SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

Final Project Report

Title:	HEAT STRESS PROTECTION IN ABNORMALLY HOT ENVIRONMENTS
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PREFACE

Emergency work and rescue operations often have to be undertaken in environments where heat loads exceed limits prescribed for routine work, i.e. where the wet-bulb temperature exceeds 32,5 °C or the dry-bulb temperature 37,0 °C.

The Heat Stress Management guidelines contained in COMRO User Guide No 22 are relevant only under humid conditions of up to 32,5°C wet-bulb. Some guidance is given for working in environments above 32,5°C wet-bulb, but this is limited to a number of general precautions not based on rigorous research; specifically, no limiting exposure times associated with the various levels of heat stress have been established. Furthermore, work in non-humid conditions at very high dry-bulb temperatures (typically > 37 °C) is not covered at all in the User Guide.

In view of the above, the Sub-Committee of Group Environmental Engineers, towards the end of 1991, established a working party to investigate stress protection in abnormally hot environments. The working party decided on a two-fold course of action, namely to provide a set of interim guidelines for mines, based on the best currently available knowledge and judgement, and to prepare a proposal in respect of further work needed to address the problem in a more comprehensive and scientific manner. This latter proposal was submitted by COMRO to SIMRAC under the reference GAP 045 'Heat Stress Protection in Abnormally Hot Environments'. The present report represents the outcome of this research and provides guidelines for the performance of emergency work in abnormally hot environments.

Part One of this report deals with safe exposure limits during work in excessively high environmental temperatures and Part Two with protection through body cooling garments under these conditions. Part Three of the report provides a framework for establishing guidelines.

SUMMARY

The present report presents the findings of SIMRAC Project GAP 045 entitled ' Heat stress protection in abnormally hot environments'. It is intended as a reference to develop guidelines which, in turn, would assist mine management in establishing safe operational protocols for emergency work where environmental heat loads exceed the upper limits for routine work. In this respect 'routine work' includes all practices and procedures specifically covered by COMRO User Guide No 22 of 1991.

The report is presented in three parts. Part One deals with safe exposure limits during work in excessively hot environments. Various approaches were investigated, e.g. the internationally recognised Wet-Bulb Globe Temperature (WBGT) index, the Israeli Discomfort Index (DI), the German mines rescue brigades' standards and, of course, the traditional South African methods. Taking into account practical considerations, the findings suggest that a modified DI, provisionally termed the Emergency Heat Stress Index (EHSI), would be the most feasible for local application.

Part Two examines the effectiveness of commercially available body cooling garments in extending tolerance times. Presently available jackets, although offering much in terms of ergonomic and infrastructural acceptability, do not make a significant impact in terms of the primary criterion. However, from the point of view of providing protection which, in fact, may be crucial in the prevention of heat stroke, a strong case exists for routine deployment.

Part Three provides a framework for establishing the necessary protocols for emergency work in excessively hot environments. This framework is based extensively on Part One and Part Two.

The general conclusion is that, although scientifically-derived guidelines are quite feasible, full implementation could be handicapped by (a) the lack of instrumentation for the rapid assessment (and re-assessment) of the thermal load and tolerance times, and (b) the limitations of present commercially available body cooling garments.

Against this background the most important current consideration is to obtain the views of SIMRAC and other specialist committees, e.g. the Sub-Committee of Group Environmental Engineers. The main issues are:

a) acceptance of the framework provided here for the formulation of guidelines,
b) the format of a quick reference chart for estimating the EHSI and tolerance times, and
c) decision and direction on further development with respect to instrumentation and body cooling garments, both of which would be especially relevant to rescue brigades operations.

As a point of departure it is recommended that a specially constituted forum be established to discuss these issues.

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PART ONE

SAFE EXPOSURE LIMITS DURING WORK IN EXCESSIVELY HIGH ENVIRONMENTAL TEMPERATURES

1. INTRODUCTION

Certain mining activities, such as emergency work and rescue operations, have to be undertaken in environments where heat loads often exceed limits prescribed for routine work. In this regard an excessively hot environment is defined as one where either the dry-bulb temperature exceeds 37,0 °C or the wet-bulb temperature exceeds 32,5 °C, and it is therefore not surprising that heat stroke mortality escalates rapidly when these limits are exceeded.

The Heat Stress Management guidelines contained in COMRO User Guide No. 22 [4] are only applicable to conditions which do not exceed the above limits. Some guidance is nevertheless given in the User Guide for working temperatures above 32,5 °C wet-bulb, but this is limited to a number of general precautions not based on rigorous research; specifically no limiting exposure times associated with various levels of heat stress have been established.

A review of both local and international standards indicated that the available information on safe exposure times under abnormal heat stress conditions is very limited. Where available, such standards are aimed at the general population, including both sexes, and also the least heat tolerant worker, and not at a medically-screened, all-male population free of grossly heat intolerant individuals, as is the case in the South African mining industry. It is suggested that available norms and limits are too conservative for local application and, therefore, unrealistic.

In view of the definite need to protect workers when exposed to abnormally high environmental temperatures, the present study was undertaken to establish a scientifically derived database, applicable to local conditions, to determine safe exposure times. Any exposure limit, especially in an emergency situation, should be easy to administer, valid and reliable. These aspects, therefore, form an integral part of this study.

2. METHODS

2.1 Experimental Design

The formulation of heat stress limits was based on the criterion that a heat exposed individual should experience a negligible risk of developing dangerously elevated body temperatures. In order to provide a database for risk assessment, certain physiological responses of heat tolerant men were determined at various combinations of thermal conditions and work rate in a climatic chamber. These physiological responses were analysed statistically in order to predict survival rates and tolerance times as a function of thermal conditions and work rate.

2.2 Subjects

A total of 212 randomly selected mine workers volunteered for the study on the basis of informed consent. This sample included black mineworkers, as well as white mineworkers drawn from the ranks of the Rescue Brigades. These men were considered to be inherently heat tolerant in as far as they had successfully completed a heat tolerance test [3, 16] or the standard climatic room acclimatisation procedure on a gold mine [3]. On the basis of their physical characteristics (Table 1), the subjects could be considered to be representative of the general mining population [15, 16].

Table 1 PHYSICAL CHARACTERISTICS OF SUBJECTS (n = 212)

Measurement	Mean	Standard Deviation	Range
Age (years)	35,20	5,50	21 - 53
Mass (kg)	68,11	5,47	52,18 - 102,20
Height (m)	1,71	0,02	1,56 - 1,86
Body Fat (%)	14,75	1,60	7,12 - 29,10

2.3 Procedures

Medically-fit subjects were allocated randomly to 15 experimental groups and each group was exposed in a climatic room to one of the conditions given in Table 2. All exposures were consistently conducted in the morning (07h00 to 12h00) under close supervision and monitoring.

With the exception of Group 15, all subjects were required to perform four hours of continuous bench-stepping at a specified work rate. Subjects in Group 15 performed a work - rest cycle consisting of 45 minutes of bench-stepping at an external work rate of 70 W followed by 15 minutes of rest per hour. During all the heat exposures wind velocity was controlled within 0,3 and 0,5 m.sec.

Only athletic shorts were worn during the course of the experiment. Subjects were allowed to drink water ad libitum and any subject who complained of exhaustion or fatigue, or who showed any sign or symptom of heat illness, was withdrawn from the climatic room. The same procedure was followed in the case of subjects who registered rectal temperatures of 39,5 °C or above.

Rectal temperature was measured at one-minute intervals by means of a fine wire copper-constantan thermocouple inserted 8 cm into the rectum.

Table 2 EXPERIMENTAL CONDITIONS

Group	n	External Work Rate (W)	Temperature (°C)	
			Wet-bulb	Dry-bulb
1	15	54	32,5	34,0
2	15	54	32,5	35,0
3	15	54	32,5	40,0
4	15	54	32,5	45,0
5	15	54	32,5	50,0
6	15	54	35,0	40,0
7	15	54	35,0	45,0
8	15	54	35,0	50,0
9	15	54	37,5	40,0
10	15	54	37,5	45,0
11	15	54	37,5	50,0
12	12	54	40,0	45,0
13	15	54	40,0	50,0
14	10	70	32,5	45,0
15	10	*	32,5	45,0

* Work- rest cycle: 45 minutes work at 70 W followed by 15 minutes of rest per hour.

2.4 Statistical Methods

Two statistical methods were used to analyse the data, namely survival analysis and regression analysis.

2.4.1 Survival Analysis

Survival analysis refers to a set of techniques for analysing data from laboratory or clinical studies on humans. The response variable represents the time from a certain stimulus (the beginning of the experiment) until a certain condition (withdrawal from experiment) is observed. In the present study the response variable, survival or tolerance time, is defined as the time taken by a subject to develop a rectal temperature of 39,5 °C, or the time period completed before a subject had to be withdrawn from the climatic chamber after showing early signs and symptoms of heat illness.

Survival time data are often censored which then requires special analytical techniques. Censoring, broadly speaking, occurs when experimentation stops before all the subjects have 'dropped out'. The data of those remaining must be used in the analysis but the actual time at which the subject would have dropped out, had the experiment continued, is unknown. Survival data are said to have a Type I censoring (or time censoring) if the censoring time is pre-specified. For example, in the present study the maximum exposure time was set at 240 minutes. Another type of censoring (Type II) occurs if the test is stopped after the n-th failure. The number of failures is fixed, and the length of the test is random. The data in the present study can be classified as Type I.

In order to carry out the survival time analysis, the Number Cruncher Statistical System (NCSS) was used [12]. The NCSS fits six parametric survival distributions, namely Normal, Lognormal, Gamma,Weibull, Exponential and Rayleigh. The distribution that best summarises the available data was selected on basis of the log likelihood fit criterion.

Following the selection of the survival distribution, the survival rates for the various times were calculated. For a specific time t, the survival rate S(t) is defined as the probability of a subject surviving longer than t. The probability of dropping out earlier than t will be 1- S(t). In the present study any subject who had developed a rectal temperature of 39,5°C or above, or who had to be withdrawn from the climatic room after displaying early signs and symptoms of heat illness, was considered to be a 'drop out'.

The survival curve was used to determine the tolerance time which corresponds to a particular 'drop out' rate. Thus, if p % is a specific 'drop out' rate and *T* the corresponding tolerance time, one expects p % of subjects to 'drop out' before *T* is reached.

2.4.2 Regression Analysis

Following the fitting of the survival distribution, regression analysis was done in order to determine whether any of the measured factors (independent factors) could be used to predict tolerance time corresponding to a particular drop out rate (the dependent variable) as obtained from the survival analysis. The procedure followed was to include all the available dependent variables in the model and then to remove those which were not statistically significant (alpha = 0,05).

A Box -Wetz criterion [14] was used to test the adequacy of the calculated regressions, the Durbin Watson test for autocorrelation and the Cook's D test [14,19] for influential points and residual plots for randomness of the observed errors. The multiple correlation coefficient *R*-square was also computed as a measure of correlation between the dependent and independent variables (*R*-square is defined as the proportion of variation explained by the regressor variables).

3. RESULTS

3.1 Survival Rates

On basis of the analyses performed, it was evident that the lognormal distribution best fitted the data pertaining to the 15 test conditions. The parameter estimates for the mean and standard deviation (sigma) are given in Table 3. Effectively the lognormal distribution is obtained by taking logs of the data and fitting a normal distribution by computing estimates of the mean and standard deviation with due consideration of censors. Thus, the estimates of the mean and standard deviation in Table 3 are measures of centrality and spread of the logged data.

Table 3 LOGNORMAL PARAMETER ESTIMATES FOR THE SURVIVAL DISTRIBUTION

Wet-Bulb (°C)	Dry-Bulb (°C)	Number of cases (n)	Work Rate (w)	Estimate (mean)	Std. Error	Estimate (sigma)	Std. Error
32,5	34,0	13	54	5,51	0,06	0,17	0,05
32,5	35,0	14	54	5,46	0,07	0,20	0,06
32,5	40,0	10	54	5,02	0,10	0,32	0,07
32,5	45,0	10	54	5,39	0,06	0,19	0,05
32,5	50,0	15	54	4,68	0,09	0,33	0,06
35,0	40,0	15	54	4,27	0,05	0,17	0,03
35,0	45,0	11	54	4,14	0,04	0,14	0,03
35,0	50,0	12	54	4,12	0,03	0,10	0,02
37,5	40,0	14	54	3,7	0,02	0,07	0,01
37,5	45,0	14	54	3,75	0,03	0,12	0,02
37,5	50,0	15	54	3,65	0,03	0,11	0,02
40,0	45,0	10	54	3,34	0,06	0,19	0,04
40,0	50,0	14	54	3,33	0,05	0,2	0,04
32,5	45,0	9	70	4,53	0,13	0,38	0,09
32,5	45,0	10	*	5,46	0,25	0,64	0,23

* Work- rest cycle: 45 minutes work at 70 W followed by 15 minutes of rest per hour.
n: number of subjects completed the test and those who registered rectal temperatures of 39,5 °C and above.

By using the distributions contained in Table 3, the survival rates associated with the respective test conditions were computed for 30-minute intervals. These results are given in Table 4.

Table 4 SURVIVAL RATES AT 30-MINUTE INTERVALS

Wet- Bulb (^{0}C)	Dry-Bulb (^{0}C)	30 min	60 min	90 min	120 min	150 min	180 min	210 min	240 min
32,5	34,0	1,000	1,000	1,000	0,999	0,997	0,964	0,820	0,558
32,5	35,0	1,000	1,000	1,000	0,999	0,988	0,913	0,722	0,470
32,5	40,0	1,000	1,000	1,000	0,999	0,978	0,858	0,603	0,330
32,5	45,0	1,000	0,998	0,949	0,768	0,512	0,293	0,152	0,073
32,5	50,0	0,999	0,960	0,702	0,368	0,156	0,059	0,021	0,007
35,0	40,0	1,000	0,817	0,086	0,001	0,000	0,000	0,000	0,000
35,0	45,0	1,000	0,638	0,006	0,000	0,000	0,000	0,000	0,000
35,0	50,0	1,000	0,599	0,000	0,000	0,000	0,000	0,000	0,000
37,5	40,0	0,999	0,000	0,000	0,000	0,000	0,000	0,000	0,000
37,5	45,0	0,997	0,002	0,000	0,000	0,000	0,000	0,000	0,000
37,5	50,0	0,985	0,000	0,000	0,000	0,000	0,000	0,000	0,000
40,0	45,0	0,378	0,000	0,000	0,000	0,000	0,000	0,000	0,000
40,0	50,0	0,370	0,000	0,000	0,000	0,000	0,000	0,000	0,000
32,5	45,0 (70 watt)	0,998	0,873	0,532	0,251	0,104	0,041	0,016	0,006
32,5	45,0 (*)	0,999	0,983	0,933	0,853	0,759	0,663	0,572	0,489

* Work- rest cycle: 45 minutes work at 70 W followed by 15 minutes of rest per hour.

From Table 5 it is evident that, when working continuously at a moderate intensity in an environment with a wet-bulb temperature of 32,5 °C and a dry-bulb temperature of 34,0 °C, the probability to survive in this environment for longer than 210 minutes without developing hypothermia or a heat disorder is 0,820 or 82 %. At the same wet-bulb temperature with a dry-bulb temperature of 50,0 °C, the corresponding probability is 0,021 or 2,1 %.

3. 2 Tolerance time

The tolerance times for various survival rates were computed and are given in Table 6.

