 (Cont.)

AVERAGE DENSITY OF UPCAST AIR = 0.077379

NATURAL VENTILATION PRESSURE = 1.821151 INCHES W.G.

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*) The input data used for the computations:

Shaft diameter: 24 ft.

Air flow input: 500000 cuft/minute.

Geothermic gradient of strata: 1.5 °F/100 ft descent.

Surface rock temperature: 65 °F

Input air conditions: drybulb = 75 °F , wetbulb = 61 °F.
barometric pressure at surface = 29.92 in.Hg.

Age of shafts: 1.0 year, age of stope: 0.2 year.

The actual output data were printed out for every 50 ft depth interval in downcast shaft and 20 ft depth interval in the upcast shaft.

APPENDIX D-2 (Cont.)

Symbols used in Appendix D-2, Computer Output:

A = Depth, ft.

B = Barometric Pressure, lbf/sqin.

C = ,, ,, , in.Hg.

D = Dry-bulb Temperature, °F.

E = Wet-bulb Temperature, °F.

F = Wet-bulb Depression, °F.

G = Wet-bulb Gradient, °F/100 ft.

H = Specific Volume, cuft/lbm.

I = Density, lbm/cuft.

J = Moisture Content, lbm vapor/lbm dry air.

K = Enthalpy, Btu/lbm.

L = Relative Humidity, per cent.

