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Lessons to be learned from Deep Gold Mining in South Africa

Expériences des travaux dans les mines d'or en Afrique du Sud

Erfahrungen beim Arbeiten in den Goldminen in Südafrika

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SUMMARY
The greatest problems arising from working in extremely hot and humid conditions are centred around man's physical limitations in working in such environments. Experiences and practice in South Africa's deep gold mines can be beneficial to those having to undertake work in very hot humid conditions.

RESUME
Les plus graves problèmes dans l'exécution de travaux en atmosphère extrêmement chaude et humide sont fonction des limites physiques humaines. Les expériences gagnées dans les mines d'or de l'Afrique du Sud peuvent servir à d'autres qui sont obligés d'exécuter des travaux de génie civil dans des conditions de climat chaud et humide.

ZUSAMMENFASSUNG
Die schwierigsten Probleme bei der Ausführung von Arbeiten unter extrem heissen und feuchten Umweltbedingungen bilden die Grenzen der physischen Belastbarkeit der beteiligten Menschen. Entsprechende Erfahrungen aus den unterirdischen Goldminen in Südafrika geben wertvolle Hinweise für jene, die in heiss-feuchten Verhältnissen Bauarbeiten ausführen müssen.

1. INTRODUCTION

Deep-level gold mining in South Africa is a large and comparatively difficult engineering operation which involves mining narrow ore bodies in hard rock at great depths. Unusual problems, such as rock fracture, and the control and casting of concrete at high temperatures, are not dealt with in this paper largely because, relatively speaking, they pale into insignificance when contrasted against the major problem of the limitations of humans to withstand the high temperatures and humidities that are experienced in the deep mines. Accordingly the paper is confined to physiological considerations that limit the ability of men to work, and that possibly endanger their health, when working in hot humid conditions such as are experienced deep underground.

The industry is the most highly centralized mining operation in the world. Some 100 million metric tons of rock are broken out and hoisted from the gold mines each year from an average depth of 1.5 kilometres below surface, to produce over 700 metric tons of gold and substantial quantities of uranium oxide each year. The mines consume over one sixth of all the power requirements of the African continent and, in addition to hoisting rock, the mine shafts provide about 300 million man kilometres of transport a year in lowering and raising workers to and from underground.

The gold bearing strata (or "reefs" as they are known colloquially) were first mined where they outcropped by individual diggers. The inclined reefs for the greater part ran to considerable depths below surface and large sums of risk capital, a high degree of technical knowledge and considerable resources were vital to the successful exploitation of the ore bodies. In consequence, the small entrepreneurs were soon replaced by privately owned corporations with strong financial, administrative and technical resources that evolved into a co-operative "group system" of which The Chamber of Mines is an integral part. Its research laboratories, the largest such private organisation in the Southern Hemisphere, are concerned with mining technology, human resources, environmental engineering, mining operations, metallurgy and engineering and assist greatly in keeping the gold mining industry in South Africa in the forefront of technical development.

2. THE PROBLEMS OF DEEP-LEVEL MINING

Underground mining can be mechanised only in part and remains highly labour intensive. The reefs extend laterally for many kilometres at a dip angle between 7^{o} and 40^{o} and vary in thickness. Stoping widths in the narrow reefs are typically 1'200 mm but only 900 mm in places. Mining extends to depths of 3'600 m below the surface, at which depth rock temperatures are about 55 ^{o}C. Present planning in the industry is for mines to extend to depths where rock temperatures will be as high as 63 ^{o}C.

The ambient temperature underground is largely dependent upon the rock temperature and when it exceeds 35 ^{o}C, thermal control underground is essential to prevent men from suffering heat exhaustion and heat stroke. About 10 tons of air per ton of rock broken is curculated to alleviate working conditions, but in spite of this, difficulty is experienced in maintaining temperatures at which men can work safely for long periods in still air. Worker's health and the environment in which they work and live has always been of the greatest concern and is one of the most severe problems facing the industry. The earliest health problem encountered centred around respiratory diseases especially pneumoconiosis and pneumonia. Fine silica-dust, from dry drilling preparatory to blasting, was a major problem in former years and the cause of pneumoconiosis and thanks to better accommodation, better feeding and better medical treatment, pneumonia has also become an insignificant factor in the health of miners. The health problems facing the industry today are those which result from having to mine at very deep levels.