Table 6 TOLERANCE TIMES CORRESPONDING TO CERTAIN DROP OUT RATES

Wet-Bulb (°C)	Dry-Bulb (°C)	Work Rate (W)	TOLERANCE TIME (minutes)					
			p=0,001	p=0,01	p=0,05	p=0,1	p=0,25	p=0,5
32,5	34,0	54	144	164	185	197	219	246
32,5	35,0	54	127	148	170	183	207	236
32,5	40,0	54	123	142	161	173	194	221
32,5	45,0	54	57	72	90	101	122	151
32,5	50,0	54	38	50	62	70	86	107
35,0	40,0	54	41	47	53	56	63	71
35,0	45,0	54	41	45	50	53	57	63
35,0	50,0	54	45	48	52	54	57	62
37,5	40,0	54	32	34	36	37	38	40
37,5	45,0	54	29	32	35	36	39	42
37,5	50,0	54	27	30	32	33	36	38
40,0	45,0	54	16	18	21	22	25	28
40,0	50,0	54	15	17	20	22	24	28
32,5	45,0	70	29	38	50	57	72	93
32,5	45,0	*	32	53	82	104	153	236

* Work- rest cycle: 45 minutes work at 70 W followed by 15 minutes of rest per hour.

On basis of the information contained in Table 6, one % of the population is expected to drop out before 164 minutes when working in an environment of 32,5°C wet-bulb and 34,0°C dry-bulb. Under the same thermal conditions, 10 % of the population is expected to drop out before 197 minutes and 50 % before 246 minutes of exposure.

Further analyses were performed to establish which measurement of the climatic factors used in the study (Table 7) would best correlate with tolerance time. Two sets of stepwise regression analyses were carried out with tolerance times at drop out rates of 5 %, 1 % and 0,1 %, respectively, as the dependent variables.

Table 7 MEASUREMENTS OF CLIMATIC CONDITIONS

Measurement	Abbreviation
Dry-bulb temperature	DB
Wet-bulb temperature	WB
Difference between dry and wet-bulb temperatures	(DB - WB)
Relative humidity	humidity
Humiture Index (sum of dry-bulb temperature and relative humidity)	humiture
Wet Bulb Globe Temperature Index (0,7 wet-bulb + 0,3 globe temperature)	WBGT
Discomfort Index (arithmetic mean of dry-bulb and wet-bulb temperatures)	DI

The first set of regressions used WB, DB, (DB - WB), WBGT and DI as independent variables while the second had WB, DB, (DB - WB), humidity and humiture as independent variables. A log transformation was applied to certain of the independent variables to obtain a better fit. The variance inflation factors calculated during regression showed that some of the above variables are highly correlated because they are a combination of each other (WBGT and DI). These variables were, therefore, excluded from the analysis.

For the first set of independent variables, log (DB) and (DB - WB) were selected as the best predictors of survival or tolerance time. In the case of the second set of independent variables, log (DB) and humidity were chosen. The results of the regression analyses are given in Tables 8 and 9.

All the regression models in Tables 8 and 9 predict the natural log of the tolerance time. The regression constants associated with a given drop out rate could be used to predict the corresponding tolerance time by using the following equation:

$$\log(\text{tolerance time}) = a + b\,(\log DB) + c\,(DB - WB)$$

where a, b and c are regression constants.

For example, the predicted tolerance time corresponding to a 5 % drop out probability ($p = 0{,}05$) can be calculated as follows:

$\log(\text{tolerance time}) = 41{,}1214 - 10{,}2639 \log(DB) + 0{,}1939\,(DB - WB)$ - (Table 6)

or

$\log(\text{tolerance time}) = 46{,}2219 - 10{,}323 \log(DB) - 0{,}0527\,(\text{humidity})$ - (Table 7)

$(\text{Tolerance time} = e^{(\log(\text{tolerance time}))})$

Table 8 REGRESSION MODELS USING LOG(DB) AND (DB - WB) AS INDEPENDENT VARIABLES

Log(tolerance time)	INTERCEPT	Log(DB)	DB - WB	R^2
	a	b	c	
$p = 0{,}001$	38,5534	-9,6014	0,1711	0,9254
$p = 0{,}01$	40,2326	-10,0438	0,1857	0,9461
$p = 0{,}05$	41,1214	-10,2639	0,1939	0,954

Table 9 REGRESSION MODELS USING LOG(DB) AND HUMIDITY AS INDEPENDENT VARIABLES

Log(tolerance time)	INTERCEPT	Log(DB)	Humidity	R^2
	a	b	c	
$p = 0{,}001$	43,1452	-9,6750	-0,0467	0,9319
$p = 0{,}01$	45,1203	-10,1012	-0,0505	0,9503
$p = 0{,}05$	46,2219	-10,3231	-0,0527	0,9583

3.2.1 Dry-bulb temperature, relative humidity and tolerance time

Appendix A consists of a table of tolerance times predicted by means of the regression models (Table 8) with log(DB) and humidity the independent variables. The log tolerance times were converted to the original scale by using the appropriate correction factor. The upper and lower bounds of a 95 % confidence interval for each individual prediction are also listed in the table.

Appendix B contains basically the same information as Appendix A, the only difference being that the tolerance times given are for selected values of relative humidity and dry-bulb temperature. A comparison of these results, and those obtained in a similar study conducted in Germany [2], is given in Table 10. The work rates used in these studies were very similar (oxygen consumption of 1,2 litre/min in the present study against 1,0 litre /min in the German study), with the exposure limit set at 120 minutes or the development of a rectal temperature of 38,5 °C in the latter study.

Table 10 COMPARISON OF PREDICTED TOLERANCE TIMES (min)

Dry-bulb (°C)	TOLERANCE TIME (minutes)					
	90 % RH			50 % RH		
	A	B	C	A	B	C
32	70	233	270			
34	50	129	146			
36	40	74	82			
38	30	44	47	90	287	359
40	25	27	28	55	173	213
42	20	17	17	45	108	130
44	20	11	11	35	68	81
46	15	7	7	30	44	52
48	10	5	5	25	29	34
50				20	20	22

A = German standards [2]
B = Drop out rate of 0,1 % (present study)
C = Drop out rate of 1,0 % (present study)
RH = Relative Humidity

From the results obtained in Table 10, it is evident that the tolerance times predicted using the regression models in the present study differ substantially from the times in the German study. At a relative humidity of 90 %, for instance, the tolerance times at dry-bulb temperatures below 40,0 °C are generally longer, almost identical at 40,0 °C and 42,0 °C, and shorter at dry-bulb temperatures above 42,0 °C. In the case of 50 % relative humidity, the tolerance times are longer, the only exception being at a dry-bulb temperature of 50,0 °C where the tolerance times of the two studies are identical.

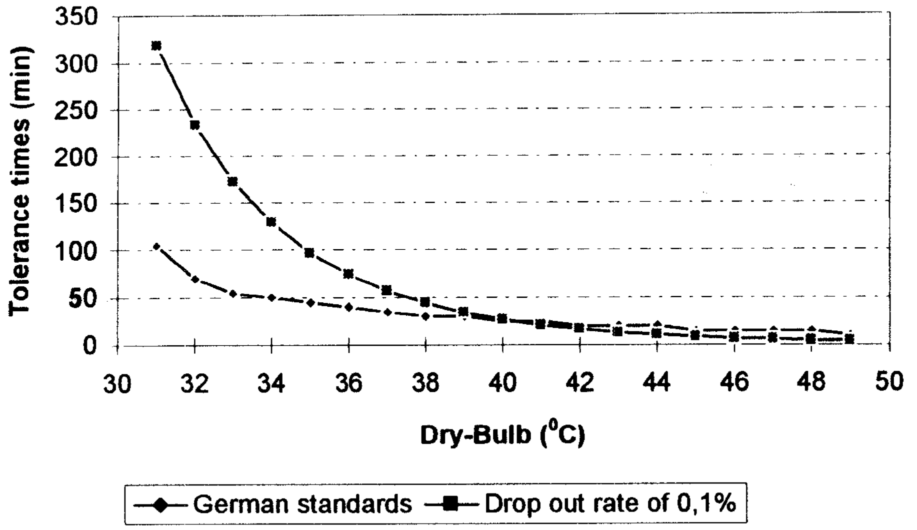

Figure 1: Comparison of predicted tolerance times (p=0,1) for given dry-bulb temperatures and constant relative humidity of 90 %

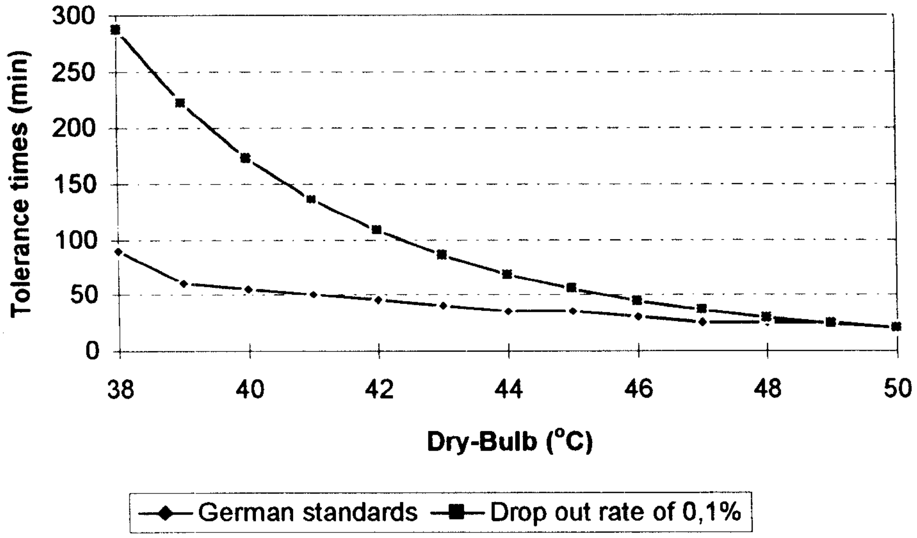

Figure 2: Comparison of predicted tolerance times (p=0,1) for given dry-bulb temperatures and constant relative humidity of 50 %.

In view of the availability of portable humidity / temperature meters, the compilation of a simplified chart using dry-bulb and humidity to estimate tolerance times has great potential for practical use under severe heat stress conditions. In Germany, for instance, rescue brigadesmen use such a chart based on the findings of the aforementioned study [2] during their operations.

3.2.2 Wet-Bulb Globe Temperature (WBGT) and tolerance time

The Wet Bulb Globe Temperature (WBGT) index is a commonly used technique to express heat stress [7] and enjoys recognition, albeit in slightly different versions, by the American Conference of Governmental Industrial Hygienists (ACGIH) and the International Standards Organization (ISO). It is calculated for indoor conditions as:

$$\text{WBGT} = 0{,}7\ \text{WB} + 0{,}3\ \text{GT}$$

where WB and GT represent wet-bulb temperature and globe temperature, respectively. The index accounts for evaporative cooling (embodied in WB) and for convective and radiant heat exchange (via GT), which are major factors in determining the contributions of environmental causes to heat stress. The relative weights for the two temperatures used were empirically developed and by implication related to the physiological response to heat stress. Commercially available WBGT measuring equipment gives the various temperatures separately or as an integrated WBGT.

The relationship between WBGT and tolerance time (at various drop out rates) was modelled by using a second degree polynomial regression. The regression constants and the associated *R*-square values are given in Table 11.

Graphs for the fitted regression models are given in Figures 3, 4 and 5. In these figures L95M and U95M represent the lower and upper bounds of a 95 % confidence interval for the expected value (mean) of the dependent variable. L95 and U95 are the lower and upper bounds of a 95 % confidence interval for an individual prediction and include the variance in the error as well as the variance in parameter estimates.

Table 11 REGRESSION MODELS USING WBGT TO PREDICT TOLERANCE TIME

Time	Intercept	WBGT a	$WBGT^2$ b	*R*-square c
p=0,001	2867,661	-136,925	1,645	0,9067
p=0,01	3260,853	-155,224	1,859	0,9179
p=0,05	3670,526	-174,303	2,082	0,9226

The tolerance times associated with a specific drop out rate can be predicted by incorporating the relevant regression constants given in Table 11 in the following equation:

$$\text{Tolerance time (min)} = a + b\,(\text{WBGT}) + c\,(\text{WBGT})^2$$

where a, b and c are the regression constants. A table of predicted tolerance times for various values of WBGT is given in Appendix C.

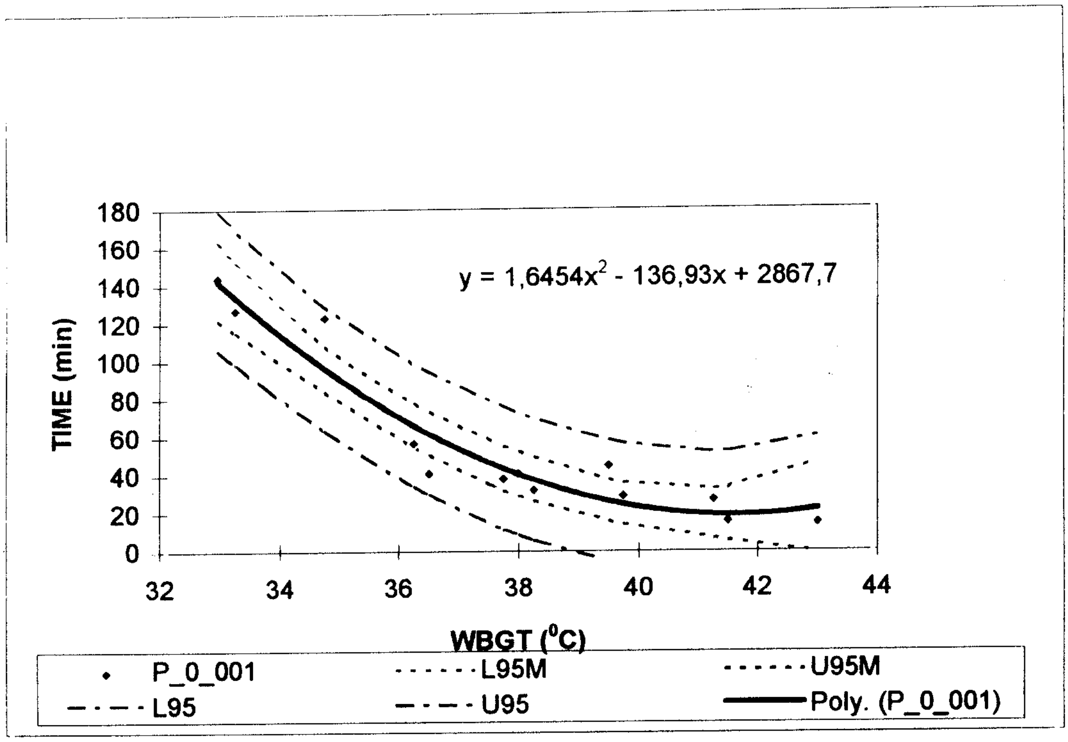

Figure 3: Nonlinear Regression for WBGT and tolerance time (p=0,001)

