School of Public Health

The Deep Body Core Temperatures, Physical Fatigue and Fluid Status of Thermally Stressed Workers and the Development of Thermal Work Limit as an Index of Heat Stress

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Abstract

Objectives:

To determine the physiological strain on industrial workers under thermal stress on extended shifts. To continuously measure deep body core temperatures, heart rates, fluid intake, changes in hydration state and physical fatigue in order to establish acceptable levels of physiological strain. To develop a rational heat stress index compatible with these limits. To design working-in-heat protocols for a self-paced workforce.

Methods:

A series of studies was conducted over 77 shifts on a group of approximately 50 male volunteers working in thermally stressful environments. Continuously-recorded deep body core temperatures, heart rates, fluid consumption, urinary specific gravity and physical fatigue were measured and recorded. A new field protocol was developed to assess physical fatigue over the working shift.

An original methodology was developed to allow any heat stress index to be assessed on a comparative basis with any other index. A review of the commonly used occupational heat stress indices was conducted.

A new rational heat stress index was developed, based on existing biophysical relationships and recommended physiological strain limits of deep body core temperature and sweat rate.

New protocols designed for self-paced work incorporating the significant risk factors for heat illness were developed and implemented in a workforce of approximately 2000 workers exposed to heat stress. The previous protocols used a shortened shift as the primary intervention to protect worker health. The subsequent protocols removed the shortened shift and replaced this with a range of other interventions. Deep body core temperature, heart rate, fluid consumption,

hydration state and fatigue were measured before and after the changes in protocols.

Results:

Comparisons of heat stress indices confirmed the wide divergence in guidance provided by many of the commonly-used indices in terms of acceptable working environments. It also highlighted a number of serious shortcomings in the most widely-used indices, especially WBGT and ISO7933.

A new, rational heat stress index called Thermal Work Limit (TWL) was developed. This included development of a computer model incorporating key thermal physiological parameters (deep body core temperature, mean skin temperature, sweat rate, skin wettedness).

There was no increase in heat stress (as indicated by average workplace environmental conditions), deep body core temperature, mean heart rate, or changes in hydration status after the changes in protocols.

Average environmental conditions were severe (WBGT 30.9^0 C, sd 2.0^0 C, range 25.7-35.2^0 C). Environmental conditions in the study were much hotter than those considered acceptable under standards such as the ACGIH[1].

The results showed that miners regularly exceeded those limits allowable under most current indices in terms of maximum deep body core temperature (avg 38.3^0 C, std dev 0.4^0 C), maximum temperature rise (1.4^0 C, 0.4 ^{0} C) and maximum heat storage (431 kJ, 163 kJ), without reporting any symptoms of heat illness. A significant component of the observed elevated core temperatures was due to the normal circadian rhythm, which was measured at 0.9^0 C (std dev 0.2^0 C). Evidence was found that workers "self-pace" when under thermal stress.

Fluid intake averaged 0.8 l/h during exposure (sd 0.3 l/h, range 0.3-1.5 l/h). Average urinary specific gravity at start-, mid- and end of shift was 1.0251, 1.0248 and 1.0254 respectively; the differences between start and mid-shift, mid and end-shift, and start and end-shift were not significant. However, a majority of workers were coming to work in a moderately hypohydrated state (urinary specific gravity avg 1.024, std dev 0.0059).

Involuntary dehydration was not found to occur in the study group. This is in contrast to several other studies and some of the leading heat stress standards, which are based on the premise that workers are unable to maintain their hydration status when working in the heat, even when their fluid consumption is equal to their sweat rate.

Continuous heart rates measured over a shift (avg 103 bpm, 14% of shifts exceeding avg 110 bpm, 5% exceeding avg 120 bpm) were in excess of those allowable under most current indices .On average, workers experienced a peak 10-minute heart rate of 140 bpm and a peak 30-minute heart rate of 130 bpm during their shifts.

There was a significant increase in fatigue in the first half of the working shift (p=0.001), with workers on average showing a significant recovery in the second half of their shift (p=0.04).

Conclusions:

Current heat stress indices provide little common agreement as to acceptable levels of thermal strain or stress for workers, at equivalent levels of environmental stress. ISO7933 is seriously flawed and the ACGIH WBGT guidelines are too conservative for acclimatised workers and are unlikely to become widely adopted by industries with well-acclimatised workers.

Many of the existing indices show internal inconsistencies.

Most of the physiological heat strain limits used in existing rational heat stress indices (in terms of deep body core temperature and heart rate) are conservative for self-paced, acclimatised, non-dehydrating male workers.

Involuntary dehydration is not unavoidable when acclimatised workers are exposed to thermal stress. Heat stress standards should not limit heat exposure durations for self-paced workers who have access to water on the basis of an unavoidable body water loss.

Physical fatigue does occur in workers under heat stress on extended shifts; however, most workers show a significant increase in fatigue in the first half of their shift; whereas data indicates self-paced workers undergo significant recovery in terms of fatigue in the second half of the shift.

As the heat exposures in this study cover a wide range of temperatures, humidity levels, wind speeds, body morphology and $\dot{V}O_{2\max}$, these conclusions are applicable to most thermally stressful settings involving well-informed, well-acclimatised and self-paced male workers. The major category of work type not covered by this study is that of workers in fully-encapsulated (vapour-barrier) protective clothing. In addition, this study examined acute effects of heat stress and strain, not effects that might only be manifest with chronic exposure to heat.

Acknowledgements

My PhD supervisor, Dr Graham Bates, for his encouragement, patience and practical support.

My colleague and friend, Dr Michael Donoghue, for his technical advice and the personal example of his own scholarship.

Mr Roy Harris, full-time Union official representing the workers at the location where this study was conducted, for his support for the research, and especially for his support for implementing the recommendations, and over-turning 56 years of tradition.

Steve McLay, General Manager – Enterprise Project, Mount Isa Mines Limited, for his foresight in recognising the importance of investigating occupational heat illness, his support for finding and implementing the solutions and his permission for these studies to be used for this Thesis.

Ms Jacqui Thomas, Science graduate, Curtin University, for her enthusiastic and professional assistance in collecting data in the first summer, over very long days and a number of night shifts.

Ms Nerida McLay, Science graduate, University of Queensland, for her equally enthusiastic and professional assistance in collecting data in the second summer, over very long days and a number of night shifts.

Finally, for all the miners who participated so willingly and enthusiastically in this study: I hope that this work will lead to a continued reduction in heat strain on themselves, and on those who come after them.

Declaration

The work described in chapters 2, 3, 4 and 5 is original. Data was obtained from the sources detailed in the text. Ms Jacqui Thomas and Ms Nerida McLay, graduate students, assisted with data collection in the first and second summers respectively using protocols that I developed. The literature review, study design, ethics committee submission, analysis, software development, conclusions and write up of the thesis and published papers were undertaken solely by the author, under the supervision of Dr Graham Bates at Curtin University. The contents of this thesis have not been submitted for any other University qualification.

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List of Abbreviations and Standard Terms

Note that each chapter introduces abbreviations used in that chapter. This list only covers abbreviations and terms used widely in the thesis. Standard *System Internationale* (SI) abbreviations are not reproduced in this list, as they are in common use and used extensively through this thesis.

Note that all temperatures in this thesis, unless otherwise annotated, are degrees Celcius.

$\dot{V}O_{2\max}$	Maximum oxygen uptake (millilitre per kg body mass per minute)
^{0} C	Degrees Celsius
ACGIH	American conference of government industrial hygienists
ACP	Air Cooling Power, W.m^{-2}
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
Avg	Average or mean
BMI	Body mass index
BP	Barometric pressure, kPa
bpm	Beats per minute
CET	Corrected effective temperature, ^{0} C (if not further annotated, is basic scale)
Clo	A non-SI unit of clothing insulation = 0.155 (m^2.K).W^{-1}

CNS	Central Nervous System
CT	Deep body core temperature, ^{0} C
DB	Dry bulb (or air) temperature, ^{0} C
E	Evaporation rate from skin, units depend on context
ECG	Electrocardiogram or electrocardiography, depending on context
E_{max}	Maximum possible evaporation rate from skin, units depend on context
EPC	Encapsulating protective clothing
EPROM	Erasable programmable read-only memory
ET	Effective temperature, ^{0} C (if not further annotated, is basic scale)
h	Hour
HR	Heart rate, beats per minute
I_{cl}	Intrinsic clothing insulation, clo
i_{cl}	Clothing vapour permeation efficiency, dimensionless
ILO	International Labor Organisation
ISO	International Standards Organisation
Kelvin	Kelvin (= ^{0} C + 273.15)
Max	Maximum

Min	Minimum
MRT	Mean radiant temperature, ^{0} C
P	Probability, context determines type of test, including one- or two-tail
P_4SR	Predicted Four Hour Sweat Rate
PPE	Personal protective equipment
Range	Highest and lowest values in a sample
RH	Relative humidity, %
RPE	Rating of Perceived Exertion (if not further annotated is the Borg 1 to 10 scale)
SG	Urinary specific gravity, the density of urine compared to the density of distilled water, dimensionless
S_r	Sweat rate, units depend on context
Std dev	Standard deviation of the Mean
TLV	Threshold limit value
TWL	Thermal work limit, $W.m^{-2}$
Tym	Tympanic temperature, ^{0} C
USARIEM	United States Army Research Institute for Environmental Medicine
w	Skin wettedness = E/E_{max} (note: not defined in terms of physical area of skin covered with sweat)

WB	Psychrometric or Ventilated Wet bulb temperature, ^{0} C (if not further annotated, is ventilated wet bulb)
NWB	Natural (unventilated) Wet bulb temperature, ^{0} C
WBGT	Wet bulb globe temperature, ^{0} C (if not further annotated, is indoor version, i.e. = 0.7 * NWB + 0.3 * DB)
WHO	World Health Organisation
WIH	Working in Heat
WS	Wind speed, m.s^{-1}
WW2	World War 2

Basic Conversion Factors

The following is a list of the more common conversions of relevance to topics in this thesis.

^{0} C = (^{0} F – 32) / 1.8

^{0} C = K + 273.15

1 lb = 0.453 592 kg

1 kPa = 1000 N.m^{-2} = 10 mbar = 7.52 mm Hg = 7.52 torr = 0.000 145 lb/inch^{2}

1 cal = 4.1868 J

1 BTU = 1055.06 J

1 inch = 25.4 mm

1 imp gallon = 4.545 litre

1 US gallon = 3.785 litre

1 clo = 0.155 m^{2}.K/W

“I will now speak of ventilating machines. If a shaft is very deep and no tunnel reaches to it, or no drift from another shaft connects to it, then the air does not replenish itself. In such a case it weighs heavily on the miners, causing them to breathe with difficulty, and sometimes they are even suffocated, and burning lamps are also extinguished. There is, therefore, a necessity for machines which the Greeks call πνενματικαί and the Latins, spiritales – although they do not give forth any sound – which enables the miners to breathe easily and carry on their work”. (Georgius Agricola, 1556).

“There is the death of 123 of the 186 British soldiers imprisoned for one night in the much quoted ‘Black Hole of Calcutta’ and a repeat performance in the Kosti disaster in the Sudan, when of 281 civilians imprisoned in one room for one night, 194 died”.

(Leithead and Lind, 1964).

“Throughout military history, major battles have been won or lost due to environmental factors. During the 1967 Six-Day War with Israel, it was reported that the Egyptians suffered 20 000 deaths with no visible wounds (apparently dehydration / heatstroke)”. (Hales et al, 1996)

For Kerry, my wife and best friend

Chapter 1 - General Introduction and Literature Review

1.1 Introduction to this thesis

Stress is a key theme in this thesis and has been defined[95] as “any stimulus or succession of stimuli of such magnitude as to tend to disrupt the homeostasis of the organism”. The associated term, strain, is defined as “the condition or state of a system exposed to stress”.

Heat stress can therefore be defined as the sum of environmental and non-environmental factors (e.g. clothing and work [metabolic] rate), which are of sufficient magnitude so as to result in heat strain,[95] with heat strain being defined as the physiological response of the body to an increase in heat storage in the deep tissues. Under this definition, the disruption to homeostasis is an increase in central body temperature, although other impacts on body homeostasis are possible and are discussed in the thesis (see section 1.3.1 page 45). For a given level of environmental heat stress, heat strain is modified by a number of factors including work rate, age, gender, body morphology, aerobic capacity, acclimatisation, state of health, clothing and personal protection equipment, and ethnic origins.[108,72] Elevated levels of heat strain can lead to a variety of forms of heat illness.[72]

1.1.1 Problems with Current Heat Stress Protocols

Heat stress is a seasonal or chronic problem in most countries and in many occupational settings. Prescribing suitable limits and guidelines continues to be highly problematic for most authorities. The ACGIH, for example, devotes only one line to most of the chemical and physical agents in the work environment; however, it devotes 16 pages to its TLV for heat stress.[1] Both the ACGIH and ISO 7933[64] standards are currently under review, indicating that the issues of heat stress are still subject to new information, new understandings and much debate.

Problems with current heat stress indices are elaborated later in this Literature Review; however, some pertinent points include:

- Many indices are “empirical” in derivation and therefore of reduced or little value outside of the conditions for which they were developed,

- Most were developed for “externally paced” work, whereas much work in the modern industrial world, with its strong focus on “duty of care”, is now self-paced. Externally paced work requires a work rate to be measured or estimated accurately as it is a critical input to the heat stress index; self-paced work, by definition, cannot use a work rate as an input to the heat stress index,

- Many do not take wind speed over the skin into account, or do it inadequately with respect to evaporation or radiant heat calculations,

- Some assume that fluid replacement cannot offset sweat rate, and that workers are therefore unable to maintain adequate hydration levels,

- Some use averaging provisions (e.g. time-weighted averages) that are not physiologically valid, e.g. averaging values over a working shift without examining the maximum values reached during that shift,

- Many handle clothing ensemble thermal parameters poorly, particularly vapour permeation or skin wettedness,

- Some are impractical to apply, e.g. those that require detailed computer-based, time-weighted estimates of metabolic rate for each worker, or use elaborate nomograms,

- Many have been found to correlate poorly with physiological measures of heat strain.

Of fundamental importance is the fact that there are many risk factors (physiological, environmental, occupational, clothing, etc) that predispose to heat illness. Clearly if a heat stress protocol is built solely around the environmental risk factors, then the environmental limits will need to be very conservative to protect workers against the wide variation in the other risk factors, such as body morphology, state of acclimatisation and hydration, etc.

Current heat stress standards are generally conservative. Most industrial indices currently in use were developed in the more temperate (Western) nations of the Northern hemisphere where occupational work is generally in cooler conditions and the living environment (non-working time) is generally much cooler than in tropical areas. Where significant heat exposures do exist in these countries, they are generally for shorter periods of the year. Adopting the limits recommended in these indices in tropical regions would create severe problems. For example, Figure 1 shows the heat stress protocols used at the workplace that was the site for this study (a major, inland, underground mining operation in Northern Australia) prior to the introduction of the interventions developed and applied in this study. The green zone shows unrestricted work, the white zone is a shortened (6-hour) shift, whilst the red zone is “stop job”. Figure 2 shows the Wet Bulb Globe Temperature (WBGT) superimposed on Figure 1. Note that under the widely-used ACGIH-recommended TLVs[1] for work by acclimatised workers, a moderate work rate (requires WBGT<26.7^0 C) would not be continuously possible at all in these workplaces, and even “light work” (requires WBGT<30.0^0 C) would only be continuously possible over a very restricted range of conditions. The climate at this workplace is typical of many types of industrial work in the tropics; therefore adopting the ACGIH TLV would simply not be practical in many workplaces located inside the tropics for a substantial portion of each year. Furthermore, as the remainder of this thesis will demonstrate, limits that are as conservative as some authorities currently suggest are not necessary to protect healthy, well-informed, self-pacing, acclimatised workers from heat illness.

Figure 1 Working in heat protocol used at site of this study from 1966 to 1998. Red zone: no work allowed; white zone: shift length reduced from 8 hours to 6 hours if exposure > 2 hours; green zone: no restrictions. There was a chart for wind speeds < 0.5 m/s but it was rarely used.

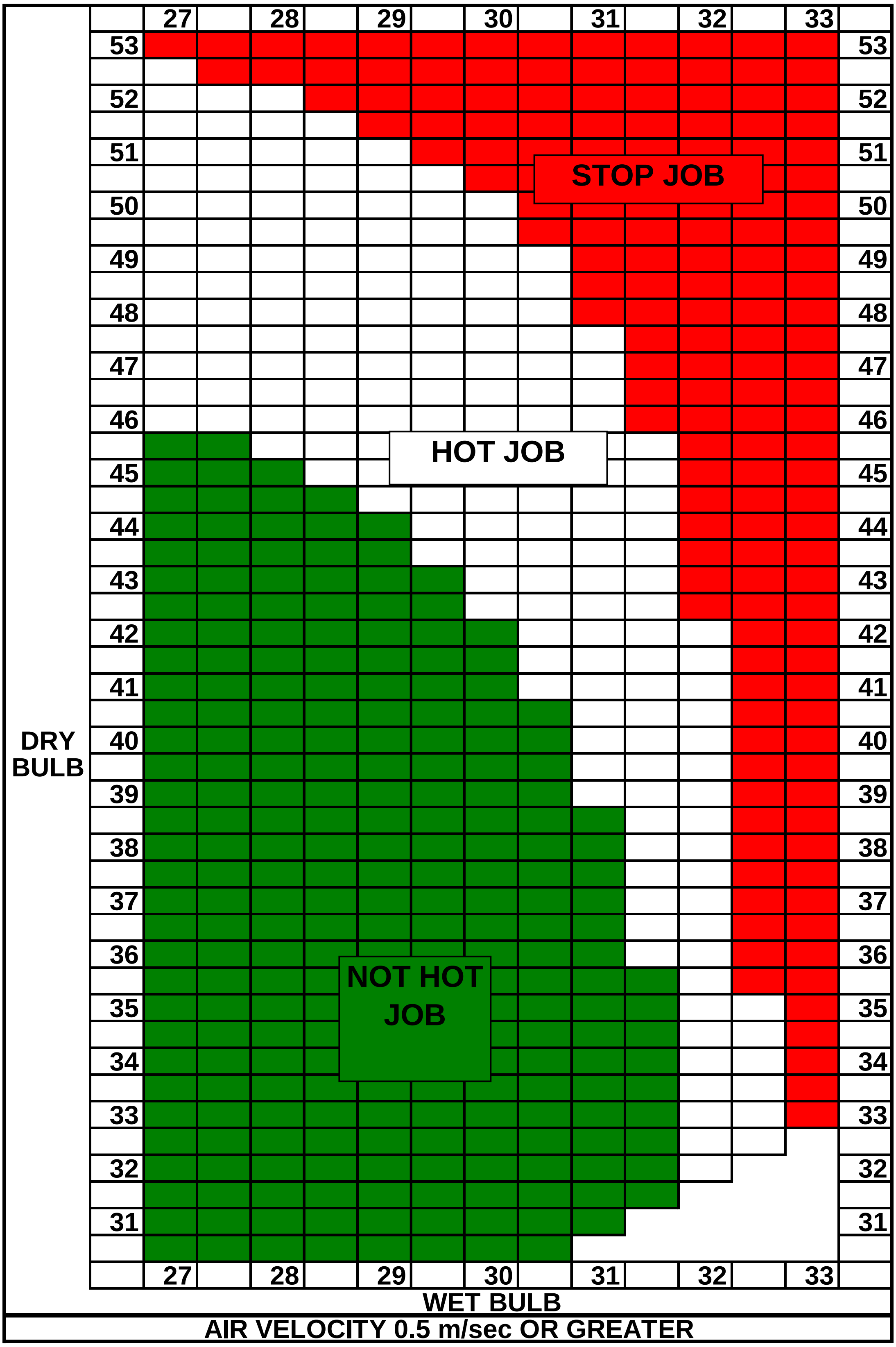

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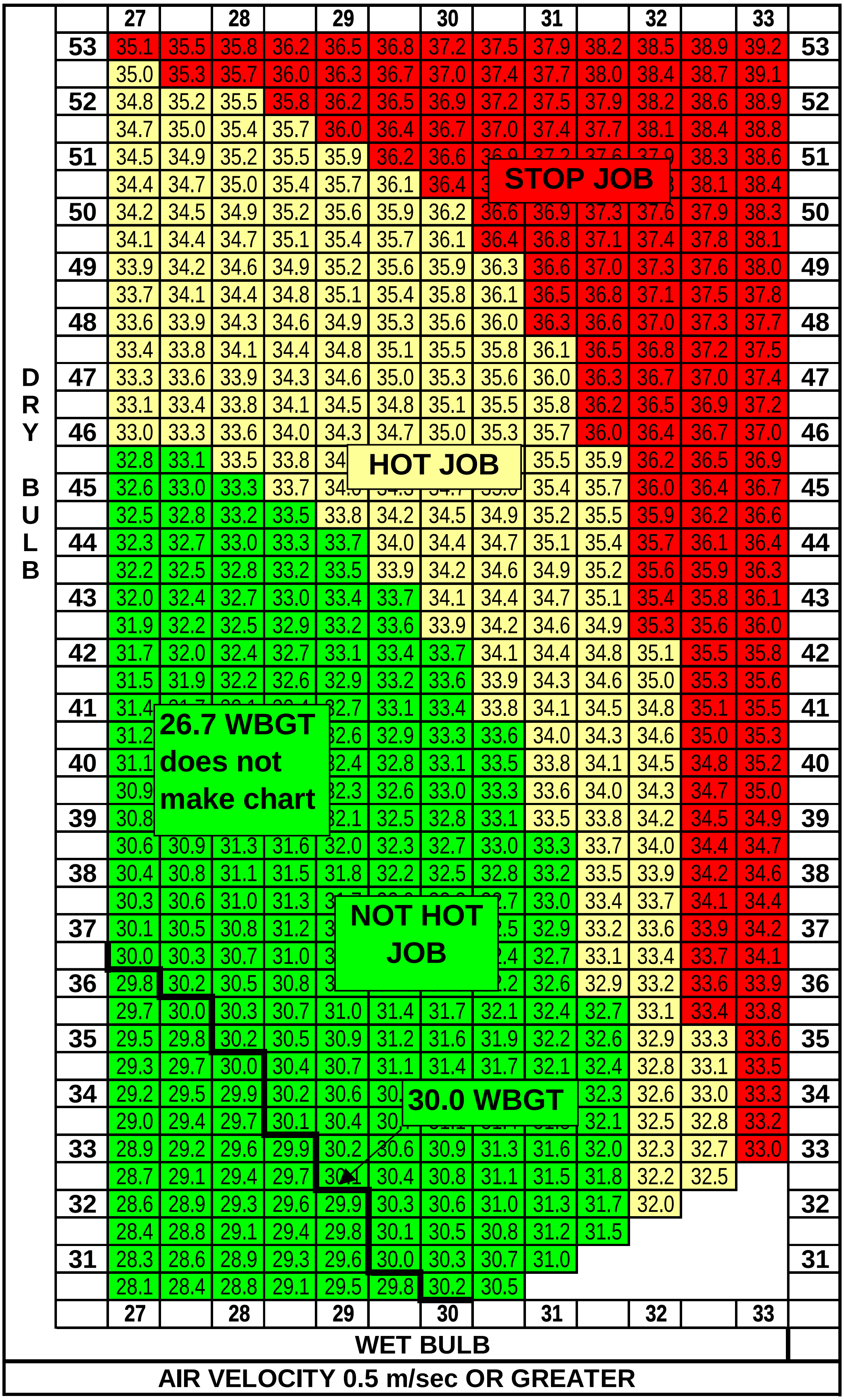
Figure 2 The protocols previously used at the site of this study, with WBGT values superimposed. The heavy line is 30.0^0 C WBGT (the ACGIH TLV for continuous light work for acclimatised workers). 26.7^0 C WBGT is the ACGIH TLV for continuous moderate work for acclimatised workers.



