Cooling power of underground environments*

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ABSTRACT

The problem of heat stress underground in the gold mines is approached on the basis of the heat transfer between the human body and the underground environment. Experimental measurements of radiant and convective heat transfer and a theoretical calculation of maximum evaporative heat transfer enable the maximum cooling power of an environment to be calculated in terms of the dry-bulb and wet-bulb temperature, the mean radiant temperature, the wind speed and the barometric pressure. For most underground applications the cooling power can be expressed as a function of wet-bulb temperature and wind speed only. The relative importance of wind speed and wet-bulb temperature can be assessed: in working places where wind speed is low additional cooling of workmen can be achieved better by increased wind speed than by decreased wet-bulb temperature. The wet kata reading proves to be of limited value as an index of heat stress because environments with equal wet kata do not necessarily have the same cooling power. Finally, thermal equilibrium with the environment is possible when cooling power equals or exceeds the rate of metabolic heat generation. The rates of metabolic heat generation for various underground tasks are indicated.

LIST OF SYMBOLS

A_b total body surface area (m^2)
A_c area of human body participating in convective heat transfer (m^2)
A_e area of human body participating in evaporative heat transfer (m^2)
A_r area of human body participating in radiant heat transfer (m^2)
P_a atmospheric pressure (mbar)
Q_{max} maximum total heat transfer rate per unit of total body area=maximum cooling power (W/m^2)
T_a dry-bulb temperature of air (C)
T_r mean radiant temperature of surroundings (C)
$\bar{T}_s$ mean body surface temperature (C)
T_w wet-bulb temperature of air (C)
V wind speed (m/s)
c_1, c_2 constants
e_a ambient water vapour pressure (mbar)
e_s saturated water vapour pressure at mean skin temperature (mbar)
e_w saturated water vapour pressure at the wet-bulb temperature (mbar)
f_r radiation posture factor$=A_r/A_b$
h_c convective heat transfer coefficient (W/m^{2}C)
h_m mass transfer coefficient (kg/m^2 mbar)
h_r radiant heat transfer coefficient (W/m^{2}C)
q_c convective heat flow (W)
q_{emax} maximum evaporative heat flow (W)
q_r radiant heat flow (W)
Δe $=(e_s-e_a)$
ϵ emissivity of skin
λ heat of evaporation (J/kg)
σ Stefan-Boltzmann constant $=5,67\times10^{-8}$ W/m^2 K^4

INTRODUCTION

Five parameters define the thermal environment underground in the gold mines. In practice the ventir lation engineer can manipulate only two of them, ai, temperature and air speed. The other three, pressure-radiant temperature, and air humidity are fixed, to all intents and purpose, by the depth of the mine, the nature of the rock, and the dust abatement procedures. Because the aim of ventilation is to provide a suitable working environment for the miner, the ventilation engineer needs to know the influence of the various environmental parameters on the heat transfer between a man and his environment. It was the patent inadequacy of available methods for predicting human heat transfer[14] that necessitated the building of the wind tunnel at the Human Sciences Laboratory. Sophisticated environmental control in the tunnel, and accurate measuring techniques, have allowed the development of reliable methods for predicting heat transfer from the human body. The ventilation engineer can now calculate the cooling power of underground environments in terms of air temperature, speed and humidity, radiant temperature and barometric pressure.

Some predictive graphs based on heat transfer equations derived in the HSL wind tunnel[12] have already been published. Those graphs, however, required the user to assess skin temperature. This limitation is removed in the current treatment.

HUMAN HEAT TRANSFER IN UNDERGROUND ENVIRONMENTS

A man exchanges heat with his environment by radiation, convection and evaporation. Conductive heat transfer is negligible unless a large proportion of the body surface is in contact with solid material at a temperature very different from skin temperature. In a given environment radiant and convective heat transfer are fixed if skin temperature and body posture are fixed. The same is not true of evaporative heat transfer. The amount of water on the skin surface depends on the sweat rate, and sweat rate is under the control of the

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nervous system. However, in response to heat stress more and more sweat is produced until the body surface is completely wet. Evaporative heat transfer is then maximum, and maximum evaporative heat transfer is a function of environmental parameters and skin temperature only.