3. PHYSIOLOGICAL CONSIDERATIONS

Why do the environmental conditions in deep mines pose such a threat to the health of the worker?

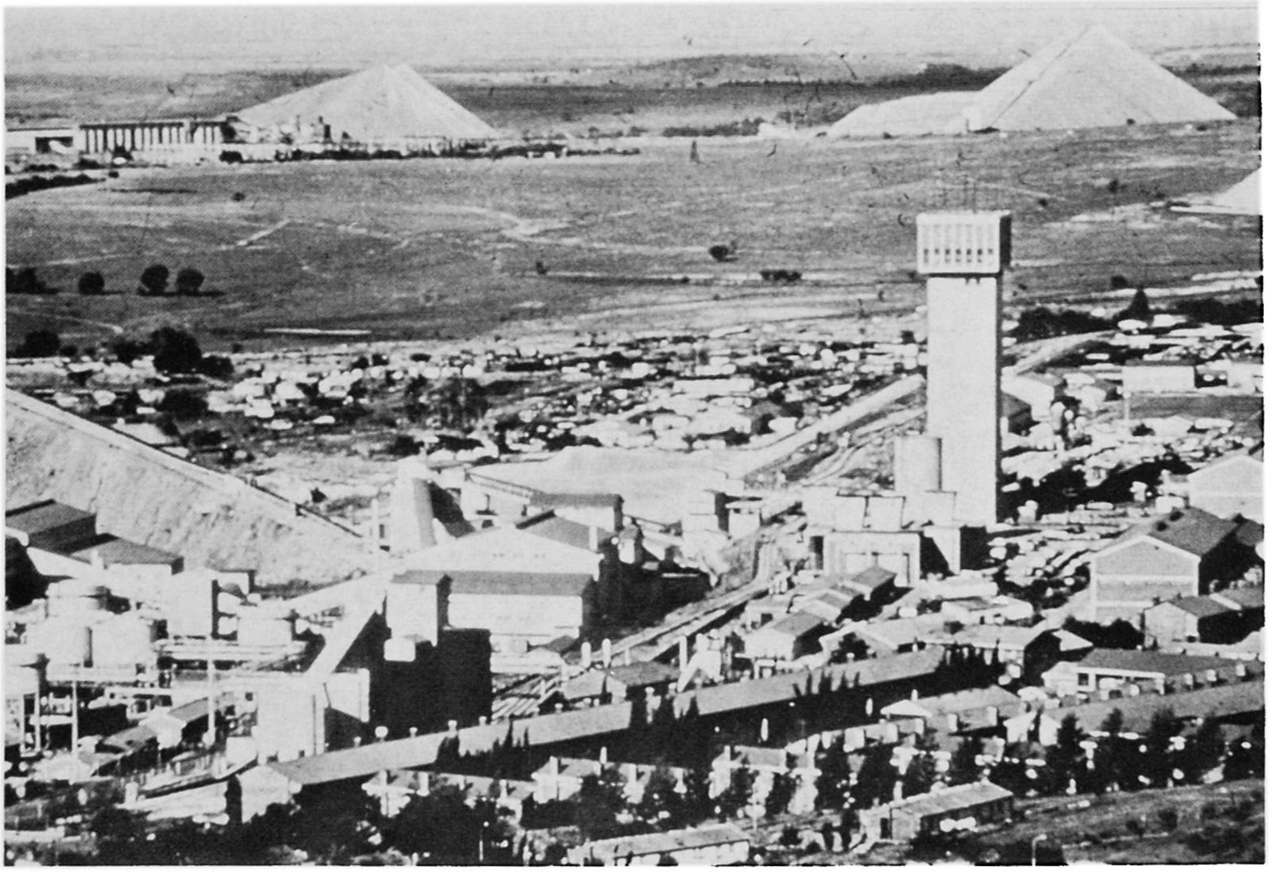
Under normal resting conditions man's body temperature remains constant and varies between the narrow limits of 36.5° and 37° only. As both hot and cold environments are threats to his existence, he is equipped with mechanisms to control body temperature within set limits: if cold, blood flow to peripheral skin areas is curbed, and shivering results in heat production: if hot, skin blood flow is greatly increased and sweating with a skin temperature of about 35 °C provides for evaporative heat loss from the body.