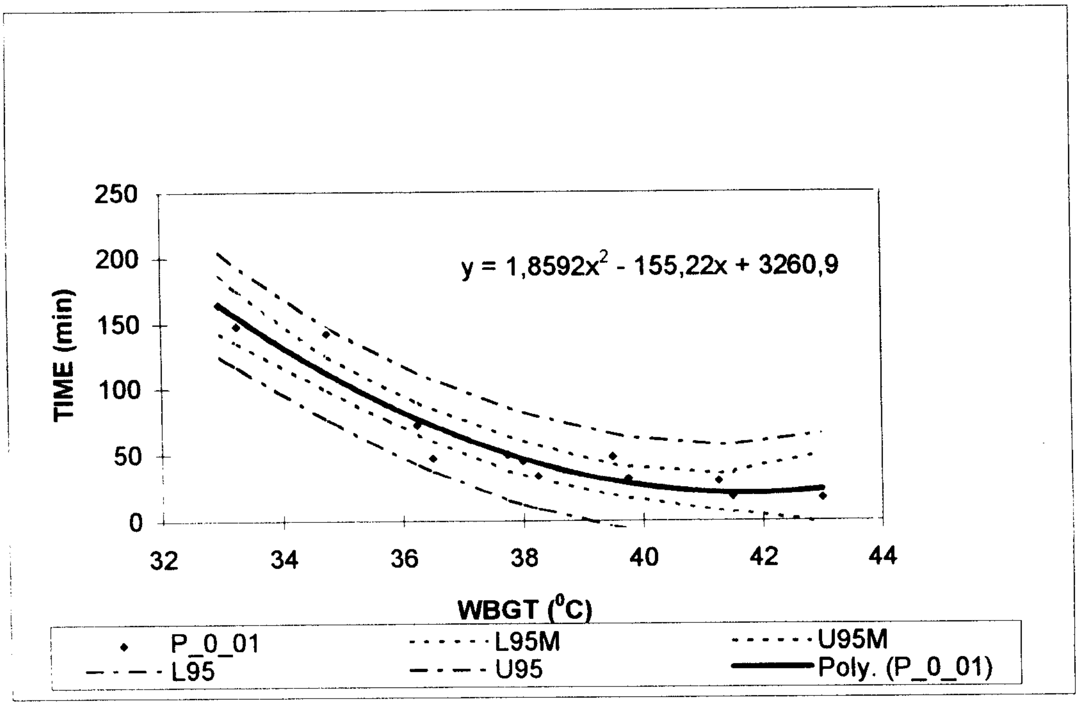

Figure 4: Nonlinear Regression for WBGT and tolerance time (p=0,01)

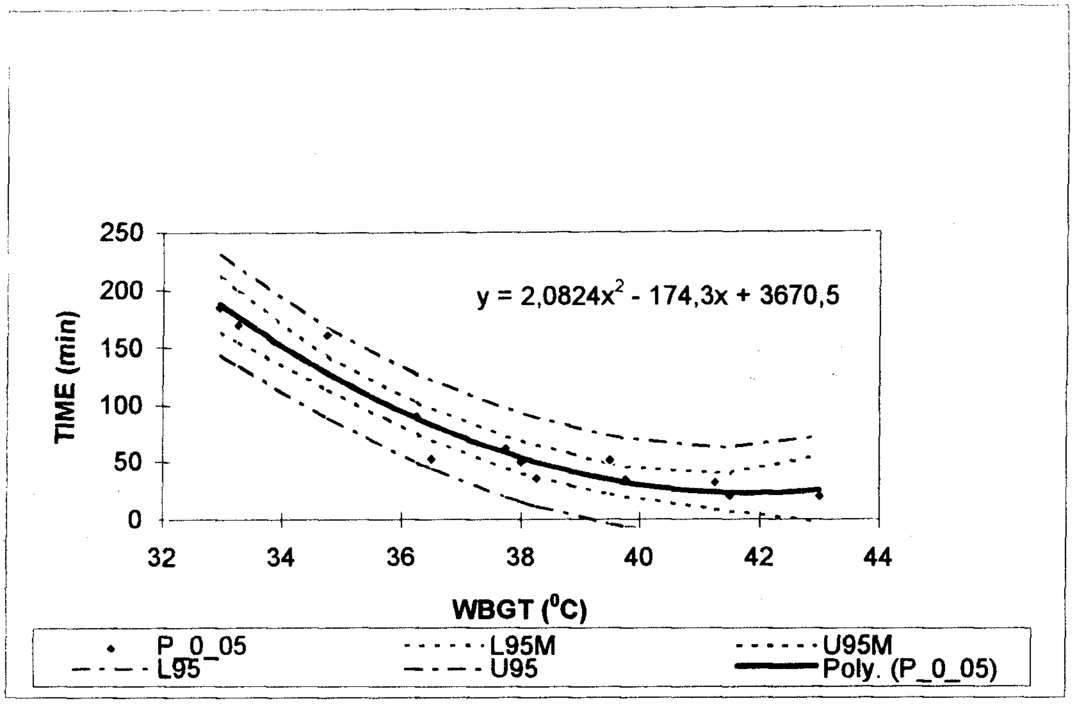

Figure 5: Nonlinear Regression for WBGT and tolerance time (p=0,05)

3.2.3 Discomfort Index (DI) and tolerance time

The Discomfort Index (DI) is the arithmetic mean of wet-bulb temperature and dry-bulb temperature[17]. It is regarded as practical and meaningful in the Israeli Defence Force and, in effect, represents WBGT with a stronger bias towards dry-bulb temperature.

The relationship between DI and tolerance time (at various 'drop out' rates) was modelled by using a second degree polynomial regression. The regression constants and associated *R*-square values are given in Table 12.

Table 12 REGRESSION MODELS USING DI TO PREDICT TOLERANCE TIME

Time	Intercept a	DI b	DI^2 c	*R*-square
p=0,001	2014,272	-90,178	1,021	0,8400
p=0,01	2259,837	-100,661	1,133	0,8321
p=0,05	2505,814	-111,086	1,245	0,8203

Graphs for the fitted regression models are given in Figures 6, 7 and 8. In these figures L95M and U95M represent the lower and upper bounds of a 95 % confidence interval for the expected value (mean) of the dependent variable. L95 and U95 are the lower and upper bounds of a 95 % confidence interval for an individual prediction and include the variance in error as well as the variance in parameter estimates.

The tolerance times associated with specific 'drop out' rates can be predicted by incorporating the relevant regression constants in Table 12 in the following equation:

$$\text{Tolerance time(min)} = a + b(DI) + c(DI)^2$$

where a, b and c are the regression constants. A table of predicted tolerance times for various values of DI is given in Appendix D.

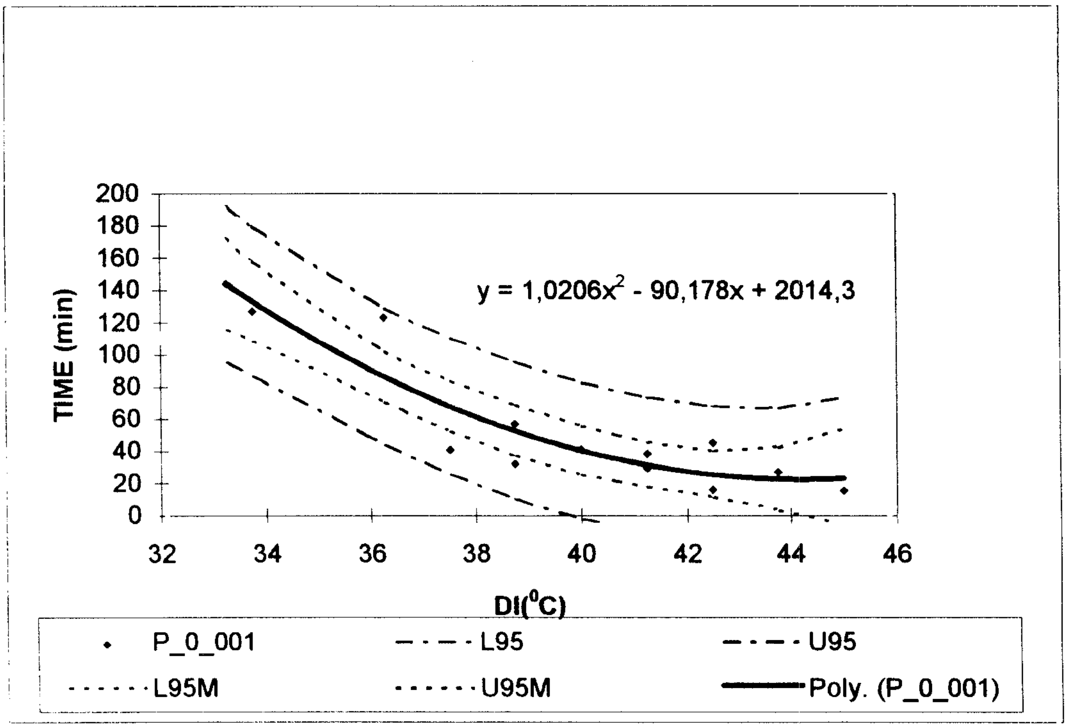

Figure 6: Nonlinear Regression for DI and tolerance time (p=0,001).

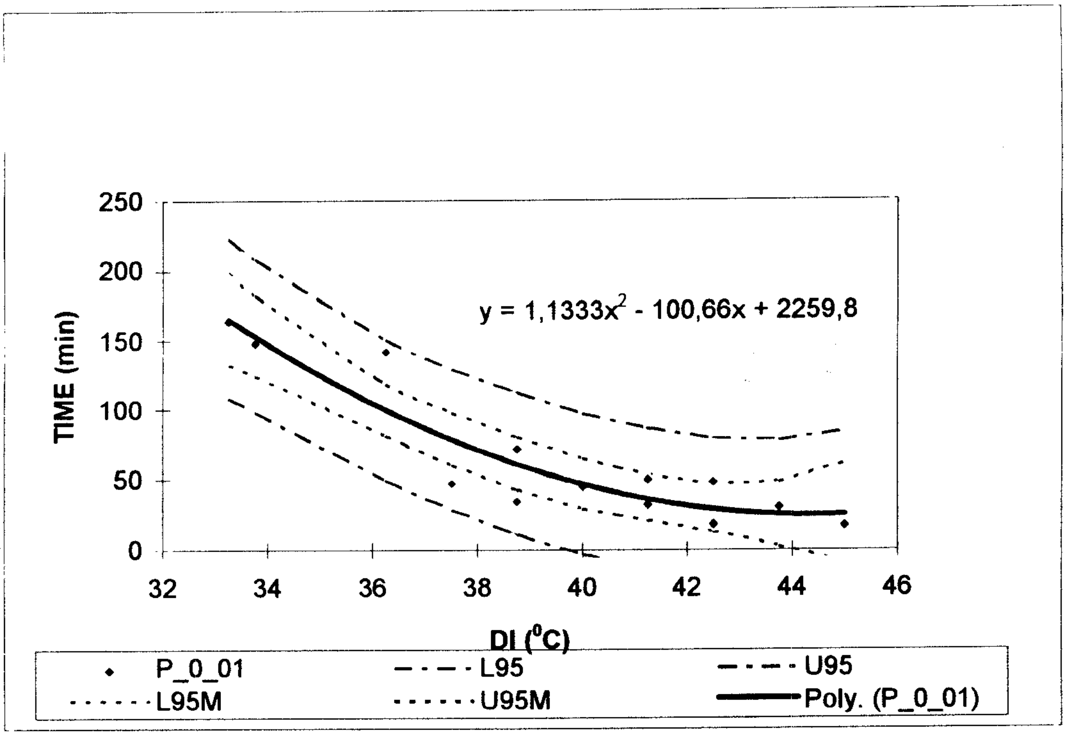

Figure 7: Nonlinear Regression for DI and tolerance time (p=0,01).

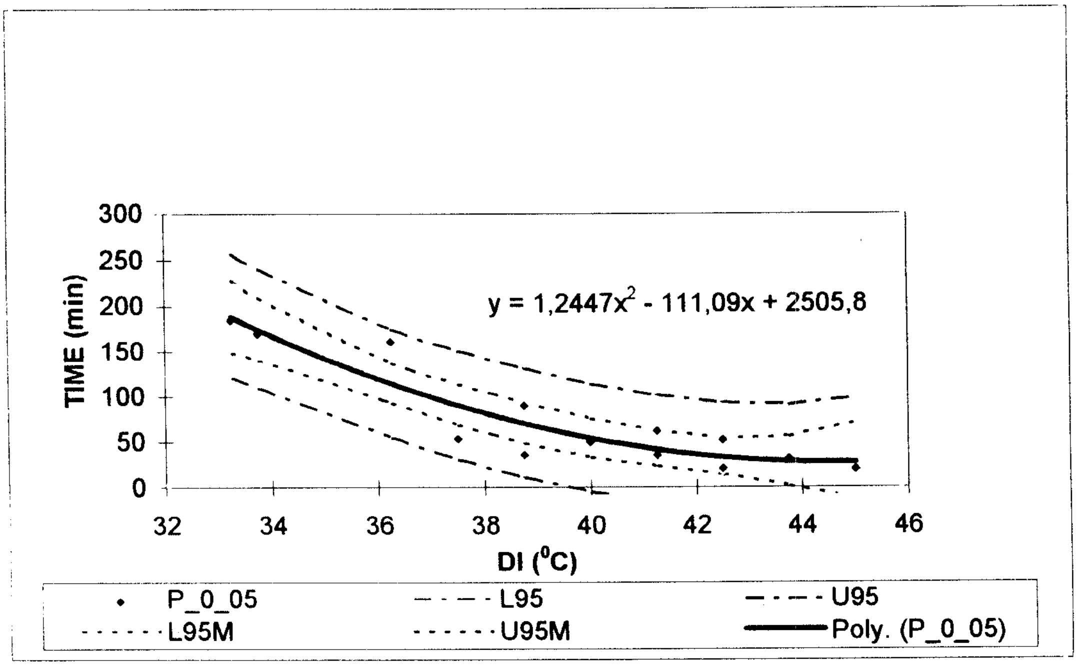

Figure 8: Nonlinear Regression for DI and tolerance time (p=0,05).

4. DISCUSSION AND GENERAL CONCLUSIONS

Historically the approach towards providing personal protection against heat as a health hazard in the South African mining industry has been based essentially on

- minimising the incidence of heat stroke by setting limits based on an unacceptable risk ($> 10^{-6}$) of developing dangerously elevated body temperatures (> 40 °C),
- achieving a satisfactory degree of heat acclimatization, and
- observing elementary precautions, e.g. fluid replacement.

In particular, the approach taken has deliberately ignored internationally recognised heat stress indices and it could be argued that there is ample justification for this in view of the uniqueness of the labour force. For example, unlike most labour forces in general industry, the underground labour force in South African gold and platinum mines exhibits the following characteristics:

- all-male, predominantly youthful,
- medically-screened,
- heat tolerance tested, and
- formally acclimatized or acclimated.

Moreover, heat stress indices attempt to integrate all factors contributing to heat stress in a single numerical value. This is a complex requirement and, not surprisingly, these indices provide assessments of heat stress which differ quite widely. For example, the use of heat stress indices to assess health risk, performance efficiency and eventually tolerance times are '..... mostly not in agreement .....' [1] and '..... not un-ambiguous .....' [8]. It has been suggested that '..... none of these indices has as yet achieved status of being enforceable by law' [6]. From a legislative point of view it would therefore be totally inappropriate, if not irresponsible, to specify a particular index since what is relevant in a given set of circumstances may, in fact, be positively dangerous in another.

Statistically, especially in view of the size of the labour force working in 'hot' areas underground and the incidence of heat disorders, the above approach has been vindicated beyond doubt. However, where established norms and limits are likely to be exceeded in order to cope with emergencies, notably rescue operations, international precedent cannot be ignored. This, of course, is most relevant in the present context.