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52	34.8	35.2	35.5	35.8	36.2	36.5	36.9	37.2	37.5	37.9	38.2	38.6	38.9	52
	34.7	35.0	35.4	35.7	36.0	36.4	36.7	37.0	37.4	37.7	38.1	38.4	38.8	
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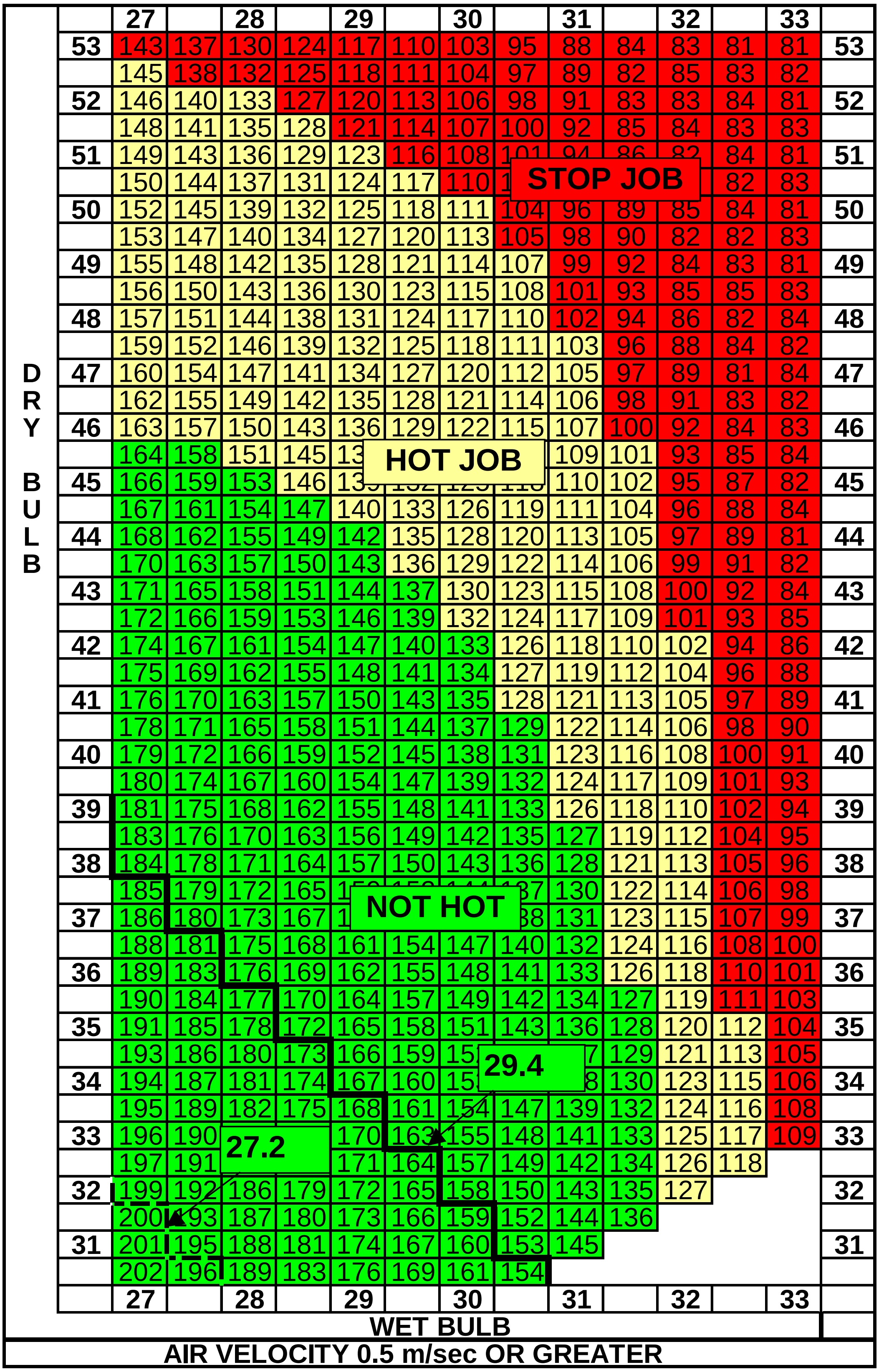
46	33.0	33.3	33.6	34.0	34.3	34.7	35.0	35.3	35.7	36.0	36.4	36.7	37.0	46
	32.8	33.1	33.5	33.8	[illegible]	[illegible]	[illegible]	[illegible]	35.5	35.9	36.2	36.5	36.9	
45	32.6	33.0	33.3	33.7	34.0	34.3	34.7	35.0	35.4	35.7	36.0	36.4	36.7	45
	32.5	32.8	33.2	33.5	33.8	34.2	34.5	34.9	35.2	35.5	35.9	36.2	36.6	
44	32.3	32.7	33.0	33.3	33.7	34.0	34.4	34.7	35.1	35.4	35.7	36.1	36.4	44
	32.2	32.5	32.8	33.2	33.5	33.9	34.2	34.6	34.9	35.2	35.6	35.9	36.3	
43	32.0	32.4	32.7	33.0	33.4	33.7	34.1	34.4	34.7	35.1	35.4	35.8	36.1	43
	31.9	32.2	32.5	32.9	33.2	33.6	33.9	34.2	34.6	34.9	35.3	35.6	36.0	
42	31.7	32.0	32.4	32.7	33.1	33.4	33.7	34.1	34.4	34.8	35.1	35.5	35.8	42
	31.5	31.9	32.2	32.6	32.9	33.2	33.6	33.9	34.3	34.6	35.0	35.3	35.6	
41	31.4	31.7	32.1	32.4	32.7	33.1	33.4	33.8	34.1	34.5	34.8	35.1	35.5	41
	31.2	[illegible]	[illegible]	[illegible]	32.6	32.9	33.3	33.6	34.0	34.3	34.6	35.0	35.3	
40	31.1	[illegible]	[illegible]	[illegible]	32.4	32.8	33.1	33.5	33.8	34.1	34.5	34.8	35.2	40
	30.9	[illegible]	[illegible]	[illegible]	32.3	32.6	33.0	33.3	33.6	34.0	34.3	34.7	35.0	
39	30.8	[illegible]	[illegible]	[illegible]	32.1	32.5	32.8	33.1	33.5	33.8	34.2	34.5	34.9	39
	30.6	30.9	31.3	31.6	32.0	32.3	32.7	33.0	33.3	33.7	34.0	34.4	34.7	
38	30.4	30.8	31.1	31.5	31.8	32.2	32.5	32.8	33.2	33.5	33.9	34.2	34.6	38
	30.3	30.6	31.0	31.3	31.7	[illegible]	[illegible]	32.7	33.0	33.4	33.7	34.1	34.4	
37	30.1	30.5	30.8	31.2	[illegible]	[illegible]	[illegible]	[illegible]	32.9	33.2	33.6	33.9	34.2	37
	30.0	30.3	30.7	31.0	[illegible]	[illegible]	[illegible]	[illegible]	32.7	33.1	33.4	33.7	34.1	
36	29.8	30.2	30.5	30.8	[illegible]	[illegible]	[illegible]	[illegible]	32.6	32.9	33.2	33.6	33.9	36
	29.7	30.0	30.3	30.7	31.0	31.4	31.7	32.1	32.4	32.7	33.1	33.4	33.8	
35	29.5	29.8	30.2	30.5	30.9	31.2	31.6	31.9	32.2	32.6	32.9	33.3	33.6	35
	29.3	29.7	30.0	30.4	30.7	31.1	31.4	31.7	32.1	32.4	32.8	33.1	33.5	
34	29.2	29.5	29.9	30.2	30.6	[illegible]	[illegible]	[illegible]	[illegible]	32.3	32.6	33.0	33.3	34
	29.0	29.4	29.7	30.1	30.4	30.7	31.1	31.4	31.8	32.1	32.5	32.8	33.2	
33	28.9	29.2	29.6	29.9	30.2	30.6	30.9	31.3	31.6	32.0	32.3	32.7	33.0	33
	28.7	29.1	29.4	29.7	30.1	30.4	30.8	31.1	31.5	31.8	32.2	32.5		
32	28.6	28.9	29.3	29.6	29.9	30.3	30.6	31.0	31.3	31.7	32.0			32
	28.4	28.8	29.1	29.4	29.8	30.1	30.5	30.8	31.2	31.5				
31	28.3	28.6	28.9	29.3	29.6	30.0	30.3	30.7	31.0					31
	28.1	28.4	28.8	29.1	29.5	29.8	30.2	30.5						
	27		28		29		30		31		32		33	

WET BULB

AIR VELOCITY 0.5 m/sec OR GREATER

Figure 3 The protocols previously used at the site of this study, along with the Thermal Work Limit (TWL) values and the 29.4^0 Basic Effective Temperature (ET) "stop job" limit and the 27.2^0 ET "shortened shift" limits used in underground coal mines in the same country. TWL is a new heat stress index and is shown for later comparison purposes.



DRY BULB

	27		28		29		30		31		32		33	
53	143	137	130	124	117	110	103	95	88	84	83	81	81	53
	145	138	132	125	118	111	104	97	89	82	85	83	82	
52	146	140	133	127	120	113	106	98	91	83	83	84	81	52
	148	141	135	128	121	114	107	100	92	85	84	83	83	
51	149	143	136	129	123	116	108	101	94	86	82	84	81	51
	150	144	137	131	124	117	110	1				82	83	
50	152	145	139	132	125	118	111	104	96	89	85	84	81	50
	153	147	140	134	127	120	113	105	98	90	82	82	83	
49	155	148	142	135	128	121	114	107	99	92	84	83	81	49
	156	150	143	136	130	123	115	108	101	93	85	85	83	
48	157	151	144	138	131	124	117	110	102	94	86	82	84	48
	159	152	146	139	132	125	118	111	103	96	88	84	82	
47	160	154	147	141	134	127	120	112	105	97	89	81	84	47
	162	155	149	142	135	128	121	114	106	98	91	83	82	
46	163	157	150	143	136	129	122	115	107	100	92	84	83	46
	164	158	151	145	13				109	101	93	85	84	
45	166	159	153	146	139	132	125	118	110	102	95	87	82	45
	167	161	154	147	140	133	126	119	111	104	96	88	84	
44	168	162	155	149	142	135	128	120	113	105	97	89	81	44
	170	163	157	150	143	136	129	122	114	106	99	91	82	
43	171	165	158	151	144	137	130	123	115	108	100	92	84	43
	172	166	159	153	146	139	132	124	117	109	101	93	85	
42	174	167	161	154	147	140	133	126	118	110	102	94	86	42
	175	169	162	155	148	141	134	127	119	112	104	96	88	
41	176	170	163	157	150	143	135	128	121	113	105	97	89	41
	178	171	165	158	151	144	137	129	122	114	106	98	90	
40	179	172	166	159	152	145	138	131	123	116	108	100	91	40
	180	174	167	160	154	147	139	132	124	117	109	101	93	
39	181	175	168	162	155	148	141	133	126	118	110	102	94	39
	183	176	170	163	156	149	142	135	127	119	112	104	95	
38	184	178	171	164	157	150	143	136	128	121	113	105	96	38
	185	179	172	165	158	151	144	137	130	122	114	106	98	
37	186	180	173	167	1			138	131	123	115	107	99	37
	188	181	175	168	161	154	147	140	132	124	116	108	100	
36	189	183	176	169	162	155	148	141	133	126	118	110	101	36
	190	184	177	170	164	157	149	142	134	127	119	111	103	
35	191	185	178	172	165	158	151	143	136	128	120	112	104	35
	193	186	180	173	166	159	15		137	129	121	113	105	
34	194	187	181	174	167	160	15		138	130	123	115	106	34
	195	189	182	175	168	161	154	147	139	132	124	116	108	
33	196	190			170	163	155	148	141	133	125	117	109	33
	197	191			171	164	157	149	142	134	126	118		
32	199	192	186	179	172	165	158	150	143	135	127			32
	200	193	187	180	173	166	159	152	144	136				
31	201	195	188	181	174	167	160	153	145					31
	202	196	189	183	176	169	161	154						
	27		28		29		30		31		32		33	

WET BULB

AIR VELOCITY 0.5 m/sec OR GREATER

Heat stress protocols also frequently contradict one another. Even within a hot country such as Australia, and even within the same State and industry, there are frequently very different allowable limits for heat stress. For example, Figure 3 shows the Queensland (Australia) *coal* mining industry heat stress limits (29.4^0 Effective Temperature [ET basic] as “stop job” and 27.2^0 ET as “short shift”) superimposed on pre-1998 Queensland *metal* mining heat stress limits. It also shows the Thermal Work Limit (TWL) values for later comparison purposes. TWL is a new heat stress index developed in this thesis and has the units of watts of metabolic heat (work rate) per square meter of body surface area. It is basically the maximum work rate possible for acclimatised workers wearing summer work uniforms in a particular environment. This chart shows that the *coal* mining limits are much more conservative than the pre-1998 *metal* mining limits, despite the workforces being very similar and being located within the same State and Country.

These differences can be even more significant between countries. South African mines, for example, tend to work to a limit of 32.5^0 WB with an allowance up to 34^0 WB under certain circumstances. German coal mines, however, bring in a shortened shift once either the DB exceeds 28^0 C or the ET exceeds 25^0 C and no work is allowable at all, even under shortened shifts, when the DB exceeds 32^0 C. UK coal mines have no mandatory limit but tend to work to a voluntary limit of 28^0 ET and 28^0 C DB, whichever is exceeded first. Many of the arid regions of the world regularly have ambient temperatures exceeding 40^0 C DB in summer, yet work is still safely performed.

The reasons why such differences exist in heat stress standards between countries and between industries are discussed further in the remainder of the thesis; however, the lack of relevant, recent research in occupational settings is a fundamental problem. Of particular note are disagreements concerning acceptable limiting physiological strain, in terms of maximum deep body core temperature, average heart rate, maximum sweat rate, the physiological ability to replace fluid lost as sweat, maximum skin wettedness and fatigue. In particular, until now there has been no way to continuously monitor deep body core temperatures in occupational workers conducting their *normal* activities in their *normal* work environment. This study is the first to do so in a non-military setting.

1.1.2 Benefits of the Study

As discussed above, the most controversial factors relating to heat stress and strain for acclimatised workers using non-EPC clothing are the choice of appropriate physiological limits for: deep body core temperatures, fluid loss and replacement rates, hydration status and physical fatigue; along with the overall issue of the choice of a valid and suitable Heat Stress Index, linked to a valid Heat Strain model. Each of these key contributing factors has therefore been addressed in this study.

For example, deep body core temperatures have been *continuously* measured for shift workers over periods of two or more shifts using new technology. This has highlighted many misunderstandings and anomalies in the current thinking concerning heat storage and deep body temperature limits in occupational workers. Simultaneous heart rates have also been *continuously* measured. Fluid consumption, change in hydration state, muscular fatigue and an overall measure of fatigue have also been assessed.

The findings from these studies, along with data collected elsewhere, have then been drawn together to develop a new heat strain model and heat stress index, along with protocols relevant to acclimatised, non-dehydrating, healthy, self-paced workers. The protocols are then extended to unacclimatised workers.

1.1.3 Limitations of the Study

This study has been conducted on generally healthy, acclimatised, non-dehydrating, and well-informed (about the issues of working-in-heat) male workers. These workers were wearing typical cotton work clothes, including safety helmet and safety boots. However, TWL has been formulated to allow for changes in clothing insulation and vapour permeability factors and can therefore be extended to other work environments and occupations.

1.1.4 Hypotheses of the Study

The thesis investigates the following hypotheses:

- Existing heat stress indices (e.g. WBGT) do not accurately reflect human heat stress and that an index based on the concept of limiting metabolic rates can be developed using accepted biophysical relationships and new limits on key physiological criteria.

- Existing limits for deep body core temperature, heart rate and sweat rate are conservative and regularly exceeded by workers without leading to heat illness.

- Extending work shifts to 12 hours when workers are under heat stress does not necessarily lead to increased levels of fatigue.

- Involuntary dehydration (the inability to replace fluids lost as sweat) does not necessarily occur in workers under heat stress.

1.1.5 Papers from Thesis

The following papers have been written from this thesis. Of the five pivotal papers (the first five listed below) four have been published and one has been provisionally accepted for publication with only minor changes. Each of these key papers has been accepted in a different leading international journal. Copies of each of these papers (as published or as provisionally accepted for publication) are included in an appendix to the thesis.

- Brake DJ and Bates GP. Limiting work rate (Thermal Work Limit) as an index of thermal stress. Journal of Applied Occupational and Environmental Health (ACGIH). Published March 2002 (reprint not yet received).

- Brake DJ and Bates GP. A valid method for comparing rational and empirical heat stress indices. Annals of Occupational Hygiene (BOHS). To be published March 2002.

- Brake DJ and Bates GP. Fatigue in industrial workers under thermal stress on extended shift lengths. Occ Med (Society of Occ Med). Vol 51, No 7, pp 456-463, 2001.

- Brake DJ and Bates GP. Deep body core temperatures in industrial workers under thermal stress. J Occup Environ Med (American College of Occ and Env Med). Vol 44, No 2, pp 125-135, 2002.

- Brake DJ and Bates GP. Fluid losses and hydration status of industrial workers under thermal stress working extended shifts. Occ Env Med. Invited to be resubmitted with only minor changes.

- Brake DJ, Donoghue AM and Bates GP. A new generation of health and safety protocols for working in heat. Proc 1998 Qld Mining Ind Health and Safety Conf. DME (Qld). pp 91-100 (1998).

- Brake, D.J.; Bates, G.P.: Occupational Heat Illness: An Interventional Study. In: Proceedings of the International Conference on Physiological and Cognitive Performance in Extreme Environments, 2000, pp. 170-172. W.M.Lau, Ed. Defence Scientific and Technology Organisation, Australian Department of Defence, Canberra (2000).

1.1.6 Layout of Thesis

The thesis covers *five* main areas relating to workers under heat stress:

- Core temperatures,

- Fatigue and heart rates,

- Fluid loss and hydration,

- The formulation of TWL, and
- A new methodology to compare heat stress indices.

The thesis is laid out in chapters, being:

- General Introduction and Literature Review,
- Methods,
- Results,
- Discussion and
- Conclusions and Recommendations.

Each of these chapters discusses (where appropriate) each of these topics in turn. As the topics are diverse, some readers may find it preferable to read all of the material in the thesis on one topic, e.g. core temperatures, by reading the relevant sections on core temperatures from each chapter, rather than by reading the thesis in page-order.

The diverse nature of the individual topics and the fact that they tend to build on one another (e.g. the formulation of TWL draws on the results of the core temperature study) has made allocation of some of the material into the conventional headings of “methods” or “results” etc somewhat problematic. Strict adherence to guidelines would at times result in a document that is confusing when read from start to end. An important consideration by the author in laying out the thesis has been for the material in the thesis to flow sensibly and logically as it is read.

In addition to the paper (hard) copy of this thesis, an electronic version in Adobe Acrobat^{TM} is also available on CD ROM and will also be available from the Curtin University web site (if passed). Adobe Acrobat reader is fully licensed free software and is provided with the CD version of the thesis, or can be downloaded from the Adobe site: www.adobe.com. It is expected that many readers will use the electronic version of the thesis for reasons outlined below.

The electronic version makes extensive use of *hyperlinks*. These are shown like this text here (this hyperlink just moves the cursor to two paragraphs above). They can also be seen by the fact that the cursor turns into a "pointed finger" when held over the hyperlink. By clicking on the hyperlink, the reader is taken directly and instantaneously to the table, figure, appendix, page, chapter title, or other information referred to in the text. To return to the previous location, use the navigation arrows provided on the Acrobat toolbar. By using the forward and reverse navigation arrows, instantaneous navigation around the document is possible via the hyperlinks. It is also possible to go immediately to any reference in the text by clicking on the reference number, or to any chapter or heading within a chapter, or any Table or Figure in the List of Tables or Figures, by clicking on the page number next to the heading, Table or Figure in the List of Contents, Tables or Figures. This makes it very quick to check any comment in the main text against the relevant table or figure, or to review a reference cited within the text, etc. In addition, it is much easier to search through an electronic text, and to store a CD rather than a paper copy. Production costs are also very much lower for the CD version than the paper version.

Wherever practicable, the text is laid out in "portrait" view; however, many figures and tables are more legible in "landscape" view and this has therefore been used where appropriate.

1.2 Location of This Study

Whilst occupational heat stress exists in virtually all countries, Australia is well positioned as the site for a substantial new study into this matter. Firstly, Australia is the world's hottest and driest continent. Ambient dry bulb temperatures exceeding 40^0 C are common for several months of the year in inland areas and, in the hot, humid, tropical regions, workplace temperatures exceeding 28^0 WB are frequent. Therefore, both the duration and extent of occupational heat exposures are high. Secondly, Australia is a first-world country with very high standards imposed by Governments on employers in terms of their “duty of care” to protect the health and safety of workers. Therefore, heat illness (even involving mild symptoms) is unacceptable in the work place, and regulators and employers are generally open to better ways of managing occupational exposures to heat.

Having said this, it is important to recognise that virtually all countries have problems with heat stress in occupational settings. Therefore, whilst these results have been obtained using subjects in Australia, there is no reason to believe that the conclusions are not applicable to hot workplaces generally.

Within Australia, many industries have significant workforce exposures to heat. However, the minerals industry is especially suited for a detailed study. Firstly, it is one of Australia’s most important industries economically, being Australia’s major export earner and a large contributor to gross national product. Secondly, for various technical reasons, more new mines in Australia are developing as underground rather than surface operations, and environmental conditions in underground mines are particularly hot for reasons discussed on page 42. Finally, due to the high cost of establishing new towns in remote areas, mines are increasingly being based on 12-hour shifts and “fly in, fly out” (FIFO) rosters frequently with 14 or more days on site before taking a break. Therefore exposure to occupational heat can be a daily occurrence for weeks at a time for mine workers.

Underground mines therefore have a number of attractive features in terms of a new detailed study of occupational exposures to heat stress and were therefore the location of choice.

The location for the study was Australia’s largest underground mining operation, a collection of five separate mines known as the Mount Isa mines, located approximately 400 km inside the tropics and 1000 km inland in northern Australia (Figure 4). Approximately 2000 underground mine workers (more than 95% male) are employed or contracted to provide skilled, semi-skilled and unskilled labour for this 363 days per year, 24 hours per day operation. The five separate underground mines are located within a distance of about 20 km. This is not a “fly-in, fly-out” operation and most miners are domiciled with their families in a nearby town of approximately 25 000 persons (the exception being some contract workers).

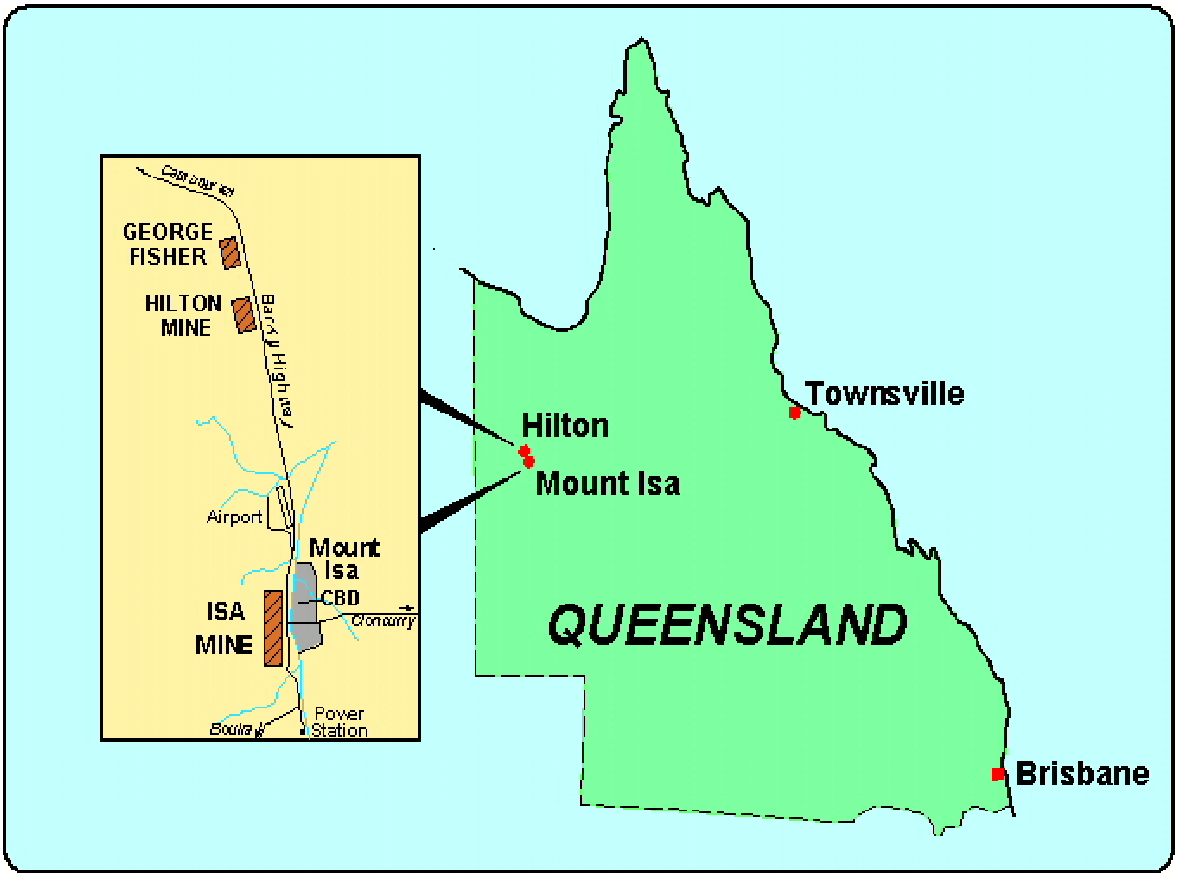
This target group for the study is entirely male, as no females regularly undertake physical work in the hottest underground workplaces. All workers were volunteers drawn from the target group and were all on 10, 12 or 12.5-hour shifts. 12 and 12.5-hour shift workers work two consecutive (12-hour) day shifts, followed by a 12-hour break and then two consecutive 12-hour night shifts, followed by four days off on a rotating 8 day roster. 10-hour shift workers work four consecutive 10-hour day shifts, followed by four days off, followed by four consecutive 10-hour night shifts, followed by four days off on a rotating 16 day roster. The target group were selected from the remaining workforce of 2000 persons on the basis of:

- Highest relative exposures to environmental heat, and
- Highest relative work rates.

Historically this sub-group had by far the highest incidence of heat illness in the operation.

As these workers are frequently exposed to severe thermal environmental conditions, they are considered to be acclimatised.

Figure 4 Location of the study: Mount Isa, Qld, Australia. The Isa mine complex includes the separate Lead mine, Copper (X41) mine and the DCM/Enterprise mine.



Workers on 12-hour shifts take two 30-minute meal ("crib") breaks during the shift, with the first break at approximately the 6-hour mark. Workers on 10-hour or 8-hour shifts take only one 30-minute break per shift, with this taken approximately mid-shift. Meal breaks are taken at a time convenient to the worker and are in clean, air-conditioned crib rooms. The actual (effective) working time *on the job* was typically 7.5 hours for 10-hour shifts and 9 hours for 12-hour shifts. This is based on prior internal reviews that demonstrated that for a shift with one meal break, workers lose 2.5 hours in travelling underground to their crib room, getting instructions from their supervisor, picking up their equipment (including pre-start checks and re-fuelling), getting to the job, returning to the crib room for lunch, returning to the workplace after crib, and returning to the hoisting shaft before the end of the shift to get back to the surface by shift end. An additional hour is lost for the longer shifts due to the extra meal break.

The climatic profile[6] for the city in which these workers live consists of near-maximum summer temperatures of 41.5^0 C dry bulb (DB) and 25^0 C wet bulb (WB) with peaks at 44^0 C DB and 27^0 WB. The near-minimum winter temperature is 3.5^0 C DB and -3^0 WB. The climate is arid-tropical, with 75% of the annual rainfall of 460 mm falling in a pronounced "wet season" comprising the four months from December to March. This period of the year is very humid.

All participants gave their written informed consent to a series of studies that was authorised by management, their Labour unions, and Curtin University's ethics committee on human experimentation (certificate 28/98).

As the underground workplaces are widely dispersed, workers are typically only visited by their supervisor twice per shift (once before and once after lunch) for approximately 10 minutes per visit. This, together with the fact that workers generally work alone or in groups of only two or three, contributes to a culture of self-pacing. It should not be concluded from the above that this operation is inefficient. Productivity is within good practice levels of other mines in the Western world.

In addition to the heat and humidity in the environment, these workers must cope with poor illumination, dust, diesel fumes, noise and broken ground underfoot. The compulsory mine workers' uniforms consist of long cotton trousers and short or long sleeved shirts, safety boots, safety helmet, eye protection, heavy safety belt, cap lamp and cap lamp battery. Where the environment is dusty or noisy, a face respirator or noise protection is also compulsory. Some activities involve cement grout or other chemical agents, and these require (compulsorily) wearing elbow-length impermeable gloves, a rubber apron, and a face visor clipped to the safety helmet. However, the workforce is highly mobile, and some work is conducted from within air-conditioned cabins of mobile equipment. Not all work on all shifts was therefore in extreme conditions, or was physically strenuous.

As these workplaces are at a depth of between 1000 m and 1800 m vertically below surface (surface is about 350 m above sea level), there is no significant change in temperature in the workplace between day and night due to the thermal damping (between the intake air and the rock strata) that occurs in the long intake airways leading from the surface to the various workplaces. Furthermore, autocompression (the increase in air temperature as it descends a shaft due solely to conversion of potential energy into heat) adds about 6^0 DB and 4^0 WB per 1000 m of vertical depth.[80,53,102] The geothermal gradient is such that "fresh" rock at 1500 m below surface in this operation is at a temperature of 58^0 C.[17] These temperature increases, along with the diminished effects of the change in seasons due to the distance to the workplace, mean that exposures to significant levels of heat stress occur throughout the year, although they are less frequent and less extreme in winter. An analysis of the incidence of heat illness with respect to surface temperatures at this operation has recently been reported.[30]

Whilst mild to moderate forms of heat illness do occur in this operation,[31,18] none of the participating workers reported symptoms of heat illness during the course of the study. In addition, it is estimated that in excess of 10 million manshifts have been worked in this mining operation under the previous heat stress protocols, without any recorded case of heat stroke.[59] Approximately 50 000 manshifts have been worked between 1965 and 1998 in the "six hour" zones of thermal stress without any heat stroke (WBGT > 32^0 C, refer Figure 2). The risk of life-threatening heat illness must therefore be considered to be negligible.

Prior to the start of any of these studies, a dehydration testing program (based on urinary specific gravity) was in place. However, dehydration tests prior to the start of the studies were generally voluntary. After the first summer, and after agreement with the Labor Unions, these tests were modified and became compulsory and are further described in section 3.2 page 107.