APPENDIX D

3. Computer Program

```
C     *COMPUTATIONS IN DOWNCAST SHAFT*
      COMMON TABLE(130),ETABLE(130),BTABLE(130)
      DIMENSION TWET(600)
      KKEY=0
      READ(1,210)DIAM,AIRCFM,DEPTH,STRAT1,STRAT2
      READ(1,205)LAYERS
      READ(1,220)SUROCK,GRAD1,GRAD2,GRAD3,CONDR1,CONDR2,CONDR3,ROCDS1,
     1ROCDS2,ROCDS3,CPROCK
      READ(1,230)AGE1,AGE2
      READ(1,199)(TABLE(I),ETABLE(I),I=1,119)
      READ(1,299)(TABLE(I),BTABLE(I),I=1,119)
      READ(1,200)DTEMSF,WTEMSF,SAPDCS,SAPUCS,SURPIN
  199 FORMAT(F5.0,F7.2)
  299 FORMAT(F5.0,F9.4)
  200 FORMAT(5F10.3)
  205 FORMAT(I3)
  210 FORMAT(5F10.2)
  220 FORMAT(7F6.3,3F6.2,F6.3)
  230 FORMAT(2F10.3)
  800 WRITE(3,215)DTEMSF,WTEMSF,SAPDCS,SAPUCS
  215 FORMAT(//10X,'ATMOSPHERIC CONDITIONS: DRYBULB=',F6.2,' F,',1X,
     1'WETBULB=',F6.2,' F',/10X,'BAR.PRESSURE: DOWNCAST=',F7.3,'PSIA,',
     21X,'UPCAST=',F7.3,'PSIA'/)
      WRITE(3,225)DIAM,AIRCFM
  225 FORMAT(10X,'DIAMETER OF SHAFT=',F5.2,' FEET,',2X,'AIR INPUT=',
     3F9.1,' CUFT/MIN'/)
      WRITE(3,224)LAYERS
  224 FORMAT(10X,'NUMBER OF LAYERS=',I3/)
      IF(LAYERS-1)172,172,173
  172 GRAD2=GRAD1
```

```
      GRAD3=GRAD1
      GO TO 174
  173 IF(LAYERS-2)172,175,174
  175 GRAD3=GRAD2
  174 WRITE(3,235)SUROCK,GRAD1,GRAD2,GRAD3
  235 FORMAT(10X,'SURFACE ROCK TEMP.=',F6.2,' F,',1X,'GEOTHERMIC GRADIEN
     4T LAYER1=',F4.2,' F/100 FT DESCENT'/59X,'LAYER2=',F4.2,' F/100 FT
     5DESCENT'/59X,'LAYER3=',F4.2,' F/100 FT DESCENT'/)
      WRITE(3,245)AGE1,AGE2
  245 FORMAT(10X,'AGE OF AIRWAY=',F6.3,' YEARS,',1X,'AGE OF STOPE=',F6.3
     6,' YEARS'/)
      IF(LAYERS-1)72,72,73
   72 STRAT1=DEPTH
      GO TO 76
   73 IF(LAYERS-2)72,74,75
   74 STRAT2=DEPTH
   76 ST2=STRAT2-STRAT1
      IF(ST2-0.0)57,57,58
   57 ST2=0.0
      ST3=0.0
      GO TO 150
   58 ST2=ST2
      ST3=0.0
      GO TO 150
   75 STRAT3=DEPTH
      ST3=STRAT3-STRAT2
      ST2=STRAT2-STRAT1
  150 WRITE(3,226)DEPTH,STRAT1,ST2,ST3
  226 FORMAT(10X,'MAXIMUM DEPTH OF SHAFTS=',F8.2,' FEET,',1X,'THICKNESS
     7OF LAYER1=',F8.2,' FEET'/62X,'LAYER2=',F8.2,' FEET'/62X,'LAYER3=',
     8F8.2,' FEET'////)
      WRITE(3,100)
  100 FORMAT(//50X,'DOWNCAST SHAFT'//)
      WRITE(3,101)
  101 FORMAT(6X,'DEPTH',7X,'PRESSURE',5X,'TEMPERATURE',2X,'WETBULB',1X,
```

```
     1'WETBULB',1X,'SPEC.VOL.',1X,'DENSITY',2X,'MOIST.CONT.',
     1'ENTHALPY',1X,'REL.HUM.')
      WRITE(3,102)
  102 FORMAT(44X,'DEPRESS',1X,'GRADIENT',19X,'(LB/LB OF')
      WRITE(3,103)
  103 FORMAT(7X,'(FT)',4X,'(PSIA)',2X,'(INHG)',1X,'(DRY F)',
     2'(WET F)',2X,'(F)',3X,'(F/100FT)','(CUFT/LB)','(LB/CUFT)',