The point of departure was that the existing risk limit (i.e. $< 10^{-6}$ risk to exceed a body core temperature of 40,0 °C) would no longer be achievable. Accordingly, a new risk factor had to be adopted with the obvious consequence of being less conservative. Firstly, the 10^{-6} criterion was relaxed to 10^{-3}, the rationale being that the population at risk during any given period associated with emergency work would certainly be less than 1 000. Secondly, as a counter, the body core temperature limit was reduced to 39,5 °C in agreement with experimental termination levels subscribed to by the US Navy Clothing and Textile Research Facility [13]. It should be noted that the WBGT index is ultra-conservative in this respect because it implies that body core temperatures in excess of 38 °C are unacceptable.

From a comparative point of view the only internationally recognised heat stress index of repute is the WBGT index and, consequently, the data recorded were translated into WBGT terms. Comparisons were also drawn with standards subscribed to by the rescue brigades on German mines and the Israeli Discomfort Index (DI). For most practical purposes the DI can be regarded as another version of the WBGT: whereas the WBGT is biased towards wet-bulb temperature with a 70 % weighting factor, the DI places equal emphasis on the dry- and wet-bulb temperatures.

The limits imposed for German rescue brigades appear to be overconservative even to the extent of being ' convenient'. The scientific merit of these limits is also a matter of speculation and from Figure 1 it is clear that a correlation with the present approach only exists from a dry-bulb temperature of 39 °C (90 % relative humidity) and above. At lower humidity levels (Figure 2) there is, for practical purposes, no correlation.

At present maximum permissible temperatures recommended for continuous routine work in South African gold and platinum mines are a dry-bulb limit of 37 °C and a wet-bulb limit of 32,5 °C. This translates to numerical values which are not dissimilar, namely
WBGT = 33,85 °C (± 34 °C), and DI = 34,75 °C (± 35 °C).

Moreover, these indices interpret the permissible limits in a remarkably similar fashion. For example, the respective p-values (Tables 11 and 12) yield tolerance times of approximately 140, 150 and 115 minutes for the WBGT index (Figures 3, 4 and 5) in comparison with corresponding DI tolerance times of 130, 140 and 100 minutes (Figures 6, and 8). By contrast, the '39,5 °C core temperature limit / 10^{-3} risk factor ' criterion suggests a maximum tolerance of about 60 minutes. This is relatively conservative where high humidity levels prevail (Figure 1).

Considering an emergency scenario with a hypothetical environment of 50° C dry-bulb and 35 °C wet-bulb, the respective indices translate this environment to
WBGT = 39,5 °C (40 °C), and DI = 42,5 °C (43 °C).

Numerically these translations are of the same order but the difference becomes apparent because of the dry-bulb bias in the DI. The respective approaches would yield the following tolerance times:

Log(Dry-Bulb) and humidity index (p=0,001) (Appendix A)	32 minutes
Log(Dry-Bulb) and humidity index (p=0,01) (Appendix A)	37 minutes
Log(Dry-Bulb) and humidity index (p=0,05) (Appendix A)	42 minutes
WBGT (p=0,001) (Appendix C)	23 minutes
WBGT (p=0,01) (Appendix C)	27 minutes
WBGT (p=0,05) (Appendix C)	30 minutes

DI (p=0,001) (Appendix D)	24 minutes
DI (p=0,01) (Appendix D)	27 minutes
DI (p=0,05) (Appendix D)	31 minutes

From a practical point of view all three approaches provide for permissible exposures of about 30 minutes.

The overall impression is that the three approaches referred to, but excluding the German rescue brigades' limits, are similar when, in the case of the WBGT index and DI, second degree polynomial regressions are used. In other words, the respective indices are not, especially from a practical point of view, significantly different.

The general conclusion is therefore that the ultimate standard or norm adopted for use in South African mines would depend on practical considerations rather than on respective merits of protection. In this respect the DI has much to offer, not only in view of the relative ease of mental calculation, but also in that it makes more allowance for high dry-bulb temperatures which, of course, become a reality in many emergencies. The appropriate modification suggested is the polynomial regression presented in Figure 8, i.e. where the 10^{-3} risk factor (1 in a 1 000 'drop-out' rate) was used.

The proposed modification of the DI represents a fundamental change with respect to adopting a second-degree polynomial regression to establish tolerance times, in conjunction with risk criteria expressed in terms of maximum permissible rectal temperatures ($\leq 39,5^{0}$C) and probability (‘drop-out’ rate $\leq 10^{-3}$). With the exception of the basic equation, the proposed modification bears little semblance to the DI and there is therefore ample justification for a new term. Moreover, in the present context the term ‘discomfort’ is certainly not an issue. A suggestion at this stage is the ‘Emergency Heat Stress Index’ or ‘EHSI’.

5. ACKNOWLEDGEMENTS

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Appendix A

Tolerance time predictions using log(dry-bulb) and humidity

DRY-BULB	HUMIDITY	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
35	40	1736	880	3423	1399	671	2915	1046	518	2427
35	45	1326	701	2508	1080	542	2151	821	434	1809
35	50	1014	558	1843	834	437	1591	645	363	1353
35	55	776	443	1359	645	352	1182	508	303	1016
35	60	594	351	1005	499	283	881	400	253	767
35	65	455	277	747	386	226	660	315	211	582
35	70	349	218	558	299	180	498	249	175	445
35	75	268	171	420	232	143	377	196	144	343
35	80	205	133	317	180	113	288	155	118	266
35	85	158	103	242	140	88	222	123	95	209
35	90	121	79	186	109	68	172	97	75	165
35	95	93	60	144	85	53	135	77	59	132
35	100	72	46	112	66	41	107	61	45	106
36	40	1292	678	2461	1047	522	2101	791	413	1758
36	45	988	540	1806	809	421	1553	621	346	1312
36	50	756	429	1329	625	339	1151	489	289	984
36	55	578	341	982	483	273	857	385	242	741
36	60	443	269	728	374	219	641	303	202	561
36	65	339	212	543	290	174	482	239	168	428
36	70	260	167	407	225	139	364	189	139	328
36	75	200	130	307	174	109	278	149	115	254
36	80	153	101	234	135	86	213	118	93	199
36	85	118	78	179	105	67	165	93	74	157
36	90	91	59	138	82	52	129	74	58	125
36	95	70	45	108	64	40	102	59	45	100
36	100	54	34	84	49	30	81	47	34	82
37	40	970	526	1788	790	408	1531	603	331	1287
37	45	742	418	1314	610	329	1133	474	277	963
37	50	567	332	969	472	265	842	373	232	724
37	55	435	263	717	365	212	628	294	194	547
37	60	333	208	534	283	170	471	232	162	416
37	65	255	163	399	219	135	355	183	135	318
37	70	196	128	300	170	107	270	144	112	245
37	75	150	99	228	132	84	207	114	91	191
37	80	116	77	174	102	66	160	90	73	150
37	85	89	59	134	80	51	124	72	58	119
37	90	68	45	104	62	39	98	57	45	96
37	95	53	34	81	48	30	77	45	34	78
37	100	40	26	64	38	23	62	36	26	63
38	40	734	410	1312	601	320	1127	463	267	952
38	45	561	326	966	464	258	836	364	224	714
38	50	430	259	714	359	208	622	287	188	538
38	55	329	204	530	278	166	466	226	157	408

DRY-BULB	HUMIDITY	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
38	60	252	161	395	216	133	350	178	131	311
38	65	194	126	297	167	105	265	141	109	239
38	70	149	98	224	130	83	203	111	90	186
38	75	114	76	171	101	65	156	88	73	145
38	80	88	59	131	78	51	121	70	58	115
38	85	67	45	102	61	39	95	55	45	92
38	90	52	34	79	47	30	75	44	34	74
38	95	40	26	62	37	23	60	35	26	61
38	100	31	19	49	29	17	48	28	19	50
39	40	559	322	972	460	253	837	358	216	711
39	45	428	255	717	356	204	622	282	182	535
39	50	328	202	531	276	163	465	222	152	405
39	55	251	160	396	214	131	349	175	127	308
39	60	193	125	296	165	104	264	138	106	236
39	65	148	98	223	128	82	201	109	88	182
39	70	114	76	170	100	65	154	86	72	142
39	75	87	59	130	77	50	119	68	58	112
39	80	67	45	100	60	39	93	54	45	89
39	85	52	34	78	47	30	73	43	35	72
39	90	40	26	61	36	23	58	34	26	58
39	95	31	19	48	28	17	47	27	20	48
39	100	24	14	38	22	13	37	22	15	39
40	40	429	253	728	355	201	628	279	176	537
40	45	329	201	538	275	161	468	220	148	405
40	50	252	159	400	213	129	351	173	124	307
40	55	193	125	298	165	103	264	137	104	235
40	60	148	98	224	128	82	200	108	87	181
40	65	114	76	170	99	64	153	85	71	141
40	70	87	59	130	77	50	118	68	58	110
40	75	67	45	100	60	39	92	54	46	88
40	80	52	34	77	47	30	72	42	35	70
40	85	40	26	61	36	23	57	34	27	57
40	90	31	20	48	28	17	46	27	20	46
40	95	24	15	38	22	13	37	21	15	38
40	100	18	11	30	17	10	30	17	11	32
41	40	332	201	549	276	160	476	219	144	409
41	45	254	159	407	214	128	356	173	121	310
41	50	195	125	303	166	103	267	136	102	236
41	55	149	98	227	128	82	202	108	85	181
41	60	115	77	172	100	64	154	85	71	140
41	65	88	59	131	77	51	118	67	58	110
41	70	68	46	100	60	39	92	53	46	87
41	75	52	35	77	47	30	72	42	36	69
41	80	40	27	60	36	23	57	33	27	56
41	85	31	20	47	28	18	45	27	20	45
41	90	24	15	37	22	13	36	21	15	37
41	95	18	11	30	17	10	29	17	11	31
41	100	14	8	24	13	8	24	13	9	26
42	40	258	159	419	216	128	364	173	119	315
42	45	198	126	311	167	103	273	136	100	239

DRY-BULB	HUMIDITY	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
42	50	152	99	233	130	82	206	108	84	183
42	55	116	77	175	101	65	156	85	70	141
42	60	89	60	133	78	51	120	67	58	110
42	65	69	46	101	61	40	92	53	47	86
42	70	53	36	78	47	31	72	42	36	69
42	75	41	27	61	37	24	57	33	28	55
42	80	31	21	48	29	18	45	27	21	45
42	85	24	15	38	22	14	36	21	16	37
42	90	19	12	30	17	10	29	17	12	30
42	95	14	9	24	14	8	23	13	9	25
42	100	11	6	19	11	6	19	11	7	21
43	40	202	127	322	170	103	281	137	98	244
43	45	155	100	240	132	82	211	108	82	186
43	50	119	79	180	102	65	160	86	69	143
43	55	91	61	136	79	51	122	68	57	111
43	60	70	47	104	61	40	94	54	47	87
43	65	54	36	80	48	31	73	42	37	69
43	70	41	28	62	37	24	57	34	29	55
43	75	32	21	48	29	19	45	27	22	44
43	80	25	16	38	23	14	36	21	16	36
43	85	19	12	30	18	11	29	17	12	30
43	90	15	9	24	14	8	23	13	9	25
43	95	11	7	19	11	6	19	11	7	20
43	100	9	5	15	8	5	15	8	5	17
44	40	159	102	249	134	83	218	110	81	191
44	45	122	80	187	104	66	165	87	68	146
44	50	94	63	140	81	52	125	68	57	113
44	55	72	49	107	63	41	96	54	47	88
44	60	55	37	82	49	32	74	43	38	69
44	65	42	29	63	38	25	58	34	29	55
44	70	33	22	49	29	19	46	27	22	44
44	75	25	16	38	23	15	36	21	17	36
44	80	19	12	30	18	11	29	17	13	30
44	85	15	9	24	14	8	23	14	9	24
44	90	12	7	19	11	6	19	11	7	20
44	95	9	5	15	8	5	15	9	5	17
44	100	7	4	12	7	4	13	7	4	14
45	40	126	82	195	107	67	171	88	67	151
45	45	97	64	146	83	53	130	70	56	116
45	50	74	50	111	64	42	99	55	47	90
45	55	57	39	84	50	33	76	44	38	71
45	60	44	30	65	39	25	59	34	30	56
45	65	34	23	50	30	20	46	27	23	45
45	70	26	17	39	24	15	37	22	17	36
45	75	20	13	31	18	11	29	17	13	30
45	80	15	10	24	14	9	24	14	10	24
45	85	12	7	19	11	7	19	11	7	20
45	90	9	5	16	9	5	15	9	5	17
45	95	7	4	12	7	4	13	7	4	14
45	100	5	3	10	5	3	10	6	3	12

DRY-BULB	HUMIDITY	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	J95
46	40	100	66	154	86	54	135	71	56	120
46	45	77	51	116	66	43	103	56	46	93
46	50	59	40	88	52	34	79	44	38	73
46	55	45	31	67	40	26	61	35	31	57
46	60	35	24	52	31	20	48	28	24	46
46	65	27	18	40	24	16	38	22	18	37
46	70	21	14	32	19	12	30	18	14	30
46	75	16	10	25	15	9	24	14	10	24
46	80	12	8	20	11	7	19	11	8	20
46	85	9	6	16	9	5	16	9	6	17
46	90	7	4	13	7	4	13	7	4	14
46	95	6	3	10	5	3	10	6	3	12
46	100	4	2	8	4	2	8	4	2	10
47	40	80	53	122	69	44	108	58	46	97
47	45	62	41	92	53	35	82	46	38	75
47	50	47	32	70	41	27	64	36	31	59
47	55	36	25	54	32	21	49	29	24	47
47	60	28	19	42	25	16	39	23	19	37
47	65	22	14	33	20	12	31	18	14	30
47	70	17	11	26	15	9	24	14	11	25
47	75	13	8	20	12	7	20	11	8	20
47	80	10	6	16	9	5	16	9	6	17
47	85	8	4	13	7	4	13	7	4	14
47	90	6	3	10	6	3	10	6	3	12
47	95	5	2	8	4	2	9	5	3	10
47	100	4	2	7	3	2	7	4	2	8
48	40	65	43	98	56	36	87	47	38	78
48	45	50	33	74	43	28	67	37	31	61
48	50	38	26	57	34	22	52	29	25	48
48	55	29	20	44	26	17	40	23	20	38
48	60	23	15	34	20	13	32	19	15	31
48	65	17	11	27	16	10	25	15	11	25
48	70	13	8	21	12	8	20	12	8	21
48	75	10	6	17	10	6	16	9	6	17
48	80	8	5	13	7	4	13	7	5	14
48	85	6	4	11	6	3	11	6	4	12
48	90	5	3	9	5	2	9	5	3	10
48	95	4	2	7	4	2	7	4	2	8
48	100	3	1	6	3	1	6	3	1	7
49	40	52	35	79	45	29	70	39	31	64
49	45	40	27	60	35	23	54	30	25	50
49	50	31	21	46	27	18	42	24	20	40
49	55	24	16	36	21	14	33	19	16	32
49	60	18	12	28	16	10	26	15	12	26
49	65	14	9	22	13	8	21	12	9	21
49	70	11	7	17	10	6	17	10	7	17
49	75	8	5	14	8	5	13	8	5	14
49	80	6	4	11	6	3	11	6	4	12
49	85	5	3	9	5	3	9	5	3	10
49	90	4	2	7	4	2	7	4	2	8