The study was conducted over two summers (1st summer and 2nd summer), with a major change (the introduction of TWL and its associated protocols) to the existing working-in-heat protocols occurring between the summers. The earlier protocols (Figure 1) were based on the Predicted Four Hour Sweat Rate (P_4SR) (as refined by Wyndham et al),[139] and relied heavily on the "shortening" of the working shift to 6 hours when environmental conditions exceeded approximately 32^0 WBGT for more than two hours (refer Figure 2). A shortened working shift has historically been seen as an important approach to controlling heat stress and heat illness in occupational settings and is still recommended by standards such as ACGIH and ISO. The "six hour shift" had been in use at this operation since 1942, although prior to 1966 it was only granted when the WB exceeded 28^0 C and there was "no flow of air". The "six hour shift" came to Mount Isa in 1942 from the Broken Hill mines in Southern Australia. In turn, the short shift came to Broken Hill in the 1920s, probably from Europe, with a shortened shift being introduced into German underground collieries in 1905 when the dry bulb temperature exceeded 28^0 C.[50] The new protocol removed the "six-hour shift", thereby increasing nominal shift length, even when exposed to 12 hours of thermal stress, and replaced it with a graduated management response, based on a new thermal stress index now called Thermal Work Limit. The studies were designed, in part, to ensure that the introduction of the new protocols and longer shift lengths did not increase the incidence of hyperthermia, hypohydration or fatigue.

Prior to the change in protocols, shortened shifts had a serious impact on productivity, but appeared to have little impact on reducing heat illness. For example, there were 106 cases of heat illness from underground operations in summer 97/98, but only 6 of these occurred in persons who were granted a "hot job" [i.e. who were "caught" in the formal temperature/time protocol designed specifically to protect workers from heat illness]. Conversely, there were over 1000 "hot jobs" (i.e. persons working in a "hot job") granted during that summer, but only 4 of these persons granted a "hot job" developed heat illness. The fact that heat illness was occurring in workers not being granted a hot job and wasn't occurring in workers receiving a hot job indicated that the design of the existing protocols and limits needed substantial additional research and review.

It should be remembered that the workers at this operation are all relatively well-informed about the issues of working in heat, and work in a largely self-paced context.[19] Workers are not generally subject to any regular form of health screen, apart from a pre-employment medical. Due to self-pacing, the observed work rate reduces as workplace temperatures increase; hyperthermia is therefore generally due to exposure to extreme thermal environments (*exogenous* heat) rather than high metabolic loads (*endogenous* heat). There are significant physiological differences between internal and external heat loads. These are further described on page 158.

Where relevant, further background information to the study is given within subsequent sections of the thesis.

1.3 Literature Review

1.3.1 Heat Illness

There are a wide variety of pathologies associated with excessive levels of heat strain. Parsons[97] illustrates some of these in Figure 5 (which was derived in turn from Belding,[12] and in turn from Leithead and Lind[73]). Other aetiologies have also been created.[84]

Note that there are three broad types of heat illness:

- Those associated with elevated deep body core temperatures
- Those associated with dehydration
- Other heat-related conditions associated with skin damage (such as heat rash [usually prickly heat]), electrolyte imbalances (e.g. cramps and salt-deficiency heat exhaustion), other fluid imbalance problems (e.g. oedema), or other causes.

The most common potentially serious heat illnesses in occupational workers are those associated with either an elevated core temperature or dehydration (or, frequently, with both) and it is these that are regarded as constituting “heat illness” in this thesis.

1.3.2 Heat Stress Indices

Thermal stress, with its attendant problems of heat illness, safety incidents, lowered productivity, poor morale and higher costs, affects many industrial operations. Over the past 80 years, over 50 heat stress indices have been developed to assist with the management of these problems.[97,141] These indices typically fall into one of two broad categories:

- Empirical indices. These have been developed from field experiments, and the heat stress limits are generally expressed in terms of some environmental parameter, not a physiological parameter. Examples include the Effective Temperature (Basic and Normal), Corrected Effective Temperature, Oxford Index, Kata Thermometer, Wet Bulb, Wet Bulb Globe Temperature (WBGT) Index and many others. Empirical indices can be sub-divided into those that are in use in only one location, area, industry or employer (e.g. Kata, used principally in South African underground mines), and those that are more widely employed (e.g. WBGT).

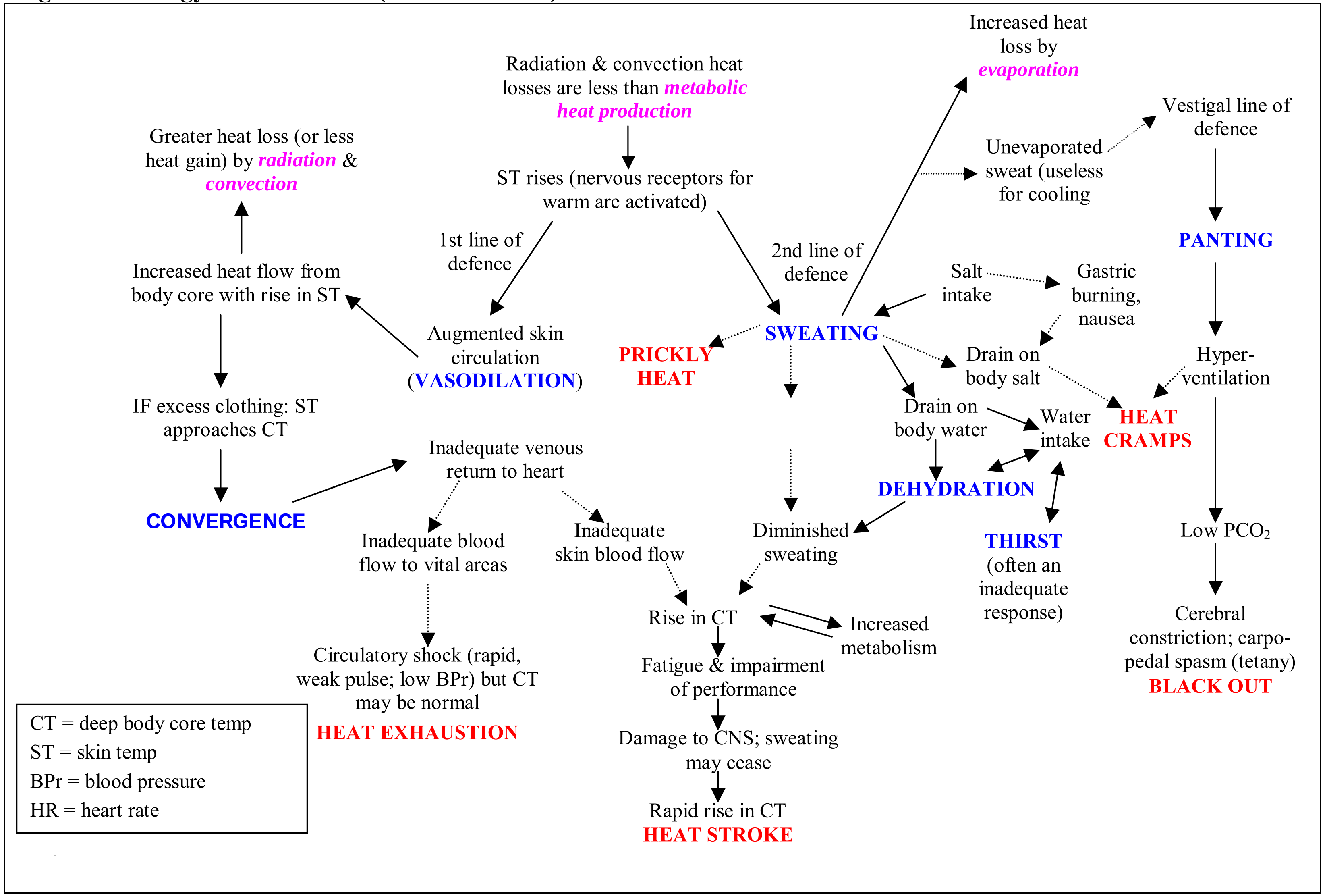


Figure 5 Etiology of Heat Illness (from Parsons[97])

- Rational indices. These include indices that predict sweat rate (Belding and Hatch,[223] Predicted Four Hour Sweat Rate,[78] ISO7933[64]), those that predict 'core' temperature or core temperature increase (ISO7933[64]), those that predict heart rate (Fuller and Brouha[37]) and those that predict a combination of two or more of these physiological parameters. Rational indices can be sub-divided into those that are predictive (i.e. measure environmental conditions and predict thermal strain for a *population* accordingly) and those that are essentially reactive (i.e. those that measure thermal strain for an *individual* and react accordingly). Reactive indices typically monitor a vital sign associated with heat strain in an individual, and advise action depending on the result, whereas the intention of predictive indices is to estimate heat strain in a population or sub-population, when exposed to particular levels of heat stress.

One of the intriguing and complicating issues of heat stress is that, unlike most other physical or chemical agents in the occupational environment, heat is a natural stressor and man, as a homeotherm, is generally well-adapted to deal with heat. Belding[13] noted some time ago that "…man's adaptations to heat exposure are so well developed (and when naked his adaptations to cold stress are so poor) that he must be classed as a tropical animal". Sawka et al[112] also noted that, "Humans are tropical animals because:

- They rely on physiological thermoregulation in the heat but behavioural thermoregulation (adjustments) in the cold;

- The thermoneutral ambient temperature for nude humans and the temperature necessary for undisturbed sleep are relatively high (approximately 27^0);

- Humans demonstrate substantial heat acclimatisation but only modest cold acclimatisation".

Despite heat stress being widely distributed and naturally occurring, many of the current heat stress indices have been developed for particular industries and the majority are empirically derived. They frequently have little validity outside the narrow range of conditions for which they were designed, and are often revised or simplified "in-house" to fit particular circumstances.

Most existing heat stress indices therefore have significant shortcomings, being technically flawed, inappropriate, impractical or poorly applied.[49,76,20,22] Typical problems include:

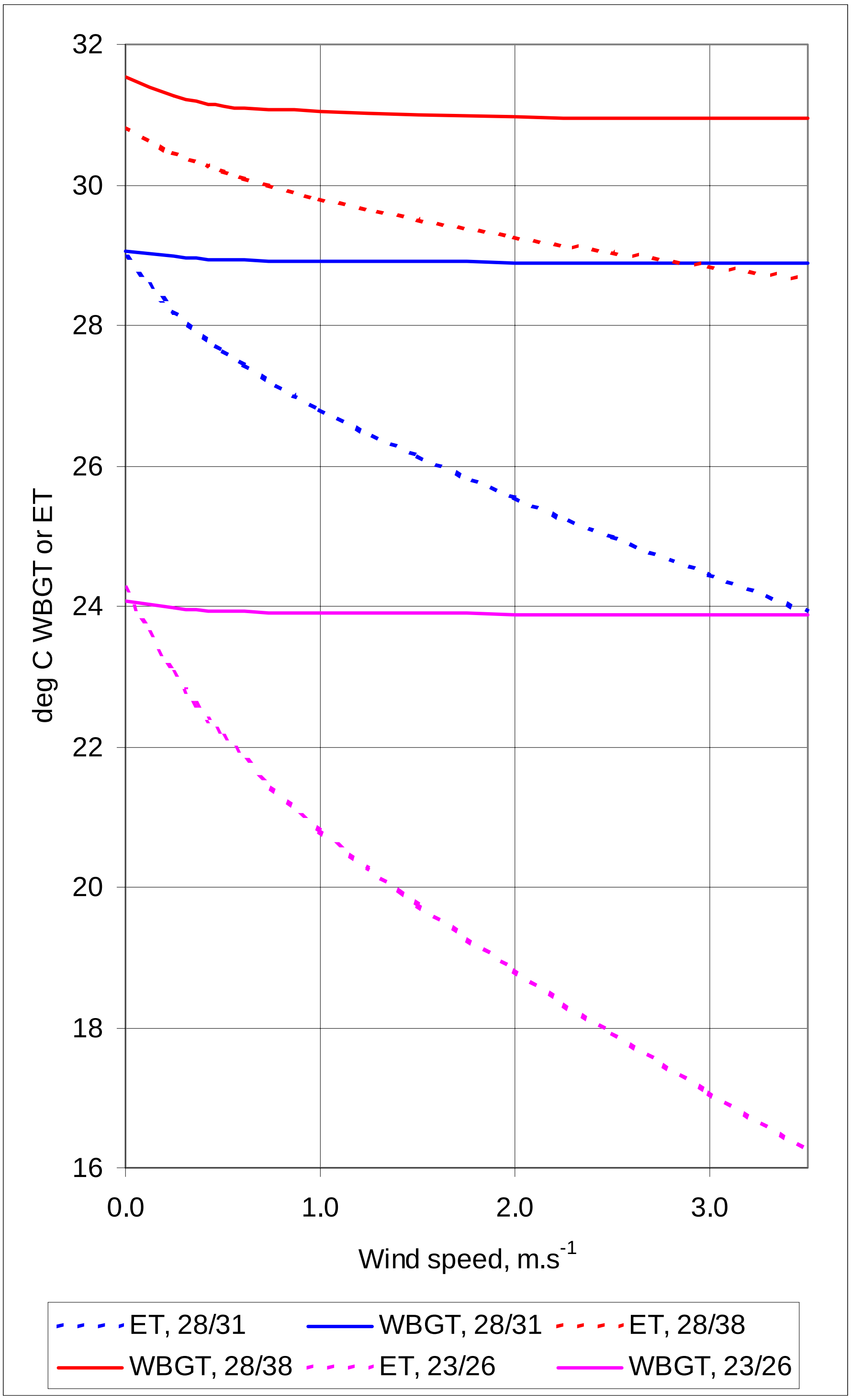
- Some indices are only poorly correlated to heat stress. One such index is the ambient air temperature (or dry bulb temperature). Despite being widely quoted around the world as an indicator of the "heat and cold" stress on humans, it correlates very poorly to physiological heat strain.[97] Another common index is the wet bulb temperature, frequently used in hot, humid workplaces such as underground mines. The wet bulb temperature is basically the temperature at which liquid water evaporates into the air and, as it is the evaporation of sweat (water) from the skin that is the principal cooling mechanism for humans under heat stress, the wet bulb is much better correlated to human heat stress than the dry bulb temperature due to its strong influence on skin temperatures. However, the wet bulb temperature by itself still ignores important factors such as any radiant heat loads and the wind speed.[73]

- Many indices require the metabolic rate as well as the environmental conditions to be assessed and then propose a time exposure limit or a work/rest cycle. However, the most common adaptations to working in hot environments are behavioural ones: reduction of the work rate (and thus of the considerable metabolic heat generated)[127,33,128] and removal of clothing. Parsons[97] notes that the realistic accuracy in estimating metabolic rate in the field is only ± 50%. Historical assessments of metabolic rates in the workplace often overestimate the true value, due to interaction of observer and subject (subject works harder when under observation), or where rates are measured using indirect calorimetry, due to the short period (frequently only 15 minutes) in which the Douglas bag or other device can be worn in the workplace.[128] Job tasks are also becoming more varied due to increasing mechanisation and "multi-skilling" of the workforce. Combined with the trend towards longer working hours (e.g. 12 hour shifts), it is common for work rates to vary significantly during a shift, and for workers to move frequently from one location to another (with potentially very different levels of thermal stress). It could therefore be argued that indices that require estimation of metabolic rates from field observations are not very practical and are prone to considerable error. This is a key shortcoming with a rational heat stress index such as ISO 7933,[64] when it is introduced into a workplace where workers are mobile, and work at varying tasks and metabolic rates during their work shift.

- Some indices do not explicitly take wind speed over the skin into account. This includes the widely used WBGT (Wet Bulb Globe Temperature), originally developed as a proxy for the Corrected Effective Temperature (CET), discussed further on page 55. WBGT uses the natural wet bulb temperature, which is almost totally insensitive to wind speed; however, CET, from which WBGT was derived, is moderately sensitive to wind speed (see Figure 6 and the later discussion of this figure in section 2.3.4 page 76). In addition, the natural wet bulb used to calculate WBGT is not generally shielded from radiation, so that it will be insensitive to wind speed but quite sensitive to high radiant heat loads, such as solar or other radiation.

- Some do not provide easily or at all for important clothing ensemble properties.[10,16,52,98] For example, ISO7933 does not include a variable clothing (water) vapour permeation term.[64]

Figure 6 Comparison of Effective Temperature (ET-Basic scale) and WBGT to wind speed for three environmental conditions: Hot-Humid (28^0 WB, 31^0 DB), Hot-Dry (28^0 WB, 38^0 DB) and Mild-Humid (23^0 WB, 26^0 DB). Note the very low sensitivity of WBGT to wind compared to ET.



- Some also incorporate radiant heat very poorly. For example, the ACGIH TLV (which uses WBGT) only incorporates a radiant heat term when the radiant heat is solar in origin. Any other "terrestrial" radiant heat loads are ignored under the ACGIH TLV, including the sometimes very substantial radiant heat loads found in smelters, refineries, bakeries or other such workplaces.

"Externally paced work" has been traditional in many industries and countries. However, the increasing degree of mechanisation of heavy tasks and the "duty of care" style of legislation that has now become common are resulting in better-informed workers and in re-designed jobs that do promote self-pacing for persons under considerable heat stress.

In this thesis, self-paced workers are defined as those who can and do regulate their own work rate, are not subject to excessive peer or supervisor pressure or monetary incentives and are well-informed about the issues of working-in-heat and the importance of self-pacing. This qualification does not necessarily mean they will be unproductive workers. In fact, self-pacing should provide the most productive overall work output for any organisation; with external-pacing (the alternative approach) resulting in some workers working below their potential, whilst others are so seriously stressed as to develop heat illness. Alternately, to ensure *no* worker develops heat illness, the limits selected by the organisation for externally-paced work (in terms of either maximum environmental temperatures or mandatory work/rest cycle) will need to be very conservative, and therefore generally unproductive, compared to self-pacing. In this thesis, the "environment" is defined as the full combination of factors outside the worker that lead to heat stress: air temperature and humidity, radiant heat, wind speed, barometric pressure and clothing (including PPE).

Acclimatisation, as alluded to above by Belding and Sawka, is another factor that impacts significantly on the thermal strain produced from equivalent levels of environmental stress.[72,42] It is difficult to have a simple, practical measure of (heat) "acclimatisation". However, acclimatisation is known to be an important adaptation to working in heat and a robust protocol needs to provide for this. Some protocols such as the ACGIH TLV[1] have adopted various corrections in an attempt to take acclimatisation into account; however, many indices do not provide advice for both acclimatised and unacclimatised states.

Other problems exist with rational indices such as ISO7933,[64] especially when applied to hot, humid environments with low wind speeds. These problems include:

- An adjustment is frequently made within the index formulation to increase the relative wind speed (between body surface and the air) when the actual wind speed is low. This is justified, firstly, on the basis of step test experiments, which indicate that at low wind speeds, an artificial air movement is induced over the skin by virtue of the work rate of the body, including arms and legs. This is not always the case, for example, where the metabolic work is produced predominantly by arm or upper body movements (not whole body) or is sometimes work done against gravity (e.g. lowering objects). In these cases, work can be mainly isometric or negative muscle contraction. When under extreme thermal stress, static muscle work can be as demanding as dynamic muscle work but may produce little induced air movement over the skin. From the author's observations of self-paced workers in thermally stressful situations, it is not valid and may even be dangerous to justify an increased relative wind speed on this basis. Secondly, it is based on the minimum convection currents that are set up between a "hot" body and the fluid environment (in this case the ambient air) around that body. This is an acceptable use of minimum wind speeds and is supported by many authors. Refer to literature reviews by ASHRAE[3] and Hólmer.[55]

- Clothing thermal properties, which have generally been established using laboratory techniques at nil airflow and using "dry" fabrics, are also known to be significantly affected by wind speed and clothing wetness.[51,56,74] This latter factor will be significant when a worker is sweating, as his clothing rapidly becomes wet and, at least in hot, humid environments, saturated as typically only 20% to 50% of his sweat will be evaporating.[69] Note that ISO7933 assumes that the intrinsic clothing insulation (I_{cl}) and vapour permeation efficiency (i_{cl}) of the clothing ensemble do not change as thermal conditions change. However, when clothing becomes wet, the intrinsic clothing insulation is reduced as most of the thermal resistance to dry heat in clothing comes from the air trapped between the clothing and the skin, and within the cloth fibres. The thermal conductivity of water is twenty times that of air, which largely accounts for the reduction in insulation of wet clothes. The loss of insulation when dry clothing becomes wet is well recognised as a major contributing factor to hypothermia during cold exposures. Some of these problems have been recognised and are currently being addressed in the European research project on heat stress and the proposal for revision of ISO 7933. [49,76,55]

- The absence of a fluid replacement term in the ISO protocol is a weakness. ISO assumes that fluid replacement will not match sweat loss during the working shift, probably because the phenomenon of "voluntary dehydration" has been reported by many authors.[2,88] However, workplaces have been observed where workers are careful to replace the fluids they are losing[38] and do not build up a water deficit.

- The ISO model is based on a simple overall weighted average thermal strain value for a shift. This is a problem as the standard does not use the "ending" stress values from one work segment as the "starting" values for the next, and check that limiting physiological criteria are not exceeded during each segment in turn. Averaging values over a shift may or may not be a weakness in practice, but is inconsistent in a protocol that is intended to provide advice on either external pacing (mandatory work/rest cycles) or the duration of exposure, and which simultaneously sets up limits in terms of heat storage (deep body core temperature) and sweat rate.

The fact that the ISO7933 is currently under review and has not been implemented to any significant extent in industrial workplaces, despite being published for over 10 years, reinforces the fact that there is still a major gap in the research for a practical, rational, heat stress index and associated protocols.

The other heat stress index that was critical to many subsequent developments in the field of heat stress and comfort in the 20th Century is the Effective Temperature (ET), referred to above. This was originally derived in 1923 by ASHVE (the American Society of Heating and Ventilation Engineers, the predecessor to ASHRAE) in private research that was investigating comfort conditions.[58] In the early 1900s, the vapour-compression refrigeration system had been invented and found immediate application in movie theatres, where windows could not be opened due to the ingress of light. This created significant heat problems in summer and a series of studies was undertaken to establish the comfort conditions for theatre audiences. A series of rooms each with different temperature, humidity and wind speed was set up, and three near-nude males were asked to move between rooms, giving their instantaneous perception as to which condition was hotter. From this, a series of nomograms were developed for “lines of equal comfort”. Even though it was never intended for such a purpose, ET was soon introduced as a heat *stress* index, due to the non-availability of other stress indices at the time. Further experiments were then completed with three subjects wearing normal “office clothing”, which lead to a separate nomogram called the “normal” effective temperature scale (the earlier scale then being designated as the “basic” scale). Shortly before WW2, Bedford proposed that the same scales be used but with the globe temperature instead of the dry bulb temperature, resulting in the “corrected” effective temperature scales (in both “basic” and “normal” versions). CET therefore allowed radiant heat loads to be incorporated into the original ET formulations. However, by the end of WW2, ET was found to have significant shortcomings particularly for moderate to hard work. Leithhead and Lind[72] comment:

- “…the {ET} scales do not give sufficient weight to the deleterious effects of low air movements in hot and humid conditions.

- "…climates of similar severity as judged by rectal temperature, pulse rate, weight loss or tolerance times do not have corresponding values of Effective Temperature.
- "…it is clear that there is an inherent error in the construction of the {ET} scales if they are to be used as an index of physiological effect, an error that increases as the severity of environmental conditions increase. This is hardly surprising since the scales were originally devised from instantaneous appreciation and comparison of the sensory warmth of different climates; thus if the error is concerned with, for example, changed physiological circumstances … in which the skin becomes fully wetted, the method by which the scales were devised … is unsuitable for this type of evaluation".

Parsons[97] also comments on the ET scale as follows:

> "A comprehensive series of studies was conducted on behalf of ASHVE in their Pittsburgh laboratory, USA, which led to the influential effective temperature (ET) index. Incredibly, the studies contained a fundamental experimental error. Three subjects were used and each walked between two chambers and compared different combinations of air temperature and humidity in terms of subjective impressions of warmth. However, subjects gave their immediate impressions which would be largely determined by the effects of transient absorption and evaporation of moisture from skin and clothing. The data may therefore be useful for studies of transient effects but overestimates the effects of humidity when considering steady-state conditions which was the aim of the study."

The shortcomings with the ET scale and major heat-related problems with troops in hot, humid and hot, dry battle theatres in WW2 led to a substantial body of work being completed during and immediately after WW2. This led in turn to the development of the P_4SR scale.[78] However, the P_4SR required the use of an even more complicated nomogram than did ET, and still required measurement of the wind speed, something that was difficult to do in the early 1950s with any accuracy using a small portable instrument in the field.

The widely-acknowledged physiological shortcomings with ET (and CET), and the practical problems concerning the need for complex nomograms to be consulted and the need for wind speed to be measured in the field for both ET and P_4SR led to the US Navy developing in 1957 a “simplified” ET scale which they called the Wet bulb globe temperature (WBGT).[140] The concept behind WBGT was to ignore wind speed (impractical to measure in the field in the 1950s), but to incorporate some measure of wind speed into the index by using the “natural” wet bulb, rather than the ventilated wet bulb. Natural wet bulb was postulated to be a better reflection of the actual “cooling power” of the air for a human, compared to the ventilated wet bulb. This was a similar rationale as the concept behind using the “Wet Kata” thermometer in hot, humid gold mines.

ET was therefore generally superseded as an index of occupational heat stress by the WBGT from the late 1950s, and ET was subsequently also abandoned as a comfort index by ASHRAE in 1961.

The number of heat stress indices developed over the years, the lack of broad acceptance of any single index, the recognised shortcomings of the most common index in use, the WBGT,[105] the unwillingness of ISO7933 to be recognised by practitioners, and the fact that heat is a naturally occurring stressor, all emphasise the dilemmas and uncertainties in managing heat stress, especially in an occupational setting.

Furthermore, most indices are used to predict whether continuous work is possible or some sort of work/rest cycle is required, under particular conditions. Where a comparison is made between two indices, and both indices indicate continuous work is possible, the investigator has no simple means to know just how close each of the indices is to requiring a work/rest cycle. In other words, many current indices give the condition a “simple pass” when the investigator really wants to have a “graded pass”.

In addition, due to the many different types of physiological limits used by different indices (e.g. sweat rate, heart rate, skin wetness, core temperature), it is very difficult for an investigator to compare different indices on an equivalent basis.

For both these reasons, comparing indices in a valid way is currently very difficult and occupational health and safety practitioners are therefore often reluctant to replace an existing index for something that may (or may not) be better or in which the business implications may or may not be quantifiable.

Therefore, with respect to heat stress indices, the literature indicates that:

- There continues to be a significant need for a more accurate (but no less practical) index of heat stress and physiological strain. Such an index has been developed in this thesis, and implemented in many workplaces, and is called the Thermal Work Limit (TWL).

- There is a need for heat stress protocols designed specifically for self-paced workers. This also has been developed in this thesis.

- Most of the definitive research into occupational heat stress involving human experiments was conducted between the outbreak of World War II and the end of the 1960s. Whilst there has been some research into heat stress since the 1960s, particularly for military subjects and elite athletes and for some special groups such as the Mecca pilgrims and the elderly, occupational heat stress limits are still based substantially on experimental data collected 30 to 80 years ago. Societal norms, medical science, industrial work practice, population morphology, statutory regulations and the management theory and practice of occupational health and safety have all changed significantly in this time. There is therefore a need for new human experimental studies using modern industrial workers, and using the new technology now available to assess physiological strain. This thesis reports such a series of major experiments on human subjects in the areas of deep body core temperature, heart rate, sweat rate, fluid replacement and fatigue;

- There is no valid, quantitative means to compare the wide range of heat stress indices in use. Such a tool would allow a more informed discussion of the relative merits and quantitative impact of the various indices on health, safety, productivity and costs. It would make it substantially easier for regulators, hygienists, engineers, occupational physicians and operational managers to consider changing heat stress indices or protocols. This thesis also develops a new method to allow a valid comparison of all occupational heat stress indices.