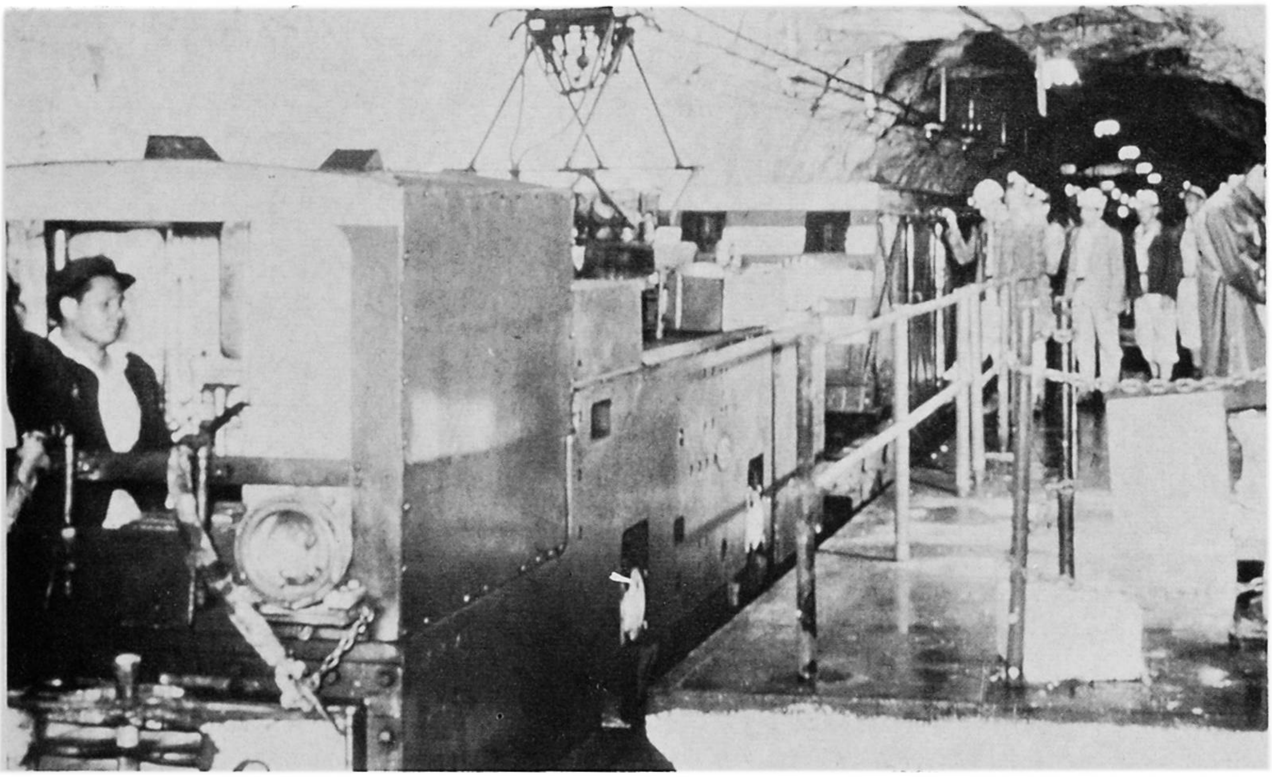
All physical activity produces heat, and body temperature rises if this heat is not dissipated by the body, normally be evaporation of sweat. Evaporation of 1 ml of sweat represents a loss of about 2'400 joules from the body. In hot conditions working men may produce up to 2 l of sweat per hour. Evaporation of sweat is greatly assisted by air movement around the body, and is severely impaired by high humidity. The data in the table below give an indication of the relationships between work rate, wet-bulb temperature, air speed and acclimatization (see later) which determine heat tolerance in the mines.