DRY-BULB	HUMIDITY	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
49	95	3	2	6	3	1	6	3	2	7
49	100	2	1	5	2	1	5	2	1	6
50	40	42	28	64	37	24	57	32	26	53
50	45	33	22	49	29	18	44	25	21	41
50	50	25	17	38	22	14	35	20	16	33
50	55	19	13	29	17	11	27	16	12	27
50	60	15	10	23	13	8	22	13	9	22
50	65	11	7	18	10	6	17	10	7	18
50	70	9	5	14	8	5	14	8	5	15
50	75	7	4	11	6	4	11	6	4	12
50	80	5	3	9	5	3	9	5	3	10
50	85	4	2	7	4	2	7	4	2	8
50	90	3	2	6	3	2	6	3	2	7
50	95	2	1	5	2	1	5	3	1	6
50	100	2	1	4	2	1	4	2	1	5

APPENDIX B

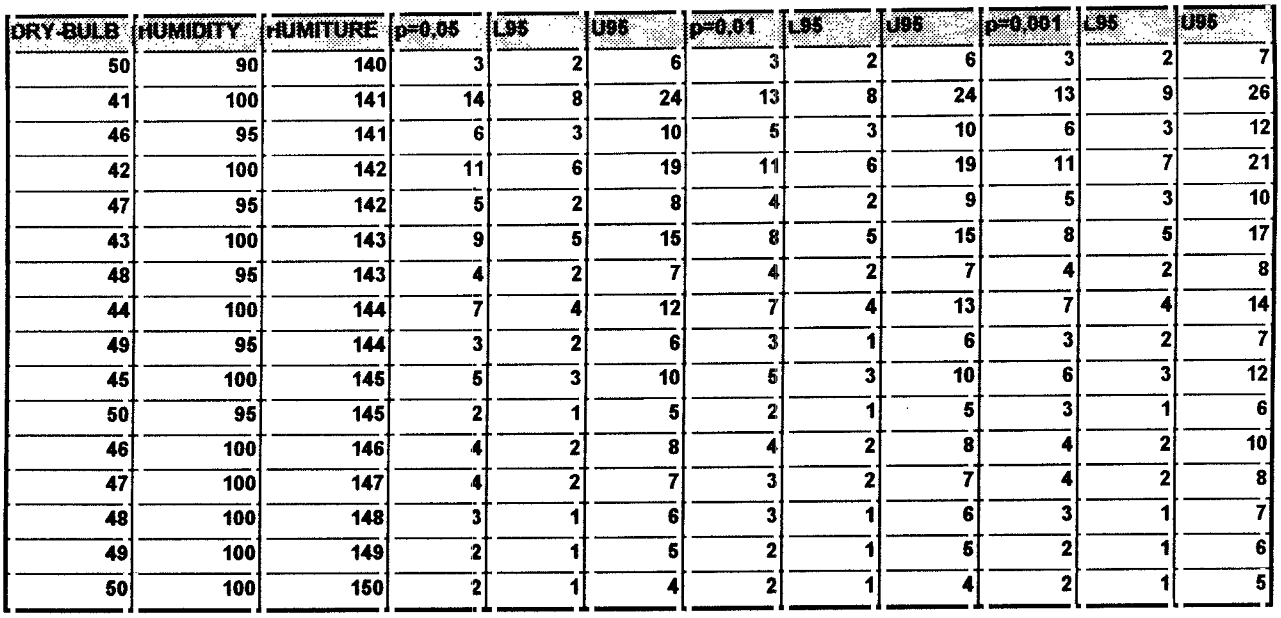
Tolerance time predictions using log(dry-bulb) and humidity; humiture is shown

DRY-BULB	HUMIDITY	HUMITURE	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
35	40	75	1736	880	3423	1399	671	2915	1046	518	2427
36	40	76	1292	678	2461	1047	522	2101	791	413	1758
37	40	77	970	526	1788	790	408	1531	603	331	1287
38	40	78	734	410	1312	601	320	1127	463	267	952
39	40	79	559	322	972	460	253	837	358	216	711
35	45	80	1326	701	2508	1080	542	2151	821	434	1809
40	40	80	429	253	728	355	201	628	279	176	537
36	45	81	988	540	1806	809	421	1553	621	346	1312
41	40	81	332	201	549	276	160	476	219	144	409
37	45	82	742	418	1314	610	329	1133	474	277	963
42	40	82	258	159	419	216	128	364	173	119	315
38	45	83	561	326	966	464	258	836	364	224	714
43	40	83	202	127	322	170	103	281	137	98	244
39	45	84	428	255	717	356	204	622	282	182	535
44	40	84	159	102	249	134	83	218	110	81	191
35	50	85	1014	558	1843	834	437	1591	645	363	1353
40	45	85	329	201	538	275	161	468	220	148	405
45	40	85	126	82	195	107	67	171	88	67	151
36	50	86	756	429	1329	625	339	1151	489	289	984
41	45	86	254	159	407	214	128	356	173	121	310
46	40	86	100	66	154	86	54	135	71	56	120
37	50	87	567	332	969	472	265	842	373	232	724
42	45	87	198	126	311	167	103	273	136	100	239
47	40	87	80	53	122	69	44	108	58	46	97
38	50	88	430	259	714	359	208	622	287	188	538
43	45	88	155	100	240	132	82	211	108	82	186
48	40	88	65	43	98	56	36	87	47	38	78
39	50	89	328	202	531	276	163	465	222	152	405
44	45	89	122	80	187	104	66	165	87	68	146
49	40	89	52	35	79	45	29	70	39	31	64
35	55	90	776	443	1359	645	352	1182	508	303	1016
40	50	90	252	159	400	213	129	351	173	124	307
45	45	90	97	64	146	83	53	130	70	56	116
50	40	90	42	28	64	37	24	57	32	26	53
36	55	91	578	341	982	483	273	857	385	242	741
41	50	91	195	125	303	166	103	267	136	102	236
46	45	91	77	51	116	66	43	103	56	46	93
37	55	92	435	263	717	365	212	628	294	194	547
42	50	92	152	99	233	130	82	206	108	84	183
47	45	92	62	41	92	53	35	82	46	38	75
38	55	93	329	204	530	278	166	466	226	157	408
43	50	93	119	79	180	102	65	160	86	69	143

DRY-BULB	HUMIDITY	HUMITURE	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
48	45	93	50	33	74	43	28	67	37	31	61
39	55	94	251	160	396	214	131	349	175	127	308
44	50	94	94	63	140	81	52	125	68	57	113
49	45	94	40	27	60	35	23	54	30	25	50
35	60	95	594	351	1005	499	283	881	400	253	767
40	55	95	193	125	298	165	103	264	137	104	235
45	50	95	74	50	111	64	42	99	55	47	90
50	45	95	33	22	49	29	18	44	25	21	41
36	60	96	443	269	728	374	219	641	303	202	561
41	55	96	149	98	227	128	82	202	108	85	181
46	50	96	59	40	88	52	34	79	44	38	73
37	60	97	333	208	534	283	170	471	232	162	416
42	55	97	116	77	175	101	65	156	85	70	141
47	50	97	47	32	70	41	27	64	36	31	59
38	60	98	252	161	395	216	133	350	178	131	311
43	55	98	91	61	136	79	51	122	68	57	111
48	50	98	38	26	57	34	22	52	29	25	48
39	60	99	193	125	296	165	104	264	138	106	236
44	55	99	72	49	107	63	41	96	54	47	88
49	50	99	31	21	46	27	18	42	24	20	40
35	65	100	455	277	747	386	226	660	315	211	582
40	60	100	148	98	224	128	82	200	108	87	181
45	55	100	57	39	84	50	33	76	44	38	71
50	50	100	25	17	38	22	14	35	20	16	33
36	65	101	339	212	543	290	174	482	239	168	428
41	60	101	115	77	172	100	64	154	85	71	140
46	55	101	45	31	67	40	26	61	35	31	57
37	65	102	255	163	399	219	135	355	183	135	318
42	60	102	89	60	133	78	51	120	67	58	110
47	55	102	36	25	54	32	21	49	29	24	47
38	65	103	194	126	297	167	105	265	141	109	239
43	60	103	70	47	104	61	40	94	54	47	87
48	55	103	29	20	44	26	17	40	23	20	38
39	65	104	148	98	223	128	82	201	109	88	182
44	60	104	55	37	82	49	32	74	43	38	69
49	55	104	24	16	36	21	14	33	19	16	32
35	70	105	349	218	558	299	180	498	249	175	445
40	65	105	114	76	170	99	64	153	85	71	141
45	60	105	44	30	65	39	25	59	34	30	56
50	55	105	19	13	29	17	11	27	16	12	27
36	70	106	260	167	407	225	139	364	189	139	328
41	65	106	88	59	131	77	51	118	67	58	110
46	60	106	35	24	52	31	20	48	28	24	46
37	70	107	196	128	300	170	107	270	144	112	245
42	65	107	69	46	101	61	40	92	53	47	86
47	60	107	28	19	42	25	16	39	23	19	37
38	70	108	149	98	224	130	83	203	111	90	186
43	65	108	54	36	80	48	31	73	42	37	69
48	60	108	23	15	34	20	13	32	19	15	31
39	70	109	114	76	170	100	65	154	86	72	142

DRY-BULB	HUMIDITY	HUMITURE	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
44	65	109	42	29	63	38	25	58	34	29	55
49	60	109	18	12	28	16	10	26	15	12	26
35	75	110	268	171	420	232	143	377	196	144	343
40	70	110	87	59	130	77	50	118	68	58	110
45	65	110	34	23	50	30	20	46	27	23	45
50	60	110	15	10	23	13	8	22	13	9	22
36	75	111	200	130	307	174	109	278	149	115	254
41	70	111	68	46	100	60	39	92	53	46	87
46	65	111	27	18	40	24	16	38	22	18	37
37	75	112	150	99	228	132	84	207	114	91	191
42	70	112	53	36	78	47	31	72	42	36	69
47	65	112	22	14	33	20	12	31	18	14	30
38	75	113	114	76	171	101	65	156	88	73	145
43	70	113	41	28	62	37	24	57	34	29	55
48	65	113	17	11	27	16	10	25	15	11	25
39	75	114	87	59	130	77	50	119	68	58	112
44	70	114	33	22	49	29	19	46	27	22	44
49	65	114	14	9	22	13	8	21	12	9	21
35	80	115	205	133	317	180	113	288	155	118	266
40	75	115	67	45	100	60	39	92	54	46	88
45	70	115	26	17	39	24	15	37	22	17	36
50	65	115	11	7	18	10	6	17	10	7	18
36	80	116	153	101	234	135	86	213	118	93	199
41	75	116	52	35	77	47	30	72	42	36	69
46	70	116	21	14	32	19	12	30	18	14	30
37	80	117	116	77	174	102	66	160	90	73	150
42	75	117	41	27	61	37	24	57	33	28	55
47	70	117	17	11	26	15	9	24	14	11	25
38	80	118	88	59	131	78	51	121	70	58	115
43	75	118	32	21	48	29	19	45	27	22	44
48	70	118	13	8	21	12	8	20	12	8	21
39	80	119	67	45	100	60	39	93	54	45	89
44	75	119	25	16	38	23	15	36	21	17	36
49	70	119	11	7	17	10	6	17	10	7	17
35	85	120	158	103	242	140	88	222	123	95	209
40	80	120	52	34	77	47	30	72	42	35	70
45	75	120	20	13	31	18	11	29	17	13	30
50	70	120	9	5	14	8	5	14	8	5	15
36	85	121	118	78	179	105	67	165	93	74	157
41	80	121	40	27	60	36	23	57	33	27	56
46	75	121	16	10	25	15	9	24	14	10	24
37	85	122	89	59	134	80	51	124	72	58	119
42	80	122	31	21	48	29	18	45	27	21	45
47	75	122	13	8	20	12	7	20	11	8	20
38	85	123	67	45	102	61	39	95	55	45	92
43	80	123	25	16	38	23	14	36	21	16	36
48	75	123	10	6	17	10	6	16	9	6	17
39	85	124	52	34	78	47	30	73	43	35	72
44	80	124	19	12	30	18	11	29	17	13	30
49	75	124	8	5	14	8	5	13	8	5	14

DRY-BULB	HUMIDITY	HUMITURE	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
35	90	125	121	79	186	109	68	172	97	75	165
40	85	125	40	26	61	36	23	57	34	27	57
45	80	125	15	10	24	14	9	24	14	10	24
50	75	125	7	4	11	6	4	11	6	4	12
36	90	126	91	59	138	82	52	129	74	58	125
41	85	126	31	20	47	28	18	45	27	20	45
46	80	126	12	8	20	11	7	19	11	8	20
37	90	127	68	45	104	62	39	98	57	45	96
42	85	127	24	15	38	22	14	36	21	16	37
47	80	127	10	6	16	9	5	16	9	6	17
38	90	128	52	34	79	47	30	75	44	34	74
43	85	128	19	12	30	18	11	29	17	12	30
48	80	128	8	5	13	7	4	13	7	5	14
39	90	129	40	26	61	36	23	58	34	26	58
44	85	129	15	9	24	14	8	23	14	9	24
49	80	129	6	4	11	6	3	11	6	4	12
35	95	130	93	60	144	85	53	135	77	59	132
40	90	130	31	20	48	28	17	46	27	20	46
45	85	130	12	7	19	11	7	19	11	7	20
50	80	130	5	3	9	5	3	9	5	3	10
36	95	131	70	45	108	64	40	102	59	45	100
41	90	131	24	15	37	22	13	36	21	15	37
46	85	131	9	6	16	9	5	16	9	6	17
37	95	132	53	34	81	48	30	77	45	34	78
42	90	132	19	12	30	17	10	29	17	12	30
47	85	132	8	4	13	7	4	13	7	4	14
38	95	133	40	26	62	37	23	60	35	26	61
43	90	133	15	9	24	14	8	23	13	9	25
48	85	133	6	4	11	6	3	11	6	4	12
39	95	134	31	19	48	28	17	47	27	20	48
44	90	134	12	7	19	11	6	19	11	7	20
49	85	134	5	3	9	5	3	9	5	3	10
35	100	135	72	46	112	66	41	107	61	45	106
40	95	135	24	15	38	22	13	37	21	15	38
45	90	135	9	5	16	9	5	15	9	5	17
50	85	135	4	2	7	4	2	7	4	2	8
36	100	136	54	34	84	49	30	81	47	34	82
41	95	136	18	11	30	17	10	29	17	11	31
46	90	136	7	4	13	7	4	13	7	4	14
37	100	137	40	26	64	38	23	62	36	26	63
42	95	137	14	9	24	14	8	23	13	9	25
47	90	137	6	3	10	6	3	10	6	3	12
38	100	138	31	19	49	29	17	48	28	19	50
43	95	138	11	7	19	11	6	19	11	7	20
48	90	138	5	3	9	5	2	9	5	3	10
39	100	139	24	14	38	22	13	37	22	15	39
44	95	139	9	5	15	8	5	15	9	5	17
49	90	139	4	2	7	4	2	7	4	2	8
40	100	140	18	11	30	17	10	30	17	11	32
45	95	140	7	4	12	7	4	13	7	4	14



DRY-BULB	rHUMIDITY	rHUMITURE	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
50	90	140	3	2	6	3	2	6	3	2	7
41	100	141	14	8	24	13	8	24	13	9	26
46	95	141	6	3	10	5	3	10	6	3	12
42	100	142	11	6	19	11	6	19	11	7	21
47	95	142	5	2	8	4	2	9	5	3	10
43	100	143	9	5	15	8	5	15	8	5	17
48	95	143	4	2	7	4	2	7	4	2	8
44	100	144	7	4	12	7	4	13	7	4	14
49	95	144	3	2	6	3	1	6	3	2	7
45	100	145	5	3	10	5	3	10	6	3	12
50	95	145	2	1	5	2	1	5	3	1	6
46	100	146	4	2	8	4	2	8	4	2	10
47	100	147	4	2	7	3	2	7	4	2	8
48	100	148	3	1	6	3	1	6	3	1	7
49	100	149	2	1	5	2	1	5	2	1	6
50	100	150	2	1	4	2	1	4	2	1	5

