CHAMBER OF MINES OF SOUTH AFRICA

RESEARCH ORGANIZATION

REPORT

ON

A GUIDE TO THE MEASUREMENT AND ASSESSMENT OF
HEAT STRESS IN GOLD MINES

BY

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REFERENCE WORDS: HEAT STRESS; STRESS (PHYSIOLOGY); COOLING POWER.

APRIL, 1978
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This report is intended primarily for ventilation staff on mines, but is also of importance to management.

In the gold mining industry the assessment of heat stress is likely to be for one of three purposes: to assess either the **average** or the **worst** heat stress of a work area, or to assess the **particular** heat stress experienced by an individual at a specified work place. A sharp distinction is drawn between a **work area** and a **work place**. The many factors involved in the assessment of heat stress have been considered systematically and this has led to the development of recommended procedures for assessing heat stress in each of the three instances cited above. The recommended procedures are summarized in the table given below.

<table>
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<tr>
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<th>RECOMMENDED MEASUREMENTS</th>
</tr>
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1. **INTRODUCTION**

In the gold mining industry the assessment of environmental conditions, or heat stress, is likely to be for one of three purposes.

1. To assess the **average** condition, or average heat stress of a given work area (usually a stope or a development end) with a view to designing ventilation and refrigeration so as to optimise production, improve worker morale and reduce the incidence of accidents.

2. To assess the **worst** heat stress which may be experienced in a given work area, such as a stope or development end, in order to ensure that the heat stroke risk for people working in that area is kept within acceptable limits.

3. To assess the **particular** heat stress experienced by an individual working at a specified work place, e.g. a winch driver.

**Work Areas:** Although the difference between a work place and a work area should be clear from the examples quoted above, from a practical point of view the physical size of a work area requires closer definition. Underground workings may be extensive, and environmental conditions may vary considerably throughout these areas. If variations in environmental conditions are too large the use of average values can be misleading, or even meaningless. In order to obtain a meaningful average of the heat stress to which people are exposed, measurements should therefore be averaged for areas no larger than 40 or 50 m of working face, and including the ventilated area 5 to 10 m back from the face in which men are likely to be working. In an area of this size the wet-bulb temperature will usually vary by not more than 1°C. Averages should not be used for areas larger than this unless it has been shown that essentially constant conditions prevail throughout such areas. In the case where conditions are highly variable it would be more meaningful to indicate the number, or proportion of men who are working within specified intervals.

**Measuring the Thermal Environment:** When considering the measurement of heat stress there are important differences between the abovementioned three purposes for assessing the heat stress.
In the first case it is the average heat stress which is important. In the second it is the worst potential heat stress situation, such as might be found behind an obstruction or in other sheltered areas; i.e. it is the highest wet-bulb temperature and lowest wind speed which are important. In the third case it is the actual or particular heat stress experienced by a man at his workplace which is important.

To a large extent this report is concerned with recommending how these heat stress measurements should be made. However, to promote a better understanding of human heat stress, the various factors upon which heat stress depends are reviewed briefly, with comments indicating their degree of importance to the gold mining industry.

2. HEAT STRESS FACTORS IN UNDERGROUND ENVIRONMENTS

The factors which contribute most to heat stress may be divided into three groups, as follows.

Environmental Factors: Air temperature and humidity, wind speed, radiant heat load, and ambient pressure.

Physical Factors: Skin surface area, clothing, body movements and work rate.

Limiting Physiological Factors: Skin area which is wet with sweat, maximum possible sweat rate, skin temperature, rectal temperature, and maximum physical working capacity.

Other factors such as age and state of health are known also to be important in the assessment of heat stress but these are not considered in this report; it is assumed that the working labour force is young and healthy. Men who are ill or older than 40 should not be exposed to limiting heat stress conditions since they are particularly susceptible to the effects of heat.

Quantitative consideration of all the other factors listed above is necessary for the proper assessment of heat stress.
2.1. Clothing

An adequate quantitative description of heat exchange between clothed men and their thermal environment has still to be developed; work is presently being devoted to this problem. In this report the assessment of heat stress is limited to essentially nude men. It must be realized that the procedures outlined later are likely to cause the heat stress level to be underestimated in situations where significant amounts of clothing are worn.