     31X,'DRY AIR)',2X,'(BTU/LB)',3X,'(%)'//)
C     *CONSTANTS USED IN CALCULATIONS
      CPVAP=0.44
      CPAIR=0.24
      RCAIR=53.345
      RCVAP=85.760
      RCABTU=0.06854
      RCVBTU=0.11019
      CVVAP=CPVAP-RCVBTU
      CVAIR=CPAIR-RCABTU
      AIRCON=0.0155
      AIRVIS=0.0435
C
      DTEMSR=DTEMSF+459.69
      WTEMSR=WTEMSF+459.69
      T=DTEMSF
      CALL TABEL(T,VAPOR)
      SATPS1=VAPOR
      T=WTEMSF
      CALL TABEL(T,VAPOR)
      SATPSW=VAPOR
      PVAP1=SATPSW-0.0003613*SURPIN*(DTEMSF-WTEMSF)
      PV1PSI=PVAP1*0.491
      W=(0.622*PV1PSI)/(SAPDCS-PV1PSI)
      DEN=1.3225*(SURPIN-(0.3777*PVAP1))/DTEMSR
      SPVOL=1./DEN
      CPM=(CPAIR+W*CPVAP)/(1.+W)
      CVM=(CVAIR+W*CVVAP)/(1.+W)
```

```
      CK=CPM/CVM
      RELHUM=100.*PVAP1/SATPS1
      ENTHAL=CPAIR*DTEMSF+W*(1061.+CPVAP*DTEMSF)
      DEP=DTEMSF-WTEMSF
      WRITE(3,104)SAPDCS,SURPIN,DTEMSF,WTEMSF,DEP,SPVOL,DEN,W,ENTHAL,
     1RELHUM
  104 FORMAT(6X,'SURFACE',1X,F7.3,2X,F5.2,1X,F7.3,1X,F7.3,1X,F6.3,2X,
     2'0.000',2X,F8.3,3X,F8.6,2X,F9.7,F8.2,2X,F6.2)
      SECTS=5.00
      AREA=3.14*DIAM*SECTS
      CROS=(3.14*DIAM**2.)/4.
      AIRATE=AIRCFM/CROS
      VOLUM=CROS*SECTS
      FLOW=SECTS/(AIRATE*60.)
      PERIM=3.14*DIAM
      DELTAZ=0.
      DLTBTU=0.
      CUMBTU=0.
      TOTDEN=0.
      SUMDEN=0.
      X=1000.
      L=1
      N=1
      TDUMMY=WTEMSF+0.001
C     *CALCULATIONS OF CORRECTION FOR AGE OF OPENINGS*
      CONSTA=0.0939034
      CONSTB=0.195659
      RADIUS=2.*CROS/(1.414*PERIM)
      A=RADIUS-2.
      IF(A-0.0)8,9,9
    8 A=A*(-1.)
      S=1./(0.811**A)
      Q=1./(1.109**A)
      GO TO 7
    9 S=0.811**A
      Q=1.109**A
```

```
C     *CALCULATIONS OF HEAT TRANSMITTED BY COMPRESSOR LINE*
    7 COMPRS=2000.
      TCOMP1=250.
      TCOMP2=100.
      BTUCOM=COMPRS*DEN*(0.24*(TCOMP1-TCOMP2)+DEPTH778.26)
C
   25 DO 5 I=1,10
      DELTAZ=DELTAZ+SECTS
      TEMP=DELTAZ*(1.+W)/(CPM*778.26)+DTEMSF
      TEMPR=TEMP+459.69
      P=SAPDCS*(TEMPR/DTEMSR)**(CK/CK-1.))
      PIN=P*29.92/14.696
      AIRDEN=144.*(P-PV1PSI)/(RCAIR*TEMPR)
      DST=1.3225*(PIN-(0.3777*PVAP1))/TEMPR
      TOTDEN=TOTDEN+DST
      AIRFLO=(CROS*AIRATE*60.*DST)/CROS
      CP=CPM*DST
      CONVEC=(0.023*AIRCON/DIAM)*((AIRFLO*DIAM/AIRVIS)**0.8)*(AIRVIS*CPM
     4/AIRCON)**0.4
      BETA=CONVEC/CP
      T=TEMP
      CALL TABEL(T,VAPOR)
      SATPS1=VAPOR
      DELTAW=BETA*70.7259*(SATPS1-PVAP1)/(RCVAP*TEMPR)
      DWATER=DELTAW*AREA*FLOW
      WDRAIR=CROS*60.*AIRATE*FLOW*AIRDEN
      WATER=((W*WDRAIR)+DWATER)/WDRAIR
      W=WATER