Evaporation is by far the most powerful avenue of body cooling so that body cooling in hot environments will be maximum when evaporation is maximum. We can therefore define a maximum cooling power (Q_{max}) for any particular environment:

$$Q_{max} = \text{radiant cooling} + \text{convective cooling} + \text{maximum evaporative cooling} \quad . \; . \; . \; . \quad (1)$$

After a series of systematic studies in the wind tunnel it is now possible to write equations for radiant and convective cooling. The equations are based on measurements of the heat transfer of nude men, or men wearing shorts only. The restriction that the equations apply only to nudity, or near-nudity, is not serious in underground conditions. If men working in hot wet environments wear anything other than helmets, shorts and boots the type of clothing they wear interferes only slightly with heat transfer. About a thousand measurements each of radiation and convection have been made, in environments spanning the complete range of temperature, wind speed and humidity experienced underground. The equations* are:

radiant cooling (W/m²)

$$= 17{,}0 \times 10^{-8}(T_r/2 + 290{,}7)^3(\bar{T}_s - T_r) \quad . \; . \quad (2)$$

convective cooling (W/m²)

$$= 8{,}32(P_a/1\,013)^{0{,}6} V^{0{,}6}(\bar{T}_s - T_a) \quad . \; . \; . \; . \; . \quad (3)$$

Because of the analogy between heat transfer and mass transfer across a boundary layer, the evaporation from a fully wet surface can be calculated if the convection from that surface is known. For underground environments*:

maximum evaporative cooling (W/m²)

$$= 15\,140(P_a/1\,013)^{0{,}6} V^{0{,}6} \Delta e/P_a \quad . \; . \; . \; . \quad (4)$$

$$\text{where } \Delta e = 6{,}105 \exp\,[17{,}27\,\bar{T}_s/(\bar{T}_s + 237{,}3)] - 6{,}105 \exp[17{,}27\,T_w/(T_w + 237{,}3)] + 6{,}6 \times 10^{-4} P_a(T_a - T_w)\,[1 + 1{,}15 \times 10^{-3}(T_a - T_w)] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

The calculation of maximum cooling power involves the simultaneous solution of equations $\bar{T}_s$, (1) to (5) for various combinations of the parameters T_s, T_a, T_r, T_w, V and P_a. A digital computer is the most suitable

*The derivation of these equations is discussed in more detail in the appendix.

CALCULATION OF MAXIMUM HEAT TRANSFER RATES FOR THE HUMAN BODY IN UNDERGROUND ENVIRONMENTS

Insert air (dry bulb) temperature Ta (in degrees celsius)

34

Insert rock surface temperature or mean radiant temperature (in degrees celsius)

35

Do you wish to insert a skin temperature other than 35 degrees celsius (95 degrees F)? If "Yes" type chosen temperature (in celsius), else type "0.".

0

Insert barometric pressure (in millibars)

1000

The program increments wet bulb temperature stepwise from 20 degrees C to the air temperature. Specify the size of the step required (not less than 0.1 degrees C)

1

Do you wish the results to be printed on the terminal or line-printer (ie remote)? If terminal type "6", else type "9".

6

TABLE OF WIND VELOCITIES (in metres/sec) AT VARIOUS WET BULB TEMPERATURES GIVING MAXIMUM HEAT TRANSFER RATES BETWEEN 0 AND 500 WATTS/M.SQ.. (Valid only between .1 & 5 m/s)

Conditions: Ta=34., Tr=35., Ts=35., P=1000.

Wet bulb temp	0	50	100	150	200	250	300	350	400	450	500	(watts/m.sq.)
20.0	-----	-----	-----	-----	.133	.193	.262	.338	.423	.515	.613	
21.0	-----	-----	-----	-----	.145	.211	.285	.369	.461	.561	.669	
22.0	-----	-----	-----	-----	.160	.232	.314	.406	.507	.617	.735	
23.0	-----	-----	-----	.110	.177	.257	.349	.451	.563	.685	.817	
24.0	-----	-----	-----	.123	.199	.289	.391	.506	.632	.769	.917	
25.0	-----	-----	-----	.140	.227	.329	.446	.576	.720	.876	1.044	
26.0	-----	-----	-----	.162	.262	.381	.516	.667	.833	1.014	1.208	
27.0	-----	-----	-----	.192	.310	.450	.609	.788	.984	1.198	1.427	
28.0	-----	-----	.118	.233	.376	.545	.739	.955	1.194	1.452	1.731	
29.0	-----	-----	.149	.292	.472	.685	.928	1.199	1.498	1.823	2.173	
30.0	-----	-----	.196	.385	.621	.901	1.221	1.578	1.972	2.400	2.860	
31.0	-----	-----	.276	.542	.876	1.270	1.721	2.225	2.780	3.383	4.032	
32.0	-----	.137	.434	.852	1.377	1.997	2.706	3.499	4.371	*****	*****	
33.0	-----	.263	.834	1.639	2.647	3.840	*****	*****	*****	*****	*****	
34.0	-----	.832	2.642	*****	*****	*****	*****	*****	*****	*****	*****	