2.2. Radiant Heat Load

As humans are totally surrounded by rock in underground environments, all radiation occurs in the long wave region, and emissivity can therefore be taken equal to 1. Furthermore, as the surface temperature of the rock is seldom more than 1°C different from the dry-bulb temperature of the air, mean radiant temperature may be assumed to be equal to air temperature. Small errors in the assessment of the mean radiant temperature are not important as the radiant heat load of underground environments is small when compared to the heat produced by a working man.

Measurements have shown that the radiant area of men working underground is about 0.75 of their total surface area and the value of 0.75 is assumed in this report.

2.3. Body Movements

Body movements have the same effect as increasing the wind speed over the human body. If a person is in a zone of high wind speed then the benefit gained from movements of the body is small. However, in zones of low wind speed, movements of the body can increase substantially the cooling experienced by the man. Experiments have shown that the body movements of a working man are approximately equivalent to increasing the wind speed by 0.3 m s⁻¹ (1). This effect is taken into account in the tables presented later in this report.

2.4. Wind Speed

A recent survey (3) of conditions in six large gold mines showed that nearly 40 per cent of all men underground work in areas
where the wind speed is less than 0.5 m/s. Obstructions and dead spaces are inevitable, and it is impractical to ensure that every underground work place has a good wind speed.

These comments lead to the conclusion that when assessing the worst heat stress situation which could occur in a given work area it is necessary to assume a 'still air' condition. For the purpose of this report, a wind speed of 0.2 m/s is taken to be equivalent to still air. However, when assessing the average heat stress of a work area, or the actual heat stress experienced by a particular individual, the prevailing wind speeds must be taken into account.

Wind speed is one of the most important heat stress parameters of underground environments; it is accounted for quantitatively in the cooling power equations (4) and the latter may be used to establish how variations in wind speed affect the prevailing heat stress. Suitable tables of cooling power at different wind speeds have been prepared for this purpose and they are included at the back of this report.

2.5. Air Temperature and Humidity

The dry-bulb temperature is a relatively unimportant factor in hot humid underground environments. This is confirmed by the cooling power equations, as illustrated in Fig. 1. Fig. 1 shows the relatively small effect of increasing the gap between the dry- and wet-bulb temperatures from 2 to 5°C. The reduced cooling power at the higher gap is primarily the result of the increased radiant heat load on the man.

In hot working places underground the gap between the wet- and dry-bulb temperatures is usually about 2°C and very rarely as much as 5°C. Consequently, the cooling power of mining environments can be determined with sufficient accuracy from the wet-bulb temperature and wind speed, without reference to dry-bulb temperature.

For still air environments the cooling power can be determined from Fig. 1, which is drawn for an assumed air speed of 0.2 m/s.
2.6. Ambient Pressure

Although ambient pressure does affect the cooling power of underground environments the effect is not significant from the point of view of achieving a practical assessment of the average heat stress of these environments. This assertion is confirmed by the three curves for different pressures (85, 100, 115 kPa) that are presented in Fig. 1. In assessing the average heat stress of a work area, it is thus sufficient to assume a pressure of 100 kPa. However, when assessing the worst heat stress it is not sufficient to assume a standard barometric pressure of 100 kPa. Comparing curves 1, 2 and 3 in this figure shows that the cooling power of the air at a given wet-bulb temperature decreases with increasing pressure. As such, either the actual pressure should be used, or a pressure of 115 kPa may be assumed, in which case curve No. 3 in Fig. 1 should be used.

2.7. Skin Surface Area

For a particular rate of doing a specific type of work, the rate of metabolic heat generation is fixed, therefore, a man with a large surface area will experience less heat stress than a man with small surface area since his greater area will enable him to dissipate more easily the metabolic heat being generated. For Black men, the skin surface area is usually within the range 1.5 m² to 2.1 m²; an average value of 1.8 m² is usually assumed, as is the case in this report.

2.8. Maximum Physical Working Capacity

It is known that men who have a high physical working capacity are better able to cope with the effects of heat stress. In this regard physical working capacity is similar in effect to skin surface area; for a fixed work rate an increase in either of these factors would be equivalent to a reduction in the heat stress. The cooling power values used in this report are based on a random distribution of physical work capacities.

However, in most mines the allocation of labour is based on a physical selection test, so that men with high physical working
capacities are assigned to the more strenuous tasks. Where this practice is in force the margin of safety will be greater than would otherwise be the case.

