Suggested thermal stress limits for safe physiological strain in underground environments

by J. M. STEWART* M.Sc. (Eng) (Witwatersrand) (Visitor) and
C. H. WYNDHAM* M.B., D.Sc. (Witwatersrand), F.R.C.P. (Lond) (Fellow)

SYNOPSIS

A comparison of safe temperature limits, based on Mitchell and Whillier's equations for specific cooling power (SCP), with similar limits determined experimentally shows the SCP-based limits to be unnecessarily conservative. It is argued that, while a small part of this conservatism may be attributed to an erroneous extrapolation of the heat transfer dependence on wind speed, the major part is probably due to the use of too low a limiting mean skin temperature in the calculation of SCP. A combination of Mitchell's basic data with results available in the literature permits the derivation of modified heat transfer equations based on data that fully cover the range of wind speeds of interest. These equations, using a mean skin temperature of 36°C as the basis for the calculation of safe temperature limits, are then shown to agree favourably with those determined empirically. Furthermore, values of SCP based on these equations are shown to correlate reasonably well with wet kata readings, giving positive support to the wet kata thermometer as a heat stress meter.

SAMEVATTING

'n Vergelyking van veilige temperatuurgrense gebaseer op Mitchell en Whillier se vergelykings vir spesifieke verkoelingsvermoë (SCP) met dergelike perke wat eksperimenteel vasgestel is, toon dat die perke wat op die spesifieke verkoelingsvermoë gebaseer is, onnodig konserwatief is. Daar word aangevoer dat, terwyl 'n klein deel van hierdie konserwatisme toegeskryf kan word aan 'n foutiewe ekstrapolering van die warmteoordragafhanklikheid van windsnelheid, die grootste deel daarvan waarskynlik toe te skryf is aan die gebruik van 'n te lae bepalende gemiddelde veltemperatuur by die berekening van die spesifieke verkoelingsvermoë. 'n Kombinasie van Mitchell se basiese data met resultate wat in die literatuur beskikbaar is, maak die afleiding moontlik van gewysigde warmteoordragvergelykings op grond van data wat die reeks windsnelhede wat van belang is, volledig dek. Daar word dan getoon dat hierdie vergelykings, wat 'n gemiddelde veltemperatuur van 36°C as basis vir die berekening van veilige, temperatuurgrense gebruik, gunstig vergelyk met dié wat empiries bepaal is. Verder word daar getoon dat die waardes vir die spesifieke verkoelingsvermoë wat op hierdie vergelykings gebaseer is, redelik goed met natkatalesings korreleer wat positiewe steun verleen aan die katatermometer as 'n warmtespanningsmeter.

INTRODUCTION

A major advance in the technology of mine ventilation was the introduction of the concept of specific cooling power, SCP, by Mitchell and Whillier in 1972[1]. SCP has not, however, gained the wide acceptance in the gold-mining industry that was originally expected of it. The reason for this is eminently simple. The safe thermal limits prescribed by SCP, particularly at low wind speeds and moderate work rates, are lower than those in which acclimatized men work at present; furthermore, they are considerably lower than those considered safe in previous reports from the Human Sciences Laboratory (HSL)[2, 3].

COMPARISON BETWEEN SCP AND HSL SAFE LIMITS

Fig. 1 shows the limits of wet-bulb temperature for three rates of work at two wind speeds that have been recommended by the HSL for well-acclimatized Black miners. These limits are based on the one-in-a-million probability of a miner's rectal temperature reaching 40°C during four hours of continuous work[3]. The limits for the lower wind speed, 0,5 m s^{-1}, have been fully substantiated in a recent HSL report[2]. Also plotted on this graph, in the form of broken lines, are the wet-bulb temperatures, calculated from the equations for SCP, at which men would be in thermal equilibrium with a mean skin temperature of 35°C for the same combination of work rate and wind speed. This figure demonstrates, both quantitatively and clearly, the discrepancy