Fig. 1—Example of computer calculation of cooling power Output in tabular form.

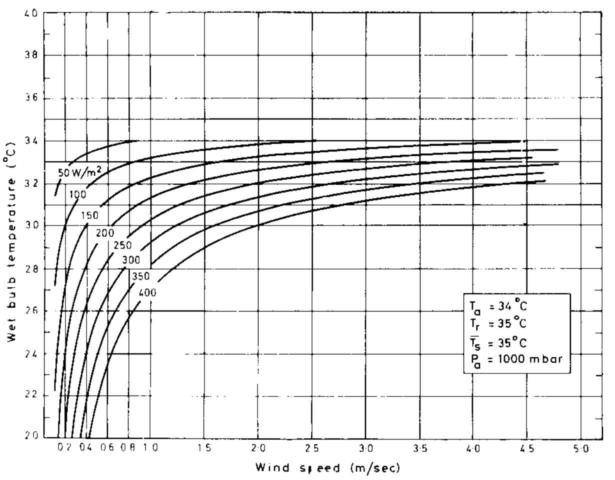

Fig. 2—Example of computer calculation of cooling power. Output in graphical form. Curved solid lines are lines of equal cooling power.

means. Programs have been written by means of which cooling power can be calculated and reported either in tabular or in graphical form.

An example of the tabulating program is given in Fig 1. The program has been written in conversational mode. The user carries out a number of instructions issued by the computer. For given values of the air temperature, radiant temperature, skin temperature and barometric pressure, the computer prints out the values of wind velocity which, together with a particular wet-bulb temperature, give a particular maximum cooling power.

An example of the plotting program is given in Fig 2. The lines in Fig 2 are lines of equal maximum cooling power.

SPECIFIC COOLING POWER

Maximum cooling powers have been calculated on the computer for environments in which the five variables T_a, T_w, V, P_a and T_r span the entire range of conditions found underground. The calculations reveal wind speed and wet-bulb temperature to be the most important environmental parameters affecting cooling power. The result provides a theoretical basis for the experimental findings of Wyndham *et al*[13, 15, 16] who twenty years ago established wet-bulb temperature and wind speed as the most important environmental determinants of physiological reactions to heat.

Over the range of pressures found in the gold mines, cooling power is changed only a few per cent by changes in pressure, the cooling decreasing as pressure increases. Except for very newly-blasted areas rock temperature is always close to air temperature. Also, in very humid environments much of the radiation incident on a man arises from the water vapour in the air and not from the solid surroundings. Wet-bulb temperature, as an environmental parameter, adequately combines the effects of dry-bulb temperature and atmospheric humidity on cooling power, when the gap between wet-bulb temperature and dry-bulb temperature is small (less than 5 or 10 °C).

Because the influence of pressure, rock temperature and dry-bulb temperature *per se* (that is, at fixed wet-bulb) on the cooling power of underground environments is small, it seems reasonable to calculate the cooling power of underground environments for fixed values of pressure, rock temperature and wet-bulb depression. The following values are considered typical of underground conditions:

$P_a = 1\,000$ mbar

$T_a = T_w + 2\,°C$

$T_r = T_a$

If skin temperature could be specified, maximum cooling power in underground environments, to a very good approximation, would be a function only of wet-bulb temperature and wind speed. That skin temperature can indeed be specified, at least for acclimatized men, is evident from the results of measurements of skin temperature made at the Human Sciences Laboratory.