Wet bulb °C	Air speed	Safe work rate
27	still air	hard even if not acclimatized
	Acclimatization essential	
28	still air	hard
31	still air	moderate
31	1,2 m/s	hard
32	2 m/s	hard

A moderate rise in body temperature usually accompanies severe exercise or strenuous work but this poses no threat to the body. However, when conditions become so extreme that the body is unable to equal the heat production by heat loss, the mechanisms that promote heat loss reach their limit and the body temperature rises precipitously and heat stroke results. Heat stroke is often fatal and is characterised by a body temperature of over 41 °C and usually an absence of sweating.

The most severe natural climatic conditions occurring on the surface (humid tropical areas) have a maximum wet-bulb temperature of about 30 °C with 31 °C or 32 °C being exceptional. Hard work involves a metabolic heat production rate of 500 watts and hard-working men must lose this heat by evaporation of sweat to the surrounding air at this rate if body temperatures are not to rise unduly. So wet-bulb temperature and air velocity are the two environmental parameters of greatest importance.





When working in the sun, an additional heat load of 100 watts or more may be imposed upon men, and the dry-bulb temperatures are often high, causing added strain on the individual and reducing his ability to work effectively.

4. INFLUENCE OF DEPTH ON AIR TEMPERATURES

The ability of air to remove heat from a deep mine is severely restricted because of the increase in temperature as a result of auto-compression of the air descending the mine, where energy (in the earth's gravitational field) is converted into thermal energy. The increase in wet-bulb temperature due to auto-compression during the summer months is about 4 °C/km of depth, so it can be appreciated that the wet-bulb temperature of air increases by about 12 °C when delivered from the surface down the depths of 3'000 m. When the wet-bulb temperature of the air reaching any level exceeds about 23 °C, refrigeration of the air is necessary if wet-bulb temperatures are to be kept below 28 °C. For South African conditions this means that refrigeration becomes necessary at depths greater than about 1'500 m under which condition in still air practically all fit, healthy men are able to work with negligible risk even if they are not acclimatized.

5. SOLUTIONS

It is clear that the only feasible solutions are those that ease the physiological stress of the worker underground.

5.1 Reduction of Wet-Bulb Temperatures

- All incoming ventilation air must be refrigerated before entering the working places in order to remove the heat of auto-compression. Evaporation of sweat is dependent upon air velocities surrounding the workers, so air speeds must be kept above 1 m/sec in work places.