      CPM=(CPAIR+WATER*CPVAP)/(1.+WATER)
      CVM=(CVAIR+WATER*CVVAP)/(1.+WATER)
      CKM=CPM/CVM
      TRMASS=CONVEC/(DST*CPM*RCVAP*TEMPR)
      PV2PSI=WATER*P/(0.622+WATER)
      PV1PSI=PV2PSI
      PVAP2=PV2PSI*29.92/14.696
      PVAP1=PVAP2
```

```
    GO TO (1,2,3),LAYERS
 1  IF(DELTAZ-50.)41,41,42
41  ROCKTF=SUROCK
    GO TO 43
42  ROCKTF=SUROCK+(GRAD1/100.)*(DELTAZ-50.)
43  CONDUC=CONDR1
    ROCDST=ROCDS1
    DIFFUS=CONDUC/(ROCDST*CPROCK)
    TFKTOR=AGE1*DIFFUS
    CFKTOR=(S*CONSTA)/(TFKTOR**(CONSTB*Q))
    GO TO 143
 2  IF(DELTAZ-50.)44,44,45
44  ROCKTF=SUROCK
    GO TO 43
45  IF(DELTAZ-STRAT1)47,47,48
47  ROCKTF=SUROCK+(GRAD1/100.)*(DELTAZ-50.)
    ROCKT1=ROCKTF
    GO TO 43
48  ROCKTF=ROCKT1+(GRAD2/100.)*(DELTAZ-STRAT1)
46  CONDUC=CONDR2
    ROCDST=ROCDS2
    DIFFUS=CONDUC/(ROCDST*CPROCK)
    TFKTOR=AGE1*DIFFUS
    CFKTOR=(S*CONSTA)/(TFKTOR**(CONSTB*Q))
    GO TO 143
 3  IF(DELTAZ-50.)49,49,50
49  ROCKTF=SUROCK
    GO TO 43
50  IF(DELTAZ-STRAT1)51,51,52
51  ROCKTF=SUROCK+(GRAD1/100.)*(DELTAZ-50.)
    ROCKT1=ROCKTF
    GO TO 43
52  IF(DELTAZ-STRAT2)53,53,54
53  ROCKTF=ROCKT1+(GRAD2/100.)*(DELTAZ-STRAT1)
    ROCKT2=ROCKTF
    GO TO 46
```

```
   54 ROCKTF=ROCKT2+(GRAD3/100.)*(DELTAZ-STRAT2)
      CONDUC=CONDR3
      ROCDST=ROCDS3
      DIFFUS=CONDUC/(ROCDST*CPROCK)
      TFKTOR=AGE1*DIFFUS
      CFKTOR=(S*CONSTA)/(TFKTOR**(CONSTB*Q))
  143 T=ROCKTF
      CALL TIBLE(T,ELATEN)
      CALL TABEL(T,VAPOR)
      SATROC=VAPOR
      WALL=PERIM*SECTS*(CFKTOR*CONDUC*(ROCKTF-TEMP)+(ELATEN*TRMASS*
     3(SATROC-PVAP1)))
      DBTU=WALL*FLOW
      DLTBTU=DLTBTU+DBTU
C     *HEAT FROM COMPRESSOR LINE*
      BTUCPR=BTUCOM*FLOW*60.
      DLTEM=BTUCPR/(WDRAIR+DWATER)*CPM
      TEMP=TEMP+DLTEM
C    **HEAT FROM EXPOSED ROCK STRATA**
      IF(ROCKTF-TEMP)93,93,95
   93 DTEMP=(DWATER*ELATEN)/(WDRAIR+DWATER)*CPM
      TNET1=TEMP-DTEMP
      TEMP=TNET1
      GO TO 84
   95 DLTT=DBTU/(WDRAIR+DWATER)*CPM
      TNET2=TEMP+DLTT
      TEMP=TNET2
   84 T=TDUMMY
      CALL TABEL(T,VAPOR)
      XSAT=VAPOR
      VALUE=XSAT-0.0003613*PIN*(TEMP-TDUMMY)
      IF(PVAP1-VALUE)86,86,85
   85 TDUMMY=TDUMMY+0.00115
      GO TO 84
   86 GO TO 5
    5 CONTINUE
```

```
      TWET(N)=TDUMMY
      TF=TEMP
      SEVOL=1./DST
      RLHUM=100.*PVAP1/SATPS1
      ENTLPY=CPAIR*TEMP+WATER*(1061.+CPVAP*TEMP)
      CUMBTU=CUMBTU+DLTBTU
      AVEDEN=TOTDEN/10.
      SUMDEN=SUMDEN+AVEDEN
      TOTDEN=0.
      DLTBTU=0.
      IF(DELTAZ-X)11,37,11
   11 WRITE(3,105)DELTAZ,P,PIN,TF,TWET(N),SEVOL,DST,WATER,ENTLPY,RLHUM
  105 FORMAT(5X,F8.2,1X,F7.3,2X,F5.2,1X,F7.3,1X,F7.3,16X,F8.3,