1.3.3 Background to rational heat stress indices based on the human heat balance equation

For human thermoregulation,[89,91] the heat balance equation is expressed[3,122,131] as:

$M - W \quad = Q_{sk} + Q_{res} - F + S$ .... equation 1

where M is the metabolic rate, in $W.m^{-2}$

W is the external (mechanical, useful) work rate, in $W.m^{-2}$

Q_{sk} is the heat loss through the skin, in $W.m^{-2}$

Q_{res} is the heat loss through respiration, in $W.m^{-2}$

F is the heat loss due to fluid replacement, in $W.m^{-2}$

S is the heat storage in the body, in $W.m^{-2}$

The units of all terms in equation 1 are $W.m^{-2}$ where W is the metabolic rate in watts and m^2 is the skin surface area (for a “standard” person, this is usually taken to be 1.8 m^2).

Under most circumstances, the W term in equation 1 is small and is generally ignored because it is small, because it cannot be estimated with accuracy in the field, and because doing so usually adds a degree of conservatism to the estimate of the amount of heat that must be rejected via the skin and respiration. However, in some circumstances (e.g. manually lowering heavy objects, the W term is actually negative as the useful work done resisting gravity becomes an additional heat load on the body).

Most authorities have traditionally overlooked the F term in equation 1. However, for a person under thermal stress drinking 1 litre per hour of water at 12^0 C, and this being absorbed into the body at (say) 38^0 C, the net cooling effect is 30 W, or 17 $W.m^{-2}$ for a standard person. This is substantially greater than the typical heat losses due to respiration, and can be a significant proportion (>10%) of the total heat exchange when conducting light work (e.g. 115 $W.m^{-2}$) under very thermally stress circumstances. However, when making comparisons between heat stress indices, F can be considered to be zero, as no index to date takes this term specifically into account and there is no certainty about the temperature of the water being ingested by workers under heat stress. It also adds some further degree of conservatism into the heat balance equation.

The purpose of most heat stress indices is to develop a guideline for safe work in particular environmental conditions. For *continuous* work to be safe in a particular environment, the core temperature must plateau at a safe level, i.e. the S term in equation 1 (heat storage in the body) must become zero. For any particular heat stress index, there will be a unique maximum metabolic rate at which continuous work (at a given environmental condition) is regarded as safe under that index. This is the *limiting* (or maximum) metabolic rate predicted as being safe for the particular environmental and clothing conditions. This limiting metabolic rate is usually expressed in $W.m^{-2}$.

At this limiting condition (with W = 0 and S = 0),

$$M = Q_{sk} + Q_{res} \quad \text{......... equation 2}$$

In other words, the metabolic heat generated by work is just equal to the heat rejected by the body. Ignoring the effects of fatigue and assuming hydration is maintained, equation 2 describes the maximum metabolic rate that can be sustained, without any rest pauses (i.e. without a formal work/rest cycle), in this particular environment wearing a nominated clothing ensemble. This maximum (limiting) metabolic rate is what is defined in this thesis as the Thermal Work Limit (TWL). The full derivation of TWL is provided in section 3.1 page 95.

1.3.4 Air Cooling Power (ACP)

Whilst there are many rational heat stress indices (e.g. ISO7933 discussed above), all of which rely at least conceptually on solving the human heat balance equation, some are early precursors to TWL and therefore warrant further discussion.

Mitchell[85] originally coined the term “Specific Cooling Power” to describe the maximum work rate for a particular environment, which he saw as being a fundamental property of the environment (hence “cooling power”). His formulation suffered from using a fixed skin temperature, was only for nude, acclimatised workers in hot, humid environments relevant to underground mines in South Africa (defined as environments where the DB temperature was exactly 2^0 C above the WB temperature), only considered the situation in which a worker had a fully wet skin, and did not provide for any net radiant heat loads.

Stewart subsequently conducted an extensive research program and developed an index he termed “Air Cooling Power”.[117,118,119,120] The A scale was for acclimatised workers and the B scale for unacclimatised workers. Stewart’s A and B scales did relax the requirement for a fixed skin temperature, but all the other constraints of Mitchell’s earlier formulations remained.

Howes developed a modified ACP formula (referred to here as the “H” scale) although this has never been published.[60] The Howes scale does not correctly extrapolate data from Stewart’s experiments on hot, humid environments into hot, dry environments and assumes an unlimited vapour permeation from wet clothes, which is incorrect.

McPherson has also developed and published a formulation for ACP, the “M” scale. The M scale was intended to also cover the “non-limiting” conditions but assumes a uniform skin temperature in cool environments, which is not correct, and draws heavily on Stewart's data for hot, humid conditions without validly extending these into hot, dry conditions or to non-limiting metabolic rates.

None of the above ACP formulations have ever been implemented in an occupational setting.

TWL is an entirely original derivation to any of the existing formulations of ACP, although it does draw on some of the original tabulated experimental data from Wyndham, Stewart and others. The derivation is discussed in detail in section 3.1 starting on page 95.

1.3.5 Deep Body Core Temperature

Excessive heat strain in the workplace can lead to a continuum of medical conditions with symptoms ranging from headache and nausea through vomiting and syncope to more severe central nervous system disturbances. The end point of most forms of acute heat illness is heat stroke, which if untreated or sufficiently severe, can lead to death and frequently leads to permanent tissue damage.[136,114,87] In a recent study, one sub-class of heat illness (heat exhaustion) has been shown to have a clear clinical profile[31] and is relatively common in the mining industry. This condition may well have been under-reported in other industries during periods of high ambient temperature.

The principal pathophysiological factor responsible for heat illness is generally considered to be hyperthermia, due to an extreme environment (high ambient temperatures), high metabolic loads (strenuous physical work), a reduction in the body's heat rejection ability (vapour-barrier or heavily insulating protective clothing) or any combination of these. In addition, it could be hypothesised that the rate of increase in deep body core temperature is an additional potential factor in the development of heat illness.[35,47] Circulatory insufficiency, which results from an excessive call on cardiac output to transport heat from the deep body core to the skin, and dehydration due to inadequate replacement of fluids lost in sweat, are factors that frequently lead to hyperthermia and possibly heat exhaustion. To date no major field study has been conducted to continuously document the actual core temperature of workers in hostile environments undertaking their normal tasks. Such a study would better define the relationship between environmental heat stress and the physiological strain on the worker. In addition, it would allow the validation of currently recommended limits for the prevention of occupational hyperthermia.

These recommended limits generally fall into one of three categories:

- Limiting (maximum) deep body core temperature, with a typical limit being 38^0 C or 38.5^0 C,[1,126,107,28,96,14,137]

- Limiting (maximum) increase in deep body core temperature, with a typical limit being 1^0 C,[1,126]

- Limiting (maximum) heat storage in the body, with a typical limit being 60 W.hr.m^{-2} for acclimatised workers or 50 W.hr.m^{-2} for unacclimatised workers.[64,3] These figures translate to 389 kJ and 324 kJ of heat storage respectively for “standard” persons of 1.8 m^2 skin surface area.

Frequently these authorities advise evaluating the thermal stress using two or more of these criteria, and using the most conservative as the relevant limit. Some of these indices are extremely difficult to monitor as prescribed. For example, to administer a workplace using the ISO7933 standard,[64] a range of environmental parameters need to be monitored continuously near each worker and an assessment of metabolic rates and clothing ensemble (including personal protection equipment) is required. Exposure limits and exposure times must then be calculated and then weighted to find the overall allowable exposure.

Apart from the technical difficulties, there are a number of complications in measuring and setting limits for industrial hyperthermia:

- In practice, the temperature of the important deep tissues in the body of any particular individual at any given time varies within about a 0.5^0 C range even when at rest in thermoneutral conditions (conditions of no heat strain).[72] "Core" temperatures can be estimated by a number of methods, including sub-lingual, tympanic, rectal, oesophageal and gastrointestinal. There is no broad acceptance of a single superior site within the body as defining, from a physiological point of view, a critical "core" temperature.[112,118,65,97,122,110] However, due to the pivotal role of the blood in collecting heat from the core and transmitting it to the skin where the heat can be rejected, oesophageal temperature (measured at about the level of the heart) is considered a very close indicator of the temperature of blood leaving the heart, and is therefore probably the most valid single indicator of deep body core temperature. Unfortunately, it can only be safely measured in a laboratory.

- Even when unstressed and in identical environmental conditions, the "average" temperature of deep body tissues can differ by up to 1^0 C for different individuals, indicating that a range, rather than a single set point, exists for humans.[72,61]

- There is a daily (circadian) rhythmicity, which includes temperature, for virtually every organ of the body.[25] The "average" deep body core temperature can vary diurnally by 1^0 C or more[122,112] for any individual, even when unstressed and in thermoneutral conditions. For resting, thermoneutral conditions, deep body core temperature is at its lowest about 4 am and at its highest about 6 pm. As will be seen later, this daily variability has practical consequences when attempting to set limits for nightshift workers, or workers on extended (12-hour) shifts.

- There is also a change of about 0.5^0 C in the overall deep body core temperature for females, associated with their menstrual period.[36,122,112]

- In the past, most information about deep body core temperatures has been obtained using rectal thermometers or transducers. This location has effectively prevented the continuous measurement of core temperatures in actual work environments and generally meets with strong resistance from subjects. Where measurements have been taken rectally in field studies, they have been intermittent, and therefore are unlikely to have captured the full temperature response in the body, particularly where environmental conditions or work rates have varied significantly with time.

For this reason, only modest amounts of reliable information are available from field studies. Extrapolation of laboratory work to occupational settings is generally prone to some error and uncertainty due to the very different environments involved, the artificial nature of the laboratory setting, and the interaction of the experimenter with the subject.[100]

Improved information on deep body core temperatures of occupational workers in their work environment would therefore assist significantly with the development of appropriate heat stress indices and protocols. The information needed for these decisions falls into several areas:

- What upper values of core temperature are reached regularly and safely in a typical thermally stressful workplace where workers are self-pacing?
- What is the time duration over which elevated core temperatures prevail?
- What is the rate at which core temperatures increase, and decrease?
- Is heat exhaustion likely to be related to hyperthermia, or to something else, e.g. hypohydration?
- What is a safe and realistic core temperature increase for workers on 12-hour shifts where the working day is a significant proportion of their overall circadian body temperature cycle?

1.3.6 Fluid Losses, Replacement and Hydration Status

Dehydration is known to produce a wide range of physical, mental and psychological decrements in performance[1,72,45,70,28, 90] and has been implicated in 50% of all heat stroke cases in South African miners.[71] Therefore the ability of industrial workers to replace fluid lost in sweat is crucial when establishing protocols for working in heat, and particularly in the design of protocols for extended work shifts (i.e. greater than 8 hours duration).

In this regard, there is disagreement in the literature about acceptable sweat rates for industrial workers. Whilst sweat rates of 1.5 to 2.5 l/h have been demonstrated over short periods (with peaks of 3 l/h),[38,109] acceptable figures for a working shift are generally considered to be lower. ISO7933[64] and Belding and Hatch[11] advocate a limit of 1.04 and 1.0 l/h respectively for acclimatised persons (although note that ISO9886 states that the values in ISO7933 "…must be considered not as maximum values but rather as minimal values that can be exceeded by most subjects in good physical condition". Nunneley[94] reports that humans can sweat indefinitely at rates of 1.5 to 2.0 l/h, whilst McArdle[78] recommended a limit of 4.5 litres over 4 hours. This relatively wide range of acceptable sweat rates is in part related to the wide range of views on acceptable skin wettedness, with ISO7933 accepting a fully wet skin (1.0 wettedness) for acclimatised workers over extended periods, but Azer[7] recommending a maximum value of 0.5 for similar, fully acclimatised persons. A much higher sweat rate is required to maintain a fully wet skin than a 50% wet skin.[64,69]

Various authors have found that fluid replacement when under thermal stress is only ½ to $^2/_3$ of the fluid loss.[2,71,23] This observation has subsequently been endorsed as an unavoidable water loss in thermal stress standards such as ISO7933, and therefore has a major impact on allowable exposure times in hot conditions with high sweat rates. This fluid deficit has been attributed to two phenomena.

- The first is "voluntary dehydration", in which persons dehydrate while under thermal stress despite having access to plentiful supplies of palatable water. Adolf[2] attributed this to an inadequate thirst response, i.e. that the thirst response is delayed and/or insufficient to provide for adequate fluid replacement. Other authors have found that the thirst sensation does not begin until about 1% to 2% of body weight[72] or 2% of total body water[113] has been lost. There is still disagreement as to whether the thirst response is inadequate or merely delayed or both.[48,113,46]

- The second phenomenon is rather confusingly called "involuntary dehydration". It refers to the fact that during the dehydration process (or once hypohydrated), the rate of fluid retention (or rate of rehydration), even when the fluid intake exceeds the sweat rate, is governed largely by the ability to replace the solutes lost in sweat, principally sodium.[92,86,88,75]

Other authors have found and described a condition called "sweat gland fatigue".[112,69,72,2] Its pathogenesis remains unclear;[111] however, it has been implicated in reductions in sweat rates of up to 50% after continuous exposures of four hours.[67,121] Sweat gland fatigue should not be confused with hidromeiosis, which is a localised reduction in sweat rate; several mechanisms have been proposed for this but the most probable is that localised swelling (hydration) of the stratum corneum results in mechanical obstruction of the sweat duct.[111,124,69]

A further issue for review in this study was to examine the importance of the meal break in maintaining the hydration state. Initial researchers such as Adolf[2] found that the meal break had an important role in rehydration. He reported that the ingestion of food during a meal break (and perhaps the rest pause itself) stimulated the thirst response and led to the intake of additional fluids, which he suggested was essential to restoring total body water. With the trend towards longer (e.g. 12-hour) shifts, the number of meal breaks and their location within the working shift and duration could be more significant than in traditional 8-hour shifts.

Therefore key issues for further investigation include:

- What are typical sweat rates in modern industrial workers? What is a reasonable upper limit?
- How does the hydration state of workers change during their shift?
- Are either "voluntary" or "involuntary" dehydration (or both) unavoidable responses when working under thermal stress?

1.3.7 Fatigue

Fatigue is a general term used to describe a wide variety of conditions. Craig and Cooper[29] comment that "our technical use of the term fatigue is just as ill-defined as the lay usage. It is applied to effects that develop over minutes – perhaps even seconds – or hours, and to effects that take weeks or months to develop". They describe fatigue as having three broad modes: *Subjective fatigue* where the person may feel fatigued and disinclined to apply any more effort to the activity, *Performance fatigue* where performance may deteriorate or, if skilled, lose its smoothness or timing and *Organic fatigue* where the body's physiological functioning or its chemistry may be affected. Perhaps the best overall definition of fatigue is simply a "decrement in performance".

Acute fatigue can be divided into *mental* fatigue, due to mental overload or underload (associated with monotony and boredom) and *physical* fatigue. Physical fatigue has been noted in heat exhaustion and attributed to several possible physiological disturbances: hyperthermia,[107,66] circulatory strain due to excessive call on cardiac output to deal with hyperthermia and/or reduced circulating volume due to dehydration,[99] sweat gland fatigue,[111] depleted muscular glycogen concentration[35] and muscle soreness due to overuse.[40]

In addition, a condition of *central* fatigue has been described. This is a condition of depressed central nervous system activity characterised by a lack of willingness to continue the activity, described as being not unlike the fatigue that occurs during hypoglycaemia. It could be due to a redistribution of blood flow away from certain brain areas.[99]

Therefore acute fatigue, the focus of this study, has a number of potential sources including central command (CNS), hyperthermia, circulatory disturbances, dehydration, carbohydrate depletion, altered sweat rate function, electrolyte imbalance and muscle damage.

For an industrial worker who performs physical work in an environment of considerable thermal stress, acute fatigue is likely to be related either directly or indirectly to muscular fatigue or the effects of the thermal environment as these are the two main stressors on the worker. In turn, the strain from these stressors can be characterised by an elevated deep body core temperature, heart rate, blood lactic acid or pulmonary ventilation.

In terms of physical fatigue, several authors have found that endurance is not limited if work rate does not exceed 33% to 50% of $\dot{V}O_{2\max}$.[15,43,3] This is the aerobic capacity (defined as the $\dot{V}O_2$ at which no significant oxygen debt accumulates),[99] or the anaerobic threshold.[34] Most humans' aerobic capacity is about that of a brisk walk ($\dot{V}O_2$ of 1 l/min or 5 kcal/min or 195 W/m^2).

Whilst $\dot{V}O_2$ is difficult to measure in an occupational setting, $\%\dot{V}O_{2\max}$ is known to be approximately equivalent to % cardiac reserve.[34] As % cardiac reserve is a function of working, maximum and resting heart rates only, and maximum and resting heart rates do not change for a particular individual over short periods, changes in working heart rates serve as a valid approximation for changes in work rates and changes in $\dot{V}O_2$.

Heart rate is known to be affected by physical and psychological factors. However, it has been found to be a good index of strain if an appreciable stress is already imposed as a baseline.[72]

Therefore, changes in heart rate are considered an important indicator of strain, and also fatigue when measured in workers performing physical work in thermally stressful environments, over the course of a working shift.

Minard[83] found impaired performance did not occur until the mean heart rate over a full shift (8 hours) was 120 bpm or higher, with the WHO[134] recommending a lower figure of 110 bpm whilst allowing brief excursions (< 2 hours) above 120 bpm for acclimatised, fit persons. ISO9886[65] recommends an increase in heart rate due to thermal strain to not exceed 30 bpm with an absolute limit from all causes to not exceed the individual's maximum heart rate less 20 bpm. However, this advice presents problems if strictly interpreted; for example, a worker with a resting heart rate of 60 bpm sitting in a thermally stressful environment would need to be withdrawn once his heart rate exceeds 90 bpm, a very low level of overall stress.

Except for new workers or new activities, muscle soreness is unlikely to be a cause of physical fatigue unless it involves excessively repetitive or forceful activities, as work hardening (e.g. muscle hypertrophy) results in rapid adaptation.

Short, heavy exercise is known to result in a decline in pH due to an accumulation of lactate in the muscle cells, which can result in fatigue.[44] A level of approximately 4 $mmol.l^{-1}$ in arterial blood is considered to indicate the anaerobic threshold.[77]

In terms of thermal fatigue, heat exhaustion is generally defined as a circulatory deficiency due to water or salt depletion. It is characterised by thirst, weakness, fatigue, dizziness, anxiety, oliguria, tachycardia and moderate hyperthermia,[129] weakness, inability to continue work and frontal headaches.[27] Its biochemical and haematological profile has been recently reported in an occupational setting.[31]

Adolf[2] also described a condition he called dehydration exhaustion. This was not associated with hyperthermia but is related to non-working subjects exposed to hot environments who gradually dehydrated to the point of total exhaustion, i.e. a survival situation. Its onset was at 12% or more hypohydration. This is not a level of dehydration likely to be encountered in an occupational setting.

Sawka[113] found that hypohydration of 4% to 6% was frequent during situations of prolonged sweating, even with ad libitum access to water. This supports Adolf's earlier finding that uninformed and unsupervised humans are unlikely to replace fluid losses due to either an inadequate or delayed thirst response (or both).

Dehydration and hyperthermia have both been found to independently result in decrements in mental performance,[103] and especially attention overload (inability to properly process all the various stimuli reaching the brain).[63]

Mental and physical decrements in performance have been associated with hypohydration of as little as 2% total body water,[82] with pronounced effects at 4%.[99,41] Fatigue due to hyperthermia has been associated with deep body temperatures of as little as 38^0 C,[64,129] with most persons suffering fatigue at deep body temperatures exceeding 38.5^0 C.[28]

Hypohydration also results in muscle fatigue.[125] Both hyperthermia and dehydration are known to result in cardiovascular strain,[112,28] and hence are manifest as an increase in heart rate.

Therefore key issues for further investigation include:

- Is there evidence of a time-related fatigue in self-paced workers subject to thermal stress on extended shifts?
- How are fatigue and hydration linked?
- Are deep body core temperature and heart rate related during the working shift?

Chapter 2 - Methods

2.1 Experiment Codes Used in Thesis

Throughout this thesis, a code (e.g. CLI05M8) is used to describe each experiment. This has been done to protect the identity of the human subject in the experiment. However, some details can be given concerning these codes without compromising ethical requirements. The first three letters is a scrambled code representing the subject's name (not his initials). The next two digits are the date of the month when the test started (some tests went for two or three days); the next letter represents the month of the year (as all work was done over the southern hemisphere summer period between December and April [months with unique starting letters], a one-letter month code was sufficient) and the final digit is the final digit (x) of the year, 199x. Hence CLI05M8 represents a test conducted using subject CLI starting 5 March 1998.

On the various charts, a "shift code" is also given. Thus "NDN (12)" means that the experiment was conducted over two consecutive 12-hour working night shifts with an intervening day rest period also monitored. A code of NN (10) would mean that two consecutive 10-hour working night shifts were monitored (but not the intervening rest period).

Other explanatory information regarding individual experiments is given within the section concerned.

2.2 General information on subjects

As the same subjects were frequently used for the several different experiments reported in the various chapters, the anthropometric, body morphology and $\dot{V}O_{2\max}$ data for the entire group is shown in Appendix D. Summarised data is shown in Table 1. The data for the particular subject group used in each particular study (core temperature, fatigue, etc) is summarised in the relevant section. The average and median BMI of these workers, at 27.7, is within the middle of the overweight range (BMI 25.0 to 30.0) as recommended by the World Health

Organisation,[133] and the average $\dot{V}O_{2\max}$ of 39.1 $ml.kg^{-1}.min^{-1}$ (median 37.8) is at the lower limit of the normal range of 39 to 48 $ml.kg^{-1}.min^{-1}$ for "non-athletes" aged 30 to 39.[132] These workers are therefore no more than moderately fit.

Table 1 Summarised anthropometric, body morphology, $\dot{V}O_{2\max}$ and working shift data for all target subjects. For details, refer to Appendix D. Of the 45 workers, 14 were on 10 hour shifts, 28 were on 12 hour shifts and 3 were on 12.5 hour shifts.

Code	Age, years	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$ $ml.kg^{-1}.min^{-1}$
n	45	45	45	45	26
Average	34.8	178.1	88.1	27.7	39.1
Median	35.0	178.0	86.0	27.7	37.8
Std Dev	7.1	8.5	14.9	3.6	7.0
Range	21.0 to 52.0	147.3 to 196.0	65.0 to 125.0	22.1 to 38.2	28.0 to 56.3

Environmental conditions were measured approximately every 60 to 90 minutes and are shown in Appendix E. The aggregate environmental data for the sample group used in each particular study is summarised in the relevant section. To avoid the need for replicating long tables of 'hourly' data in the individual chapters with little additional information, all 'hourly' information is shown in Appendix E, including Rating of Perceived Exertion (RPE), fluid consumption, urinary specific gravity and tympanic temperatures. Note, however, that whilst the data was collected, RPE and tympanic temperatures have not been analysed nor discussed in this thesis.

2.3 Comparison of TWL with Other Indices

One important feature of the concept of a "limiting work rate" is that it makes it possible for all heat stress indices to be compared on an equal, and valid, basis. This is because all heat stress indices are based (rationally or empirically) on fulfilling the requirements of the human heat balance equation (to avoid hyperthermia) and therefore all indices, either explicitly or implicitly, include a metabolic rate when setting a limit.

By solving for this “limiting” rate at a particular set of environmental conditions (combination of temperature, humidity, wind speed and barometric pressure), clothing parameters and acclimatisation state, each index can be compared with the other.

The method used to calculate the limiting metabolic rate for a different type of index is best illustrated by way of example.

2.3.1 WBGT

The ACGIH[1] recommends using the Wet Bulb Globe Temperature (WBGT) as the heat stress index. For outdoor work with a radiant heat load, the WBGT is defined as follows:

$$\text{WBGT} = 0.7 \times \text{NWB} + 0.2 \times \text{GT} + 0.1 \times \text{DB} \quad \text{............................. equation 3}$$

Where NWB is the natural wet bulb temperature, GT is the globe temperature, and DB is the dry bulb temperature.

The recommended Threshold Limit Values (TLVs) for acclimatised and unacclimatised workers are given in Figure 1 of the 1998 Heat Stress TLV[1].

Standard curve-fitting techniques show that the ACGIH curves can be expressed by the following equations, with regression coefficients (r^2) better than 0.9995:

$$\text{WBGT}_{\text{max, acclim}} = 125.63 - 76 \times \text{Met}^{0.04418} \quad \text{.................................. equation 4}$$

$$\text{WBGT}_{\text{max, unacclim}} = 70.91 - 22.04 \times \text{Met}^{0.1317} \quad \text{............................... equation 5}$$

Where Met is the metabolic rate, in W.m^{-2} and WBGT_{max} is the maximum wet bulb globe temperature:

These can be transposed as:

$$\text{Met}_{\text{max, acclim}} = [(125.63 - \text{WBGT}) / 76]^{22.634} \quad \text{equation 6}$$

$$\text{Met}_{\text{max, unacclim}} = [(70.91 - \text{WBGT}) / 22.04]^{7.592} \quad \text{equation 7}$$

By then selecting any particular values of natural wet bulb, dry bulb and globe temperatures, the corresponding WBGT and ACGIH limiting metabolic rates can be calculated.

Specific issues associated with other indices selected for comparison in this thesis are as follows:

2.3.2 ISO7933

ISO7933 limiting metabolic rate was found by calculating the unique value of metabolic rate, at which the rate of heat storage was nil for acclimatised persons, using the ISO heat balance equations, recommended limits for acclimatised persons, and 0.6 and 0.7 for clothing thermal insulation and "body area fraction exposed" respectively.

2.3.3 USARIEM (United States Army Research Institute of Environmental Medicine)

USARIEM has developed a sophisticated model of human thermoregulation for military use[96]; however, it does not directly provide a limiting metabolic rate. The limiting metabolic rate was found by finding the highest value of the target parameter (e.g. wet bulb temperature) for which work was continuously possible (work/rest cycle = 60 minutes per hour) whilst holding the other environmental parameters constant. These limiting WB temperatures were then plotted over the range of metabolic rates and environmental conditions of interest, and interpolated for the actual condition of interest.

The USARIEM limiting data for Trousers, Long-sleeved shirt, Safety helmet and Safety boots (Itc = 1.13, Itvc = -0.23, Imc = 0.45, Imvc = 0.44) is summarised in Table 2 Page 76.

Table 2 USARIEM limiting wet bulb temperatures for hot/humid and hot/dry environments.