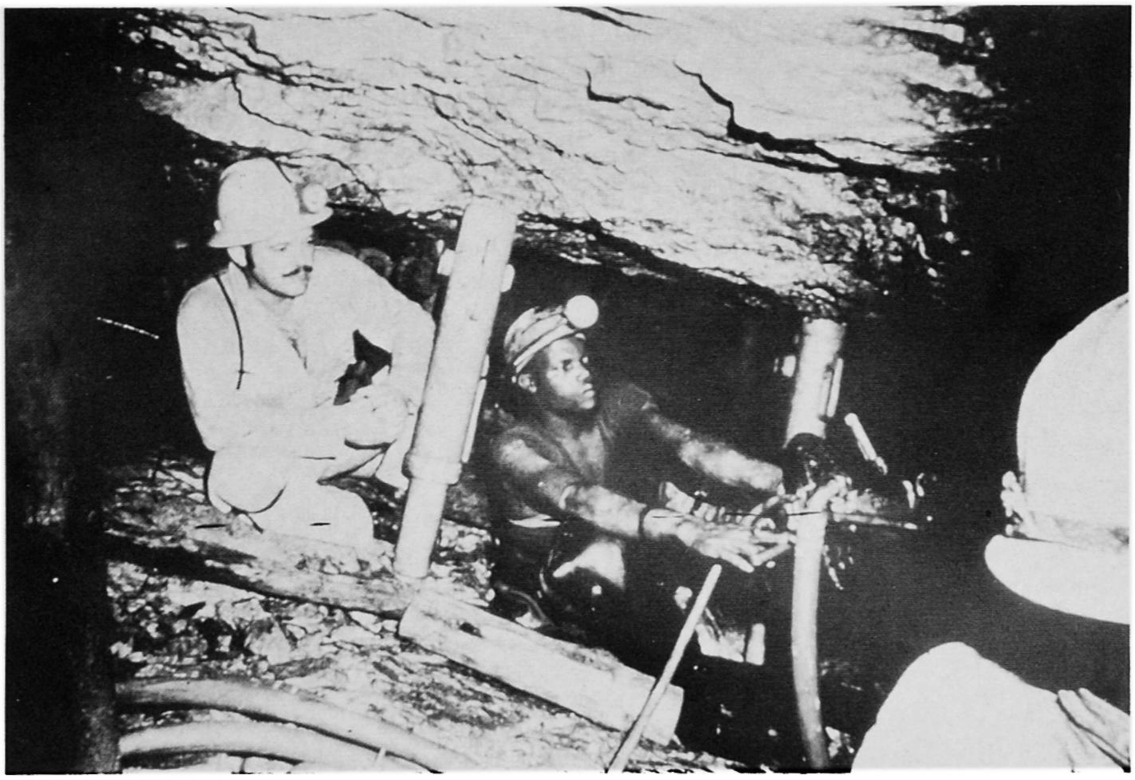
- Service water used underground for drilling and dust supression, if refrigerated, makes a substantial contribution to reducing temperatures in work places. In many deep mines unrefrigerated service water would reach the stope face at typically 30-35 °C and it is not possible to maintain cool air conditions when the free water on the rock floor is so hot. The temperature of this free water must be reduced and the logical way to do this is to refrigerate the service water before it is used.

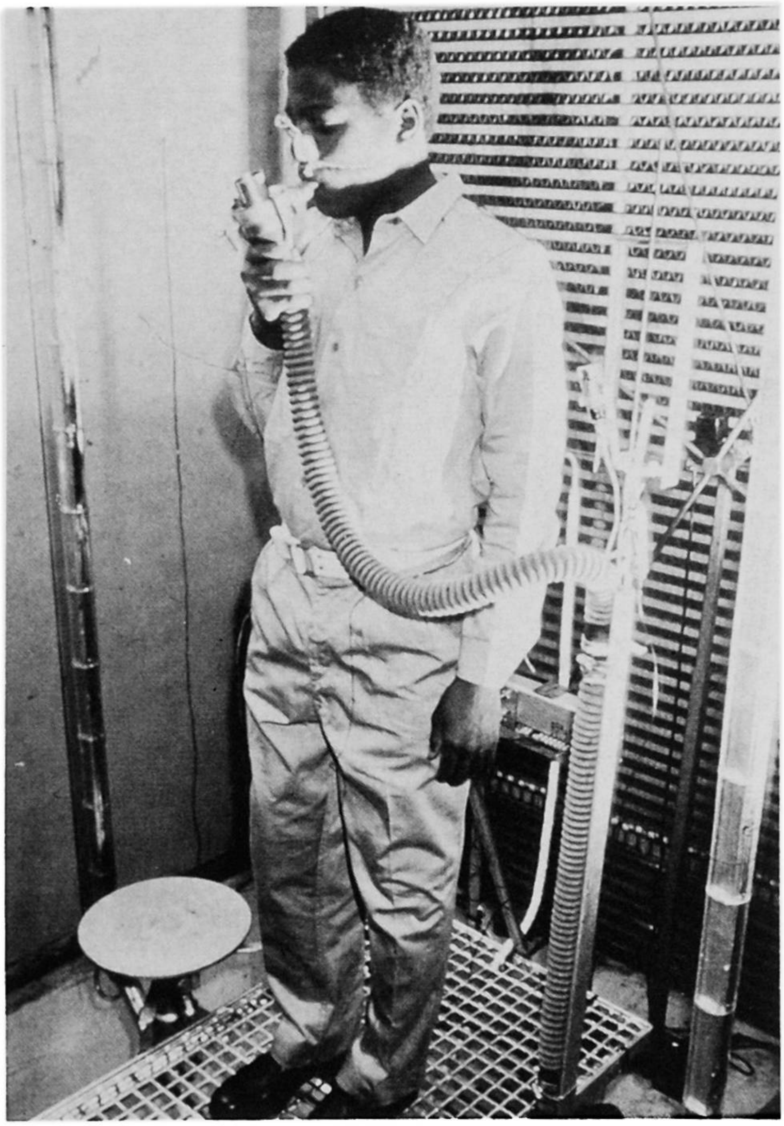
- Since the amount of cooling that can distributed with water is vastly greater than with air (per unit volume) it becomes feasible for mines to locate some or all of their refrigeration plant on the surface rather than underground.