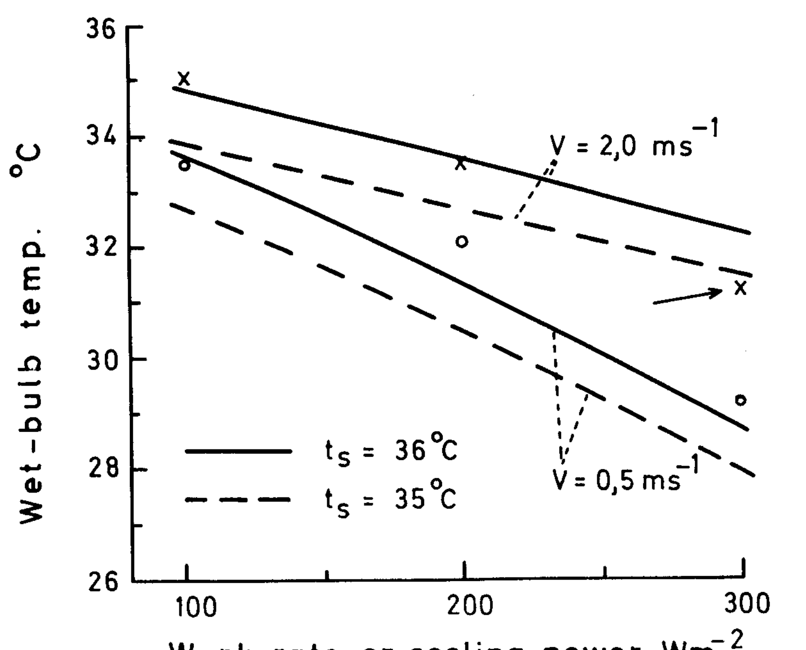

Fig. 1—Comparison of SCP with HSL 'safe' limits for two wind speeds (x = 1:10^6 risk of rectal temperature rising above 40°C in 4 h at wind speed = 2,0 m s^{-1}; o = 1:10^6 risk at wind speed = 0,5 m s^{-1})

*Industrial Hygiene Division, Chamber of Mines of South Africa.

between the limits prescribed by SCP and those established by experimentation. (The solid lines in Fig. 1 will be referred to later.)

It should be noted that, in Figs. 1 and 4, the wet-bulb temperatures calculated from cooling power are based on wind speeds that are 0,2 m s^{-1} greater than those shown. This is to account for the effect of body movement during work[4].

It is thus clear that SCP based on a skin temperature of 35 °C underestimates either the cooling power of the air or the safe limit of mean skin temperature, or perhaps both. An examination of the equations for SCP and their derivation supports this contention. Firstly, for wind speeds of less than 0,67 m s^{-1}, SCP is calculated from equations based on an extrapolation of the heat transfer dependence on wind speed and, secondly, the selection of 35 °C as the limiting safe mean skin temperature has not been adequately justified. These two aspects of the cooling-power concept therefore require closer consideration.

Regarding the first of these aspects, the following should be noted.

(a) Radiant heat transfer does not depend on wind speed.
(b) As the evaporative and convective heat transfer coefficients are related simply[5, 6], the problem of extrapolating the heat transfer dependence on wind speed may be considered in terms of convective heat transfer only.

Convective Heat Transfer

The convective heat transfer between the skin surface and air is calculated from the following equation:

$$J_c = h_c A\,(t_s - t_a). \qquad (1)$$

To use this equation, h_c must be determined. Theoretical considerations (given in standard heat transfer texts) lead to a specification of the variables upon which h_c depends and ultimately to the following generalized equation:

$$\frac{h_c D}{k} = F\left(\frac{\rho V D}{\mu}, \frac{\mu C_p}{k}\right), \qquad (2)$$

where $\frac{h_c D}{k}$ = Nu the Nusselt number,

$\frac{\rho V D}{\mu}$ = Re the Reynolds number, and

$\frac{\mu C_p}{k}$ = Pr the Prandtl number.

As Pr is constant for air (Pr ≈ 0,71)[6], it can be omitted from further consideration, and equation 2 becomes

$$\frac{h_c D}{k} = F\left(\frac{\rho V D}{\mu}\right). \qquad (3)$$

The specific relationship between Nu and Re has to be determined experimentally. However, the graphical and analytical form of the relationship can be deduced by argument from a consideration of the well-known correlation of Nu against Re for long cylinders[7]. The form of the relationship is shown graphically in Fig. 2. It is now argued that the human body may be represented by a number of cylinders of different diameter. In terms of such a model, for a single wind speed there are an equal number of values of Nu and Re that have to be combined, in some way, into single effective Nu and Re numbers applicable to the approximate human body that the cylinders represent. Furthermore, if the wind speed is allowed to vary by a factor of ten, clearly the relationship between the effective Nu and Re numbers must contain, in some integrated way, the Nu-Re relationships applicable to the individual cylinders. This argument leads to the conclusion that various sections of the curve in Fig. 2 have to be combined to produce the relationship between Nu and Re for the human body over a tenfold variation in effective Re (i.e., a tenfold variation in wind speed). Mathematically, it can be shown that such a combination results in a relationship between Nu and Re of the following form:

$$\mathrm{Nu} = \alpha + \beta\,\mathrm{Re}^{\gamma}, \qquad (4)$$

where α, β, and γ can be determined experimentally.

In Mitchell's analysis[4] it was assumed that the Nu-Re relationship could be represented by an equation of the form

$$\mathrm{Nu} = \beta\,\mathrm{Re}^{\gamma};$$

that is, the logarithmic plot of Nu against Re was assumed to be linear over the range of interest.