It has been shown previously[4] that acclimatized men resting in hot dry environments have mean skin temperatures very close to 35 °C irrespective of air temperature or wind speed. In a recent experiment in the wind tunnel two men were exposed nude to environments with air temperatures of 35 °C and 41 °C, water vapour pressures between 20 mbar and 47 mbar and wind speeds of 0,67 and 3,11 m/s. The men rested and worked at two rates: 45W and 113W. Skin temperature was measured using a roving thermocouple. Mean skin temperature was obtained by averaging over 15 critically chosen sites on the body[3]. Fig 3 shows mean skin temperature as a function of wet-bulb temperature.

It would seem that men in equilibrium with hot environments have skin temperatures close to 35 °C whatever the air temperature, wind speed, humidity or work rate within the range studied. In the experiments on which this conclusion is based the subjects (five in number) did not exhibit excessive physiological strain. Body core temperatures and heart rates were well below those associated with significant risks of heat stroke. It seems reasonable to suggest (although further validation is clearly necessary) that equilibrium skin temperatures of 35 °C in acclimatized men are associated with combinations of work and heat which offer little or no risk to the safety of the man. This being so, it is convenient to define the *specific cooling power* (SCP) of an underground environment to be the maximum cooling power assuming $P_a = 1\,000$ mbar, $T_a = T_r = (T_w + 2\,°C)$, and $T_s = 35\,°C$.

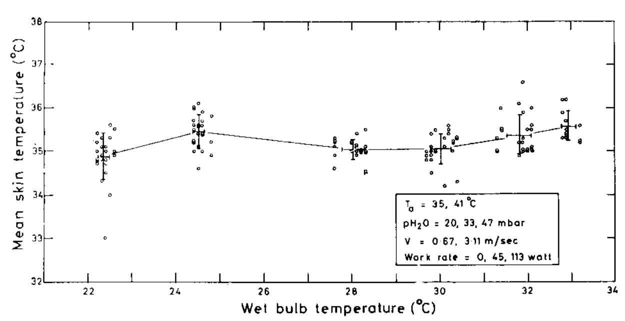

Fig. 3—Mean skin temperature as a function of wet-bulb temperature for nude acclimatized men in hot environments

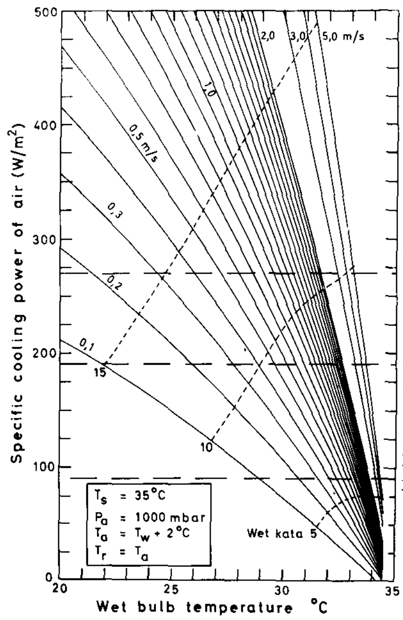

Fig. 4—Specific cooling power: simplified calculation of cooling power for general use underground.

Specific cooling power is then a function of wet-bulb temperature and wind speed only. Fig 4 shows specific cooling power plotted as a function of wet-bulb temperature with wind speed as parameter.

RELATIVE IMPORTANCE OF WIND SPEED AND WET–BULB TEMPERATURE

The solid curved lines in Fig 2, or any of the horizontal lines in Fig 4, are lines of equivalent environmental cooling power. Each point on such a line represents a combination of wet-bulb temperature and wind speed. Therefore each line represents all the combinations of wind speed and wet-bulb temperature which will produce the same cooling power.

Ventilation procedures underground are traditionally orientated towards reducing wet-bulb temperatures. The calculations of cooling power indicate that this strategy may not be the best. Wind speeds in the working places underground are generally low. In most working places the wind speeds are below 1 m/s and in a considerable number, wind speeds are below 0,5 m/s. In the region of low wind speed the cooling power of the environment increases rapidly with increasing wind speed, but only slowly with decreasing wet-bulb temperature. For example, using Fig 4, the specific cooling power at 32 °C wet-bulb and 0,1 m/s wind speed is about 40 W/m². Increasing the wind speed to 1 m/s increases the cooling power to 160 W/m². In order to reach the same cooling power by decreasing wet-bulb temperature rather than by increasing wind speed, it is necessary to reduce the wet-bulb temperature to about 24 °C. In working places where wind speeds are low, a great deal of benefit would be gained by local recirculation of air, provided the build-up in airborne dust, gases, and other toxic materials is not excessive.