5.2 Acclimatization of Workers

The ultimate aim in deep-level mining is the creation of air conditions in working places in which the risk of heat stroke is negligible and the effects of heat stress on productivity are minimal. A wet-bulb temperature of 28 °C would ensure this but this goal always achievable economically.

In addition to modifying and improving the environmental conditions under which men are required to work deep down underground, it is also necessary and most beneficial to acclimatize men before they are sent underground. Acclimatization involves training men to work at progressively higher work rates. The heart beat for unacclimatized men increases continuously during a 4 hour work shift and may finally reach values in excess of 160 beats/min, whereas those who are fully ac-





climatized and given adequate water during similar work periods, have heart rates below 120 beats/min. This indicates how acclimatization improves the ability to men to work with greatly reduced strain. Acclimatized men have higher sweat rates than their non-acclimatized counterparts and are able to sweat for many hours longer, and have for the same work rate and environmental conditions, body temperatures that are controlled at a lower body temperature. This acclimatization greatly improves the physiological responses to working in heat and humidity.

Men returning from leave and novices or new recruits are required to spend up to 5 days in surface acclimatization centres. For reasons that are not known, the administration of ascorbic acid (Vitamin C) enhances the acclimatization process. It is possible to acclimatize 96% of the men within 5 days with the taking of ascorbic acid, and some are even acclimatized in 3 days whereas without ascorbic acid only 80% of the men are acclimatized in 8 days.

Once heat-acclimatized, returnees from leave or absence are very quickly re-acclimatized, It is remarkable how readily potentially heat tolerant persons can become acclimatized to the relatively severe underground heat and humidity conditions.

Particular attention is paid to developing and refining heat tolerance tests. Individuals differ in their tolerance to heat stress e.g. low tolerance can be expected from individual with either low or excessive body mass (less than 45 kg or over 100 kg), from those who are under 18 or over 45 years of age, from those with low physical working capacities, from those subjected to drug treatment or abuse (including alcohol intoxication) and from those suffering from dehydration, malnutrition or other diseases. Such men are excluded from employment in hot conditions underground.

In the heat tolerance tests presently being used highly heat-tolerant individuals are identified and allowed to proceed to normal underground duties withour undergoing acclimatization. By adhering to precautions during their first dew days underground, these men become acclimatized naturally and show no risk of developing high body temperatures or heat stroke.

The excellent progress made in acclimatization of miners and in developing tests to identify heat intolerant men has reduced the annual incidence of fatal heat stroke in the mines from 100 in 100'000 in 1930 to 1 in 300'000 today.

Intake of Water

In earlier years, miners considered it unwise to drink any fluid while underground. However if they are to stave off heat exhaustion and heat stroke by sweating, it is essential that the fluid loss consequent on sweating is replaced. Salt tablets are not recommended as they give too much salt at a time and men should rather be encouraged to use sufficient salt at meal times.

Men have had to be trained to drink correctly. Experiments have shown that the most sensible way of taking in fluids when working hard or in hot conditions is to swallow small amounts (200 ml - 300 ml) at frequent intervals (15 - 30 minutes). Men who perform moderate or hard physical work in hot or humid conditions should be provided with at least 3 l of drinking water over an 8 hour shift.

The effects of dehydration are, at best, to decrease incentive and productivity, ant at worst, fatal. Dehydration causes a depletion of blood volume and to maintain blood flow through active tissue, heart rate is forced to increase. More serious is the problem of heat dissipation during dehydration, as with the lower blood volume, blood flow to the skin is compromises and heat dissipation from the body surface is greatly decreased.