     23X,F8.6,2X,F9.7,F8.2,2X,F6.2)
      N=N+1
      IF(DELTAZ-DEPTH)25,35,35
   37 J=20*(L-1)
      QQ=0.
      V=TWET(N)
      DO 38 I=1,19
      K=I+J
      N=K
      U=TWET(N+1)-TWET(N)
   38 QQ=QQ+U
      RAD=2.*QQ/19.
      DPS=TEMP-V
      L=L+1
      X=X+1000.
      N=N+2
      WRITE(3,106)DELTAZ,P,PIN,TF,V,DPS,RAD,SEVOL,DST,WATER,ENTLPY,RLHUM
  106 FORMAT(5X,F8.2,1X,F7.3,2X,F5.2,1X,F7.3,1X,F7.3,1X,F6.3,2X,F5.3,3X,
     6F7.3,3X,F8.6,2X,F9.7,F8,2,2X,F6.2)
      IF(DELTAZ-DEPTH)25,35,35
   35 AVEDST=(SUMDEN+DEN)/121.
      WRITE(3,109)AVEDST
  109 FORMAT(5X,'AVERAGE DENSITY OF DOWNCAST AIR=',F8.6)
```

```
C     *COMPUTATIONS IN UNDERGROUND LEVELS*
      JNCTON=1
      READ(1,410)AERCFM,CROS1,PRIME,LENGTH
  410 FORMAT(3F10.2,I5)
      LSECT=10
      WTEMP=TDUMMY
      DLTBTU=0.
      CUMBTU=0.
      TTIME=0.
      KEY=0
      DIFFUS=CONDUC/(ROCDST*CPROK)
      TFKTOR=AGE2*DIFFUS
      REDIUS=2.*CROS1/(1.414*PRIME)
  450 DIAMT=4.*CROS1/PRIME
      AERATE=AERCFM/CROS1
      SECT=LSECT
      AFLOW=SECT/(AERATE*60.)
      AAREA=PRIME*SECT*0.6
      AA=REDIUS-2.
      IF(AA-0.0)308,309,309
  308 AA=AA*(-1.)
      SS=1./(0.811**AA)
      SQ=1./(1.109**AA)
      GO TO 310
  309 SS=0.811**AA
      SQ=1.109**AA
  310 CFKTOR=(SS*CONSTA)/(TFKTOR**(CONSTB*SQ))
      T=ROCKTF
      CALL TIBLE(T,ELATEN)
      CALL TABEL(T,VAPOR)
      SATROC=VAPOR
      TDUMMY=WTEMP+0.001
      N=LENGTH/LSECT
C
      DO 55 I=1,N
      P=P
```

```
      PIN=PIN
      TEMPR=TEMP+459.69
      CPM=(CPAIR+WATER*CPVAP)/(1.+WATER)
      CVM=(CVAIR+WATER*CVVAP)/(1.+WATER)
      AERFLO=(CROS1*AERATE*DST)/CROS1
      CP=CPM*DST
      CONVEC=1.7*(0.023*AIRCON/DIAMT)*((AERFLO*DIAMT/AIRVIS)**0.8)*
     6(AIRVIS*CPM/AIRCON)**0.4
      BETA=CONVEC/CP
      T=TEMP
      CALL TABEL(T,VAPOR)
      SATPS1=VAPOR
      T=WTEMP
      CALL TABEL(T,VAPOR)
      SATPSW=VAPOR
      PVAP1=SATPSW-0.0003613*PIN*(TEMP-WTEMP)
      DELTAW=BETA*70.7259*(SATPS1-PVAP1)/(RCVAP*TEMPR)
      DWATER=DELTAW*AAREA*AFLOW
      PV1PSI=PVAP1*0.491
      AERDEN=144.*(P-PV1PSI)/(RCAIR*TEMPR)
      WDRAER=CROS1*60.*AERATE*AFLOW*AERDEN
      WATER=((WATER*WDRAER)+DWATER)/WDRAER
      DST1=1.3225*(PIN-(0.3777*PVAP1))/TEMPR
      TRMASS=CONVEC/(DST*CPM*RCVAP*TEMPR)
      WALL=PRIME*SECT*(CFKTOR*CONDUC*(ROCKTF-TEMP)+(ELATEN*TRMASS*
     5(SATROC-PVAP1)))
      DST=DST1
      DBTU=WALL*AFLOW
      DLTBTU=DLTBTU+DBTU
      IF(ROCKTF-TEMP)593,593,595
  593 DTEMP=(DWATER*ELATEN)/(WDRAER+DWATER)*CPM
      TNET1=TEMP-DTEMP
      TEMP=TNET1
      GO TO 584