APPENDIX C

Tolerance times predictions based on WBGT

WBGT	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	L95	U95
30.00	316	243	388	277	212	343	241	181	301
31.00	268	208	328	236	182	289	204	155	254
32.00	225	175	275	197	152	243	171	129	213
33.00	186	142	230	163	124	203	141	105	177
34.00	151	111	192	132	96	169	114	81	148
35.00	121	82	160	106	70	141	91	59	123
36.00	94	56	133	82	47	117	71	39	103
37.00	72	33	111	63	28	98	54	22	86
38.00	54	15	93	47	12	82	41	8	73
39.00	40	1	79	35	0	70	30	-2	62
40.00	30	-8	69	27	-8	61	23	-9	55
41.00	25	-15	64	22	-13	57	20	-13	52
42.00	23	-18	65	21	-16	58	19	-15	54

APPENDIX D

Tolerance times predictions based on DI

DI	p=0,05	L95	U95	p=0,01	L95	U95	p=0,001	.95	J95
30	293	184	403	260	167	353	227	149	306
31	258	165	351	228	150	307	200	133	266
32	226	146	305	199	132	267	174	117	230
33	195	125	266	172	113	232	150	100	200
34	168	104	232	148	93	202	128	82	174
35	143	81	204	125	73	177	108	65	152
36	120	60	180	105	54	155	91	48	133
37	100	40	159	87	36	137	75	32	117
38	82	22	142	71	21	122	61	19	104
39	67	7	127	58	7	108	50	7	92
40	54	-5	113	47	-3	97	40	-2	82
41	44	-15	103	38	-12	88	33	-9	75
42	36	-23	95	31	-18	81	27	-15	69
43	31	-29	90	27	-24	77	24	-19	66
44	28	-35	91	25	-28	78	22	-22	67
45	28	-42	97	25	-33	84	23	-26	72

APPENDIX E

PREDICTED TOLERANCE TIME (MINUTES) USING LOG(DRY-BULB) AND HUMIDITY

PROBABILITY P=0,05

DRY-BULB	RELATIVE HUMIDITY (%)												
°C	100	95	90	85	80	75	70	65	60	55	50	45	40
30	**354**	**461**	**601**	**784**	**1023**	**1336**	**1745**	**2282**	**2986**	**3909**	**5120**	**6711**	**8802**
31	**252**	**328**	**427**	**557**	**726**	**948**	**1238**	**1618**	**2116**	**2769**	**3625**	**4749**	**6226**
32	**181**	**236**	**307**	**400**	**522**	**680**	**888**	**1160**	**1517**	**1984**	**2596**	**3399**	**4454**
33	**132**	**171**	**223**	**290**	**379**	**494**	**644**	**841**	**1099**	**1437**	**1879**	**2460**	**3221**
34	**97**	**126**	164	213	278	362	472	616	804	1051	1374	1798	2353
35	**72**	**93**	121	158	205	268	349	455	594	776	1014	1326	1736
36	**54**	**70**	91	118	153	200	260	339	443	578	756	988	1292
37	**40**	**53**	68	89	116	150	196	255	333	435	567	742	970
38	**31**	**40**	52	67	88	114	149	194	252	329	430	561	734
39	**24**	**31**	40	52	67	87	114	148	193	251	328	428	559
40	**18**	**24**	31	40	52	67	87	114	148	193	252	329	429
41	**14**	**18**	24	31	40	52	68	88	115	149	195	254	332
42	**11**	**14**	19	24	31	41	53	69	89	116	152	198	258
43	**9**	**11**	15	19	25	32	41	54	70	91	119	155	202
44	**7**	**9**	12	15	19	25	33	42	55	72	94	122	159
45	**5**	**7**	9	12	15	20	26	34	44	57	74	97	126
46	**4**	**6**	7	9	12	16	21	27	35	45	59	77	100
47	**4**	**5**	6	8	10	13	17	22	28	36	47	62	80
48	**3**	**4**	5	6	8	10	13	17	23	29	38	50	65
49	**2**	**3**	4	5	6	8	11	14	18	24	31	40	52
50	**2**	**2**	3	4	5	7	9	11	15	19	25	33	42

APPENDIX F

PREDICTED TOLERANCE TIME (MINUTES) USING LOG(DRY-BULB) AND HUMIDITY

PROBABILITY P=0,01

DRY-BULB	RELATIVE HUMIDITY (%)												
°C	100	95	90	85	80	75	70	65	60	55	50	45	40
30	314	404	521	673	869	1122	1452	1879	2433	3153	4089	5307	6893
31	225	289	373	481	621	802	1036	1340	1735	2247	2913	3778	4904
32	163	210	270	348	449	579	748	967	1251	1620	2099	2721	3529
33	119	153	197	254	328	423	546	705	912	1180	1528	1980	2567
34	88	113	146	188	242	312	402	520	672	868	1124	1455	1886
35	66	85	109	140	180	232	299	386	499	645	834	1080	1399
36	49	64	82	105	135	174	225	290	374	483	625	809	1047
37	38	48	62	80	102	132	170	219	283	365	472	610	790
38	29	37	47	61	78	101	130	167	216	278	359	464	601
39	22	28	36	47	60	77	100	128	165	214	276	356	460
40	17	22	28	36	47	60	77	99	128	165	213	275	355
41	13	17	22	28	36	47	60	77	100	128	166	214	276
42	11	14	17	22	29	37	47	61	78	101	130	167	216
43	8	11	14	18	23	29	37	48	61	79	102	132	170
44	7	8	11	14	18	23	29	38	49	63	81	104	134
45	5	7	9	11	14	18	24	30	39	50	64	83	107
46	4	5	7	9	11	15	19	24	31	40	52	66	86
47	3	4	6	7	9	12	15	20	25	32	41	53	69
48	3	4	5	6	7	10	12	16	20	26	34	43	56
49	2	3	4	5	6	8	10	13	16	21	27	35	45
50	2	2	3	4	5	6	8	10	13	17	22	29	37

APPENDIX G

PREDICTED TOLERANCE TIME (MINUTES) USING LOG(DRY-BULB) AND HUMIDITY
PROBABILITY P=0,001

RY-BULB	RELATIVE HUMIDITY (%)												
°C	100	95	90	85	80	75	70	65	60	55	50	45	40
30	**274**	**346**	**438**	**555**	**704**	**894**	**1136**	**1445**	**1840**	**2346**	**2992**	**3820**	**4883**
31	**199**	**251**	**318**	**402**	**510**	**647**	**821**	**1044**	**1328**	**1691**	**2156**	**2751**	**3513**
32	**146**	**184**	**233**	**295**	**373**	**473**	**600**	**762**	**969**	**1233**	**1571**	**2003**	**2556**
33	**108**	**136**	**172**	**218**	**276**	**349**	**443**	**562**	**715**	**909**	**1157**	**1474**	**1879**
34	**81**	**102**	129	163	206	261	330	419	532	676	860	1095	1395
35	**61**	**77**	97	123	155	196	249	315	400	508	645	821	1046
36	**47**	**59**	74	93	118	149	189	239	303	385	489	621	791
37	**36**	**45**	57	72	90	114	144	183	232	294	373	474	603
38	**28**	**35**	44	55	70	88	111	141	178	226	287	364	463
39	**22**	**27**	34	43	54	68	86	109	138	175	222	282	358
40	**17**	**21**	27	34	42	54	68	85	108	137	173	220	279
41	**13**	**17**	21	27	33	42	53	67	85	108	136	173	219
42	**11**	**13**	17	21	27	33	42	53	67	85	108	136	173
43	**8**	**11**	13	17	21	27	34	42	54	68	86	108	137
44	**7**	**9**	11	14	17	21	27	34	43	54	68	87	110
45	**6**	**7**	9	11	14	17	22	27	34	44	55	70	88
46	**4**	**6**	7	9	11	14	18	22	28	35	44	56	71
47	**4**	**5**	6	7	9	11	14	18	23	29	36	46	58
48	**3**	**4**	5	6	7	9	12	15	19	23	29	37	47
49	**2**	**3**	4	5	6	8	10	12	15	19	24	30	39
50	**2**	**3**	3	4	5	6	8	10	13	16	20	25	32

PART TWO

AN EVALUATION OF THE EFFECTIVENESS OF COMMERCIALLY AVAILABLE BODY COOLING GARMENTS

1. INTRODUCTION

High environmental temperatures encountered by mine workers during emergency situations may cause severe physiological strain even to the extent of jeopardising rescue and recovery missions. Several cases have been reported where rescue and recovery teams were forced to drastically shorten their operation time because of severe exhaustion due to heat stress. Heat stroke deaths have, in fact, been recorded under such circumstances.

As a countermeasure, several types of cooling garments have been developed in recent years and, in general, the operational principle is to provide a cool micro-environment around the wearer to facilitate the removal of metabolic heat from his body. Available micro-climate cooling systems can range from approaches as simple as an ice vest, prefrozen and worn under the clothing, to more complex systems where special fluids are mechanically pumped and circulated through thin tubes running throughout the garment [3].

For a number of practical considerations, self-contained systems with frozen water or solid carbon dioxide ('dry-ice') as coolant have been used in the South African mining industry [6, 7]. These garments have been shown to be effective in alleviating heat stress encountered by wearers at temperatures normally experienced underground and subjective observations also indicated a marked benefit. However, the 'dry-ice' system is presently viable only if deployed for mass heat acclimatization. In view of the introduction of Heat Stress Management as a more cost-effective alternative, this option is therefore no longer viable unless the technology can be modified for small scale applications.

The present study was undertaken to establish the protective properties of commercially available body cooling garments during work in abnormally high temperatures. These garments are particularly attractive, at least in principle, because of the ease of providing infrastructural support.

2. METHODS

2.1 Subjects

A total of 130 randomly selected mine workers volunteered for the study on the basis of informed consent. These men were considered to be inherently heat tolerant in as far as they had successfully completed a heat tolerance test [1, 5] or the standard climatic room acclimatisation procedure on a gold mine [1]. On the basis of their physical characteristics

(Table 1) the subjects could be considered to be representative of the general mining population [4, 5].

Table 1 PHYSICAL CHARACTERISTICS OF SUBJECTS (n = 130)

Measurement	Mean	Standard Deviation	Range
Age (years)	35,24	6,06	21 - 56
Mass (kg)	69,23	10,45	51,05 - 99,95
Height (m)	1,72	0,02	1,57 - 1,89
Body Fat (%)	15,62	5,00	6,81 - 32,63

2.2 Body Cooling Garments

Four commercially available garments were evaluated.

2.2.1 Jacket A

The Supreme Protector Cool Vest C - 140 is a poncho-type garment. It is fitted with four insulated pockets (two in front and two on the back) with Velcro closures, which hold 0,5 kg frozen Supreme Protector Gel Packs. The chemical composition of the gel used has not been divulged to Miningtek. The C - 140 comes in one size and has two Velcro straps to tighten it around the upper body. The total mass of the jacket and coolant is 2,52 kg. Expended gel packs can be refrozen for reuse.

2.2.2 Jacket B

The SteeleVest has six pockets (three in front, three on the back) with Velcro closures, which hold six frozen gel packs. The gel packs contain mainly a cornstarch and water mixture. The vest has a cotton canvas shell and the pockets are externally isolated. In the present evaluation, 0,75 kg packs were used, making the total mass of the system 5,15 kg (4,5 kg of gel packs plus the vest). The vest comes in one size only and two Velcro straps are used to tighten the vest around the torso. The gel packs can be refrozen for further usage.

2.2.3 Jacket C

Jacket C was also a Supreme Protector Cool Vest C - 140 and the design features are identical to that of Jacket A. Jacket C, however, uses four "frozen" Supreme Protector Powder Packs, containing silica sand as coolant. The total mass of the system is 1,72 kg (1,2 kg of coolant plus the vest). Expended power packs can be refrozen.

2.2.4 Jacket D

Jacket D was a poncho-type vest used on mines for purposes of microclimate acclimatization. Adjustments by means of tie-strings attached to the sides of the vest allow a comfortable fit for most individuals. This jacket was included in the study since it had been used in several instances to protect workers exposed to abnormally hot environments on mines.

Cooling was achieved by means of solid carbon dioxide ('dry-ice') blocks fitted into four pockets (two in front and two at the back) of the vest. The total mass of the garment plus the dry-ice blocks was approximately 5 kg.

2.3 Procedures

The subjects were allocated randomly to 10 experimental groups and each group was exposed in a climatic room to one of the test conditions given in Table 2. All the subjects underwent a medical examination and the actual heat exposure, under close supervision, took place between 08h00 and 13h00.

Table 2 EXPERIMENTAL CONDITIONS

Group	n	External Work Rate (W)	Temperature (^{0}C)		Protection
			WB	DB	
1	15	54	35,0	45,0	None
2	15	54	35,0	45,0	Jacket A
3	15	54	35,0	45,0	Jacket B
4	10	54	35,0	45,0	Jacket C
5	10	54	35,0	45,0	Jacket D
6	15	54	37,5	45,0	None
7	15	54	37,5	45,0	Jacket A
8	15	54	37,5	45,0	Jacket B
9	10	54	37,5	45,0	Jacket C
10	10	54	37,5	45,0	Jacket D

The subjects were required to perform four hours of continuous bench-stepping at an external work rate of 54 W. During all the heat exposures wind velocity was controlled at between 0,3 and 0,5 m.sec.

Two control groups (Groups 1 and 6) wore only athletic shorts during the course of the experiment while the other groups donned the body cooling garments on entering the climatic room. Subjects were encouraged to drink water during the heat exposures to prevent significant dehydration.

Rectal temperature was measured at one-minute intervals by means of a fine wire copper constantan thermocouple inserted 8 cm beyond the anal sphinter.

Any subject who complained of exhaustion or fatigue, or who showed any early sign or symptom of heat illness, was withdrawn from the climatic room. The same procedure was followed in the case of subjects who registered rectal temperatures of 39,5 ^{0}C or above.

3. RESULTS AND DISCUSSION

The extent of protection afforded by the respective cooling garments was assessed by comparing tolerance times while wearing body cooling garments with those recorded during unprotected exposure. Tolerance time was defined as the time period between the commencement of work in heat and the termination of heat exposure, either as result of withdrawal from the climatic room or on successful completion of the test.

The relevant tolerance times pertaining to the two test environments used are given in Tables 3 and 4, and the means for the different environments and jackets are plotted in Figure 1.