At high wind speeds the beneficial effect of an increase in wind speed diminishes. The benefits of increasing wind speeds above 2 m/s are small. This supports the earlier conclusion of Wyndham *et al*[13] that there is little advantage in terms of physiological strain in increasing wind speed from 2 m/s to 4 m/s in hot environments.

COMPARISON WITH WET KATA

The wet kata reading, measured or, more usually, calculated, is used commonly in the gold mining industry as an index of heat stress. If it is a good index of heat stress, lines of equal kata reading should be parallel to lines of equal cooling power. In other words, lines of equal kata reading should be horizontal on Fig 4. The dotted lines in Fig 4 are lines corresponding to calculated wet katas of 5, 10 and 15 mcal/cm² s, and are clearly far from horizontal, particularly at low wind speeds.

It is clear from Fig 4 that all environments having a wet kata of 5 also have a low specific cooling power. Environments with low wet katas, therefore, which have come to be recognised as dangerous by the industry, are indeed environments with low cooling power. In the intermediate range of wet kata readings, however, there is poor agreement between wet kata reading and cooling power. A kata of 10 corresponds to a specific cooling power of about 150 W/m² at a wind speed of 0,2 m/s and a cooling power of 250 W/m² at a wind speed of 2 m/s.

Environments having the same kata reading do not necessarily have the same cooling power. The value of the wet kata as an index of heat stress is therefore limited.

COOLING POWER AND METABOLIC HEAT

The adverse physiological reactions shown by men working hard in hot humid environments such as those occurring underground are the result not of environmental heat stress *per se* but of an inability of the body to reject metabolic heat to the environment. In order to prevent heat accumulation within the body, and the concomitant rise in body temperature, heat must be transferred from body to environment at least as fast as it is generated within the body.

Human physical work is mechanically inefficient. Even in the most efficient of the tasks performed underground, only about 20 per cent of the energy liberated in the muscles leaves the body in an energy form other than heat. In a great many underground tasks all energy is converted to heat within the body. To a good approximation, therefore, it is acceptable to assume that all metabolic energy liberated in the body must leave the body in the form of heat. A working man will then reach thermal equilibrium if the cooling power of the environment equals, or exceeds, his rate of metabolic heat generation.

Each task has a particular rate of metabolic heat generation associated with it, the metabolic heat generation being directly proportional to the oxygen uptake necessary for the task. The oxygen uptake for various mining tasks has been determined experimentally[7]. Fig 5 shows the oxygen consumptions and metabolic heat generation rates for various tasks, calculated for men with low (1,5 m²), average (1,75 m²) and high (2 m²) surface areas.

Fig 5 can be used in conjunction with calculations of cooling power to assess whether men performing a particular task will be capable of reaching thermal equilibrium in a particular environment.

ENVIRONMENTAL LIMITS BASED ON COOLING POWER

The three dashed, horizontal lines in Fig 4 are lines of specific cooling power equal to 90, 190 and 270 W/m². Metabolic heat generation rates of 90, 190 and 270 W/m² are typical of light work (eg winch driving), moderate work (eg sweeping, machine, barring) and hard work (eg tramming and shovelling) respectively. Men can reach thermal equilibrium with a skin temperature of 35 °C if the point defining the environment in which they are working lies above the line relevant to their work rate in Fig 4. As stated previously skin temperatures of 35 °C appear to be associated with conditions in which physiological strain is not high in acclimatized men. The limits imposed by the dashed lines in Fig 4 may be regarded, therefore, as safe or very low risk limits for acclimatized men, working at light, moderate and hard rates respectively.

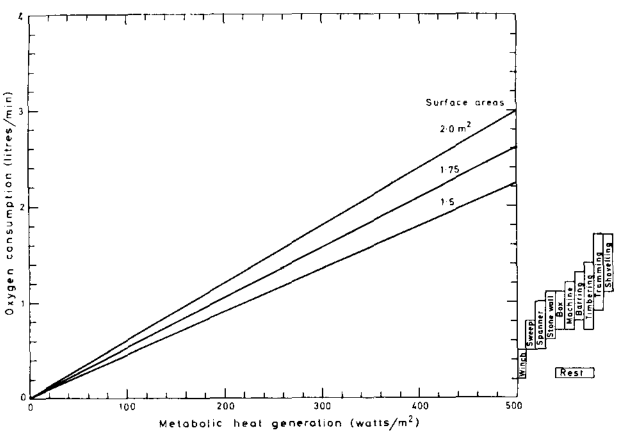

Fig. 5—Oxygen consumptions and metabolic heat generation rates associated with various underground tasks.