  595 DLTT=DBTU/(WDRAER+DWATER)*CPM
      TNET2=TEMP+DLTT
```

```
      TEMP=TNET2
  584 T=TDUMMY
      CALL TABEL(T,VAPOR)
      XSAT=VAPOR
      VALUE=XSAT-0.0003613*PIN*(TEMP-TDUMMY)
      IF(PVAP1-VALUE)586,586,585
  585 TDUMMY=TDUMMY+0.00115
      GO TO 584
  586 GO TO 55
   55 CONTINUE
      DISTAN=LENGTH
      TIME=DISTAN/AERATE
      BTU=DLTBTU/TIME
      CUMBTU=CUMBTU+DLTBTU
      TTIME=TTIME+TIME
      WTEMP=TDUMMY
      DLTBTU=0.
C     *COMPUTATIONS OF HEAT PROBLEMS FOR DIFFERENT UNDERGROUND AIRWAYS*
      IF(KEY-1)458,457,457
  458 TTERMN=TEMP
      WRITE(3,851)JNCTON,TTERMN,WTEMP
      GO TO 456
  457 JNCTON=JNCTON+1
      WRITE(3,851)JNCTON,TEMP,WTEMP
      GO TO 456
  851 FORMAT(/5X,'AIR CONDITIONS AT JUNCTION',I3,1X,'DRYBULB=',F7.3,' F'
     2,2X,'WETBULB=',F7.3,' F')
  456 KEY=KEY+1
      IF(KEY.EQ.1) GO TO 460
      IF(KEY.EQ.2) GO TO 470
      IF(KEY.EQ.3) GO TO 480
      IF(KEY.EQ.4) GO TO 490
      IF(KEY.EQ.5) GO TO 495
      IF(KEY.EQ.6) GO TO 496
      IF(KEY.GT.6) GO TO 497
  460 READ(1,410)AERCFM,CROS1,PRIME,LENGTH
```

```
      GO TO 450
  470 READ(1,410)AERCFM,CROS1,PRIME,LENGTH
      GO TO 450
  480 READ(1,410)AERCFM,CROS1,PRIME,LENGTH
      TSTOPE=TEMP
      MSTOPE=TRMASS
      PSTOPE=SATROC
      VSTOPE=PVAP1
      GO TO 450
  490 READ(1,410)AERCFM,CROS1,PRIME,LENGTH
      GO TO 450
  495 READ(1,410)AERCFM,CROS1,PRIME,LENGTH
      GO TO 450
  496 READ(1,410)AERCFM,CROS1,PRIME,LENGTH
      GO TO 450
  497 AIR3=AERATE
      DST3=DST
      CPM3=CPM
      TEMWET=TDUMMY
      TEMDRY=TEMP
      DPRS=TEMDRY-TEMWET
C     *ADDITIONAL HEAT SOURCES*
C     *200 MINERS WORKING UNDERGROUND, 18.4 BTU/MIN PER MINER*
      CURENT=20000.
      WORKER=200.*18.4
      ALLAMP=100.
      COMPRS=8000.
C     *STOPE: 30 X 100 FT, THREE WORKING AREAS*
      CROS=30.*10.
      PERIM=80.
      AIRCUM=50000.
      SECT=100.
      AIRATE=AIRCUM/CROS
      FLOW=SECT/(AIRATE*60.)
      WALL= PERIM*SECT*(CFKTOR*CONDR3*(ROCKTF-TSTOPE)+(ELATEN*MSTOPE*
     4(PSTOPE-VSTOPE)))
```

```
      WALL=3.*WALL
      DBTU=WALL*FLOW
      CUMBTU=4.*CUMBTU
      ROKBTU=CUMBTU/TTIME
      TTLBTU=CURENT+WORKER+ALLAMP-COMPRS+ROKBTU
      AIR23=AIR3*12.*12.*DST3
      BTUAIR=TTLBTU/AIR23
      ADTEMP=BTUAIR/CPM3
      DRYST3=TTERMN+ADTEMP
      DRYGRD=(DPRS/TEMDRY)*DRYST3
      WETST3=DRYST3-DRYGRD
      WRITE(3,501)DRYST3,WETST3
  501 FORMAT(//5X,'BOTTOM OF UPCAST SHAFT, DRYBULB=',F7.3,2X,'WETBULB=',
     2F7.3)
      T=DRYST3
      CALL TABEL (T,VAPOR)
      SATSIN=VAPOR
      WRITE(3,600)
  600 FORMAT(////50X,'UPCAST SHAFT'//)