The equipment available to the authors is not suitable for heat transfer measurements at wind speeds of less than 0,6 m s^{-1}, so that the range of Mitchell's experimental data cannot be conveniently extended. Analogous results for lower wind speeds have therefore been sought in the literature. Only the results published by Nelson *et al.*[8] are analogous and sufficiently detailed to be suitable for analysis. The major problem in the use of these two sets of data lies in the evaluation of the respective values of D. Unfortunately, while it is not possible to evaluate directly the

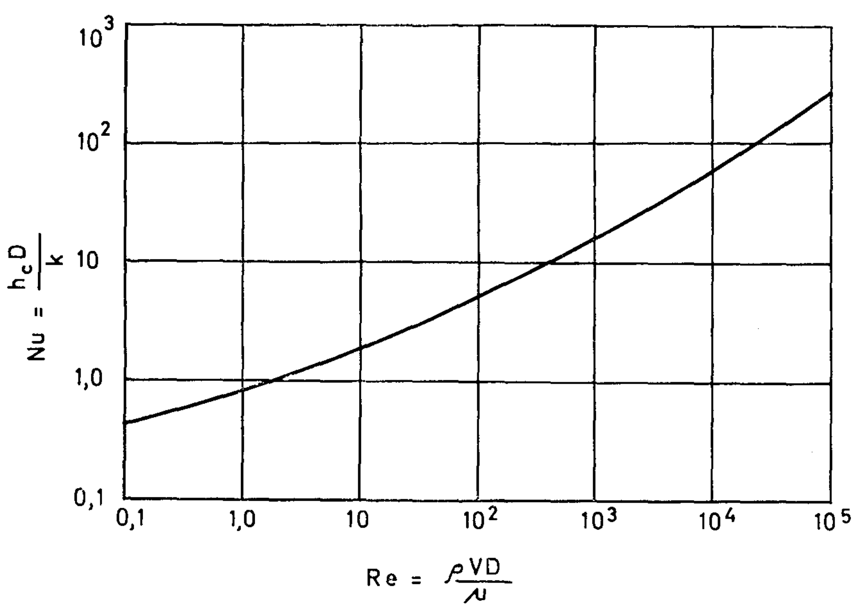

Fig. 2—The relationship between Nu and Re for long cylinders

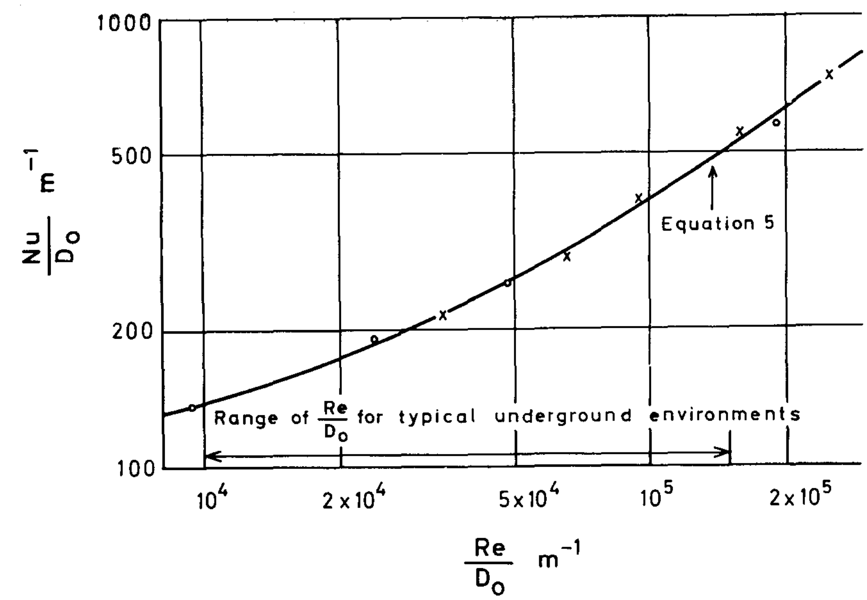

Fig. 3—The relationship between Nu/D and Re/D for nude men (x = Mitchell's data and o = Nelson *et al.*'s data)

dimension that characterizes the heat transfer process for each of the two groups of men involved, it is still possible to combine the two sets of data. This is achieved by defining the one dimension to be some fraction, x, of the other and then, by iteration, to establish which value of x corresponds to the case where equation 4 best fits the combined data (least sum of squares on a logarithmic plot).