2.9. Work Rate

For the purpose of evaluating heat stress, the rate at which a man works must be converted into a rate of metabolic heat generation. For a man of average size (skin surface area of 1.8 m²) light work would correspond to a metabolic rate of about 115 W/m², moderate work to approximately 175 W/m² and hard work to about 280 W/m². Since an average skin area is assumed, it will be appreciated that the above rates of metabolic heat generation are subject to an uncertainty of ±15 percent.

A guide to the work rate corresponding to different mining tasks is given in Table I.

<table>
<thead>
<tr>
<th>LIGHT WORK</th>
<th>MODERATE WORK</th>
<th>HARD WORK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winch</td>
<td>Stonewall</td>
<td>Tramming</td>
</tr>
<tr>
<td>Sweep</td>
<td>Box</td>
<td>Shovelling</td>
</tr>
<tr>
<td>Spanner</td>
<td>Machine</td>
<td></td>
</tr>
<tr>
<td>Walking</td>
<td>Boring</td>
<td></td>
</tr>
<tr>
<td>Drain-Cleaning</td>
<td>Timbering</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Team Leader</td>
<td></td>
</tr>
</tbody>
</table>

2.10. Maximum Possible Sweat Rate

Acclimatized men are able to produce more than enough sweat for the purpose of body cooling. Unfortunately not all of this sweat evaporates from the skin surface since some of it drips off without providing any cooling benefit. Maximum possible sweat rate is therefore not a limiting factor in the mining industry, when working
with acclimatized men. With unacclimatized men the maximum possible sweat rate is a limiting factor because such men are not able to sweat for long periods at the rates required. However, this report is concerned with hot environments and with acclimatized men only.

2.11. **Skin Area Wet with Sweat**

It is known that acclimatized men can produce more sweat than can be evaporated in the typical hot humid conditions found underground and hence it is assumed that the entire skin area is wet.

2.12. **Limiting Skin and Rectal Temperatures**

These two parameters are fundamental to the assessment of what constitutes an acceptable level of heat stress. It has been shown that rectal temperature, skin temperature and rate of metabolic heat generation bear well defined relationships with each other (4). For the one-in-a-million chance of the rectal temperature of an acclimatized workman rising above 40°C, mean skin temperature and rate of metabolic heat generation are related linearly, as shown in Fig. 3. This graph is used in this report to define a limiting value of mean skin temperature for any given work rate. The tables of cooling power at the end of the report take this variation of skin temperature into account.

3. **COOLING POWER OF THE ENVIRONMENT**

For a man to be able to work steadily for a full shift it is necessary that the cooling power of the environment must equal or exceed a minimum value which is equal to the rate at which he is generating heat. All the factors discussed above must be taken into account when calculating cooling power. The minimum cooling power equation that is developed in reference (4) is based on the particular values of the factors which have been discussed above; furthermore the tables at the back of this report derive from this equation.

It must be emphasized that different scales of cooling power (for the same wet-bulb temperature and wind speed) will be needed if situations different from those referred to above are involved.
For example, in the case of clothed men, or unacclimatized men, the same scales cannot be expected to apply. Also, a change in the risk criterion would result in different scales. Hence as new knowledge becomes available, or new criteria are introduced it may be necessary to introduce different scales of cooling power.

In order to avoid confusion it would be desirable to designate the presently used scale perhaps as the "A" scale of cooling power, with subsequent scales to be designated appropriately.

3.1. **Wet kata**

In typical mining environments wet-kata readings have been found to correlate closely with the values of cooling power that are given in the table at the end of this report (4). The relationship between wet-kata and cooling power is given in Fig. 2. This means that wet-kata readings can be interpreted in the same way as the cooling power in the assessment of heat stress, and that the wet-kata thermometer can be used to measure the actual cooling power directly.

It should be emphasized, though, that the interpretation of kata readings would differ for men who are not acclimatized since their physiological response to heat stress is substantially different from that of acclimatized men, as has been pointed out in section 2.10 above.

4. **RECOMMENDED PROCEDURE FOR MEASURING HEAT STRESS**

Before setting about the problem of measuring the heat stress it is most important that the purpose for making the measurements be established clearly, since the procedure for measuring the heat stress will vary, depending on the purpose.

4.1. **To Assess the Average Heat Stress**

The average heat stress of a given work area should be assessed from a number of measurements of the wet-bulb temperature and wind speed, or from a number of measurements with the wet-kata thermometer. The measurements should be made in the immediate vicinity of where men are found to be working. The values of
wet-bulb temperature and wind speed should be converted into equivalent values of cooling power using the tables provided, and these values of cooling power should then be averaged. The measured wet-kata readings can be averaged before being converted into equivalent values of cooling power, although strictly speaking it should be done the other way round because the relation between the two (Fig. 2) is not exactly linear.