Maximum WB (^{0} C) for unlimited work cycle for DB=MRT=WB+3^0 C “Hot, humid”				
Met rate, W	0.2 m.s^{-1}	0.5 m.s^{-1}	1.0 m.s^{-1}	3.0 m.s^{-1}
100	>36.0	>36.0	>36.0	>36.0
150	35.0	36.0	36.0	36.0
250	32.5	32.5	33.5	34.0
350	29.5	30.0	30.5	32.0
425	27.0	27.5	28.5	30.0
600	16.5	17.5	19.0	22.0
Maximum WB (^{0} C) for unlimited work cycle for DB=MRT=WB+10^0 C “Hot, dry”				
Met rate, W	0.2 m.s^{-1}	0.5 m.s^{-1}	1.0 m.s^{-1}	3.0 m.s^{-1}
100	>36.0	>36.0	>36.0	>36.0
150	35.0	35.0	35.0	35.5
250	31.5	32.0	32.5	33.5
350	28.0	28.5	29.5	31.0
425	25.5	26.0	27.0	29.0
600	12.5	13.0	15.5	17.5

Note: these metabolic rates are W, not W.m^{-2}, as USARIEM provides values in W.

2.3.4 Corrected Effective Temperature (CET – normal scale)

CET – normal scale (hereafter CET(n)) values were found directly from published charts of CET(n). Table 3, page 77 gives the acceptable upper limits for continuous work in terms of CET(n).[130]

Table 3 Corrected Effective Temperature (CET – normal scale) limiting values according to Weiner.[130]

Description of work	Metabolic rate, kcal.hr^{-1}	Metabolic rate, W.m^{-2}	Acclimatised limit, ^{0}CET(n)	Unacclimatised limit, ^{0}CET(n)
Light work	150	175	32.0	30.0
Moderate work	300	350	30.6	28.0
Hard work	450	525	28.9	26.5

The resulting values of maximum wet bulb temperatures, based on the *normal* scale of corrected effective temperature, were then calculated for four wind speeds at each of the three work rates and two environments (hot, dry and hot, humid) and are shown in Table 4.

Table 4 CET- normal scale limiting wet bulb temperatures for combinations of work rate, wind speed, and environmental conditions

			Maximum WB for wind speed, m.s^{-1} of:				
		Met rate, W.m^{-2}	0.2	0.5	1.0	3.0	Subject to:
Light work	32.0^0 CET	175	31.7	32.0	32.3	33.3	Hot, humid DB = MRT = WB+3^0 C
Mod work	30.6^0 CET	350	29.8	30.2	30.7	31.9	
Hard work	28.9^0 CET	525	28.1	28.5	28.9	30.4	
Light work	32.0^0 CET	175	29.7	30.0	30.4	31.2	Hot, dry DB = MRT = WB+10^0 C
Mod work	30.6^0 CET	350	27.5	27.8	28.3	29.4	
Hard work	28.9^0 CET	525	25.3	25.7	26.1	27.4	

These values were then plotted and interpolated for the conditions of interest (i.e. 140 $W.m^{-2}$ or 28^0 WB). No recommended CET(n) values were available from this source for work rates less than 175 $W.m^{-2}$.

2.3.5 Air Cooling Power (ACP)

2.3.5.1 Stewart

Unfortunately it has not proved possible to re-create Stewart's formulation mathematically. However, tabulated values of Stewart's A and B scales are available for a narrow range of interest (basically hot, humid environments).

2.3.5.2 Howes

A Visual Basic computer program (refer Appendix A) was written to solve Howe's unpublished formulation.

2.3.5.3 McPherson

A Visual Basic computer program (refer Appendix B page 174) was written to solve a published formulation of ACP from McPherson.[81]

2.4 Deep Body Core Temperature

2.4.1 Objective

The objectives of the study are described previously in the Literature Review.

2.4.2 Equipment

Core temperature monitoring equipment consisted of "CorTemp"[62] temperature-sensing pills each with an in-built miniature radio transmitter, and "BCTM"[101] ambulatory data recorders (Figure 7). The pills, which are about 10 mm long, transmit the temperature of the surrounding tissues for their transit time in the gastrointestinal tract, which is typically 24 to 48 hours. The pills are not recovered. The manufacturer's reported accuracy of the pill is $\pm 0.05^0$ C. Each pill is individually calibrated during manufacture and can be set, in the field, to transmit the temperature at an interval between 5 seconds and 1 minute. In this study, the transmission interval was 1 minute. Gastrointestinal temperature is considered to be more closely related to rectal temperature than to oesophageal temperature[26] and is therefore likely to be about 0.5^0 below the temperature of blood leaving the heart and diffusing through the body core.[38] However, rectal temperatures have the advantage that they can be compared with numerous historical studies, as these invariably measured core temperatures rectally.

2.4.3 Subjects and Study Design

The study was conducted on 36 workers (all males) within the target group (refer Table 5 for a summary and Appendix D for full details). $\dot{V}O_{2\max}$ data was not obtained on all subjects due to some subjects not reporting for this test.

Table 5 Anthropometric and body morphology of the 36 workers in the core temperature study (target group).

	Age, yrs	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$, ml.kg^{-1}.min^{-1}
n	31	31	32	31	19
Avg	35.4	179.4	88.8	27.5	37.7
Std Dev	7.56	8.36	13.96	2.77	4.67
Range	24-52	163-198	65-125	23-33	31.1-47.4

A control group of six office workers (all males) working in the same operation, but in sedentary jobs in an air-conditioned office (typically 24^0 C, 50% relative humidity) was also tested. Office workers commenced work between 6:45 am and 8 am and finished between 5 pm and 6:30 pm daily. They were heat unacclimatised in comparison with the target group.

Figure 7 CorTemp^{TM} core temperature pill and BCTM ambulatory core temperature recorded. Each pill is individually factory-calibrated with its own serial number and calibration number and is provided in a sealed plastic bag. The pill is "activated" (starts measuring and transmitting temperature) by removing the small magnet attached to the pill.

Elapsed recording time was typically an hour less than the 9 and 7.5 effective hours in the 12 and 10 hour shifts respectively, as the monitoring equipment was set up on each individual after the start of the shift, and removed before the conclusion of the shift.

2.4.4 Environmental Conditions

Environmental conditions were measured at each workplace approximately every 60 to 90 minutes using a Heat Stress Meter[123] (Figure 8) which provides digital readouts of ventilated wet bulb temperature (WB), dry bulb temperature (DB), wind speed, globe temperature, calculated mean radiant temperature, barometric pressure and Wet bulb globe temperature (WBGT). Sling (whirling) psychrometers and vane anemometers were also used to obtain redundant measurements of the most important environmental parameters in these workplaces: WB, DB and wind speed. WBGT was evaluated in accordance with ACGIH guidelines.[1] Thermal Work Limit (TWL) values were calculated assuming a barometric pressure of 110 kPa (an approximate average barometric pressure for this location; TWL is insensitive to small changes in barometric pressure).

2.4.5 Data Collection and Analysis

Data was collected on day shift, night shift, and, for most individuals, for work conducted over two consecutive day shifts or two consecutive night shifts, along with “recovery/resting” core temperatures between shifts.

Due to the extreme environmental conditions which include exposure to water and chemicals, and also because workers sometimes removed their heavy belts (containing cap lamps, cap lamp batteries and associated tools), to which the data recorders were also attached, for their lunch break, some gaps in the core temperature records occurred. These gaps were omitted from the data set for subsequent analysis.

Figure 8 Heat Stress Meter (HSM). This pocket-sized electronic device measures DB to ± 0.2^0 C, RH to ± 2% (non-condensing), Globe temperature to + 0.2^0 C, Wind speed to ± 0.2 m/s or 10% (whichever is greater) and Barometric pressure to ± 1.5 kPa. The sensors fold up into the device when not in use. The HSM has an EPROM microprocessor that provides calculated values on the LCD screen for WBGT, WB, TWL and other thermal parameters.

A data set needed more than four hours of valid data points to be included in the analyses. Data sets excluded on this basis are identified in the comments column of Appendix F.

Core temperature data was analysed in the following manner:

For each individual shift, and for the aggregated data, the following was calculated:

- Maximum core temperature,
- Minimum core temperature,
- Average core temperature,

- Highest 10 consecutive minute average core temperature,
- Highest 30 consecutive minute average core temperature,
- Duration spent in the following core temperature zones: 36 to 37^0 C, 37 to 37.6^0 C, 37.6 to 38.2^0 C, 38.2 to 38.8^0 C, 38.8 to 39.4^0 C and 39.4 to 40^0 C.
- Core temperature rise during the shift (defined here as the difference between maximum and minimum temperatures during the working shift).
- Calculated maximum heat storage in the body (defined here as the temperature rise multiplied by the average thermal capacity of body tissue multiplied by the body weight).
- Highest 10-minute temperature increase and highest 10-minute temperature decrease during the shift. These are indicators of the rate at which the body undergoes thermal strain and the rate at which this strain attenuates respectively.
- Highest 30-minute temperature increase and highest 30-minute temperature decrease during the shift.
- Highest 60-minute temperature increase and highest 60-minute temperature decrease during the shift.

All statistical tests were based on the unpaired, two-tailed Student’s t-test assuming equal variances, unless otherwise noted.

2.5 Fluid Losses, Replacement and Hydration Status

2.5.1 Objectives

The objectives of the fluid loss and hydration study are discussed previously in the Literature review.

2.5.2 Subjects and Study Design

The target group within the workforce were those workers most exposed to severe thermal environmental conditions. They are acclimatised and work hardened and are generally well-informed about the importance of drinking water. A personal 4 litre water bottle is a compulsory component of their PPE (personal protective equipment). The employer at this operation provides low-joule cordial essence (flavouring) at no cost, and some workers add this to their drinking water. All subjects in the study were drawn from the target group.

$\dot{V}O_{2\max}$ was estimated using the sub-maximal Astrand and Rodahl protocol and a calibrated cycle ergometer (Figure 9 and

Figure 10).

The main study (hydration study 1) measured the hydration state of 39 male workers most exposed to heat stress before, at the mid-point, and at the end of their shift. The environmental conditions in which they were working and their fluid intake (fluid replacement study) were also measured or estimated regularly during the shift.

For comparison purposes, the specific gravity of a sample of 64 workers prior to commencing their work shift was also measured (hydration study 2). No further interaction occurred with these workers.

The end-of-shift specific gravity of all workers (n = 546) who were working in such extreme environments that their shift length had been reduced to six-hours duration (locally called a "hot job") was also collected over a period of approximately 12 months (hydration study 3). Temperatures in a "hot job" had to exceed a WBGT of approximately 32^0 to 33^0 C; the actual values were based on an adaptation of the Predicted 4-hour sweat rate (P_4SR).[139] If work continued in these conditions for at least two hours, the shift duration was reduced to 6 hours (which includes a meal break). The maximum exposure time to heat stress under a "hot job" would therefore be about 4 hours.

Figure 9 Cycle ergometer, used for the physical fatigue study and used to measure $\dot{V}O_{2\max}$ by the Astrand Rodahl protocol.

Figure 10 Cycle ergometer in use, showing miners work uniform and the underground environment used for the cycle fatigue studies

Part of the reason for the comparison studies was to ensure that workers who were studied in the main study did not modify their behaviour, compared to workers who were not monitored during their work shift.

The hydration study 1 and fluid replacement study were conducted on the same individuals. A summary of their anthropometric and body morphology data and their $\dot{V}O_{2\max}$ is shown in Table 6.

Table 6 Anthropometric and body morphology for workers in Hydration study 1

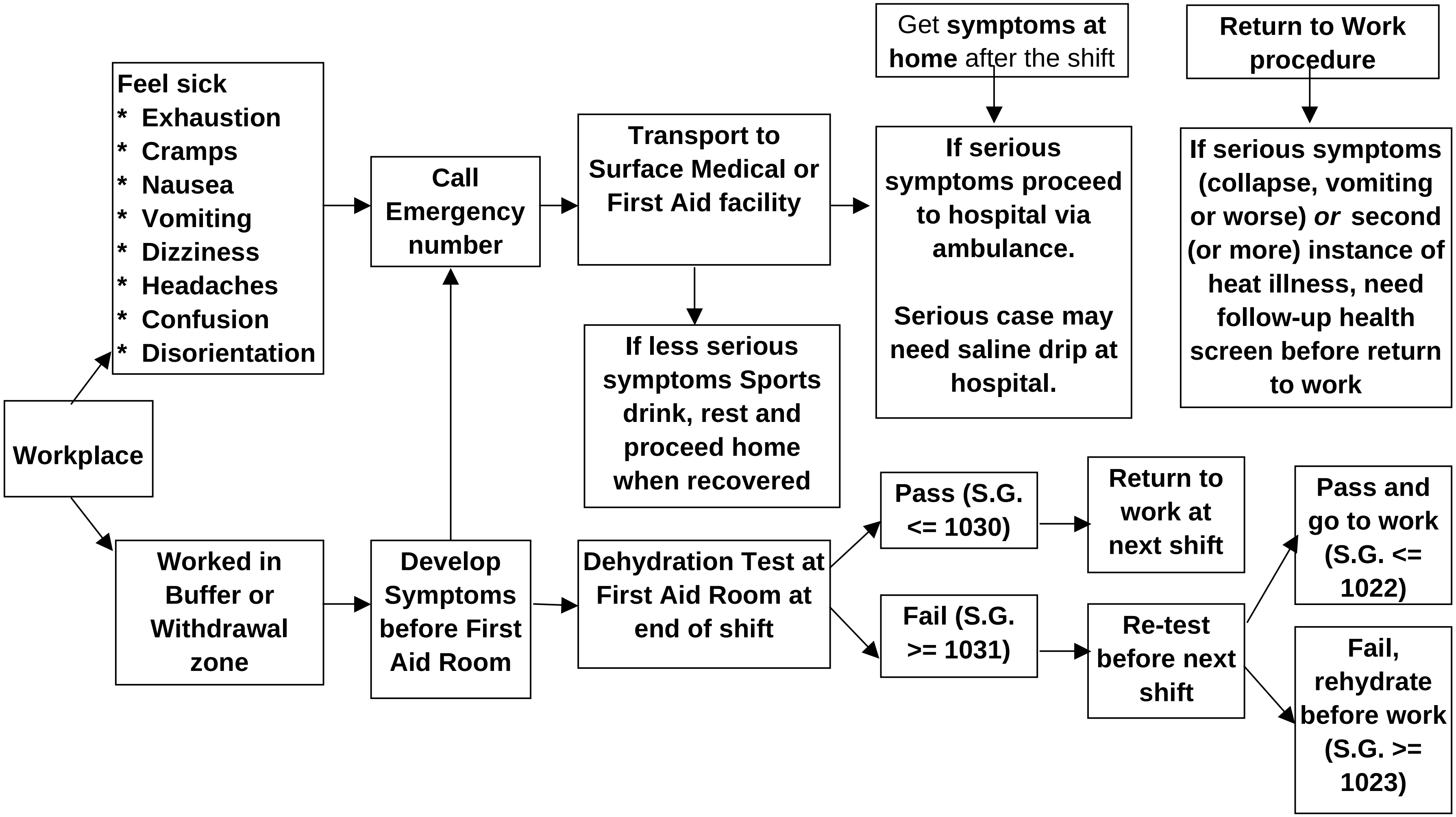
Name	Age, yrs	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$, ml.kg^{-1}.min^{-1}
n	39	38	38	37	18
avg	35	178	88	27.9	39.1
std dev	8	9	16	4.0	7.7
range	21-52	147-196	65-125	22.1-38.2	28.0-56.3

Similar data is not available for the subjects in Hydration studies 2 and 3; however, a test of 469 contract employees joining the organisation for project work under similar levels of heat stress during this period had a measured $\dot{V}O_{2\max}$ of 39.0 ml.kg^{-1}.min^{-1} (std dev 7.8 ml.kg^{-1}.min^{-1}) and a BMI of 25.9 (std dev 5.4).

2.5.3 Urinary Specific Gravity

A combined "dehydration and heat illness protocol" (Figure 11) was introduced at this operation immediately prior to these studies[19]. Up to and including the first summer, it operated on a voluntary basis; after the first summer, it was made compulsory. Hydration status was estimated from urinary specific gravity, which is considered to be an important indicator of the absolute hydration status of the body and of relative changes in hydration status over time, although it does not mimic body water loss in a perfectly linear relationship,[4] and may be in error where the subject is experiencing diuresis due to alcohol or caffeine intake, or is taking vitamin supplements or some drugs.

Figure 11 Dehydration and heat illness protocol



Distilled water has a specific gravity of 1.000, whilst the maximum concentrating capacity of the renal system is about 1.050. In this study, a dehydrated state was considered to be a specific gravity exceeding 1.030, based on the criterion used by the Australian Pathology Association. A euhydrated state was considered to be 1.015, based on work by Donoghue et al[31] and the fact that 1.015 is one standard deviation below the average start-of-shift value for workers in this study. However, Armstrong et al[4] reported that a euhydrated state is a specific gravity of 1.004 ± 0.002, using a carefully controlled protocol to ensure euhydration in 9 male athletes; this is well outside the range of 1.015 to 1.024 considered to be "normal" by Reaburn and Coutts.[106] Armstrong's definition of euhydration as being a fully hydrated condition (i.e. no net body water deficit), is different to the more common usage of the term as being a normally hydrated condition. Further work is needed to adequately define euhydration in an occupational setting using urinary specific gravity as a criterion.

Under the dehydration protocol introduced at this operation, workers under significant levels of thermal stress were tested at the end of shift, and if their specific gravity exceeded 1.030, were required to re-present and have a specific gravity not exceeding 1.022 prior to commencing their next shift. The value of 1.022 was an arbitrary value approximately halfway between a euhydrated (1.015) and dehydrated (1.030) state.

Urinary specific gravity was measured using a handheld, optical refractometer (Atago Uricon-NE) at the start, mid (just before the meal break [called "crib"]) and end of shift (Figure 12).

Figure 12 Handheld optical refractometer used for measuring urinary specific gravity. The device consists of a glass slide, a plastic cover and an eyepiece (with focus) with graduated scales in the viewing screen providing direct read-out of specific gravity.

2.5.4 Environmental Conditions

Environmental conditions were measured using the same equipment, techniques and intervals as for the Core Temperature study discussed previously.

2.5.5 Fluid Consumption

Fluid consumption was estimated by allocating a separate 4-litre water bottle to each worker participating in the study. The cup on each water bottle had a capacity of 400 ml. Each worker was visited approximately every 60 to 90 minutes and the water consumption estimated from the cups drunk and checked against water levels in the bottle.

The effective heat stress exposure hours were 9.5 hours for 12-hour shifts and 7.5 hours for 10-hour shifts (refer earlier comments).

As an additional 30 minutes was typically lost at the start and end of each subject's shift, for administrative reasons associated with the test protocol, the fluid consumption rates calculated as litres per hour in this study may be somewhat conservative.

The main study provided pairs of data (before-mid shift, mid-end shift, before-end shift) and the differences were assessed using the paired, two-tailed Student's t-test assuming equal variances. For the other tests, paired data was not available so the unpaired, one-tailed Student's t-test assuming equal variances was used.

2.6 Fatigue

2.6.1 Objectives

The objectives of the fatigue and heart rate study are discussed previously in the Literature review.

2.6.2 Subjects and Study Design

This fatigue investigation consisted of three separate studies over two consecutive summers. In the first summer, prior to the change in the working-in-heat (WIH) protocols, there was a working (continuous) heart rate study and a *separate* cycle ergometer fatigue study (see below). In the second summer, after the change in the protocols, a single study was able to combine both the measurement of continuous working heart rates and cycle ergometer fatigue. In both summers, the heart rate data was collected contemporaneously with the core temperature data.

In aggregate, the results consist of the following:

- Heart rates recorded continuously using Polar^{TM} ECG-type sports heart rate recorders (Figure 13) (hereafter called the "continuous heart rate results"). The receiver "wrist watch" component of the heart rate monitor could not be worn on the wrists due to the extreme environment, and was sealed in a plastic bag and placed in a heavy duty canvas pouch attached to the subject's waist. This study was done contemporaneously with the deep body core temperature study. The same subjects were used and the data was collected concurrently with the Core Temperature data.

Figure 13 Heart Rate Monitor and receiver. The ECG device and radio transmitter is housed in the adjustable chest strap. The "watch" contains the radio receiver and memory unit, and the other device is a cradle that allows data from the "watch" to be easily downloaded into a personal computer.

- Steady-state heart rates collected on a cycle ergometer pedalling at 50 rpm at 100 watts under a standardised test at the start and end of each shift (and at the middle of each shift for one series of tests) (hereafter called the "cycle fatigue results"). The same warm-to-hot location was used for each cycle fatigue test. Heart rates typically plateaued after three to six minutes. This test was effectively a measure of $\dot{V}O_2$.

- Blood lactate measured at the earlobe immediately at the conclusion of the shift (for one series of tests) using a field test kit (Figure 14), collected in the second continuous heart rate study only.

Anthropometric, body morphology and $\dot{V}O_{2\max}$ data on the 45 subjects in the study are shown in Table 7.

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Figure 14 Blood lactate test kit. A drop of arterial blood is placed on the test strip and inserted into the reading device. A direct read-out in mmol/litre is given.

Table 7 Anthropometric, body morphology and $\dot{V}O_{2\max}$ data for 45 subjects in fatigue study

	Age, yrs	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$, ml.kg^{-1}.min^{-1}
n	39	38	38	37	18
Avg	34.9	178.0	88.4	27.9	39.1
Std Dev	7.6	9.4	15.7	4.0	7.7
Range	21-52	147-196	65-125	22.1-38.2	28-56.3

A negative (non-fatigued) control group of workers (all males) working in the same operation in sedentary work in thermoneutral conditions was also tested over several shifts using the cycle ergometer protocol.

2.6.3 Environmental Conditions

Environmental conditions, including wet and dry bulb temperatures (WB, DB), globe temperature (GT), WBGT, wind speed and barometric pressure (BP) were collected in the continuous heart rate studies only.

2.6.4 Data Collection and Analysis

Data was collected on both day and night shifts, and also, for some individuals, for work conducted over two consecutive day shifts or two consecutive night shifts.

A data set needed more than four hours of valid data points to be included in the analyses. Data sets excluded on this basis are identified in the comments column in Appendix G.

Heart rate data was analysed in the following manner:

For each individual shift, and for the aggregated data, the following statistics were calculated: average heart rate, highest 10 consecutive minute average heart rate, highest 30 consecutive minute average heart rate and time spent in the following heart rate zones: less than 60 bpm, 60 to 80 bpm, 80 to 100 bpm, 100 to 120 bpm, 120 to 140 bpm and more than 140 bpm.

Aggregate data was produced for each summer (before and after the changes to the WIH protocols), and also as a combined set for both summers.

The difference in continuous heart rates before and after the change in protocols was tested using the unpaired, two-tailed Student’s t-test assuming equal variances. The cycle ergometer results were tested using the paired, one-tailed Student’s t-test, with the null hypothesis being that heart rates did not increase during the work shift.

Results are reported as (average, standard deviation, range) or (standard deviation, range).

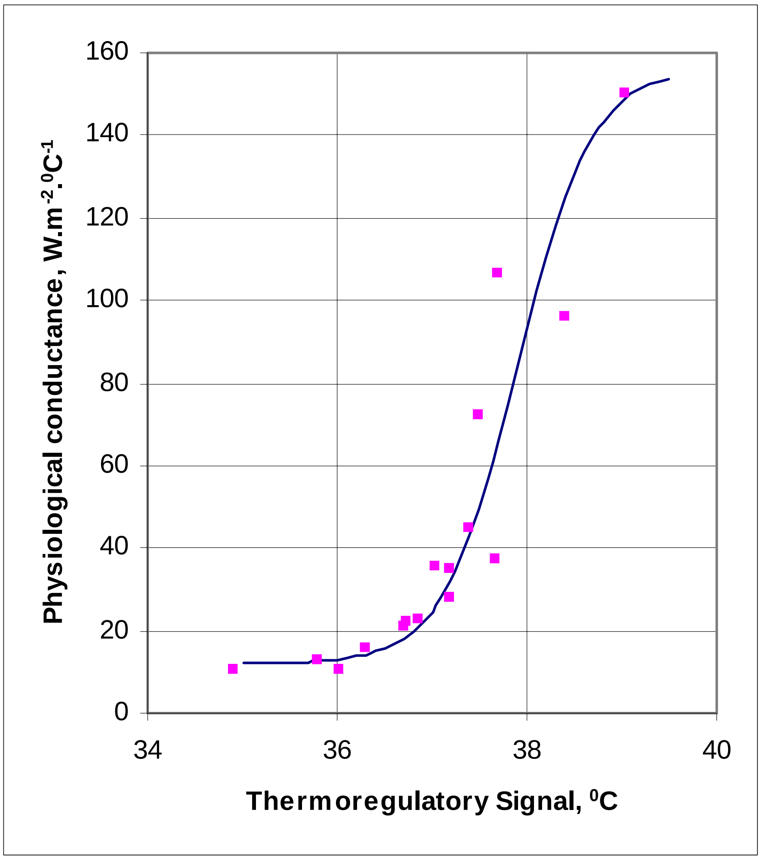
Chapter 3 - Results

3.1 Derivation of TWL

TWL has been defined previously as the maximum metabolic rate, in watts of metabolic heat per square meter of body surface area, that can be continuously expended by euhydrated, acclimatised individuals in a particular thermal environment, whilst remaining within safe limits of both deep body core temperature ($<38.2^0$ C) and sweat rate (<1.2 kg.hr^{-1}), although these can be adjusted. The derivation of TWL and the justification for these limits is provided starting on page 101. With TWL, the higher the number, the greater the sustainable work rate (in terms of thermal stress). The foundation of the TWL algorithm is derived from the following work:

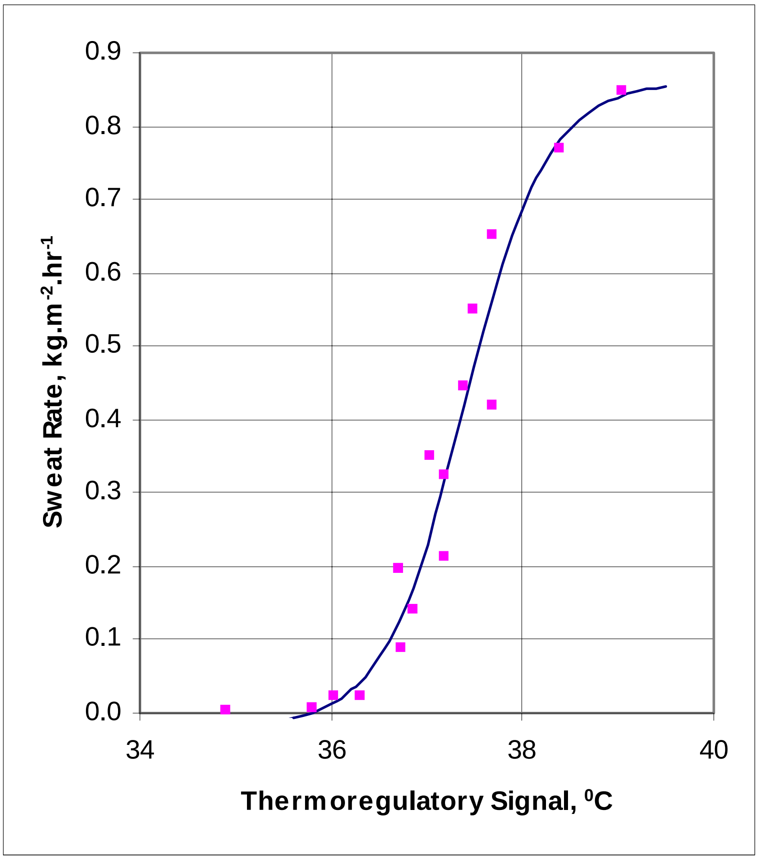
Wyndham[135] conducted a number of experiments measuring physiological conductance (the blood-borne flow of heat from its internal sources to the skin) along with steady-state deep body core and mean skin temperatures for a range of environmental conditions and metabolic rates. Complex equations were developed for these relationships. Later, Cabanac[24] and others reported that physiological conductance is a function of the thermoregulatory signal, defined as the weighted average of the deep body core and mean skin temperatures where the deep body core temperature is weighted at 90% and the mean skin temperature is weighted at 10%. This observation has allowed considerable simplification of Wyndham's otherwise complex equations. Wyndham's original data plotted against the thermoregulatory signal is shown in Figure 15.