In effect, dehydration reverses the effects of heat acclimatization; hot and humid conditions cannot be tolerated, the body's circulatory system is put under stress and physical work capacity diminishes. Thus, when water is withheld or not available to men in a dehydrated condition, there is a very severe danger of developing heat stroke.

The psychological effects of dehydration are as serious as the physiological ones. Men, when dehydrated, become morose, aggressive and disobedient, in addition to fairly obvious signs of fatigue.

5.3 Micro-Climate Cooling Systems

As the gold mines go deeper, they will reach a depth at which, even with greatly increased expenditure on conventional ventilation and refrigeration, it will be impossible to keep the wet-bulb temperature in all working places below 32 °C or even 34 °C or 35 °C. It is impossible to acclimatize men for anything more than light work at these temperatures and either the method of mining must change to one that eliminates all but light work, or unconventional methods for cooling mine workers must be adopted. Accordingly, micro-climate cooling systems for men have been investigated.

The concept of micro-climate cooling of workmen is not new. For example, liquid conditioned suits were modified for the cooling of astronauts in the Apollo series of space explorations. The liquid conditioned suits are connected to a source of cooled water by means of a trailing hose, which would present difficulties underground, These suits are also relatively expensive and not particularly robust.

It was decided to investigate a different micro-climate cooling system, consisting of a waistcoat containing plastic pockets of water. The waistcoat contains 4 to 5 kg of water and is worn under a outer protective jacket that serves also to insulate the inner jacket against heat pick-up from the atmosphere. The water in the inner jacket is frozen and the suit is then worn by the workmen over a woollen vest. The water in the waistcoat acts as a heat sink and the phase change from ice to water provides considerable cooling so that 5 kg of water would protect a man working moderately hard for about 4 hours in severe heat and humidity. The advantages of this system are that the workmen are completely mobile and the costs of the waistcoats are not exorbitant. In both the liquid-conditioned garment and the prefrozen waistcoat the trunk is covered to just below the rib margin and the arms and legs are left unencumbered. Thus the garments interfere minimally with the men when they move about or work.

Tests showed that the liquid-conditioned garment protected the workmen completely against temperatures up to 34 °C in that their body temperatures and heart rates were the same as those measured when they worked under comfortable air conditions. The pre-frozen jackets gave good protection at 32 °C and considerable protection at 34 °C, although the protection was not quite as good as that provided by the liquid-conditioned germent. Two pre-frozen jackets were needed for a 6 hour shift. The preliminary trial at 36 °C wet-bulb temperature indicated that these systems give good protection to the workmen even in such exceedingly severe, hot, humid conditions.

The psychological benefit of these cooling systems is note-worthy. The men were highly co-operative and in good humour even at the end of the shift. This contrasted markedly with the exhaustion and bad temper of men after a shift without micro-climate cooling at 34 °C wet-bulb temperature. A large scale trial in a hot mine over a period of several months proved that micro-climate jackets for workmen are indeed a practical proposistion to counteract intense heat.

The pre-frozen jackets have also been used in extremely hot, humid conditions in a copper mine in Zambia where men frive mechanical loaders in wet-bulb temperatures as high as 38 °C.

Subsequent tests have shown that dry ice (solid CO_2) is even better than frozen water in the jackets.

From these trials, it is clear that micro-climate systems have an important role in the mining industry.

6. CONCLUSION

The climatic conditions prevailing deep underground in gold mines in South Africa are extremely severe by comparison with natural hot and humid conditions that can be expected in the earth's surface. Although deep-level mining may be remote from most building and construction situations, the lessons learned from underground working are relevant when personnel are required to do physical work in hot humid conditions.

The risk of death or severe injury due to heat exhaustion or heat stroke is too great to be ignored in very hot climates and positive steps, particularly in regard to pre-selecting those people having the natural capacity or potential to heat tolerance, and to acclimatize those who are potentially suitable. Insistence on the drinking of adequate quantities of water, proper diet and regular medical examination cannot be over-emphasised.

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