This procedure yields a value of x=1,07, signifying that, on the average, the subjects of Nelson *et al.* were 1,07 times larger than Mitchell's as far as convective heat transfer is concerned. (As both sets of reported data are based on group averages, this ratio refers to the 'average' men representing the two groups.) The specific form of equation 4 that results from the regression analysis is

$$\frac{Nu}{D_o}=94{,}67+0{,}258\left(\frac{Re}{D_o}\right)^{0,81}, \quad \ldots\ldots (5)$$

where D_o is defined as the value of the dimension D for Mitchell's experimental subjects. The degree with which equation 5 represents the two sets of data can be gauged from Fig. 3.

Finally, as Mitchell's subjects were a group of typical Black mine workers, as far as the mine situation is concerned the value of D in the Nu and Re numbers of equation (5) is also equal to D_o. The introduction of appropriate values for the thermal conductivity and viscosity of the air into equation (5) reduces it to the following equation, which is then valid for an average-sized Black mine worker:

$$h_c=2{,}56+4{,}75\,\rho^{0,81}V^{0,81}. \quad \ldots (6)$$

The development of the above arguments and the derivation of equation (6) are dealt with in more detail elsewhere[9].

Equations (1) and (6) thus facilitate the calculation of convective heat transfer.

The equivalence between heat and mass transfer is well documented[1, 5, 6], and only the relevant results need to be quoted here. For the evaporation of water into air, the relationship between the convective and evaporative heat transfer coefficients, h_c and h_e, can be reduced to the following simple equation:

$$\frac{h_e}{h_c}=1613\,\frac{p_b}{(p_b-p_a)^2}, \quad \ldots (7)$$

where h_e is defined by the appropriate equation for the calculation of the evaporative heat transfer from a fully wet surface. When the human skin surface is fully wet, the evaporative heat transfer is maximal and h_e is defined by the following equation:

$$Je_{max}=h_e\,A\,(p_s-p_a). \quad \ldots (8)$$

Thermodynamic considerations[10] indicate firmly that the latent heat of vaporization of water and sweat are essentially equivalent. This contradicts the 7 per cent larger value for sweat that was previously used[1, 11]. In view of this contradiction, and supported by other arguments by the same author, it has been assumed that equivalence exists. Equation (7) is based on this assumption.

Specific Cooling Power

The maximum cooling power of the air, CP_{max}, is defined as the sum of the radiant, convective, and maximum evaporative cooling that a man would experience in the particular environment concerned. With reference to Mitchell and Whillier's work[1], and the above, these rates of cooling in Wm^{-2} can be calculated from the following three equations:

$$R=17{,}0\times10^{-8}\left(\frac{t_r+t_s}{2}+273{,}2\right)^3 (t_s-t_r) \quad \ldots\ldots (9)$$

$$C=(2{,}56+4{,}75\,\rho^{0,81}V^{0,81})\,(t_s-t_a) \quad \ldots\ldots (10)$$

$$E_{max}=1614\,\frac{p_b}{(p_b-p_a)^2}\,(2{,}56+4{,}75\,\rho^{0,81}V^{0,81})\,(p_s-p_a) \quad \ldots\ldots (11)$$

These three equations thus establish the maximum cooling power of the air as a function of six fundamental parameters; that is,

$$CP_{max}=F\,(t_s, t_r, t_a, t_w, V, p_b) \quad \ldots\ldots (12)$$

(t_a, t_w, and p_b are sufficient to specify p_a). As has been pointed out for typical South African goldmining conditions[1], it is realistic to make the following assumptions:

p_b=1000 mbar=10^5 Pa

$t_a=t_w+2\,°C$

$t_r=t_a$.

These assumptions leave CP_{max} as a function of only t_s, t_w, and V.

Whilst Mitchell and Whillier used a mean skin temperature of 35 °C in calculating specific cooling power, the basis for this choice is perhaps open to debate; that is, should the skin temperature be chosen from values that are typical of the mine situation, or should it be chosen so that cooling power will coincide with the acceptable stress limits established by empirical means[2, 3]? From the results published by Mitchell and Whillier, it is apparent that, at high wet-bulb temperatures, mean skin temperature may rise above 35 °C and sometimes even well above 36 °C. As these temperatures were measured in conditions similar to those existing underground, they indirectly suggest that a limiting mean skin temperature of 36 °C should be acceptable in terms of safety considerations. The logical extension of this observation is that t_s should be put equal to at least 36 °C in the calculation of the minimum safe cooling power for underground environments. This contention is firmly supported by Fig. 1, which shows an encouraging agreement between the empirically determined wet-bulb temperature limits and the lines of wet-bulb temperature against the modified version of SCP, based on t_s=36 °C, for the same two wind speeds. (Work rate and cooling power may be compared directly when a state of thermal equilibrium exists.) The 'cooling power', or SCP limits, indicated by the solid lines in Fig. 1 therefore refer to a state of thermal equilibrium, with mean skin temperature equal to 36 °C.