It will be apparent to those familiar with underground conditions that many men are working in environments where, according to Fig 4, they cannot be in equilibrium. If a man is not in equilibrium in a hot environment, he accumulates heat and his body temperature rises. Evaporative heat transfer rises very rapidly with rising skin temperature. The diagrams in Fig 6 differ only as regards skin temperature, the skin temperatures being 35 °C, 36 °C and 37 °C respectively. A man with a skin temperature of 35 °C, unable to attain thermal equilibrium in a particular environment, may well be able to attain equilibrium when his skin temperature has risen a few degrees. In fact, his skin temperature will continue to rise until either he succumbs or he reaches equilibrium.

There are considerable physiological disadvantages associated with rising skin temperature. Metabolic heat is transported by the bloodstream from the sites of generation (mainly the muscles) to the interface with the environment (the skin). For this transport to take place the central temperatures of the body must be higher than the skin temperature. In particular, rectal temperature is higher than skin temperature and will tend to rise when skin temperature rises.

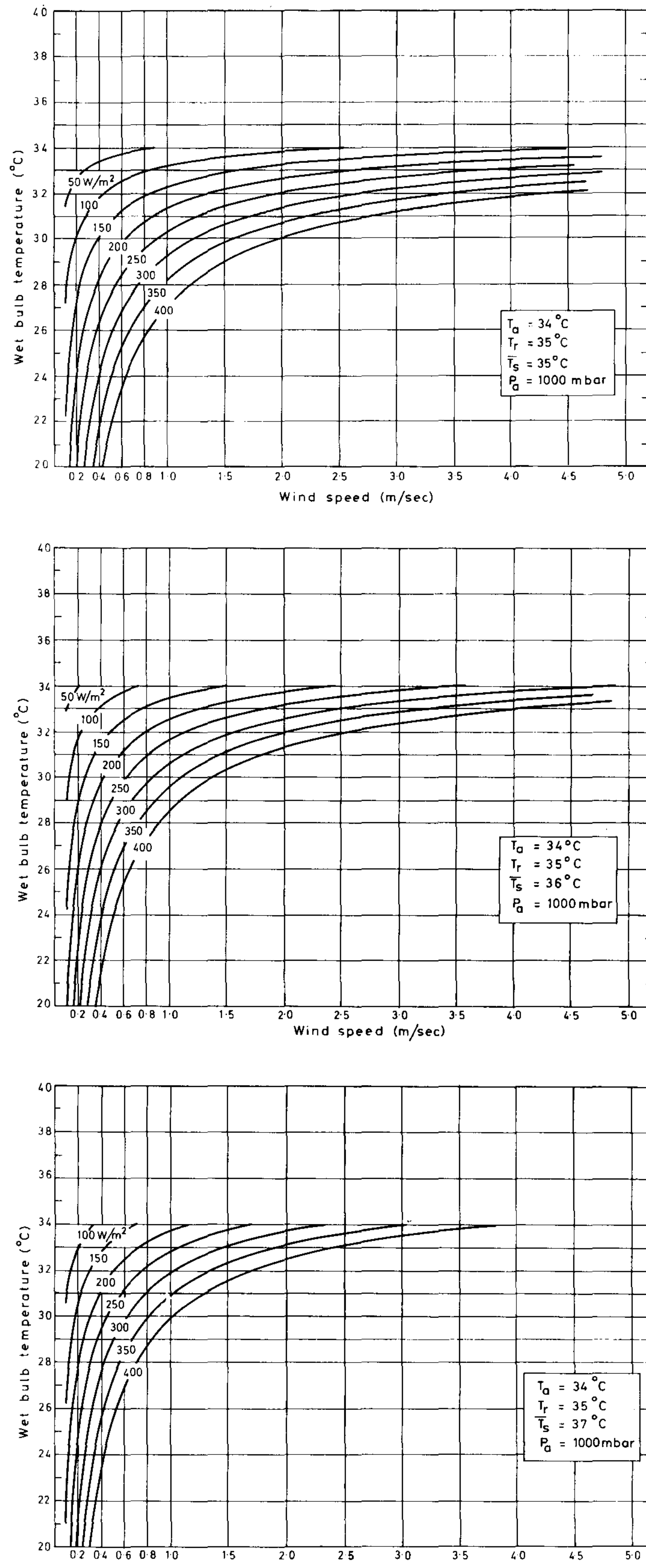

Fig. 6—Graphs of cooling power differing only in assumed skin temperature: 35 °C (top), 36 °C (middle), 37 °C (bottom).