      WRITE(3,601)
  601 FORMAT(6X,'DEPTH',7X,'PRESSURE',5X,'TEMPERATURE',2X,'DENSITY',2X,
     6'MOIST.CONT.')
      WRITE(3,602)
  602 FORMAT(7X,'(FT)',8X,'(INHG)',8X,'(DRY,F)',4X,'(LB/CUFT)',1X,
     7'(LB/LB.DRY AIR)'//)
      DRST3R=DRYST3+459.69
      DRYST4=(DRYST3-(DEPTH/(CPM*778.26)))
      DRST4R=DRYST4+459.69
      PRES3=SAPUCS*(DRST3R/DRST4R)**(CKM/(CKM-1.))
      PRIN3=PRES3*29.92/14.696
      T=WETST3
      CALL TABEL(T,VAPOR)
      SATPV3=VAPOR
      PVST3=SATPV3-0.0003613*PRIN3*DRYGRD
      PV3PSI=PVST3*0.491
      DNS3=1.3225*(PRIN3-(0.3777*PVST3))/DRST3R
```

```
      WSTA3=(0.622*PV3PSI)/(PRES3-PV3PSI)
      RELAT=100.*PVST3/SATSIN
      ENTAL3=CPAIR*DRYST3+WSTA3*(1061.+CPVAP*DRYST3)
      WRITE(3,610)DELTAZ,PRIN3,DRYST3,DNS3,WSTA3
  610 FORMAT(5X,F8.2,6X,F5.2,9X,F7.3,4X,F8.6,5X,F9.7)
C
C     *COMPUTATIONS IN UPCAST SHAFT*
      Z34=0.TOTDNS=0.
      SUMDNS=0.
      ROCKUP=ROCKTF
  900 DO 615 I=1,4
      Z34=Z34+SECTS
      TMPUP=DRYST3-(Z34*(1.+WSTA3)/(CPM*778.26))
      TMPUPR=TMPUP+459.69
      PRSUP=PRES3*(TMPUPR/DRST3R)**(CKM/(CKM-1.))
      PRSUPI=PRSUP*29.92/14.696
      AIRDST=144.*(PRSUP-PV3PSI)/(RCAIR*TMPUPR)
      DNSUP=1.3225*(PRSUPI-(0.3777*PVST3))/TMPUPR
      TOTDNS=TOTDNS+DNSUP
      AIRFLO=(CROS*AIRATE*60.*DNSUP)/CROS
      CPU=CPM*AIRDST
      CONVEC=(0.023*AIRCON/DIAM)*((AIRFLO*DIAM/AIRVIS)**0.8)*(AIRVIS*
     2CPM/AIRCON)**0.4
      BETAUP=CONVEC/CPU
      T=TMPUP
      CALL TABEL(T,VAPOR)
      SATUP=VAPOR
      DLTWAT=BETAUP*70.7259*(SATUP-PVST3)/(RCVAP*TMPUPR)
      ADWAT=DLTWAT*AREA*FLOW
      WDRYR=CROS*60.*AIRATE*FLOW*AIRDST
      WATRUP=((WSTA3*WDRYR)+ADWAT)/WDRYR
      WSTA3=WATRUP
      CPM=(CPAIR+WATRUP*CPVAP)/(1.+WATRUP)
      CVM=(CVAIR+WATRUP*CVVAP)/(1.+WATRUP)
      CKM=CPM/CVM
      TRMASS=CONVEC/(DNSUP*CPM*RCVAP*TMPUPR)
```

```
      PV4PSI=WATRUP*PRSUP/(0.622+WATRUP)
      PV3PSI=PV4PSI
      PVAP4=PV4PSI*29.92/14.696
      PVST3=PVAP4
      ZUP=DEPTH-Z34
      IF(LAYERS.EQ.1) GO TO 631
      IF(LAYERS.EQ.2) GO TO 632
      IF(LAYERS.EQ.3) GO TO 633
  631 ROCUP=ROCKUP-(GRAD1/100.)*Z34
  638 CONDUC=CONDR1
      ROCDST=ROCDS1
      DIFFUS=CONDUC/(ROCDST*CPROCK)
      TFKTOR=AGE1*DIFFUS
      CFKTOR=(S*CONSTA)/(TFKTOR**(CONSTB*Q))
      GO TO 651
  632 IF(STRAT1-ZUP)641,639,649
  641 ROCUP=ROCKUP-(GRAD2/100.)*Z34
  658 CONDUC=CONDR2
      ROCDST=ROCDS2
      DIFFUS=CONDUC/(ROCDST*CPROCK)
      TFKTOR=AGE1*DIFFUS
      CFKTOR=(S*CONSTA)/(TFKTOR**(CONSTB*Q))
      GO TO 651
  639 ROCUP1=ROCUP
      GO TO 649
  649 ROCUP=ROCUP1-(GRAD1/100.)*(STRAT1-ZUP)
      GO TO 638