Although this figure does not show total agreement between the empirically determined limits and those based on SCP, the agreement is sufficiently good to conclude that the skin temperature used in the equations for SCP should be increased to 36 °C. Until more extensive or more accurate data are available, this suggestion may be viewed as a tentative but cautious recommendation. The note of caution is unfortunately necessary as one of the empirically determined stress limits (indicated in Fig. 1 by an arrow) is lower than that suggested by the relevant cooling power curve. Clearly, until this contradiction is explained or eliminated, the above recommendation should be observed only by those fully aware of the fact that, under certain circumstances, the risk of heat stroke could be greater than one in a million. It must also be realized that values of SCP are valid only for nude, or almost nude, men in typical gold-mining conditions.

Finally, for convenient usage, Fig. 4 contains a plot of SCP, based on the revised equations with t_s=36 °C, against wet-bulb temperature for the range of wind speeds of interest in underground environments. Also included on the graph are lines of constant wet kata reading. Although the lines of constant kata reading do not correspond with lines of constant cooling power, for the range of environments where cooling power is less than 300 W m^{-2} the agreement is sufficiently close for wet kata readings to be used to indicate approximate values of specific cooling power.

For the South African gold-mining industry, Fig. 4 is of particular practical significance in that it provides for the first time clear scientific evidence to show that no man should work in environments in which the kata reading is less than 4 (obtained from a measure of the time taken for the wet kata thermometer to cool from 37 °C to 36 °C). A wet kata reading of less than 4 indicates that the specific cooling power of the air would be less than 100 W m^{-2}, and this means that the environment is not capable of cooling a man even if he is performing only light work. Furthermore, as light, medium, and hard work correspond to approximately 100, 200, and 300 W m^{-2} respectively, it is apparent from Fig. 4 that, for light work, the kata reading should be at least 4, whilst for medium and hard work the reading should be at least 7,5 and 11 respectively. Although at high wind velocities slightly lower kata readings would still indicate environments of sufficient cooling power, in the interest of safety the above figures should be regarded as

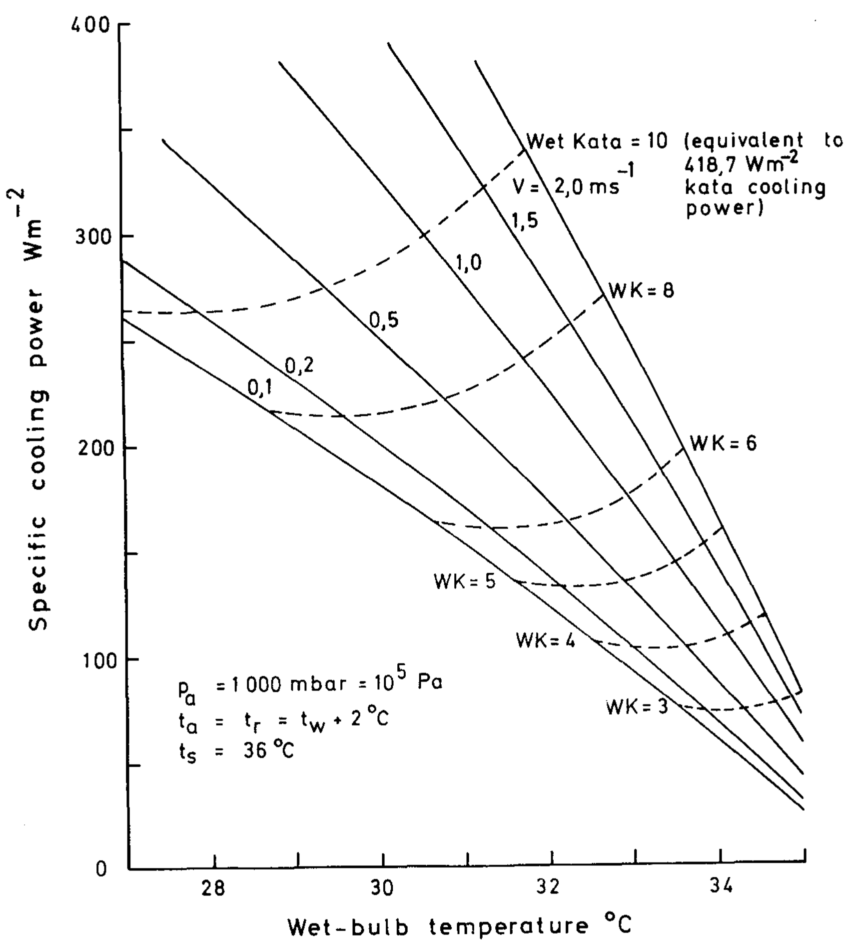

Fig. 4—Specific cooling power against wet-bulb temperature for various wind speeds (minimum air speed in working areas permitted in terms of Mining Regulations is 0,25 m s^{-1})

the absolute minimum kata readings required for safe performance of the above three rates of work.