Figure 15 Relationship between physiological conductance (blood-borne heat transfer) from deep body core to skin and the thermoregulatory signal, t_Σ, where $t_\Sigma = 0.1\ t_{skin} + 0.9\ t_{core}$. Data from Wyndham.[135]



The limiting deep body core temperature in the standard TWL formulation is 38.2^0 C, although this is adjustable. The value was chosen as it is within the generally accepted range for industrial workers, and was found in the Core Temperature study (see section 4.3 page 150) to be exceeded only infrequently by the workers in this study. The acceptable range for the thermoregulatory signal in the model is from 36^0 C to 39.5^0 C, based on the range of Wyndham's experimental data[135]. For heat to flow from the deep body core to the skin, the *maximum* mean skin temperature cannot exceed the deep body core temperature, and in practice is usually more than 1^0 C cooler than the deep body core temperature. This is true even under light work when higher skin temperatures may still be sufficient to remove the relatively low levels of metabolic heat. Continuous heavy work requires a larger gap between deep body core and mean skin temperatures for the larger amount of heat generated to flow from core to skin.[135]

Figure 16 Relationship between sweat rate and thermoregulatory signal, t_{Σ}, where $t_{\Sigma} = 0.1\ t_{skin} + 0.9\ t_{core}$. Data from Wyndham[135].



Wyndham[135] also measured sweat rates, plotted in Figure 16 against the same thermoregulatory signal. In the standard TWL formulation, maximum sweat rate (which is adjustable) is restricted to 0.67 kg.m^{-2}.hr^{-1} (1.2 litres per hour for a standard person), which is within the steep (responsive) region of the sweat rate curve. It is well within reported sustainable limits of about 0.83 kg.m^{-2}.hr^{-1} (1.5 litres per hour) noted for acclimatised workers by Taylor,[124] and is also close to the original P_4SR limit of 4.5 litres over four hours recommended by McArdle.[78] The corresponding ISO7933 sweat rate limit is 1.04 litres per hour, although ISO9886[65] comments that the 1.04 litre per hour limit in ISO7933 "must be considered not as (a) maximum value but as (a) minimal value that can be exceeded by most subjects in good physical condition."

The evaporation rate from the skin clearly cannot exceed that of a fully wet body in the same circumstances. However, even when the skin is only partly wet, not all the sweat produced is evaporated. This is because dripping commences well before the skin is fully wet, and the onset of dripping has been shown to be a function of the evaporative ability of the environment (Figure 17). This figure (redrawn from Stewart)[121] shows experimental data derived by Galimidi & Stewart[39] along with the original theoretical curve for skin wettedness derived by Kerslake[68]. In this figure:

- E is the actual evaporation rate of sweat ($W.m^{-2}$) under these conditions and E_{max} is the maximum possible evaporation rate ($W.m^{-2}$) from a fully wet skin under these conditions.

- The Y-axis ($E / \lambda\ S_r$) is the ratio of the actual evaporation rate to the actual sweat rate and is a measure of the efficiency of sweating as a cooling mechanism in this condition; the maximum Y value is 1.0 at which point all the sweat produced is being evaporated.

- λ is the latent heat of evaporation of sweat ($kJ.kg^{-1}$) and S_r is the sweat rate ($kg.hr^{-1}.m^{-2}$); therefore $\lambda\ S_r$ is the sweat rate using the units of $W.m^{-2}$ (after conversion of hours to seconds).

- The X-axis ($\lambda\ S_r / E_{max}$) is the ratio of the actual sweat rate to the maximum possible evaporation rate from a fully wet skin in this environment and is therefore a measure of the capacity of the environment to evaporate the sweat produced; where X values exceed 1.0, sweat rates exceed the maximum possible evaporation rate in this environment.

Figure 17 Comparison between Predicted and Observed Relationships for Evaporative Cooling of an Essentially Nude Male (redrawn from Stewart[121]).

Zone A: evaporating ability of the environment is high, no sweat drips, the efficiency of sweating is 100%, and the skin is not fully wet

Zone B: dripping occurs but the skin is not fully wet

Zone C: evaporating ability of the environment is low compared to the sweat rate, the skin is fully wet and dripping occurs

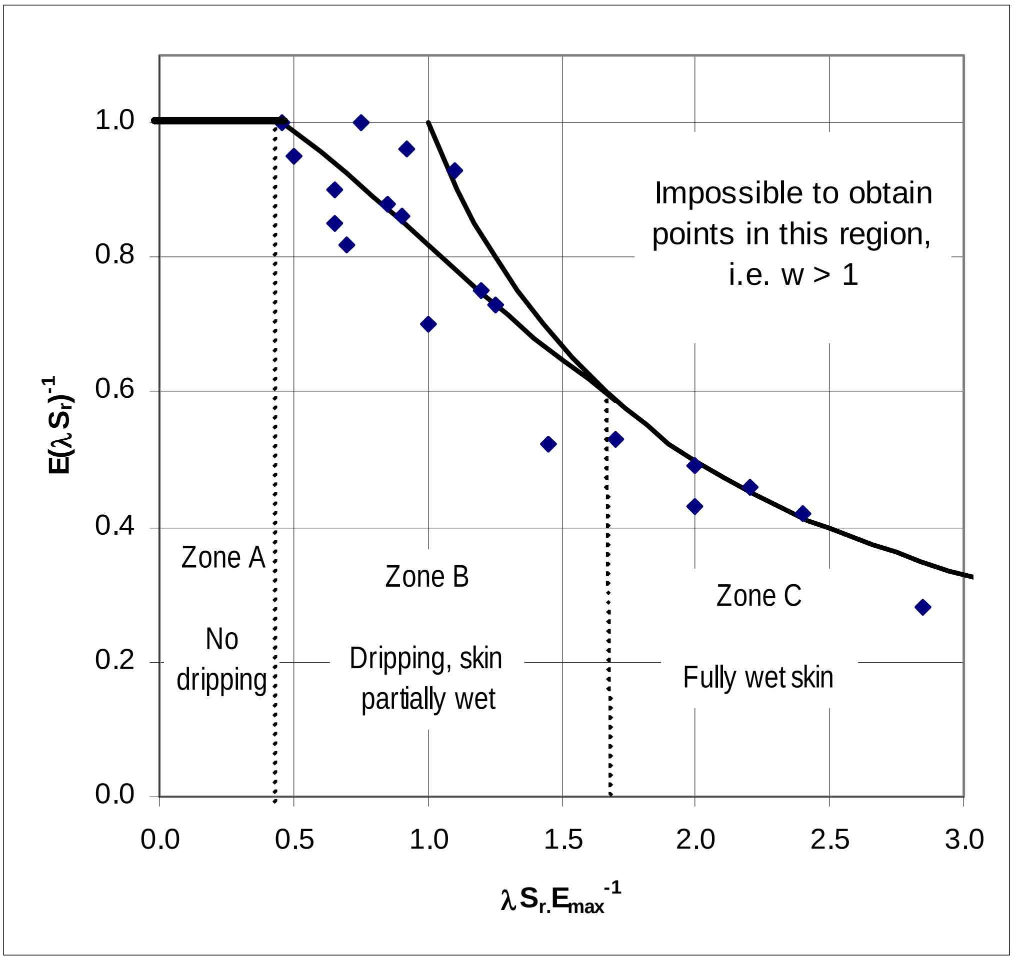
E: evaporation rate from skin, $W.m^{-2}$

E_{max}*: maximum possible evaporation rate from skin,* $W.m^{-2}$

λ*: latent heat of evaporation of sweat,* $kJ.kg^{-1}$

S_r*: sweat rate,* $kg.hr^{-1}.m^{-2}$

w: skin wettedness, fraction



- The product of any particular x-value and y-value on the solid line of this curve (described by x y = 1) is $E / \lambda S_r \times (\lambda S_r / E_{max}) = E / E_{max} = w$

(defined as the skin wettedness). Skin wettedness values greater than unity are not possible.

Galimidi and Stewart[39] and Kerslake[68] identified two reasons why sweat drips from the body before the skin is fully wet. Firstly, the evaporative heat transfer coefficient varies over the surface of the body (e.g. due to different wind speed on different areas of skin), so that areas with low coefficients are unable to evaporate all the sweat being produced and start to drip, while areas with high coefficients are still able to evaporate all the sweat produced. Secondly, some regions of the skin produce more sweat than others due in part to differences in regional sweat gland density.

The experimental data in Figure 17 shows that a fully wet skin (w = 1) only occurs when the actual sweat rate is about 170% (x-value = 1.7, y-value = 1 / 1.7 = 0.6) of the maximum evaporation rate possible in the environment, at which point about 60% of the sweat produced is evaporating. It also shows that dripping of sweat from the skin starts when the skin surface is just under 50% wetted (x-value = 0.46 and $E/ \lambda S_r$ falls below 1.0).

The efficiency of sweating therefore falls into three distinct zones:

- Zone A where the evaporating ability of the environment is high, no sweat drips, the efficiency of sweating is therefore 100%, and the skin is not fully wet,
- Zone B where dripping occurs but the skin is not fully wet, and
- Zone C where the evaporating ability of the environment is low compared to the sweat rate, the skin is fully wet and dripping occurs.

By deriving mathematical equations for these various relationships, and combining these with standard equations for heat exchange and psychrometric properties, including the influence of clothing, the maximum (limiting) metabolic rate to ensure a deep body core temperature and sweat rate remain within nominated safe upper limits can be calculated. This is the basis for the mathematical derivation of the Thermal Work Limit index, developed in the following pages.

Unless otherwise noted, in this section all references to ASHRAE are to ASHRAE.[3] All references to Stewart are to Stewart.[121] All temperatures are degrees Celcius.

In the TWL protocol, formulas for convection, radiation and evaporation were derived from Stewart[120,121,118] who derived them from Mitchell and Whillier's[85] work. Mitchell took "about a thousand measurements of each of radiation and convection…spanning the complete range of temperature, wind speed and humidity experienced underground". Mitchell's values were all derived from mine workers in a climate laboratory wearing shorts only (near nude conditions). Formulas for clothing correction are derived from ASHRAE.

The experimental data collected by Wyndham[135] has a range from resting (60 $W.m^{-2}$) to about 380 $W.m^{-2}$. These rates were sustained over three consecutive hours. The typical aerobic capacity ($\dot{V}O_{2\max}$) of modern industrial workers is 30 to 50 $ml.kg^{-1}.min^{-1}$. Assuming a sustainable rate without fatigue at 33% of $\dot{V}O_{2\max}$, this corresponds to a metabolic rate of 130 to 215 $W.m^{-2}$ for a standard person (70 kg, 1.8 m^2). Given that TWL is defined as the sustainable metabolic rate under limiting working conditions, the primary range of interest is therefore from light work (100 $W.m^{-2}$) to about 215 $W.m^{-2}$, although the experimental data collected by Wyndham ranged from 60 to 380 $W.m^{-2}$.

Ignoring heat loss via conduction (which is only significant for a worker in contact with a hot surface such as hot solids or liquids), and heat loss due to drinking cold water (for reasons discussed earlier), the Heat Balance equation for humans and other homeotherms is as follows:

$$\mathbf{M - W = C + R + E + B + S_{sk} + S_c} \qquad \text{ASHRAE eqn 1}$$

Where W = rate of mechanical work accomplished

C = rate of heat loss from skin due to convection

R = rate of heat loss from skin due to radiation

E = rate of total evaporative heat loss from the skin

B = rate of convective and evaporative heat loss from respiration

S_{sk} = rate of heat storage in skin compartment

S_c = rate of heat storage in deep body core compartment

Note that the units for each term are $W.m^{-2}$.

By definition, for steady-state conditions, both S terms must be zero.

As the maximum useful mechanical work done by a human is of the order of 20 to 24% of the metabolic rate and is often zero in occupational settings, the W term is usually assumed to be zero, which is generally a conservative position to adopt. Note, however, than where *negative* work is done (i.e. work is done *on* the human body *by* an outside force, for example, a worker lowering a heavy object against gravity), the W term becomes negative and adds to the metabolic heat which must be dissipated by the body. Therefore, assuming W to be zero is not the "worst case" scenario in all circumstances.

Heat losses due to respiration are given by the following formula:

$\mathbf{B = 0.0014\ M\ (34 - t_a) + 0.0173\ M\ (5.87 - p_a)}$ ASHRAE eqn 26

where t_a = dry bulb temperature of ambient air in degrees C

p_a = partial water vapour pressure in ambient air in kPa

Note that in all ambient environmental conditions (except the extreme cold), air leaves the lungs in a saturated condition. For ambient dry bulb temperatures in the 30^0 to 45^0 range and ambient humidity in the 40 to 100% range, the range of heat losses due to breathing is 2 to 10 $W.m^{-2}$.

Losses from radiation for an essentially nude person can be given by the following relationship:

$\mathbf{R = h_r\ f_r\ (t_{skin} - t_{rad})}$ in $W.m^{-2}$ Stewart eqn 8

where $\mathbf{h_r = 4.61\ (1 + (t_{rad} + t_{skin}) / 546)^3}$, $W.m^2.K^{-1}$ Stewart eqn 9

f_r = posture factor (dimensionless), typically 0.73 for a standing person (ASHRAE eqn 35).

t_{rad} = mean radiant temperature in degrees C

The radiant heat transfer coefficient, h_r, is a function of the difference in mean skin and mean radiant temperatures. As the difference between these two temperatures is generally small, the variation in h_r is also generally small. For example, over the range of dry bulb and globe temperatures from 22^0 to 34^0 C and wind speeds from 0 to 4 $m.s^{-1}$ (t_{rad} is a function of both globe temperature and wind speed), h_r varies within the small range of 5 to 6 $W.(m^2.C)^{-1}$, which is in accordance with ASHRAE, Eqn 35.

Losses from convection for an essentially nude person can be given by the following relationship:

$\mathbf{C = h_c (t_{skin} - t_a)}$ in $W.m^{-2}$ Stewart eqn 11

where $\mathbf{h_c = 0.608\, P^{0.6}\, V^{0.6}}$, $W.m^2.K^{-1}$ Stewart eqn 13

where P is the ambient barometric pressure in kPa

V is the wind speed over the skin in $m.s^{-1}$.

In the TWL formulation, wind speed has a minimum value of 0.2 $m.s^{-1}$, which is about the minimum ("natural") convection current between a hot body and surrounding air (ASHRAE Table 6).

The convective heat transfer coefficient, h_c, is a function of barometric pressure and wind speed only, not of temperatures. Over the range of wind speeds from 0 to 4 $m.s^{-1}$, h_c varies from 3.7 to 22 $W.(m^2.C)^{-1}$. For low wind speeds, the resulting values of h_c are very similar to those from ASHRAE Table 6, last equation, but do become more conservative compared to ASHRAE at higher wind speeds.

It is important to note that these formulations of h_c assume a reasonably uniform skin temperature. This will be true when the subject is working at the limiting condition, but will not be true for sub-maximal work in cool conditions, where the skin temperature of the extremities is typically much cooler than that of the trunk. As TWL is at the limiting condition, an assumption of uniform skin temperature is reasonable.

Clothing affects the sensible (C+R) and evaporative (E) heat losses. Sensible heat losses can be corrected using the process outlined in ASHRAE.

$\mathbf{h = h_r + h_c}$ in W.(m^2.K)$^{-1}$ ASHRAE eqn 9

$\mathbf{f_{cl} = 1.0 + 0.3\ I_{cl}}$, dimensionless ASHRAE eqn 47

$\mathbf{t_{oper} = (h_r\ t_{rad} + h_c\ t_a) / (h_r + h_c)}$ in degrees C ASHRAE eqn 8

where t_{oper} is the Operative Temperature

$\mathbf{R_{cl} = 0.155\ I_{cl}}$ in (m^2.K).W^{-1} ASHRAE eqn 41

where I_{cl} is the intrinsic clothing thermal resistance in clo units. Do not confuse I_{cl} with i_{cl}, the clothing vapour permeation efficiency (refer further elaboration on page 105). Despite the potential confusion, these are the most commonly accepted abbreviations for these quite different parameters (ASHRAE).

$\mathbf{F_{cle} = f_{cl} / (1 + f_{cl}\ h\ R_{cl})}$, dimensionless

ASHRAE Table 2 *Sensible Heat Flow* last eqn

$\mathbf{C + R = F_{cle}\ h\ (t_{skin} - t_{oper})}$ ASHRAE Table 3 *Sensible Heat Loss* third eqn

Note that for a nude body, $I_{cl} = 0$ and hence $F_{cle} = 1$, resulting in C+R = h ($t_{skin} - t_{oper}$).

There is a complex and generally inadequately understood interaction between clothing ventilation, wind penetration, moisture content, the "pumping action" due to physical work (itself partly dependent on the nature of the work and the body parts in motion) and the thermal insulation of clothing ensembles, among other factors. Real data is best obtained by the use of sweating, moving mannequins, and these are rare. Further experimental and theoretical work is currently being conducted (e.g. the European research project on heat stress and the proposal for revision of ISO 7933)[49,76,55] to better establish the impact of wetness and wind speed on dry and evaporative heat losses. These revised approaches can be incorporated into TWL as consensus develops in these areas. Note, however, that the use of a highly sophisticated clothing model may result in a complicated and poorly understood heat stress index that may be prone to misinterpretation and error.

The evaporative heat transfer coefficient for an essentially nude person, h_e (W.m^{-2}.K^{-1}), is given by the following relationship:

$\mathbf{h_e = 1587\ h_c\ P / (P - p_a)^2}$ Stewart eqn 17

where P and p_a are the barometric and water vapour pressure in the ambient air respectively, in kPa. Note that, since p_a is much less than P, and P is approximately equal to 100, this formula is almost identical to ASHRAE eqn 27, i.e. $h_e = 16.5\ h_c$. It can further be seen that in typical conditions, h_e will be about 16 times the value of h_c, which in turn is 3 to 6 times he value of h_r, illustrating the point that evaporative heat transfer is the main mechanism for heat loss when under thermal stress.

Adjustments to allow for clothing can follow the ASHRAE approach:

$\mathbf{R_{ecl} = R_{cl} / (LR\ i_{cl})}$, dimensionless

ASHRAE Table 2 *Parameters relating sensible and evaporative heat flows*, first eqn

where i_{cl} is the "clothing vapour permeation efficiency, the ratio of the actual evaporative heat flow capability through the clothing to the sensible heat flow capability as compared to the Lewis Ratio" (ASHRAE Table 1 text). For dry indoor clothing, i_{cl} is typically about 0.35 to 0.45 (ASHRAE Table 7), whilst for light cotton clothing with reasonable wicking properties, may be higher but cannot exceed 1.0 (the value if evaporative heat transfer through the clothing is unimpeded). LR is the Lewis Ratio and for typical conditions has the value of 16.5 (ASHRAE equation 27).

$\mathbf{F_{pcl} = 1 / (1 + f_{cl}\ h_e\ R_{ecl})}$, dimensionless

ASHRAE Table 2 *Evaporative Heat Flow*, last eqn

where F_{pcl} is the "permeation efficiency, the ratio of the actual evaporative heat loss to that of a nude body at the same conditions, including an adjustment for the increase in surface area due to clothing" (ASHRAE Table 1 text).

The actual heat transfer from the evaporation of sweat off the skin, E_{sk} ($W.m^{-2}$), is:

$\mathbf{E_{sk} = w\ F_{pcl}\ f_{cl}\ h_e\ (p_s - p_a)}$ ASHRAE Table 3 *Evaporative Heat Loss*, 3rd eqn

where p_s = saturated water vapour pressure at the mean skin temperature in kPa, and w = skin wettedness

The maximum possible value of E_{sk} (E_{max}) is when the skin is fully wet ($w = 1$). Fully wet skin is not possible for a full work shift; however, healthy acclimatised individuals can maintain fully wet skin for several hours. In the context of self-paced work where workers can withdraw when stressed and who take a meal break approximately every four hours, the assumption of fully wet skin is a reasonable maximum value for the design of a limiting (maximum) allowable level. It is also the limit adopted by ISO for acclimatised persons.

Note that for a nude body, $I_{cl} = 0$, hence $R_{cl} = 0$ and $R_{ecl} = 0$. Thus, as expected, the vapour permeation efficiency, i_{cl}, becomes increasingly less significant as fewer clothes are worn. Further, for a nude body, $F_{pcl} = 1$ and $E_{sk} = w\, h_e\, (p_s - p_a)$.

The heat transfer from the deep body core to the skin, H ($W.m^{-2}$), must equal the heat losses from the skin to the ambient environment via radiation, conduction and evaporation. This "core to skin" transfer can be expressed as:

$\mathbf{H = K_{cs}\,(t_{core} - t_{skin})}$ Stewart eqn 23

where K_{cs} is the physiological conductance from deep body core to skin, in $W.(m^2.K)^{-1}$

This requires the physiological conductance, K_{cs}, to be determined. K_{cs} is a function of both deep body core and mean skin temperatures as shown in Figure 15 page 96, where the Thermoregulatory Signal, t_Σ, is given by:

$\mathbf{t_\Sigma = 0.1\, t_{skin} + 0.9\, t_{core}}$ Cabanac[24]

The physiological conductance, K_{cs} ($W.m^{-2}.K^{-1}$), can then be satisfactorily described by:

$\mathbf{K_{cs} = 84 + 72 \tanh(1.3\,(t_\Sigma - 37.9))}$ curve fitted to Figure 15

Sweat rate, S_r ($kg.m^{-2}.hr^{-1}$), is also a function of the thermoregulatory signal as shown in Figure 16. This curve can be adequately described by:

$\mathbf{S_r = 0.42 + 0.44 \tanh(1.16\,(t_\Sigma - 37.4))}$ curve fitted to Figure 16

The latent heat of evaporation of sweat, λ, is given by:

$\lambda = \mathbf{2430}\ kJ.kg^{-1}$ @ 30^0 C ASHRAE eqn 14

From Figure 17 page 99, the actual evaporation rate, E, in $W.m^{-2}$, is given by:

For $\lambda S_r / E_{max} < 0.46$ **$E = \lambda S_r$**

For $0.46 <= \lambda S_r / E_{max} <= 1.7$ **$E = \lambda S_r \exp(-0.4127 (1.8 \lambda S_r / E_{max} - 0.46)^{1.168})$**

For $\lambda S_r / E_{max} > 1.7$ **$E = E_{max}$**

For a heat balance in the body,

$H = E_{sk}$, (heat flow core to skin equals heat flow skin to environment), and

$M = H + B$ (metabolic heat production equals heat flow core to skin + heat flow via respiration)

The Thermal Work Limit (TWL) for a person in this environment is then given by:

$TWL = M$

In summary, the above equations provide the heat flow from "skin to environment" due to convection, radiation and respiration, skin wettedness, maximum evaporation rate and efficiency of sweating, heat flow from "core to skin", heat flow due to respiration and sweat rate. There will then be a unique mean skin temperature and metabolic rate that provides a heat balance. This can be solved by iteration, at which point the body is in thermal equilibrium with the environment.

A computer model of TWL, which works on any PC running Excel 97 or Excel 2000, can be supplied to any interested party.

3.2 Derivation of the Protocols that Accompany TWL

Table 8 provides the guidelines that were introduced between the 1st and 2nd summers. Brake, Donoghue and Bates[19] and Donoghue, Sinclair and Bates[31] provide more details on some of these interventions, such as the health screen, acclimatisation protocol and dehydration tests.

Table 8 TWL and Environmental Recommended Action Levels and Interventions for Self-paced Work

Environmental or TWL action level (W.m^{-2})	Name of Action level/ Zone of Work	Interventions
<115 (or DB > 44^0 C or WB > 32^0 C)	Withdrawal	• No ordinary work allowed. • Work only allowed in a safety emergency or to rectify environmental conditions. • Permit to Work in Heat must be completed and authorised by manager *beforehand*. • Dehydration test at end of shift. • Personal water bottle (4 litre capacity) must be on the job at all times
115 to 140	Buffer	• Rectify ventilation or redeploy workers if possible. • No person to work alone. • No unacclimatised person to work. • If work does continue, a Corrective Action Request must be completed and signed by the manager within 48 hrs. • Wind speed must be increased to at least 0.5 m.s^{-1} wherever practical. • Dehydration test at end of shift. • Personal water bottle (4 litre capacity) must be on the job at all times
140 to 220	Acclimatisation	• Acclimatised persons allowed to work, but not alone • Personal water bottle (4 litre capacity) must be on the job at all times
>220	Unrestricted	• No limits on work due to thermal stress

The purpose of these protocols is primarily to ensure that management attention and progressively more serious intervention occurs at various threshold points.

The derivation of the protocols that accompany TWL is as follows.

The TWL value of 115 $W.m^{-2}$ for the "withdrawal" action level (the trigger limit beyond which persons are withdrawn from the environment) was selected because 115 $W.m^{-2}$ is an approximate metabolic rate for light work. When even light work is not continuously possible for acclimatised workers, they should be withdrawn for three reasons. Firstly, there is little practical benefit in keeping workers in such conditions, as productivity is excessively low. Secondly, if even light work is not continuously sustainable, a formal work-rest cycle should be initiated and this probably requires supervision to positively ensure the employer's "Duty of Care" is met. Thirdly, because productivity is so low, workers frequently become frustrated and there is a danger that they will not continue to self-pace, which could result in hyperthermia.

It is important to recognise that work can still be undertaken when the TWL is less than 115 $W.m^{-2}$, but it is not conducted on a self-paced, self-supervised basis; a formal permitting system with prior management approval is required. Because TWL is quite sensitive to wind speed, it is sometimes possible to improve the airflow over the skin and continue work (i.e. move out of the withdrawal zone), without changing the temperature or humidity.

Workers are also withdrawn (or subject to a Permit system) whenever the dry bulb temperature exceeds 44^0 C, irrespective of the TWL, as this temperature is close to the skin temperature at which several authors have found exposed skin discomfort or burning to commence.[97,55] Short exposures at ambient temperatures above 44^0 can be tolerated, but *continuous* exposure to temperatures in excess of this is undesirable, *especially under high wind speeds*, where the insulation value of the air layer (the only protection for exposed skin) reduces to almost zero.

Workers are also withdrawn (or subject to a Permit system) where the wet bulb temperature exceeds 32^0 C irrespective of the TWL. This is because relatively small errors in measuring the individual environmental parameters can generate errors up to 20 W.m^{-2} in the calculated limiting metabolic rate under certain conditions. This is not a problem for self-paced work in "cooler" conditions (e.g. 200 W.m^{-2}), as there is considerable latitude for the work rate to be adjusted downwards. However, in hot conditions (e.g. 120 W.m^{-2}), the work pace may already be very slow and it would be difficult to adjust it downward any further without taking regular rest pauses. Clearly, a relative error of 20 W.m^{-2} at a low TWL is much larger than at a high TWL, and the potential adverse consequences of the error are more severe. The additional limit of the wet bulb temperature was chosen because it has the strongest single influence on TWL, and can be measured quite accurately. The wet bulb limit does not replace the TWL action level but adds a further "backstop" to the TWL values. The value of 32^0 WB was chosen as it has historically been considered to be an upper limit for continuous, light work.