It should be pointed out that although this procedure will give a valid estimate of the average heat stress, it would be wholly incorrect to conclude that when the average work rate equals the average cooling power, there will be only a one-in-a-million risk of the rectal temperature of any man rising above 40°C. Average heat stress levels may, however, prove useful in correlating the heat stress of underground work areas with factors such as productivity (2) accidents, absenteeism and general morale.

4.2. To Assess the Worst Heat Stress

The worst heat stress in a given work area can be assessed from wet-bulb temperature measurements without measurements of wind speed. The highest measured wet-bulb temperature should be used to determine the cooling power of the environment from the curve recommended in Fig. 1.

This value of cooling power is indicative of the worst heat stress situation which any man may encounter while working in the given work area. Should his rate of metabolic heat generation equal the value of the cooling power read from Fig. 1 then it is possible that while performing his usual work the man may be exposed to a one-in-a-million risk of his rectal temperature rising above 40°C. Should the determined value of cooling power be less than the rate of metabolic heat generation then a potentially dangerous situation could arise, and appropriate remedial measures should therefore be taken.

4.3. To Assess the Heat Stress at a Specific Work Place

In order to assess the heat stress at a specific work place, either the wet-bulb temperature and wind speed, or the wet-kata,
should be measured in the immediate vicinity of the man. In the former case the tables should be used to establish the cooling power, and in the case of a wet-kata reading, Fig. 2, will enable conversion into cooling power.

Should the metabolic rate of the individual be greater than the cooling power, then either the work rate must be reduced or the cooling power of the environment must be increased. Should work rate and metabolic rate be equal there will be a one-in-a-million chance that the rectal temperature of the man will rise above 40°C.

5. SUMMARY OF RECOMMENDATIONS

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REFERENCES

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The development of a functional relationship between productivity and the thermal environment.

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A survey of underground environmental conditions in six gold mines.
Chamber of Mines, Research Report No. 34/74.
Johannesburg, 1974.

Heat stress limits for men working in the gold mining industry.

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FIG. 1.

COOLING POWER AS A FUNCTION OF WET-BULB TEMPERATURE FOR STILL AIR (WIND SPEED = 0.2 m/s)

<table>
<thead>
<tr>
<th>LEGEND</th>
<th>CURVE</th>
<th>PRESSURE kPa</th>
<th>( (t_{db} - t_{wb}) )°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>85</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>115</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>5</td>
</tr>
</tbody>
</table>
FIG. 2. COOLING POWER AS A FUNCTION OF WET KATA READING.
**Fig. 3:** Equilibrium mean skin temperatures which correspond to the $1 \times 10^{-6}$ probability of an individual worker's rectal temperature rising above $40^\circ C$ at various rates of metabolic heat generation.
### TABLES OF COOLING POWER W/m²

- **WETTED AREA FRACTION = 1.0; MRT = DB = WB + 2°C; PRESSURE = 100 kPa**

When cooling power = metabolic rate, the probability of rectal temperature rising above 40°C = one-in-a-million

<table>
<thead>
<tr>
<th>AIR SITTING (Wetted per second)</th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
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<tr>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.1</td>
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<td>1.9</td>
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<td>2.3</td>
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<td>2.9</td>
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<td>4.0</td>
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<td>4.3</td>
<td>4.4</td>
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<td>4.9</td>
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<td>10.1</td>
<td>10.2</td>
<td>10.3</td>
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</table>

Note: The table continues with values increasing in increments of 0.1 for the first column, 0.2 for the second column, and so on.
## TABLES OF COOLING POWER \( \text{W/m}^2 \)

**WETTED AREA FRACTION** - 1.0; \( \text{MRT} = 4\text{R} \); \( \text{WB} = 29^\circ \text{C} \); PRESSURE = 100 kPa

WHEN COOLING POWER = METABOLIC RATE, THE PROBABILITY OF RECTAL TEMPERATURE RISING ABOVE 40°C = ONE-IN-A-MILLION

<table>
<thead>
<tr>
<th>AIR SPEED (meters per second)</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>1.5</th>
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<tr>
<td>30</td>
<td>62.5</td>
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