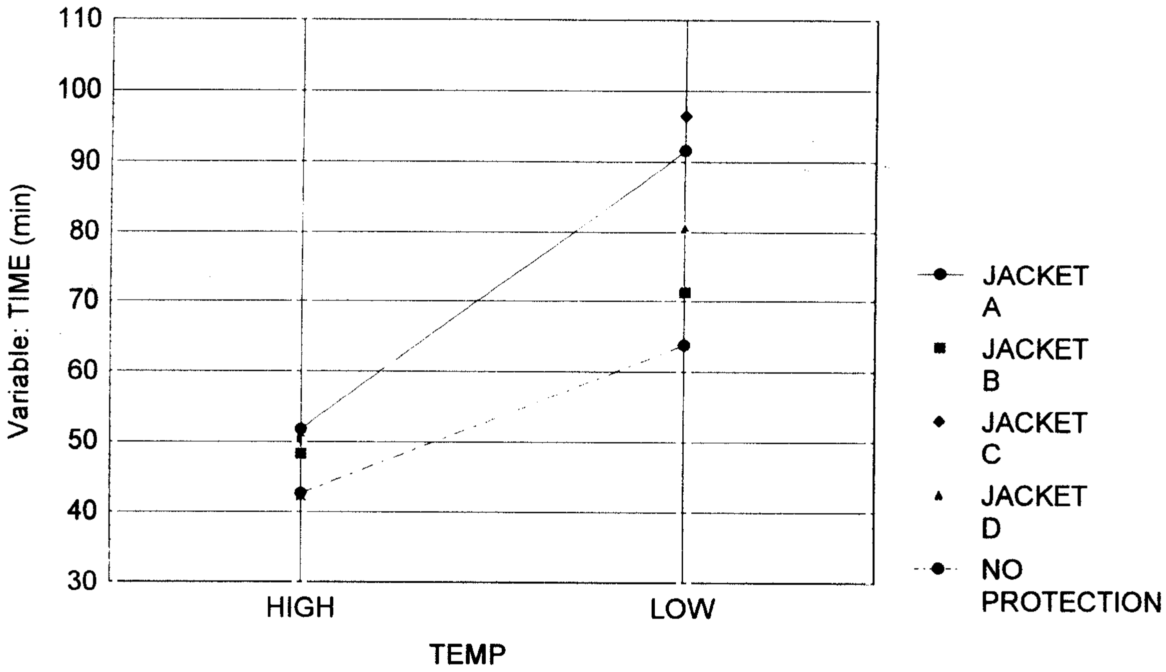


Figure 1: Plot of means, two-way interaction: F(4,109)=3,87;p<,0056

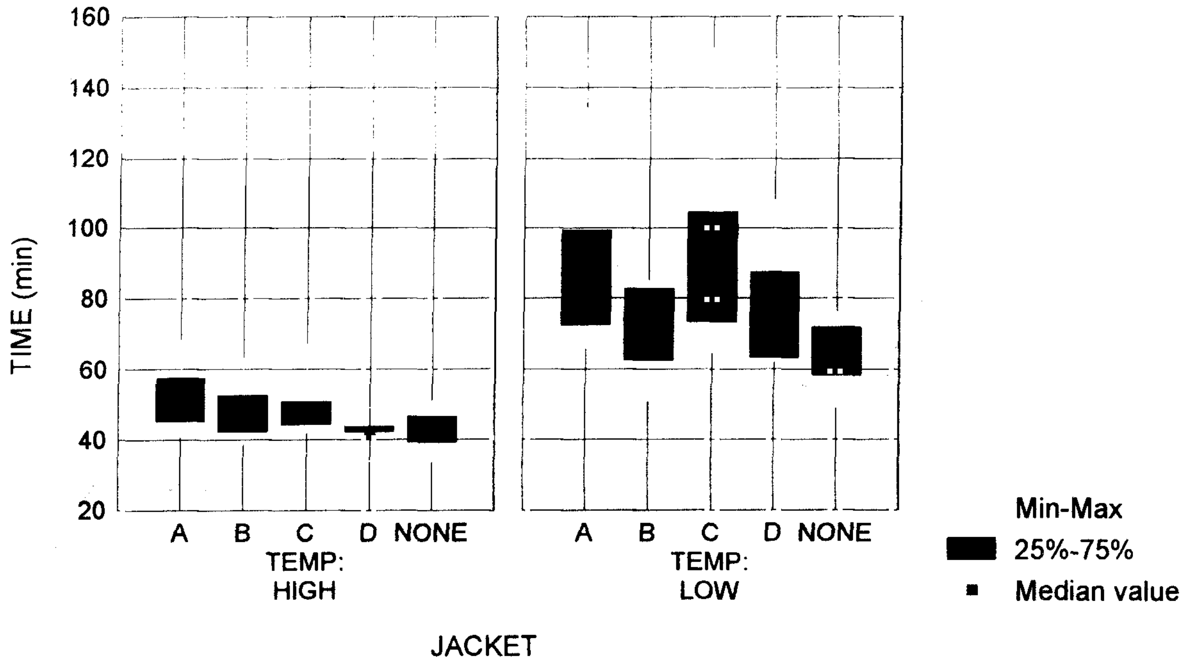


Figure 2: Categorized plot for variable TIME

Table 3 TOLERANCE TIMES (MINUTES) AT 35,0 ^{0}C WET-BULB AND 45,0 ^{0}C DRY-BULB AT A WORK RATE OF 54 W

STATISTIC	CONTROL GROUP	JACKET			
		A	B	C	D
N	11	14	15	9	9
MEAN	63,7	91,5	71,3	96,4	80,5
S.D.	9,1	20,5	11,9	29,5	16,8
MIN	49	66	51	65	62
MAX	76	134	85	151	108

From the data contained in Tables 3 and 4 and graphically displayed in Figure 1, it is evident that there is an interaction between the jackets and the two test environments. For example, at the relatively higher test condition (Table 4), the group wearing Jacket B has an average tolerance time higher than that for the group wearing Jacket D and for the control group. However, at the relatively lower test condition (Table 3) the group wearing Jacket B has a tolerance time lower than that for the group wearing Jacket D and almost identical to that pertaining to the control group. The differences in the variation between the two test environments are further highlighted in the categorized box plots for variable time (Figure 2).

Table 4 TOLERANCE TIMES (MINUTES) AT 37.5 ^{0}C WET-BULB AND 45,0 ^{0}C DRY-BULB AT A WORK RATE OF 54 W

STATISTIC	CONTROL GROUP	JACKET			
		A	B	C	D
N	14	15	15	10	7
MEAN	42,6	51,8	48,2	50,4	42,4
S.D.	5,4	7,6	6,9	7,2	4,5
MIN	34	41	39	42	34
MAX	51	68	63	67	49

The nonparametric Mann-Whitney U test was used for pairwise comparisons for each of the test environments. This test is based on ranks (thus not affected by variance hetrogeneity or extreme values) and is the most powerful of the nonparametric tests for two-group comparisons. The results obtained are given in Table 5.

Table 5 RESULTS OF THE PAIRWISE MANN-WHITNEY U TESTS

HIGH Wet-bulb: 37,5 °C Dry-bulb: 45,0 °C					
Jackets	A	B	C	D	CONTROL GROUP
A		0,184	0,617	0,008	0,002
B			0,358	0,069	0,037
C				0,010	0,007
D					0,819
LOW Wet-bulb: 35,0 °C Dry-bulb: 45,0 °C					
Jackets	A	B	C	D	CONTROL GROUP
A		0,008	0,874	0,165	0,0003
B			0,021	0,208	0,767
C				0,185	0,002
D					0,027

From the results in Table 5 it is evident that for the higher test condition the tolerance times for the groups wearing Jackets A, B and C are significantly higher than that pertaining to the control group. No significant difference could be shown between the tolerance times of the control group and the group wearing Jacket D. For the lower test environment the tolerance times of groups wearing Jackets A, C and D are significantly higher than that pertaining to the control group. Thus, in both test environments Jackets A and C showed the same trend while Jackets B and D do not.

On basis of the above it is concluded that Jackets A and C are the best performing jackets for both test environments. Under conditions of this study, however, neither cooling system fully demonstrated an advantage over the other system and it is not possible to identify a preference between Jackets A and C.

The increase in tolerance times to work in heat while wearing the respective body cooling garments is summarized in Table 6 and graphically displayed in Figure 3 and Figure 4.

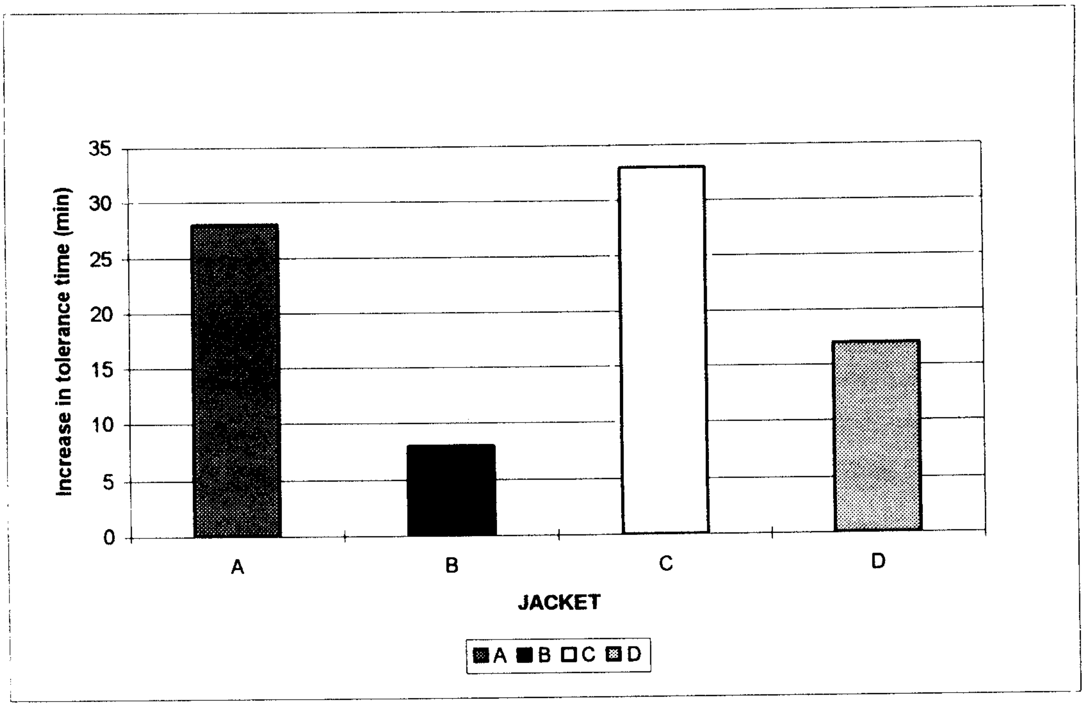


Figure 3: Increase in mean tolerance time with cooling jackets at 35,0 ^{0}C wet-bulb and 40,0 ^{0}C dry-bulb

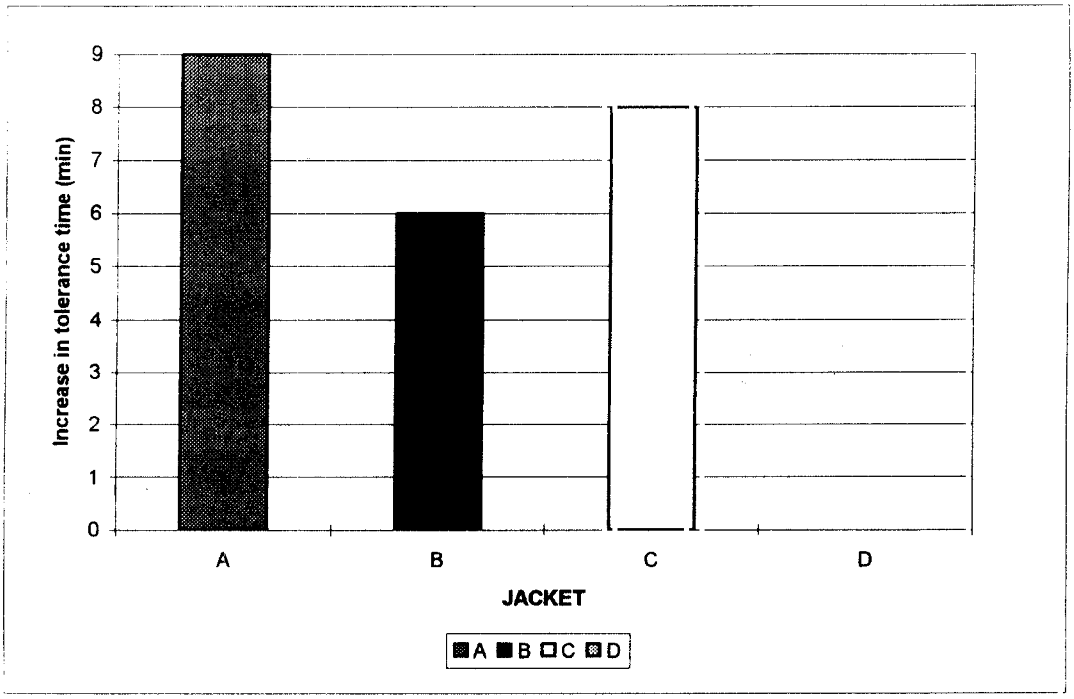


Figure 4: Increase in mean tolerance time with cooling jackets at 37,5 ^{0}C wet-bulb and 40,0 ^{0}C dry-bulb

Table 6 INCREASE IN MEAN TOLERANCE TIME WITH COOLING JACKETS

TEST CONDITIONS	INCREASE IN TOLERANCE TIME							
	JACKET A		JACKET B		JACKET C		JACKET D	
	min	%	min	%	min	%	min	%
LOW: 35,0 ^{0}C wet-bulb 40,0 ^{0}C dry-bulb	28	44	8	12	33	51	17	26
HIGH: 37,5 ^{0}C wet-bulb 40,0 ^{0}C dry-bulb	9	21	6	13	8	18	0	0

On average the increase in tolerance time at the relatively cooler test conditions was approximately 30 minutes for Jackets A and C, and 12 and 17 minutes for Jackets B and D, respectively. At the higher test condition the increases in tolerance times were almost identical for Jackets A, B and C, being 9, 6 and 8 minutes, respectively. In terms of an increase in tolerance time Jacket D afforded no advantage. The fact that all the jackets were less successful in reducing heat strain at the higher heat load is in line with findings from other studies [8] which suggest that, under milder environmental conditions, the differences between cooling and noncooling garments are more prominent.

Jackets A and C were evaluated for wearer acceptability by rescue brigadesmen at the Rescue Training Service training gallery. The men performed simulated rescue operations in breathing apparatus while wearing the body cooling garment. Feedback received from these men indicated a good measure of acceptance and that the jackets did not hinder them in the execution of their duties. Individuals who were also involved in an earlier evaluation of a poncho-type dry-ice jacket preferred the design of the current jackets. The relatively poor performance of the 'dry-ice' jacket, despite the superior cooling power of 'dry-ice', is ascribed to the particular purpose and design of this garment, i.e. to prevent excessive elevations in body temperature thus permitting safe heat acclimatization while on normal work routines.

4. CONCLUSIONS

In absolute terms it may well be concluded that commercially available body cooling garments do not provide meaningful protection under conditions where heat stress is likely to be 'severe'. However, in terms of heat stroke prevention, which is usually associated with permanent organ/tissue damage and high mortality, the amount of protection conferred by these jackets should be regarded as 'crucial' rather than 'negligible'. Moreover, subjective comfort should not be discounted.

The general conclusion which emerges is two-fold, namely that :

(a) body cooling garments should be considered as standard protective gear for emergencies in high heat stress conditions, and
(b) further research and development should be undertaken to explore the possibilities of improved body cooling garments, obviously with cost-effectiveness as a major criterion, in collaboration with selected manufacturers.

5. ACKNOWLEDGEMENTS

The assistance and co-operation of the managements from E.R.P.M. and Western Areas gold mines, and Rescue Training Services are acknowledged.