The value of 140 W.m^{-2} for the "buffer" action level was selected for two reasons. Firstly, it is desirable to have a graded response to increasing levels of heat stress, to avoid workers (even acclimatised workers) working in "near-withdrawal" conditions for several consecutive shifts. The Buffer action level does this by providing a zone of 25 W.m^{-2} (about 1 to 1.5^0 C Wet Bulb) up against the "Withdrawal" action level. Furthermore, unacclimatised workers are not allowed to work in the Buffer zone at all. Others[72] have found that acclimatisation allows safe work at a WB temperature of 1.5 to 3.5^0 above that which is possible for unacclimatised persons. The acclimatisation period lasts for the first 7 calendar days back at work after being away for more than 14 days. These durations are based both on studies of the rates of acclimatisation and de-acclimatisation and also practical considerations for a workplace.[72,97,3,42,113] Also, by requiring a "Corrective Action Request" to be completed when work is carried out in Buffer zone conditions, it ensures that environmental engineering defects are noted and generally corrected before conditions approach Withdrawal. A system of *written* Corrective Action Requests is crucial to ensure defects in the workplace environmental conditions are recognised and rectified promptly.

The value of 220 W.m^{-2} for the "acclimatisation" action level was selected because virtually all of the approximately 130 cases of heat illness found during summer 1997/98 in a cohort study[31] at the same mines occurred where the TWL was less than about 220 W.m^{-2}. This action level (typically 26^{0} WB, 35^{0} DB and globe, 0.5 m.s^{-1} wind speed and 100 kPa, or 28.7^{0} WBGT) can be compared to the "safe" condition for unacclimatised workers in summer uniforms doing light work (27.0^{0} WBGT), as indicated in ACGIH guidelines[1].

3.3 Comparison of TWL with Other Indices

Using the process described in the Methods section, the limiting metabolic rates for the following heat stress indices were evaluated:

- ISO7933,[64] using 0.6 clo insulation and 0.7 posture factor, and the limits applicable to the "acclimatisation, danger" criteria,
- ACGIH,[1] using "summer work uniform, 0.6 clo".
- USARIEM,[96] using "Trousers and long-sleeved shirt, Itc = 1.13, Itvc = -0.23, Imc = 0.45, Imvc = 0.44".
- Air Cooling Power, or ACP, using 0.55 clo (0.085 ^{0}C.m^{2}/W), 0.45 vapour permeation efficiency and 0.7 posture factor. For ACP, two formulations were used, that of Howes[60] and that of McPherson[81]. The code for these formulations is given in Appendix A and Appendix B respectively.
- Corrected Effective Temperature[58] with limits for industrial work from Wyndham, Lind and Nielsen, and the World Health Organisation as cited in Weiner.[130]
- Thermal Work Limit, or TWL, using 0.35 clo, 0.45 vapour permeation ratio and 0.73 posture factor. Typical clo values for a summer cotton work uniform are about 0.55. The lower clo value used in the TWL formulation is because this index is expressly written for "limiting" self-pacing conditions. Under limiting conditions, clothing will be at least damp, and generally saturated with sweat. With the thermal conductivity of water some 20 times that of air (which is the main insulator in dry summer clothing), a lower clo value is required for wet clothing compared to dry. Two formulations were used for TWL, the standard formulation described

above, and another formulation modified for dynamic clothing factors using the methodology of Holmer.[56] The Visual Basic^{TM} code for both formulations is shown in Appendix C page 178.

The reason that different clothing properties and posture factors are used in the comparisons is that these are the values recommended by the respective authors for similar applications (acclimatised, industrial workers wearing cotton shirt and cotton long trousers). Therefore some of the variation seen in the resulting comparisons will be due to different recommended clothing properties for similar clothing ensembles. Some of the variation will also be due to the use of different allowed physiological limits of core temperature or sweat rate. For example, the USARIEM model allows an upper limit for deep body core temperature of 38.5^0 C for continuous work and 39.0^0 C for a one-off exposure, whereas ISO and ACGIH restrict this to 38.0^0 C, and the standard TWL formulation is restricted to 38.2^0 C. Likewise, the USARIEM model allows sweat rates of 2.4 litres per hour, the standard TWL formulation is restricted to 1.2 litres per hour and ISO is restricted to 1.04 litres per hour. Higher upper limits can have a significant impact on acceptable metabolic heat generation under certain environmental conditions. Other differences may be due to different environmental limits. For example, consider a wind speed of 0.2 $m.s^{-1}$. ISO would increase this by 0.7 $m.s^{-1}$ to 0.9 $m.s^{-1}$ at a metabolic rate of 180 $W.m^{-2}$ (the increase in wind speed being justified by ISO by body movement associated with the metabolic rate), which will significantly lift the calculated evaporative cooling at low actual wind speeds, whereas TWL allows a minimum wind speed of 0.2 $m.s^{-1}$ which will significantly drop the evaporative cooling, and hence the limiting metabolic rate, at low wind speeds. For the same true wind speed of 0.2 $m.s^{-1}$, one index is basing its limiting metabolic rate on a wind speed of 0.9 $m.s^{-1}$, whereas the other is basing its limiting metabolic rate on a wind speed of 0.2 $m.s^{-1}$.

Figure 18 page 114 shows a comparison of several heat stress indices for acclimatised workers wearing typical industrial cotton clothing (shirt, long trousers, safety helmet, safety boots). Individual charts have been produced for:

- "Hot, dry conditions", defined here arbitrarily as DB = MRT = WB + 10^0 C, for wind speeds of 0.2, 0.5, 1.0 and 3.0 $m.s^{-1}$

- "Hot, humid conditions" defined here arbitrarily as DB = MRT = WB + 3^0 C, for wind speeds of 0.2, 0.5, 1.0 and 3.0 $m.s^{-1}$

Each chart shows the limiting metabolic rate recommended under the particular index, as a function of wet bulb temperature.

Superimposed on these charts are arbitrary metabolic rates of 115, 140 and 220 $W.m^2$, these being the "withdrawal", "buffer" and "acclimatisation" action levels respectively used in the TWL protocols.

These charts are discussed further in the Discussion section 4.2.1 page 143.

Recently, substantial work has been undertaken on the use of "dynamic" (rather than "static") clothing values[55]. These differences can also be investigated using this approach. TWL values calculated using dynamic clothing factors are also shown in the charts.

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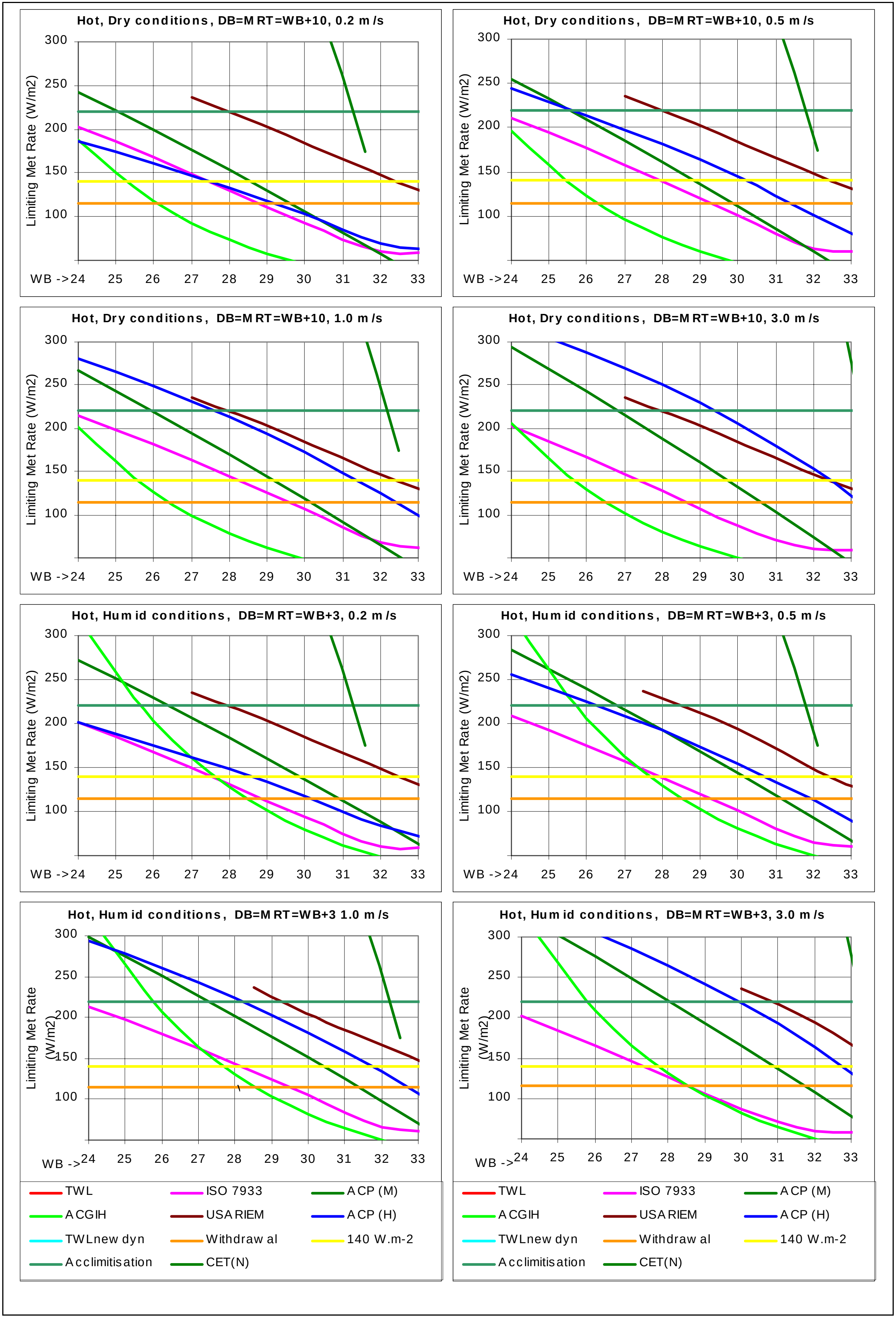
Figure 18 Comparison of various heat stress indices for two thermal conditions (hot dry and hot humid) each at four different wind speeds.



3.4 Deep Body Core Temperature

3.4.1 Subjects

A summary of the anthropometric and body morphology and $\dot{V}O_{2\max}$ data of the subjects is shown in Table 5 page 79.

3.4.2 Environmental Conditions

A total of 350 environmental observations (Table 9) were taken (excluding observations when workers were inside air-conditioned areas and therefore not under thermal stress). Fifteen observations (4 %) exceeded 32^0 WB. The average workplace WBGT temperature in the first summer with the former protocols was not significantly different (WBGT: p=0.38; TWL: p=0.44) to the second summer with the revised protocols.

Table 9 Environmental conditions in the core temperature study in the first summer and in the second summer after changes to working-in-heat protocols. There was no significant change in thermal conditions between the two summers.

	WBGT, ^{0} C		TWL, W.m^{-2}	
	1st summer	2nd summer	1st summer	2nd summer
n	164	186	164	186
Avg	30.78	30.94	178	174
Std Dev	1.729	2.144	41.7	44.9
Range	26.8-36.9	25.7-35.2	81-286	83-276

3.4.3 Deep Body Core Temperatures

A total of 38 sets of core temperature data were obtained from the target group, comprising 22 sets from the first summer and 16 sets from the second summer (Table 10 has the aggregated data, Appendix F has the individual data). Prior to aggregation, the two sets of data were compared on the basis of the average value of the maximum core temperatures reached on each shift and also on the average value over all data sets of the average core temperature reached on each shift.

The average over all data sets of the maximum core temperatures on each individual shift (standard deviation and range) for the first summer was 38.4^0 C (std dev 0.50^0 C, range 37.7 to 39.5^0 C) and from the second summer 38.2^0 C (std dev 0.31^0 C, range 37.8 to 38.8^0 C). The difference is not significant (p=0.26).

The average over all data sets of the average core temperatures on each individual shift (standard deviation and range) for the first summer was 37.65^0 C (std dev 0.45^0 C, range 37.0 to 38.9^0 C) and for the second summer was 37.58^0 C (std dev 0.22^0 C, range 37.2 to 38.0^0 C). The difference is not significant (p=0.55).

Table 10 Deep body core temperature of 36 male workers (the target group) measured continuously over 38 shifts. The thermal capacity of the body,[3] used to calculate the maximum heat storage, is taken as 3.49 kJ.^{0} C^{-1}.kg^{-1}

	Max ^{0} C	Min ^{0} C	Avg ^{0} C	Highest 10 cons mins avg, ^{0} C	Highest 30 cons mins avg, ^{0} C	Max temp rise over shift, ^{0} C	Max Heat Storage over shift, kJ
n	38	35	38	38	38	35	32
Max	39.5	37.7	38.9	39.4	39.4	2.3	942
Min	37.7	36.0	37.0	37.7	37.5	0.7	166
Avg	38.3	36.9	37.6	38.3	38.2	1.4	431
StdDev	0.4	0.4	0.4	0.4	0.4	0.5	163

For example, the intersection of the “Max” column and the “Max” row is the highest core temperature recorded on any shift in the study. The intersection of the “Max” column and “Avg” row indicates the average over all data sets of the maximum individual core temperatures recorded during each shift in the study. The intersection of the “Max” column and the “Min” row indicates the lowest single maximum core temperature reached on any shift during the study, etc.

	Highest 10 min increase, ^{0} C	Highest 10 min decrease, ^{0} C	Highest 30 min increase, ^{0} C	Highest 30 min decrease^0 C	Highest 60 min increase, ^{0} C	Highest 60 min decrease,^{0} C	
n	35	35	35	35	35	35	
Max	1.3	-0.1	1.5	-0.3	1.5	-0.3	
Min	0.2	-1.2	0.3	-1.3	0.3	-1.4	
Avg	0.5	-0.5	0.8	-0.7	0.9	-0.8	
StdDev	0.2	0.3	0.3	0.3	0.3	0.3	
Temp range	36.0-37.0^0	37.0-37.6^0	37.6-38.2^0	38.2-38.8^0	38.8-39.4^0	39.4-40.0^0	>40.0^0
% of time	29%	43%	18%	5%	2%	0%	0%

The total recorded time over the 38 shifts was 413 hours. Gaps in the record set, or invalid data (temperatures outside the range of 36^0 C to 42^0 C), constituted a total of 35 hours or 9% of the total elapsed time. Only data sets with at least four hours of core temperature data (excluding time lost on gaps) were considered for further analysis.

The results for the control group are shown in Table 11.

Table 11 Deep body core temperature during 10 working days of a control group of 6 male mine workers, all employed in sedentary work in air-conditioned offices, measured continuously. This group wore the core temperature monitor day and night for up to three days and two nights. Ten sets of "day shift" results were obtained, comprising six sets on the first day, and four sets on the second day. The control group were not weighed, so heat storage figures were not calculated for this group

	Max ^{0} C	Min ^{0} C	Avg ^{0} C	Highest 10 cons mins avg ^{0} C	Highest 30 cons mins avg ^{0} C	Max temp rise over shift, ^{0} C
n	10	10	10	10	10	10
Max	37.9	36.9	37.5	37.8	37.8	1.2
Min	36.9	36.0	36.5	36.8	36.8	0.6
Avg	37.6	36.5	37.1	37.4	37.4	0.9
StdDev	0.3	0.3	0.3	0.4	0.4	0.2

For description of the row and column headings, refer to Table 10 page 116.

	Highest 10 min increase, ^{0} C	Highest 10 min decrease, ^{0} C	Highest 30 min increase, ^{0} C	Highest 30 min decrease, ^{0} C	Highest 60 min increase, ^{0} C	Highest 60 min decrease, ^{0} C
n	10	10	10	10	10	10
Max	0.7	-0.1	0.8	-0.1	0.8	-0.3
Min	0.2	-0.5	0.3	-0.5	0.4	-0.7
Avg	0.4	-0.3	0.5	-0.4	0.6	-0.4
StdDev	0.2	0.1	0.2	0.1	0.2	0.1

Figure 19 to Figure 22 show typical core temperature traces for office workers in the control group, whilst Figure 23 to Figure 27 show typical traces for the target group.

Figure 19 Core temperature for control group subject CST26M8. Note initial dips probably due to ingestion of cold water.

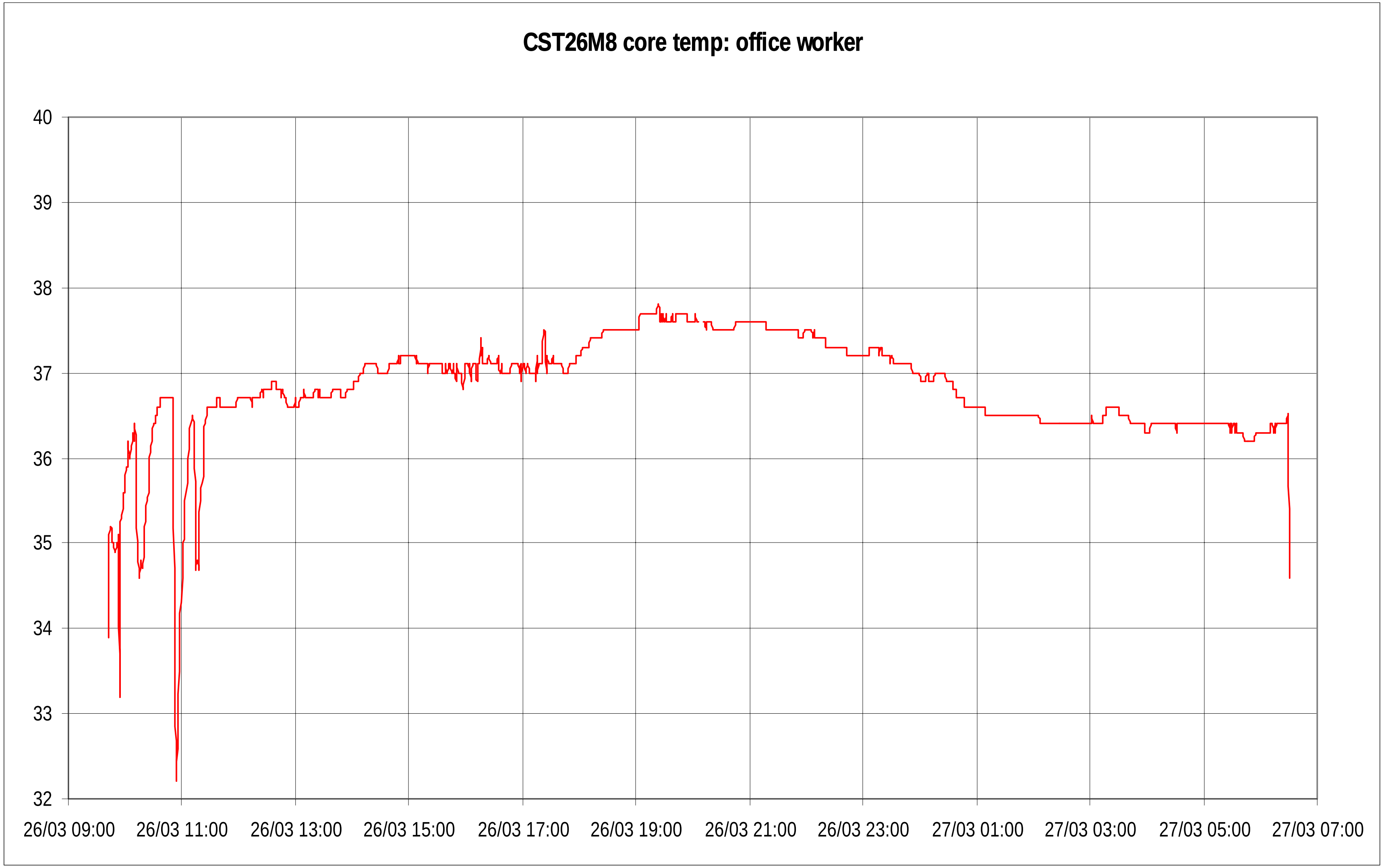


Figure 20 Core temperature for control group subject GXU25M8. Note peak at 11 am probably due to ingestion of hot beverage.

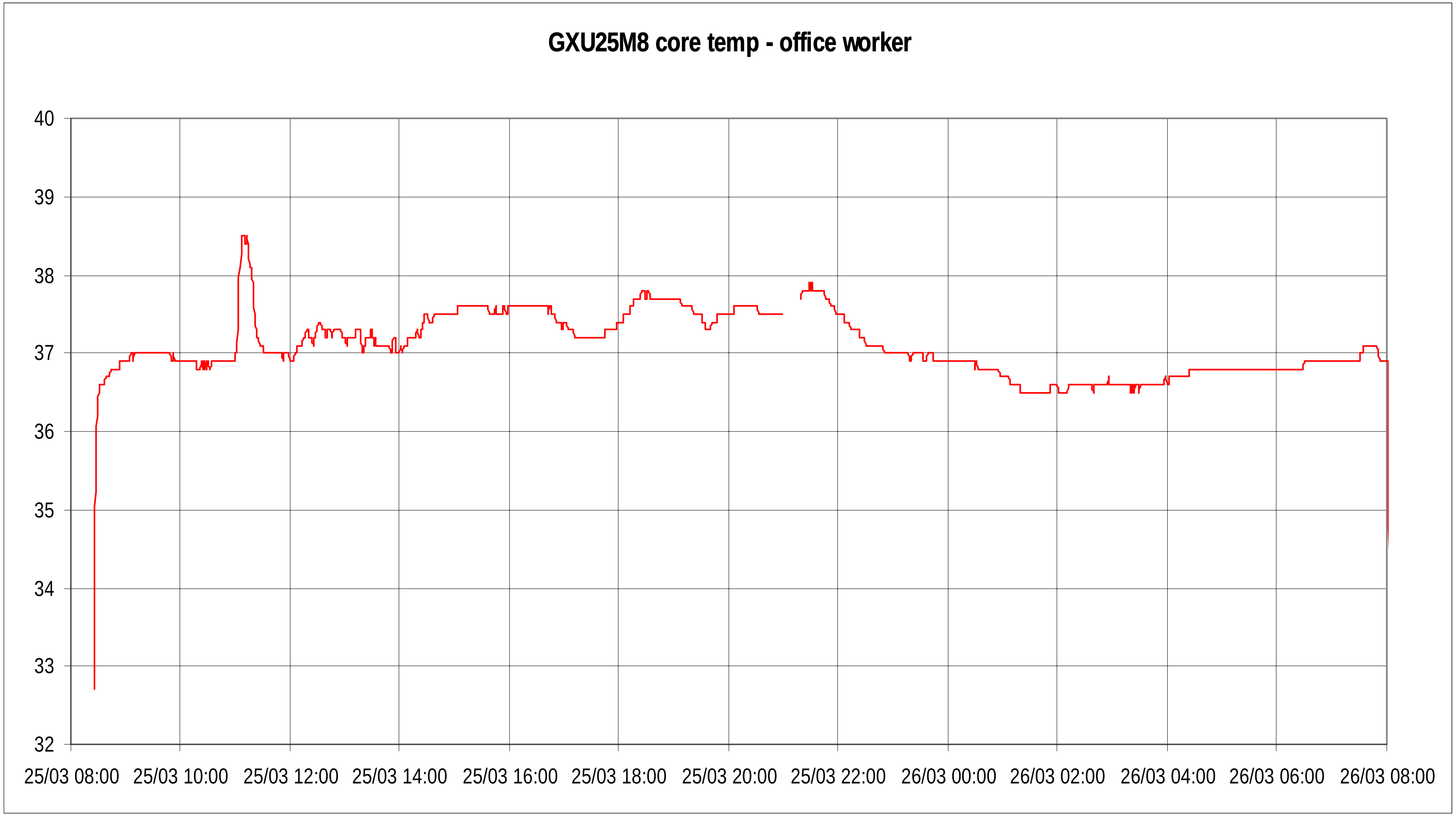


Figure 21 Core temperature for control group subject RBR06M8. This subject took considerable care to not be involved in any physical exertion or environmental stress for the 3 nights and 2 days. Typical diurnal variation is shown and is in agreement with standard norms.

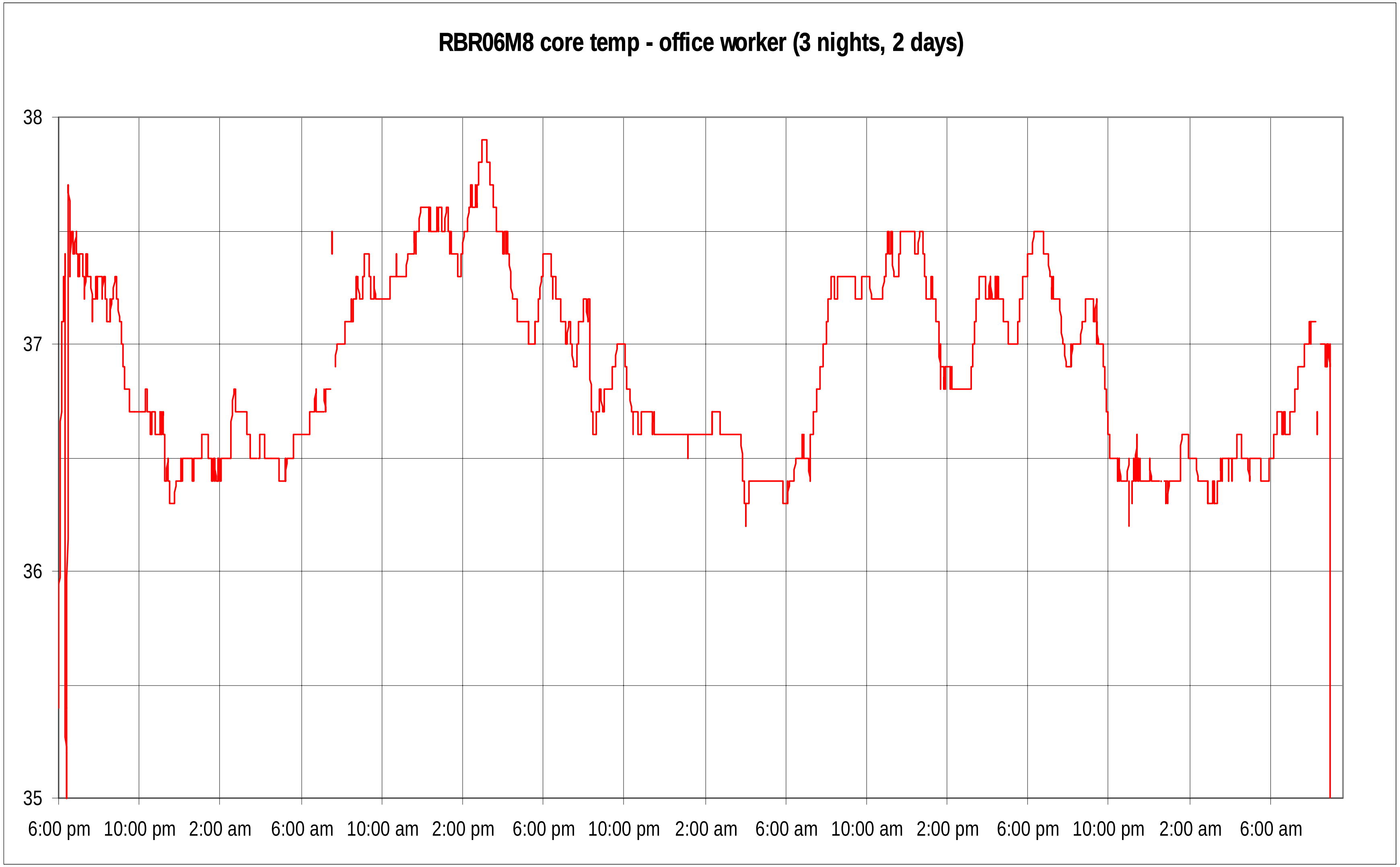


Figure 22 Core temperature for control group subject SML24M8. Note peaks at 6 pm and 7 am were exercise. The dips during the early morning hours were the receiver being out of range (when asleep, the receiver was not worn on the waist, but placed next to the bed).