In order to combat a rise in body core temperature, the circulation of blood between muscles and skin is automatically increased. Increasing the blood circulation increases circulatory strain, which usually manifests itself as an increased heart rate. Thus increases in skin temperature in the heat are associated with increases in core temperature or circulatory strain or both.

The fact that skin temperature will increase during work in hot environments until equilibrium is reached and that physiological strain increases with increasing skin temperature suggests that predicted equilibrium skin temperature might be a useful index of heat stress in the region where metabolic heat generation exceeds specific cooling power. The predicted equilibrium skin temperature can be calculated from a knowledge of the task and the environmental conditions only. This possibility is currently being pursued, and preliminary results indicate that it will be possible to develop a series of limits for which the risk of heat stroke is 1:1 000 000, 1:100 000, 1:10 000 etc. These limits will be associated with skin temperatures elevated above 35 °C.

CONCLUSION

This paper presents an approach to the problem of heat stress underground based on the transfer of heat between the man and his underground environment. Belding and Hatch[1] have presented a similar approach to the problem of heat stress in general. Their technique became untenable when they attempted to extrapolate to situations for which there was no experimental verification. Because of the assumptions made, it should not be assumed without careful analysis of each case on its merits that the approach presented here applies to any stress situation other than that prevailing in the South African gold mines.

The most important implication of the analysis is economic. The gold mining industry spends millions of rands annually on the construction, running and staffing of ventilation and refrigeration systems. Ventilation engineers are faced with the problem of optimizing the various environmental parameters over which they have control. The work presented in this paper now allows an assessment of the actual cooling provided by any particular environment, and the relative importance of the two most important parameters, wet-bulb temperature and wind speed.

ACKNOWLEDGEMENTS

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The figures were prepared by Mr D. Rabe.

Aspects of this work were presented to the Mine Ventilation Society at a meeting during December, 1969.

APPENDIX

Derivation of heat transfer equations

The rates of radiant and convective heat transfer between the human body and its environment can be calculated using equations (6) and (7) respectively

$$q_r/A_r = h_r\,(\bar{T}_s - T_r) \quad \ldots\ldots (6)$$

$$q_c/A_c = h_c\,(\bar{T}_s - T_a) \quad \ldots\ldots (7)$$

The radiant heat transfer equation is given in linear form. Strictly, radiant heat transfer depends on the difference of fourth powers of absolute temperatures but in the range of environments experienced underground, the linear approximation is more than adequate.

For a fully wet body surface the evaporative heat transfer is given by equation (8):

$$q_{emax}/A_e = \lambda\, h_m\,(e_s - e_a) \quad \ldots\ldots (8)$$

Whillier[11] has shown that, for underground conditions, by virtue of the analogy between heat and mass transfer:

$$\lambda\, h_m/h_c = c_1/P_a \quad \ldots\ldots (9)$$

Equation (8) can therefore be written

$$q_{emax}/A_e = c_1 h_c\,(e_s - e_a)/P_a \quad \ldots\ldots (10)$$

The maximum total heat transfer per unit of total body area (A_b) is therefore:

$$\begin{aligned} Q_{max} &= (q_r + q_c + q_{emax})/A_b \\ &= h_r(\bar{T}_s - T_r)\,(A_r/A_b) + h_c\,(\bar{T}_s - T_a)\,(A_c/A_b) \\ &\quad + [c_1 h_c\,(e_s - e_a)/P_a]\,(A_e/A_b) \quad \ldots\ldots (11) \end{aligned}$$