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PART THREE

GUIDELINES FOR THE PERFORMANCE OF EMERGENCY WORK IN HOT ENVIRONMENTS

1. INTRODUCTION

Part three of this report is intended to provide a framework for the formulation of guidelines for the protection of employees who, as a result of an emergency of one kind or another, are likely to be exposed to excessively hot environments. Where relevant some background is given and certain recommendations have also been included, in particular with regard to further investigation.

2. STATUS OF THESE GUIDELINES

Operations normally covered by mines' codes of practice, and approved by the Regional Mining Engineer in terms of Regulation 10.12 of the Minerals Act, are excluded because such work is deemed to be 'routine'. These guidelines apply to emergency (non-routine) work only and embrace all mines, including those generally held to be 'cool' (i.e. wet-bulb temperature of < 27,5 °C with the dry-bulb not exceeding 37,0 °C) and where the prescriptions of Regulation 10.12 do not apply.

Secondly, many mines have standards in respect of emergency work in hot environments. These standards are mine-specific and the present guidelines should therefore be viewed as complementary and not necessarily as superseding existing in-house standards or managerial instructions.

The guidelines presented are based on sound scientific investigation and the data have been subjected to rigorous statistical analysis. The intention is to present these findings to the international scientific community through appropriate forums in order to gain independent support and recognition in an area of employee protection which is largely without precedent.

The basic approach taken in establishing tolerance times has been conservative. This permits the degree of flexibility required to translate controlled laboratory simulations into practical application. Therefore, in the interests of convenience, slight discrepancies exist between experimental findings and the recommendations contained in the guidelines. In most instances these discrepancies closely observe the stated risk factor ($< 10^{-3}$ to exceed a body core/rectal temperature of 39,5 ^{0}C) but under no circumstances were 95 % confidence limits exceeded. These guidelines should therefore not be interpreted as a literal translation of the experimental findings.

3. ASSESSMENT OF THE ENVIRONMENT

In the interest of simplicity it is suggested that action levels be based on wet- and dry-bulb temperatures using a whirling hygrometer. The environmental heat load is expressed as the arithmetic mean, i.e. an index which has its origins in the Israeli Discomfort Index (DI) but which has been substantially modified to the Emergency Heat Stress Index (EHSI).

It is accepted that whirling hygrometers have a number of drawbacks (e.g. cumbersome to use, fragile, not always easy to read) but at present there are no alternatives which combine easy read-out capabilities, accuracy and mine-worthiness. (Preliminary studies conducted on a Polish instrument revealed poor accuracy and response time to changing conditions, as well as unacceptable interunit variation.)

With improved instrumentation, assuming reasonable unit costs and maintenance, the option exists to read off tolerance times for given dry-bulb temperature and relative humidity combinations. Appendix G (Part Two, p. 39) provides an example and is, in fact, the format used by the German Grubenrettungswesen. It is therefore suggested that the feasibility of instrumentation appropriate to the quantification of environmental heat loads during emergencies be investigated in some detail.

Sophisticated instruments, measuring also radiant heat and air speed, as well as converting these measurements to various indices, are not required.

In calculating the EHSI it is recommended that **all** fractions of a degree be rounded **up**. For example, if

dry-bulb = 38,2 °C
wet-bulb = 34,5 °C

then

EHSI = (39 + 35)/2
= 37 °C.

4. SPECIAL PRECAUTIONS

4.1 Supervision

Any operation regarded as 'non-routine' or as an emergency, and complicated by heat, should be undertaken only under close supervision of line management. The responsible person thus appointed should be assisted in his decisions by the environmental control manager/supervisor.

An important element of overall responsibility should be directed towards the early detection of the onset of overt fatigue and heat disorders. Proper instruction is therefore indicated.

4.2 Selection of the Task Force

The task force should consist of rescue brigadesmen or employees who have been screened or tested for heat tolerance or heat acclimatized by conventional climatic chamber procedures or by virtue of natural underground acclimatization.

The task force should not be constituted from employees already engaged in work in hot environments but most preferably from individuals who have rested since the previous shift. Apparent signs of alcohol over-indulgence represent a serious contra-indication, as would also apply in the case of incipient illness or where individuals are under medication which would increase susceptibility to premature fatigue or heat disorders. Mine medical officers or qualified medical station personnel should be available to assist in the selection process.

4.3 Assessment of the Task and General Awareness

Work rates cannot be prescribed or limited where emergency work has to be undertaken, especially not where life is at stake. However, in the assessment of the physical demands likely to be imposed, it would be essential to impress on workers the importance of self-pacing to avoid the early onset of fatigue. Once this happens it is virtually impossible to recover substantially while faced with high environmental heat loads. Reinforcing an awareness of the potential hazards associated with a particular task is therefore fundamentally important.

A distinction is warranted between, on the one hand, non-routine or emergency work undertaken by qualified mine personnel and, on the other, operations which by their very nature can only be undertaken by rescue brigadesmen. It is a fallacy to argue that brigadesmen, because of their high selection and training standards, are always superior to general workers when exposed to high environmental heat loads. Brigadesmen operations almost invariably require full dress (overalls) which significantly impede heat dissipation, while the relatively heavy and cumbersome breathing apparatus presents a further burden irrespective of its advantages. Also, with a full face mask brigadesmen may have difficulty in observing water breaks and a prior intake is therefore advisable.

4.4 Infrastructure

The key infrastructural and organizational requirements are

a) ensuring that drinking water is made available at the place of work and that regular water breaks are observed, if possible (e.g. 350 - 500 ml of water every 30 minutes),

b) the availability of emergency body cooling facilities, and

c) standby medical staff.

In this respect any employee showing early signs of heat disorders - notably behavioural changes but also premature fatigue, muscle cramps, nausea, vertigo or more advanced signs associated with heat exhaustion and heat stroke - should be removed to cool areas immediately.

4.5 Complicating Factors

While the emphasis falls on heat in the present context, cognizance should be taken of other aggravating factors. Examples are carbon monoxide and oxygen deficiency, as well as other gases or toxic fumes. Appropriate gas detection instrumentation should be on hand and, especially in the case of very dense smoke, eye protection would be necessary.

Travelling times could be affected significantly in cases of low visibility or where difficult or demanding routes have to be negotiated. Alternate escape routes, where in existence, should therefore not be ignored.

5. ACTION LEVELS AND PERMISSIBLE EXPOSURES

5.1 Action Levels

The Israeli Discomfort Index, on which the presently recommended Emergency Heat Stress Index (EHSI) is based, classifies heat loads in excess of 28 °C DI as 'severe'. Assuming temperatures of

wet-bulb = 27,5 °C

dry-bulb = 28,5 °C

then

$$\text{DI} = (27{,}5 + 28{,}5)/2 = 28\ ^\circ\text{C}.$$

Although 'convenient' temperatures were selected, the calculation shows that a DI of 28 °C (i.e. 'severe') can be equated with a wet-bulb of 27,5 °C (and a small dry-bulb/wet-bulb gap) which, in terms of the requirements of Regulation 10.12 of the Minerals Act, is critical.

The conclusion presented is that at an EHSI of above 28 °C, no emergency work should be undertaken unless by inherently heat tolerant or acclimatized employees. This would apply to mines or sections of mines generally exempt from the stipulations of Regulation 10.12.

The present upper limit for routine work is a wet-bulb temperature of 32,5 °C. It is proposed that this be equated to an EHSI of 32 °C. In other words, at environmental heat loads equal to and above 32 °C (EHSI units), work must be regarded as non-routine and subject to the recommendations emanating from these guidelines. However, a lower action level of 30 °C is proposed for emergency operations, the rationale being to introduce better control and to cater for unexpected conditions.

The data presented in Appendix D suggests that the maximum permissible upper limit should be set at 45 °C (EHSI units). Experimental subjects are generally incapable of exerting themselves under these conditions and estimates of tolerance times become too unreliable because of the lack of statistically meaningful data.

In summary the recommended action levels are

EHSI ≥ 28 °C : emergency work to be undertaken only by heat tolerant or heat acclimatized task forces, no time limits but work should proceed under supervision and with regular water breaks,

EHSI ≥ 30 °C : special precautions (See Section 4) and tolerance times (See Table 1) to be observed, and

EHSI ≥ 45 °C : maximum permissible upper limit, no work should be undertaken unless whole body cooling is feasible.

5.2 Body Cooling Garments

The benefit conferred through body cooling garments (Part Two : Table 6) suggests that at EHSI values of 40 °C and below tolerance times can be extended by about 30 minutes. This reduces quite sharply above an EHSI of 40 °C and the maximum recommended extended time should not exceed 10 minutes.

Although it could be argued that these benefits are not substantial in terms of the investment, the extent of protection, as has been pointed out in Part Two of this report, may well be crucial from a survival point of view. A further consideration is that the well-being and safety of an entire team could be jeopardised by the premature collapse of any single member.

It is proposed that, where available, body cooling garments be worn in order to provide added protection, especially where conditions cannot be predicted or change unexpectedly. The development of improved body cooling garments remains an immediate priority.

5.3 Tolerance Times

The tolerance times presented in Table 1 of these guidelines are based on the data presented in Appendix D of Part Two of this report. In particular, as motivated in Part One, the drop-out factor of 10^{-3} ($p = 0{,}001$) is recommended as an absolute limit.

From a convenience and practical application point of view, the tolerance times have generally been rounded up to the next higher 10-minute interval. This will not adversely affect the risk factor because the recommended calculation of the EHSI, i.e. using only rounded **up** temperatures, introduces a contrasting element of safety.

A complication arises when temperatures increase because initial estimates of tolerance times have to be reduced to take into account the added heat load. Inasmuch as exposure up to that particular stage, even if of a lower magnitude, cannot be discounted, it is obvious that the new tolerance time has to be adjusted downwards from the limit actually recommended for that EHSI level. The following example illustrates a hypothetical case.

At Start of Operation

Dry-bulb temperature = 32 °C
Wet-bulb temperature = 28 °C

EHSI = (32 + 28)/2
= 30 °C.

The recommended limit for an EHSI level of 30 °C is 230 minutes (Table 1) and this includes travelling time, assuming that environmental conditions remain constant.

At Point of Entry to Area of Work

Elapsed travelling time = 20 minutes
Available operational time = 230 - total travelling time
= 230 - (20 x 2)
= 190 minutes.

Following Entry to Area of Work

Dry-bulb temperature = 38 °C
Wet-bulb temperature = 34 °C
EHSI = (38 + 34)/2
= 36 °C.

The recommended limit for an EHSI level of 36 °C is 90 minutes. However, travelling time must be taken into account and an equitable 'penalty' derived. Inasmuch as the respective EHSI levels and corresponding tolerance times constitute equivalent 'doses' (i.e. identical risks of $< 10^{-3}$ to reach rectal temperature of 39,5 °C), the penalty could be expressed in terms of dose.

In the present example travelling time to the area of work amounted to 20 minutes. On the assumption that the return journey would also take 20 minutes under identical conditions, the dose from travelling only can be estimated as follows

Dose = Actual exposure/Permissible exposure
= Total travelling time/Permissible exposure
= 40/230
= 0,1739
= 17 %.

This implies that the available dose at the higher EHSI level of 36 °C would have to be 'penalised' by the dose incurred as a result of travelling to and from the area of work. This dose amounts to 17 % and consequently the available dose amounts to 83 % of the permissible tolerance time. Therefore

Available operational time = Permissible tolerance time x 0,83

= 90 x 0,83

= 74,7
≃ 75 minutes.

Although the calculation is straightforward, practical problems are likely to be experienced under most emergencies, especially since instrumentation to facilitate rapid calculation is not available at present. To overcome this problem, consideration could therefore be given to a plastic, pocket-sized, quick reference chart. Figure 1 gives an example of such a reference chart.

It is equally clear that the mental arithmetic associated with the calculation of 'dose', in order to re-assess tolerance time under conditions where thermal conditions deteriorate, would be even more daunting. Consideration should therefore be given to 'estimated dose' where convenient fractions are used, e.g. 25, 50 and 75 %. Using the above example, the following estimates would be obtained:

Elapsed dose = 40/230 ≃ 20 %
Available dose = 100 - 20
= 80 %
Available operational time = 90 x 0,8
= 72 minutes.

The principle proposed is therefore that any convenient fraction (i.e. single decimal figures) be used when reassessments of tolerance time are indicated.

6. GENERAL CONCLUSION AND RECOMMENDATIONS

The general conclusion is that, although scientifically-derived guidelines are quite feasible, full implementation could be handicapped by **(a)** the lack of instrumentation for the rapid assessment (and reassessment) of the thermal load and tolerance times, and **(b)** the limitations of present commercially available body cooling garments.

Against this background the most important current consideration is to obtain the views of SIMRAC and other specialist committees, e.g. the Sub-Committee of Group Environmental Engineers. The main issues are

a) acceptance of the framework provided here for the formulation of guidelines,

b) the format of a quick reference chart for estimating the EHSI and tolerance times, and

c) decision and direction on further development with respect to instrumentation and body cooling garments, both of which would be especially relevant to rescue brigades operations.

As a point of departure it is recommended that a specially constituted forum be established to discuss these issues.

Table 1 TOLERANCE TIMES FOR VARIOUS EHSI LEVELS WITH AND WITHOUT THE BENEFIT OF BODY COOLING GARMENTS (BCG)

TOLERANCE TIME (MINUTES)			
EHSI[1] (°C)	Experimentally Determined[2]	Recommended Limit[3]	BCG Benefit
30	227	230	+ 30
31	200	200	
32	174	180	
33	150	150	
34	128	130	
35	108	110	
36	91	90	
37	75	80	
38	61	60	
39	50	50	
40	40	40	
41	33	30	+ 10
42	27	30	
43	24	30	
44	22	20	
45	23	No work, evacuate area	

[1] Emergency Heat Stress Index = (dry-bulb + wet-bulb in °C)/2.

[2] Data from Part Two, Appendix D.

[3] Recommended limits given are based on experimentally determined limits but rounded up in the interests of convenience (See Text : Section 2).

Figure 2 PROPOSED PLASTIC POCKET-SIZED QUICK REFERENCE CHART FOR CALCULATION OF EHSI AND CORRESPONDING TOLERANCE TIME

FRONT

	EHSI °C																	
DRY-BULB	**WET-BULB °C**																	
°C	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**
28	28																	
29	29	29																
30	29	30	30															
31	30	30	31	31														
32	30	31	31	32	32													
33	31	31	32	32	33	33												
34	31	32	32	33	33	34	34											
35	32	32	33	33	34	34	35	35										
36	32	33	33	34	34	35	35	36	36									
37	33	33	34	34	35	35	36	36	37	37								
38	33	34	34	35	35	36	36	37	37	38	38							
39	34	34	35	35	36	36	37	37	38	38	39	39						
40	34	35	35	36	36	37	37	38	38	39	39	40	40					
41	35	35	36	36	37	37	38	38	39	39	40	40	41	41				
42	35	36	36	37	37	38	38	39	39	40	40	41	41	42	42			
43	36	36	37	37	38	38	39	39	40	40	41	41	42	42	43	43		
44	36	37	37	38	38	39	39	40	40	41	41	42	42	43	43	44	44	
45	37	37	38	38	39	39	40	40	41	41	42	42	43	43	44	44	45	45

See Page 65 for Reverse

REVERSE

E H S I (^{o}C)	TOLERANCE TIME (MINUTES)	
	WITHOUT BCG*	**WITH BCG***
30	230	260
31	200	230
32	180	210
33	150	180
34	130	160
35	110	140
36	90	120
37	80	110
38	60	90
39	50	80
40	40	70
41	30	40
42	30	40
43	30	40
44	20	30
45	No work, evacuate area	

*BCG : **B**ody **C**ooling **G**arments