  633 IF(STRAT2-ZUP)644,646,645
  644 ROCUP=ROCKUP-(GRAD3/100.)*Z34
      CONDUC=CONDR3
      ROCDST=ROCDS3
      DIFFUS=CONDUC/(ROCDST*CPROCK)
      TFKTOR=AGE1*DIFFUS
      CFKTOR=(S*CONSTA)/(TFKTOR**(CONSTB*Q))
      GO TO 651
  646 ROCUP2=ROCUP
```

```
      GO TO 676
  676 ROCUP=ROCUP2-(GRAD2/100.)*(STRAT2-ZUP)
      GO TO 658
  645 IF(STRAT1-ZUP)646,639,649
  651 T=ROCUP
      CALL TIBLE(T,ELATEN)
      CALL TABEL(T,VAPOR)
      SATRUC=VAPOR
      WALLUP=PERIM*SECTS*(CFKTOR*CONDUC*(ROCUP-TMPUP)+(ELATEN*TRMASS*
     3(SATRUC-PVST3)))
      DBTU=WALLUP*FLOW
      DLTBTU=DLTBTU+DBTU
      IF(ROCUP-TMPUP)693,693,695
  693 DTEMP=(ADWAT*ELATEN)/(WDRYR+ADWAT)*CPM
      TNETU1=TMPUP-DTEMP
      TMPUP=TNETU1
      GO TO 615
  695 DLTT=DBTU/(WDRYR+ADWAT)*CPM
      TNETU2=TMPUP+DLTT
      TMPUP=TNETU2
      T=TMPUP
      CALL TABEL(T,VAPOR)
      IF(PVST3-VAPOR)615,612,612
  612 PV3PSI=PVST3*0.491
      WSTA3=(0.622*PV3PSI)/(PRSUP-PV3PSI)
  615 CONTINUE
      AVEDNS=TOTDNS/4.
      SUMDNS=SUMDNS+AVEDNS
      TOTDNS=0.
      T=TMPUP
      CALL TABEL(T,VAPOR)
      IF(PVST3-VAPOR)667,668,668
  667 WRITE(3,671)ZUP,PRSUPI,TMPUP,DNSUP,WSTA3
  671 FORMAT(5X,F8.2,6X,F5.2,9X,F7.3,4X,F8.6,5X,F9.7)
      IF(Z34-DEPTH)900,666,666
  668 WRITE(3,672)ZUP,PRSUPI,TMPUP,DNSUP,WSTA3,PVST3
```

```
672 FORMAT(5X,F8.2,6X,F5.2,9X,F7.3,4X,F8.6,5X,F9.7,2X,'*SATURATED*',
   12X,'VAP.PRES.=',F9.4)
    IF(Z34-DEPTH)900,666,666
666 AVDSTY=(SUMDNS+DNS3)/301.
    VENAT=(Z34/5.2)*(AVEDST-AVDSTY)
    WRITE(3,661)AVDSTY
661 FORMAT(5X,'AVERAGE DENSITY OF UPCAST AIR=',F8.6)
    WRITE(3,662)VENAT
662 FORMAT(5X,'NATURAL VENTILATION PRESSURE=',F8.6,' INCHES W.G.')
    KKEY=KKEY+1
    IF(KKEY.EQ.1) GO TO 992
    IF(KKEY.EQ.2) GO TO 993
    IF(KKEY.GT.2) GO TO 997
992 READ(1,200)DTEMSF,WTEMSF,SAPDCS,SAPUCS,SURPIN
    GO TO 800
993 READ(1,200)DTEMSF,WTEMSF,SAPDCS,SAPUCS,SURPIN
    GO TO 800
997 STOP
    END

    SUBROUTINE TIBLE(T,ELATEN)
    COMMON TABLE(130),ETABLE(130),BTABLE(130)
    J=0
    IT=T
    DO 17 I=1,119
    J=J+1
    IF(TABLE(I)-IT)17,18,17
 17 CONTINUE
 18 ELATEN=ETABLE(J)
    RETURN
    END

    SUBROUTINE TABEL(T,VAPOR)
    COMMON TABLE(130),ETABLE(130),BTABLE(130)
    J=0
```

```
      DO 27 I=1,119
      J=J+1
      IF(TABLE(I)-T)27,28,29
   27 CONTINUE
   28 VAPOR=BTABLE(J)
      GO TO 40
   29 RATIO=(BTABLE(J)-BTABLE(J-1))/(TABLE(I)-TABLE(I-1))*(TABLE(I)-T)
      VAPOR=BTABLE(J)-RATIO
   40 RETURN
      END
```

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VII. VITA

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