The area terms in equation (11) can be simplified. The miner has virtually his whole surface available for evaporative and convective heat transfer. Thus

$$A_c/A_b = A_e/A_b = 1$$

The area available for radiant heat transfer is some fraction (f_r) of the total area, the fraction depending on posture. Thus

$$A_r/A_b = f_r$$

Expressing all body areas in terms of the total area:

$$Q_{max} = f_r h_r(\bar{T}_s - T_r) + h_c\,(\bar{T}_s - T_a) + c_1 h_c(e_s - e_a)/P_a \quad \ldots\ldots (12)$$

The heat transfer coefficients h_r and h_c can be expressed in terms of measurable quantities. The form of the radiant heat transfer coefficient may be derived theoretically:

$$h_r = 4\,\epsilon\sigma\,(T_r/2 + \bar{T}_s/2 + 273{,}2)^3 \quad \ldots\ldots (13)$$

The value of the Stefan-Boltzman constant is known and measurement has shown the emissivity of skin, black or white, to be close to unity[6]. Because the skin temperature of men working underground never differs much from 35 °C:

$$h_r \approx 22{,}68 \times 10^{-8}\,(T_r/2 + 290{,}7)^3 \quad \ldots\ldots (14)$$

The value of the radiation posture factor f_r varies from about 0,6 for the foetal posture to 0,96 for the spreadeagle posture[9]. The value for men standing upright is about 0,8. An average value of $f_r = 0{,}75$ may be used for most working postures in mines. The actual value assigned to the combined term $f_r h_r$ is not important because radiation plays a minor role in heat exchange underground. Hence:

$$f_r h_r \approx 17{,}0 \times 10^{-8}\,(T_r/2 + 290{,}7)^3 \quad \ldots\ldots (15)$$

The convective coefficient (h_c) depends predominantly on wind speed. For near-nude men exposed to air temperatures and pressure within the range in which they can live and work, the convective coefficient can be derived[5, 12] from the equation.

$h_c = c_2 (P_a/1\,013)^{0,6} V^{0,6}$ . . . . (16)

where c_2 is approximately constant and is to be determined experimentally.

The value of the constant c_2 has been measured in the HSL wind tunnel. Mitchell *et al*[5] reported measurements made on two nude Bantu male subjects resting in headwind environments at temperatures between 10 °C and 50 °C and wind speeds between 0,5 and 5 m/s. The measurements have now been extended to two more subjects. The best available value is

$c_2 = 8,32 \pm 0,39 \quad Ws^{0,6}/m^{1,4}\,C$

The equation for convective heat transfer applies only to forced convection. Vermeulen[10] has demonstrated that in the relevant range of Reynolds number the effects of natural convection (buoyancy) are not apparent experimentally at wind speeds as low as 0,5 m/s. In underground conditions the difference between skin temperature and air temperature is generally small, and it is probably safe[12] to use the equation of forced convective heat transfer for values of air speed down to 0,1 or 0,2 m/s.

The value of the constant $c_1 = P_a \lambda h_m/h_c$ connecting convective and evaporative heat transfer can be calculated theoretically. For underground conditions Whillier[11] has calculated c_1 to be 1 780 °C. Subsequent calculations have indicated 1 700 °C to be a better value (A. Whillier, personal communication). Whillier's λ was the latent heat of evaporation of water. Experiments have shown sweat to have a heat of evaporation 7 per cent higher than that of water[8]. Correcting for this difference gives

$c_1 = 1\,820\,°C$

Finally, atmospheric humidity is generally expressed in the mining industry in terms of the wet-bulb depression and not the water vapour pressure. The vapour pressure difference $\Delta e = (e_s - e_a)$ can be expressed in terms of temperature using a standard expression for the wet-bulb depression[2] and the empirical formula for saturated water vapour pressure quoted in the British Standard Specification[17] on the humidity of air. Accordingly:

$$\Delta e = e_s - e_a$$
$$= e_s - e_w + 6,6 \times 10^{-4} P_a (T_a - T_w) [1 + 1,15 \times 10^3 (T_a - T_w)]$$

and $e_s = 6,105 \exp [17,27\, \bar{T}_s/(\bar{T}_s + 237,3)]$

$e_w = 6,105 \exp [17,27\, T_w/(T_w + 237,3)]$

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NOTICES

FOURTH INTERNATIONAL CONFERENCE ON VACUUM METALLURGY

This Conference will take place in Tokyo from June 4th-8th 1973. The language used will be English.

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SYMPOSIUM ON BLAST FURNACE INJECTION (A.I.M.M.)

February 15-17, 1972

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