CONCLUSIONS

The above considerations lead to the following specific conclusions.

1. The heat transfer equations previously used for the calculation of SCP should be replaced by equations (9), (10), and (11), and the limiting mean skin temperature should be taken as 36 °C.
2. Revised in this way, SCP is a satisfactory measure of environmental stress in that it correlates acceptably with physiological strain.
3. Agreement between the wet kata thermometer and SCP based on t_s=36 °C is sufficiently close for either to be used as a measure of thermal stress.
4. Although the above results and conclusions are most encouraging, they should not be regarded as final. Confirmation or improvement of the equation's representation of the heat transfer dependence on wind speed is highly desirable. Furthermore, the variation of body size with its effect on heat transfer, and hence SCP, requires investigation in terms of the mine labour force.
5. Strictly speaking, values of SCP are meaningful only in terms of nude men. The more realistic case of clothed men should be studied in order to extend the scope of the cooling-power concept.
6. Finally, it should be noted that this study is based on experimental work in which the conditions were carefully controlled. Consequently, the validity of these findings in terms of actual mining conditions will have to be assessed from the experience gained in their implementation.

REFERENCES

1. Mitchell, D., and Whillier, A. Cooling power of underground environments. *Mine Ventilation Journal*, Aug. 1972. pp. 140-151.
2. Wyndham, C. H., Strydom, N. B., Benade, A. J. S., and Van Rensburg, A. J. Limiting rates of work for acclimatization at high wet-bulb temperatures. *J. Appl. Physiol.*, vol. 35. 1973. pp. 454-458.
3. Wyndham, C. H. Research in the human sciences in the gold mining industry. *Yant Memorial Lecture, U.S. Industrial Hygiene Association Conference*, Boston, U.S.A. May 1973.
4. Mitchell, D. Human surface temperature: its measurement and significance in thermoregulation. Ph.D. Thesis, University of Witwatersrand, 1972.
5. Whillier, A. The calculation of heat exchange between air and wet surfaces. *J. S. Afr. Inst. Min. Metall.*, Mar. 1967. pp. 396-402.
6. ASHRAE. *Handbook of fundamentals*. New York, ASHRAE, 1972.
7. McAdams, W. H. *Heat transmission*. Third Edition. New York, McGraw Hill, 1954.
8. Nelson, N. *et al.* Thermal exchanges of man at high temperatures. *Am. J. Physiol.*, vol. 151. 1948. pp. 626-652.
9. Stewart, J. M., and Van Rensburg, A. J. Cooling power in the mining environment and the design of an instrument to measure it directly. Internal report, Chamber of Mines of South Africa.
10. Wenger, C. B. Heat of evaporation of sweat: thermodynamic considerations. *J. Appl. Physiol.*, vol. 32. 1972. pp. 456-459.
11. Snellen, J. W., Mitchell, D., and Wyndham, C. H. Heat of evaporation of sweat. *J. Appl. Physiol.*, vol. 29, no. 1. 1970. pp. 40-44.

LIST OF SYMBOLS

A	= surface area of the human body	m^2
C	= convective heat transfer per unit area	$W\ m^{-2}$
C_p	= specific heat of air	$J\ kg^{-1}(°C)^{-1}$
CP_{max}	= maximum cooling power of the air	$W\ m^{-2}$
D	= a dimension characterizing heat transfer from the human body	m
D_o	= D for Mitchell's experimental subjects	m
E_{max}	= maximum evaporative heat transfer per unit area	$W\ m^{-2}$
h_c	= convective heat transfer coefficient	$W\ m^{-2}(°C)^{-1}$
h_e	= evaporative heat transfer coefficient	$W\ m^{-2}\ Pa^{-1}$
J_c	= rate of convective heat transfer	W
J_{emax}	= rate of maximum evaporative heat transfer	W
k	= thermal conductivity of air	$W\ m^{-1}(°C)^{-1}$
p_a	= vapour pressure of air	Pa
p_b	= barometric pressure	Pa
p_s	= saturated vapour pressure at temperature t_s	Pa
R	= radiant heat transfer per unit area	$W\ m^{-2}$
SCP	= specific cooling power	$W\ m^{-2}$
t_a	= ambient dry-bulb temperature	°C
t_r	= mean radiant temperature	°C
t_s	= mean skin temperature	°C
t_w	= ambient wet-bulb temperature	°C
V	= wind speed	$m\ s^{-1}$
α, β, γ	= constants of regression	
ρ	= air density	$kg\ m^{-3}$
μ	= air viscosity	$kg\ s^{-1}\ m^{-1}$

AUTHORS' FOOTNOTE

After this paper had been submitted for publication, further heat-transfer measurements were made and analysed. Although these new data largely confirm those analysed above, they will result in a minor alteration to the above derived equation for h_c, i.e., equation (6).

NIM reports

The following reports are available free of charge from the National Institute for Metallurgy, Private Bag 7, Auckland Park 2006.

Report no. 1707

The work of the Pyrometallurgy Research Group at the University of the Witwatersrand.

Past and present research in the Pyrometallurgy Research Group at the University of the Witwatersrand is reviewed, and a programme for future research on the production and utilization of ferro-alloys is outlined. The aims and problems of the Group are also discussed.

Report no. 1710

The recovery of scheelite from Shongona, north-western Transvaal.

Tabling tests on scheelite-bearing ore ground to material finer than 850 μm produced a concentrate assaying 73,8 per cent WO_3, with a recovery of 80,2 per cent of the WO_3 content of the ore. Desliming and classification prior to tabling were found to be beneficial, and close control of the grinding circuit was required to avoid overgrinding of the scheelite.

Magnetic separation of the concentrate was necessary to obtain the required grade and to reject undesirable constituents still remaining in the concentrate.

A flowsheet for a pilot-plant operation is given.

Report no. 1717

The use of isothioronium compounds as liquid-liquid extractants for the noble metals and silver.

Isothioronium compounds have been studied as extractants from acid media of the noble metals and silver, either individually or as a group. The noble metals and silver were readily extracted except for rhodium and ruthenium, which required the use of a reagent at a concentration of 1,0 M with a long period of extraction. However, because of the good forward extractions, backwashing for recovery of the extracted metals was not practical.

A number of base metals were also extracted to varying extents, but only the extraction of iron(III), cadmium(II), and antimony(III) was sufficiently high to be of potential value.

Direct determination of the extracted platinum-group metals in the organic phase is shown to be unreliable, and reversion of the extracted metal to the aqueous phase by wet oxidation, although possible, is not recommended because it is time-consuming and tedious.

Report no. 1718

The determination of silver in lead, copper, and zinc concentrates by instrumental neutron-activation analysis.

Instrumental neutron-activation analysis was used in the determination of silver in a number of copper, lead, and zinc ores and concentrates. By the use of epithermal activation, silver could be determined within 4 days of irradiation, with a limit of detection of about 10 p.p.m. and a precision of 2,7 per cent at the concentration level of 600 p.p.m. An increase in the decay time to 12 days improved the limit of detection to about 3 p.p.m. and the precision to 1,7 per cent at the same concentration level as before. The total time required for the analysis was about 1 hour per sample excluding the decay time, which varied from 4 to 12 days depending on the precision required.

Report no. 1581

The computer calculation, from fundamental parameters, of influence coefficients for X-ray spectrometry. (8th Jan., 1974. Declassified 1975.)

A system for the calculation of first-order influence coefficients for any element in any matrix is described in detail. Influence coefficients for either K or L spectra can be evaluated by the method described. The FORTRAN computer programme that was used is given in an index.

Report no. 1650

The production of medium-carbon ferrochromium alloys by solid-state reduction. (3rd Aug., 1974. Declassified 1975.)

Recent developments in the manufacture of stainless steel have changed the emphasis for the grades of ferrochromium alloys required by the stainless-steel industry, high-carbon ferrochromium alloys (6 to 8 per cent carbon) now being acceptable. However, the high carbon content represents a drawback since the carbon content of the melted material must be kept to a maximum of 1 to 2 per cent, depending on the stainless-steel process. This carbon content is obtained by dilution of the high-carbon alloy with scrap. The advantages obtainable from the use of an alloy of intermediate carbon content (1 to 4 per cent) both with respect to the scrap requirement and converter time is obvious.

This report describes a technique by which a medium-carbon ferrochromium alloy is produced by reacting the chromite ore with a carbonaceous reducing agent in the solid state, and subsequently melting the prereduced ore and effecting a separation by the addition of fluxes. Additions of ferrochromium-silicide may be made at this stage and result in an alloy composition of 50 to 54 per cent for chromium, 38 to 42 per cent for iron, and 1 to 3 per cent for carbon and silicon If the addition of ferrochromium-silicide. is not made, the carbon content of the alloy is higher, the chromium content is lower, and alloys within the composition limits 40 to 50 per cent chromium, 40 to 50 per cent iron, 4 to 5 per cent carbon, and less than 1 per cent silicon are obtained.

Matters for further investigation are defined.

Report no. 1638

The determination of trace elements in natural diamonds by instrumental neutron-activation analysis.

A total of more than 1500 individual diamonds, divided into 96 samples, was analysed. These were obtained from three South African mines: Premier, Finsch, and Jagersfontein.

The presence of 44 elements in diamonds was established from 61 isotopes and quantitative results were obtained for 34 elements.

Report no. 1712

The thermodynamics of the formation of chlorocomplexes of nickel and copper (II) in percylorate medium.

The programme for the acquisition of information on the thermodynamic properties of complexes in aqueous solution for conditions appropriate to hydrometallurgical processes is continued in the work described here for the chlorocomplexes of nickel and copper(II).

The conditional stability constants of the chlorocomplexes of nickel and copper(II) at temperatures up to 60 °C were determined by spectrophotometric measurements. Over the range of conditions of practical interest, the complexes $NiCl^+$, $CuCl^+$, and $CuCl_2$ are of importance. The constants increase with temperature and ionic strength.

Diagrams showing the extent of formation of each complex over a range of conditions are given.

Report no. 1719

An evaluation of the X-ray-fluorescence analysis of rocks and silicates under routine conditions.

This report correlates the analytical results obtained by four laboratories using X-ray-fluorescence analysis on ten reference silicate samples that were incorporated in the analytical programmes required by the Geological Survey of the Republic of South Africa over a five-year period. The results and their statistical treatment are given, together with a comparison of the results for similar material issued by the Centre de Recherches Pétrographiques et Geochimiques and the British Ceramic Research Association using wet-chemical methods.

This study shows that the analysis, by X-ray-fluorescence measurement, of rocks and silicate samples for the commonly determined constituents is more precise than analysis by classical wet-chemical procedures.

Company Affiliates

The following members have been admitted to the Institute as Company Affiliates.

AE & CI Limited.
Afrox/Dowson and Dobson Limited.
Amalgamated Collieries of S.A. Limited.
Apex Mines Limited.
Associated Manganese Mines of S.A. Limited.
Blackwood Hodge (S.A.) Limited.
Blyvooruitzicht G.M. Co. Ltd.
Boart & Hard Metal Products S.A. Limited.
Bracken Mines Limited.
Buffelsfontein G.M. Co. Limited.
Cape Asbestos South Africa (Pty) Ltd.
Compair S.A. (Pty) Limited.
Consolidated Murchison (Tvl) Goldfields & Development Co. Limited.
Deelkraal Gold Mining Co. Ltd.
Doornfontein G.M. Co. Limited.
Durban Roodepoort Deep Limited.
East Driefontein G.M. Co. Limited.
East Rand Prop. Mines Limited.
Envirotech (Pty) Ltd.
Free State Saaiplaas G.M. Co. Limited.
Fraser & Chalmers S.A. (Pty) Limited.
Gardner-Denver Co. Africa (Pty) Ltd.
Goldfields of S.A. Limited.
The Grootvlei (Pty) Mines Limited.
Harmony Gold Mining Co. Limited.
Hartebeesfontein G.M. Co. Limited.
Highveld Steel and Vanadium Corporation Limited.
Hudemmco (Pty) Limited.
Impala Platinum Limited.
Ingersoll Rand Co. S.A. (Pty) Ltd.
Kinross Mines Limited.
Kloof Gold Mining Co. Limited.
Lennings Holdings Limited.
Leslie G.M. Limited.
Libanon G.M. Co. Limited.
Lonrho S.A. Limited.
Loraine Gold Mines Limited.
Marievale Consolidated Mines Limited.
Matte Smelters (Pty) Limited.
Northern Lime Co. Limited.
O'okiep Copper Company Limited.
Palabora Mining Co. Limited.
Placer Development S.A. (Pty) Ltd.
President Steyn G.M. Co. Limited.
Pretoria Portland Cement Co. Limited.
Prieska Copper Mines (Pty) Limited.
Rand Mines Limited.
Rooiberg Minerals Development Co. Limited.
Rustenburg Platinum Mines Limited (Union Section).
Rustenburg Platinum Mines Limited (Rustenburg Section).
St. Helena Gold Mines Limited.
Shaft Sinkers (Pty) Limited.
S.A. Land Exploration Co. Limited.
Stilfontein G.M. Co. Limited.
The Griqualand Exploration and Finance Co. Limited.
The Messina (Transvaal) Development Co. Limited.
The Steel Engineering Co. Ltd.
Trans-Natal Coal Corporation Limited.
Tvl Cons. Land & Exploration Co.
Tsumeb Corporation Limited.
Union Corporation Limited.
Vaal Reefs Exploration & Mining Co. Limited.
Venterspost G.M. Co. Limited.
Vergenoeg MiningCo. (Pty) Limited.
Vlakfontein G.M. Co. Limited.
Welkom Gold Mining Co. Limited.
West Driefontein G.M. Co. Limited.
Western Deep Levels Limited.
Western Holdings Limited.
Winkelhaak Mines Limited.