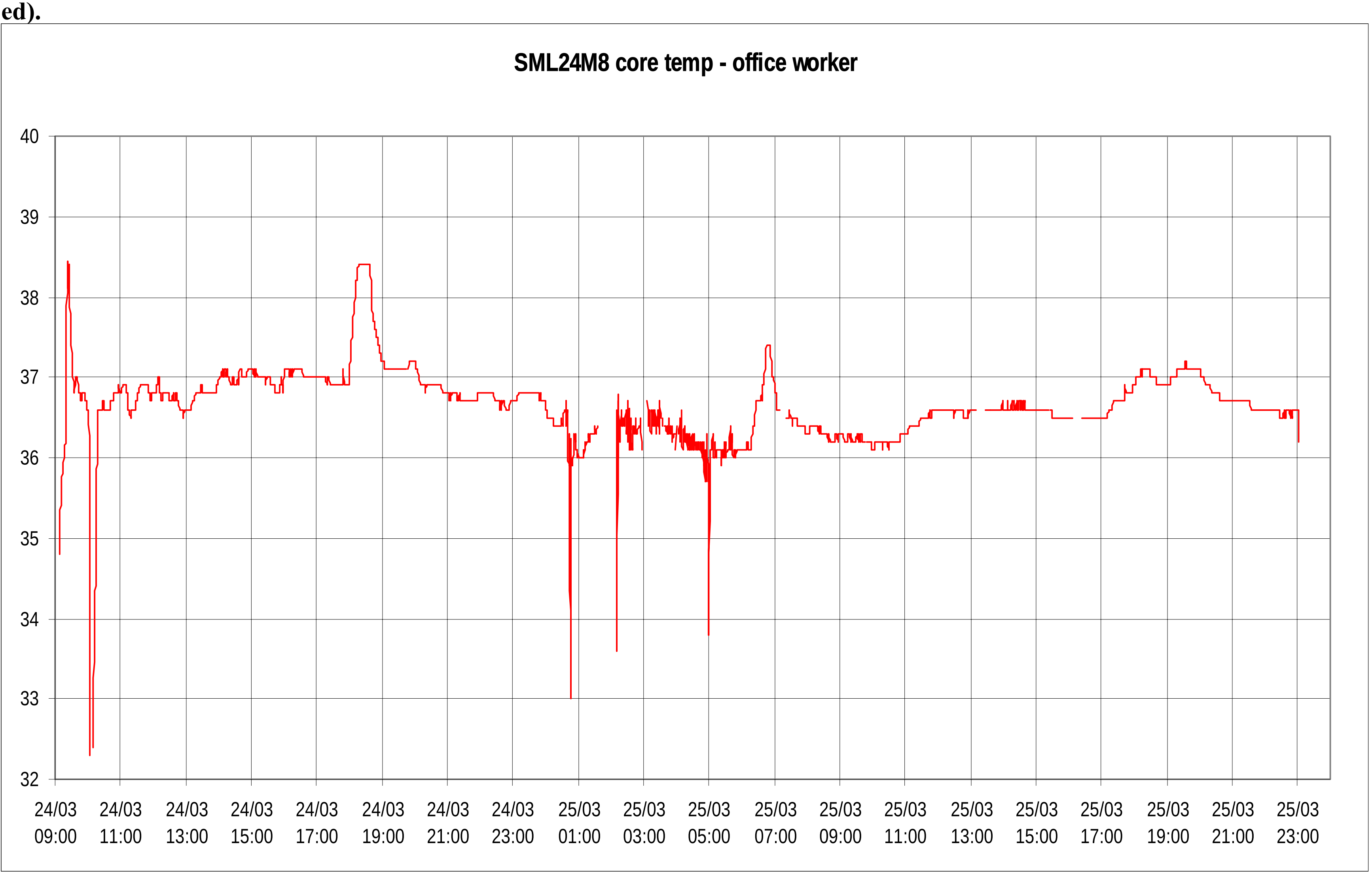


Figure 23 Core temperature and heart rate for target subject ADA10M8, 1st summer

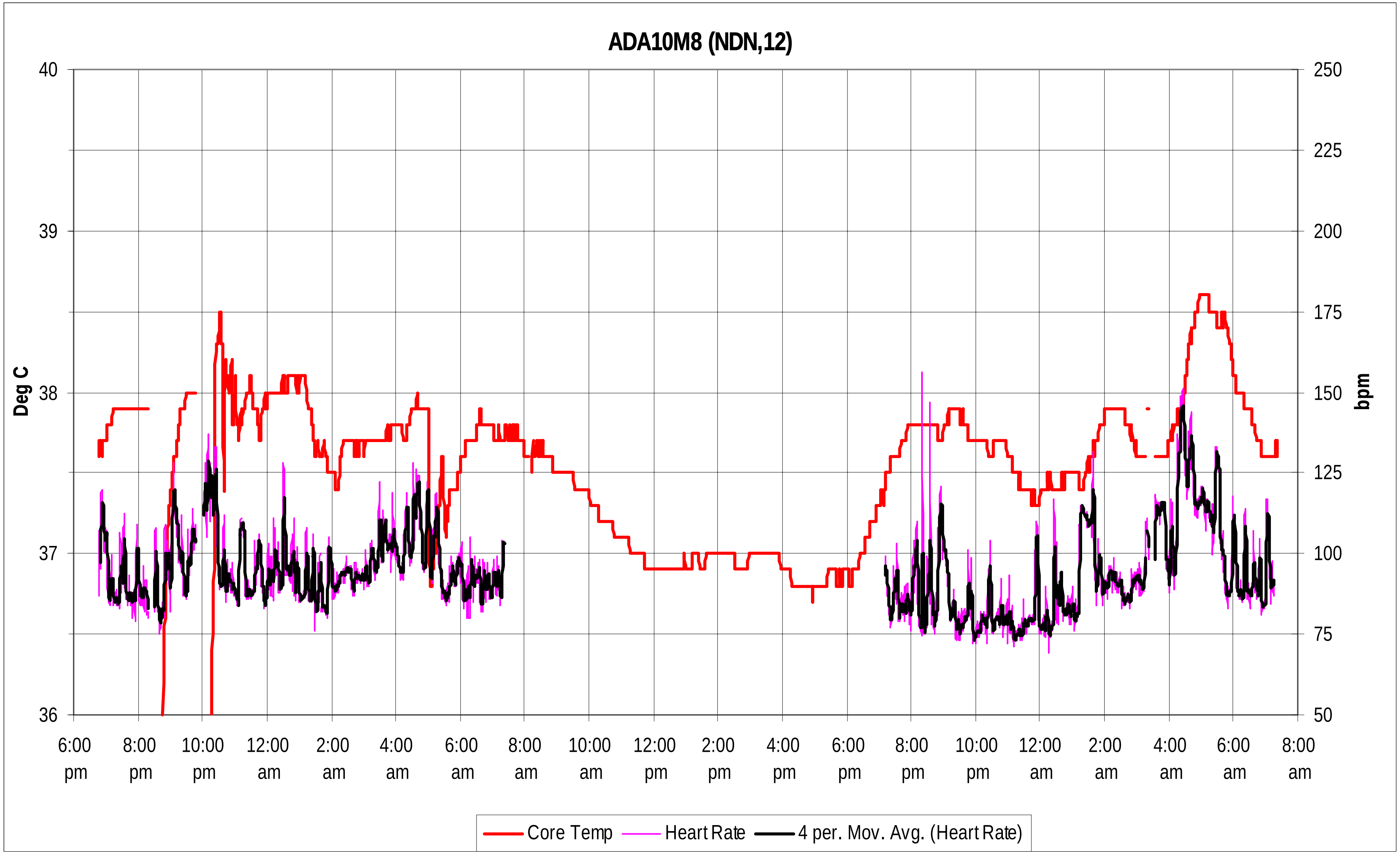


Figure 24 Core temperature and heart rate for target subject AMC03M8, 1st summer

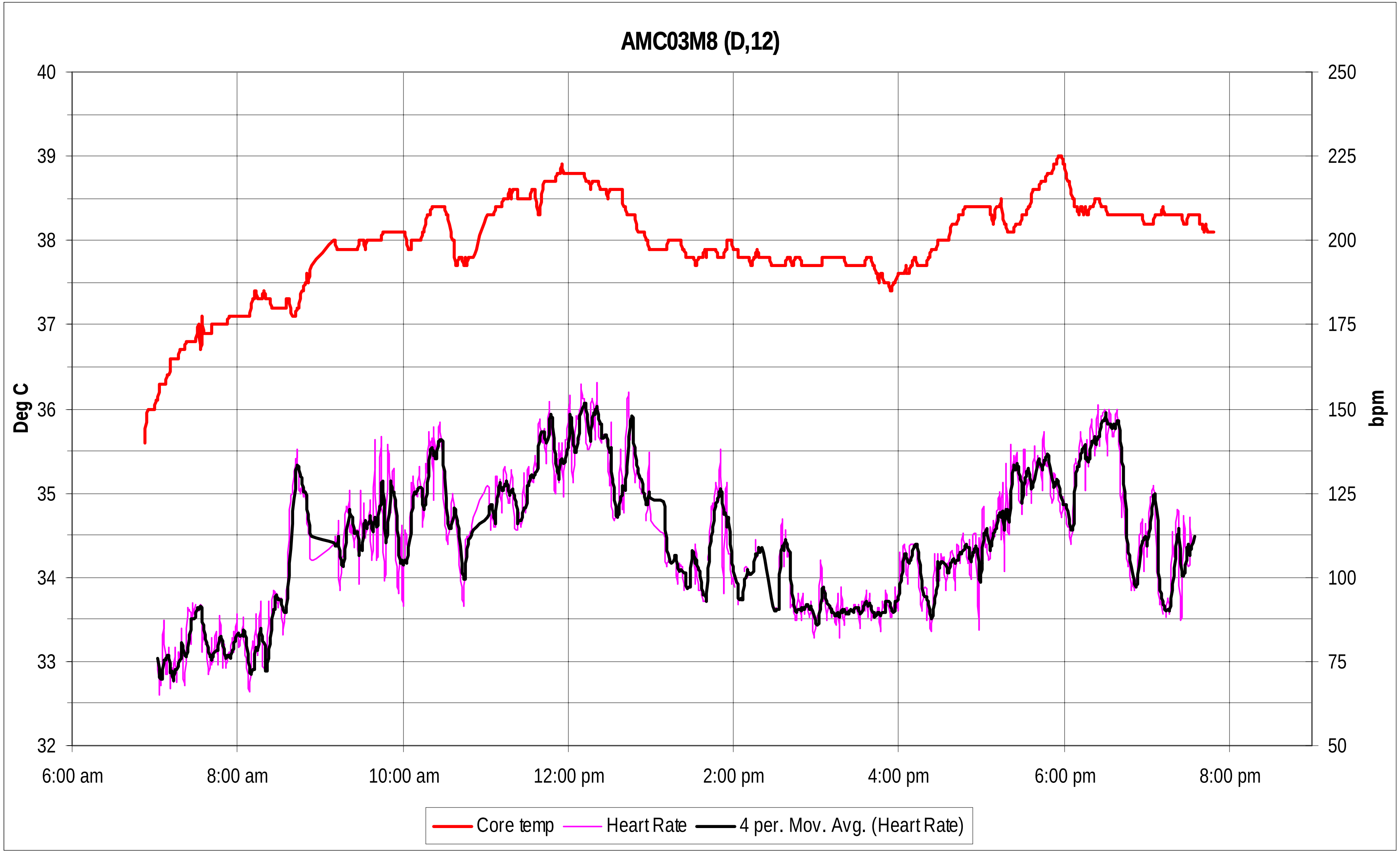


Figure 25 Core temperature and heart rate for target subject CLI05F8, 1st summer

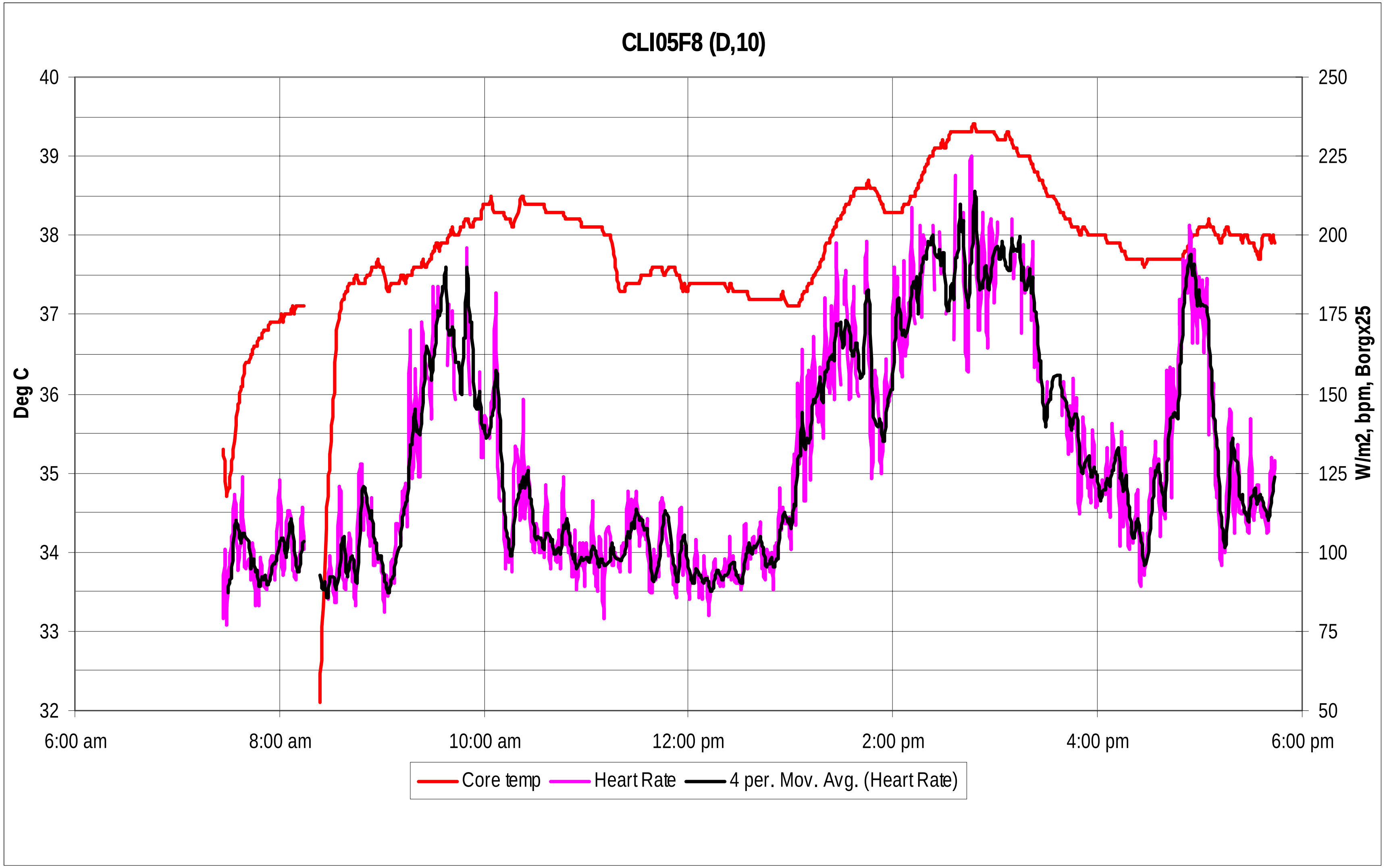


Figure 26 Core temperature and heart rate for target subject LWE06F8, 1st summer

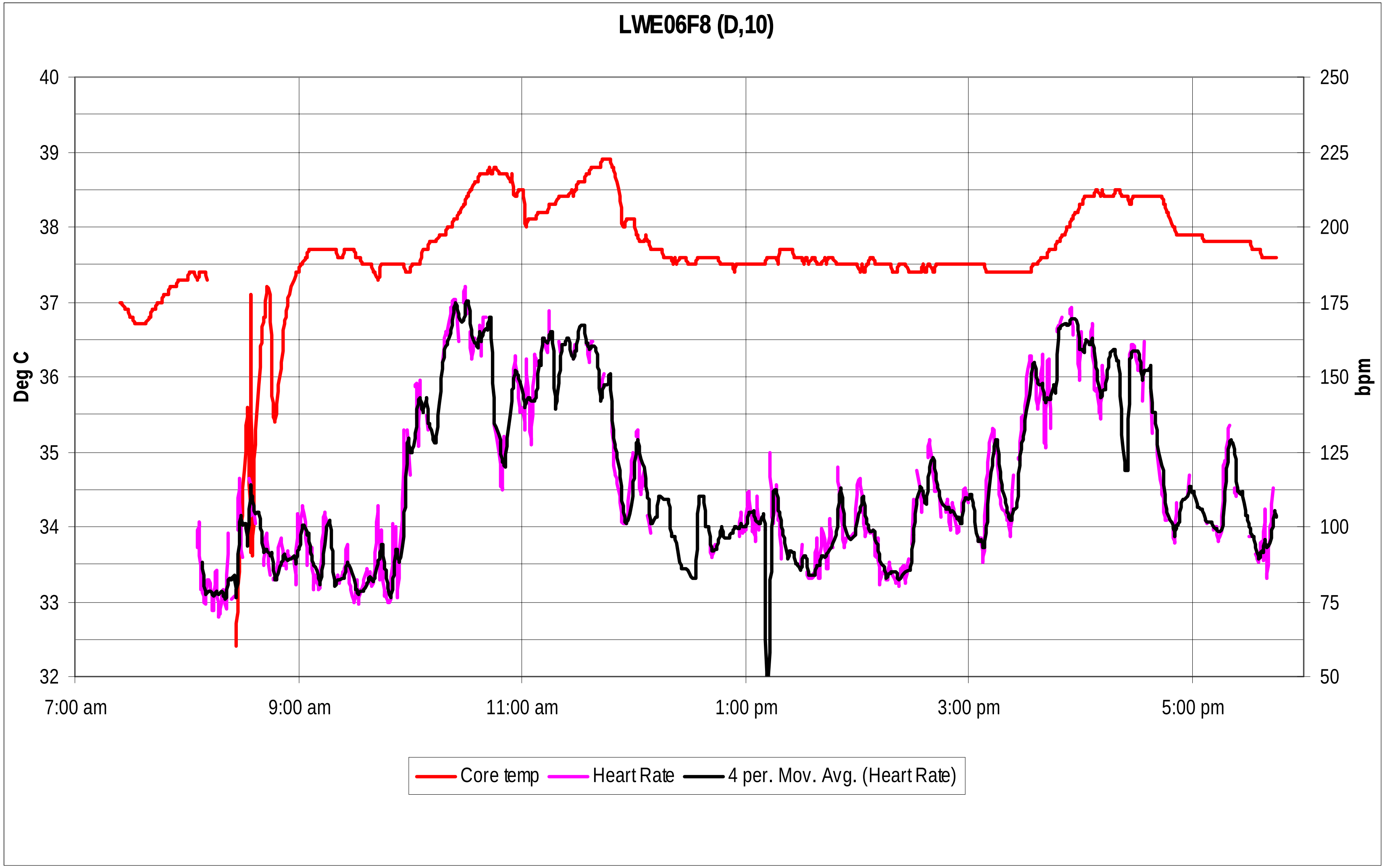
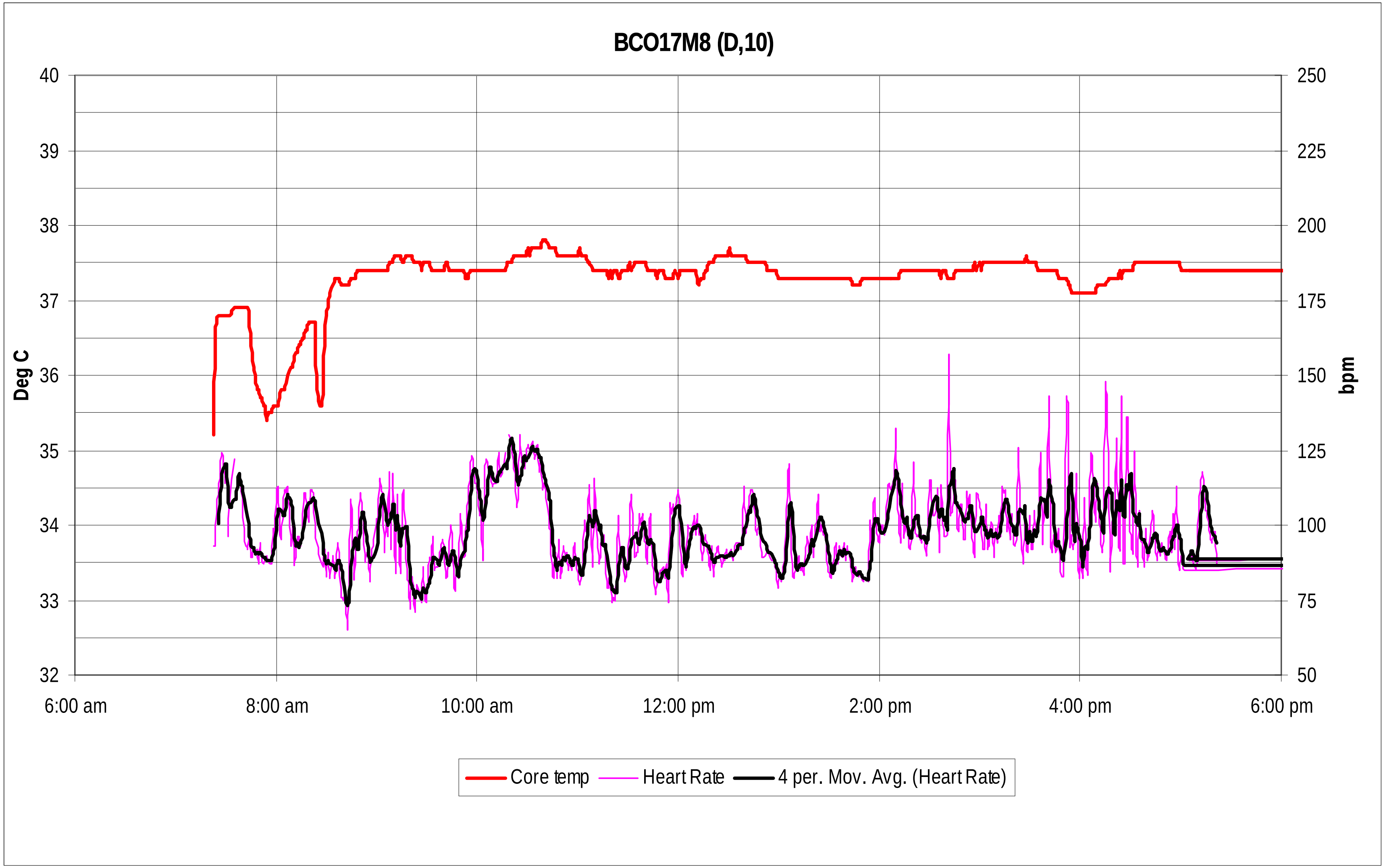


Figure 27 Core temperature and heart rate for target subject BCO17M8, 1st summer



3.5 Fluid Losses, Replacement and Hydration Status

3.5.1 Subjects

A summary of the anthropometric and body morphology data and $\dot{V}O_{2\max}$ for the subjects in the main study is shown in Table 6 page 79.

3.5.2 Environmental Conditions

Environmental conditions for the main study were measured at each workplace approximately every 60 to 90 minutes, with 233 sets of readings taken in total. Of these 233 sets, 46 observations were in the cribroom or inside air-conditioned mobile equipment cabins, leaving 187 sets from thermally exposed workplaces (refer Table 12). The unweighted average of these 187 sets was 28.4^0 WB, 36.2^0 DB, 36.3^0 globe temperature, 1.1 $m.s^{-1}$ wind speed, 30.9^0 C WBGT and a TWL of 175 $W.m^{-2}$.

Table 12 Environmental conditions for workers in Hydration study 1

	WB	DB	GT	Wind	WBGT	TWL
	^{0} C	^{0} C	^{0} C	$m.s^{-1}$	^{0} C	$W.m^{-2}$
n	187	187	187	187	187	187
avg	28.4	36.2	36.3	1.1	30.9	175
std dev	2.2	2.6	2.8	1.6	2.0	42
range	24.2-33.7	23.7-41.3	23.8-41.3	0.1-7.0	25.7-35.2	83-268

3.5.3 Hydration

3.5.3.1 The main study (hydration study 1)

The start, mid and end of shift urinary specific gravity values were measured for 39 workers. 9 of these shifts were 10-hour duration and 30 shifts were 12-hour duration. The results are summarised in Table 13 and Figure 28. There is no significant difference in the means of the paired sets of specific gravity values, either between start and mid shift (p=0.81), between mid and end of shift (p=0.70), or between start and end of shift (p=0.85).

Table 13 Urinary specific gravity data hydration study 1

	S.g. Start of shift	S.g. Mid-shift	S.g. End of shift
n	39	39	39
Avg	1.0252	1.0248	1.0254
Std dev	0.00533	0.00533	0.00686
Range	1.012-1.035	1.009-1.035	1.006-1.035
Sg > 1.030 (n, %)	5, 11%	8, 18%	10, 22%
Sg 1.023-1.030 (n, %)	23, 51%	22, 49%	22, 49%
Sg 1.015 – 1.023 (n, %)	13, 29%	7, 16%	6, 13%
Sg < 1.015 (n, %)	4, 9%	8, 18%	7, 16%
p value	Start to mid=0.85	Mid to end=0.70	Start to end=0.85

Figure 28 Urinary specific gravity of 39 workers working in thermally stressful conditions at start, middle and end of shift

3.5.3.2 Comparison with "hot job" workers at end of shift (hydration study 3)

The average end of shift specific gravity of the 546 workers granted a hot job was 1.0244 (0.0067, 1.0020 to 1.0360). None of these workers reported symptoms of heat illness. For hydration study 3, specific gravity was checked on the surface rather than underground and this could be between 30 minutes and two hours after the completion of the heat exposure, so that some workers in this study would have rehydrated to some extent prior to providing their urine samples.

The average end-of-shift specific gravity of these workers (n = 546) was significantly higher (p=0.019) than the start-of-shift specific gravity of the group of workers (n = 64) prior to commencing work. However, the absolute increase (1.0220 to 1.0244) was small.

3.5.3.3 Fluid Consumption Study

The fluid consumed ad libitum during the working shift was monitored and recorded in detail for 39 workers over 39 shifts with a total nominal shift duration of 444 hours (comprising 23 x 12 hour shifts, 3 x 12.5 hour shifts and 13 x 10 hour shifts). Estimated exposure time was 320 hours (72% of nominal work time). The remaining time was spent getting to and from the workplace, and having meal breaks, etc.

The average fluid consumption per shift was 6.48 litres (over this mixture of different shift lengths) with a standard deviation of 2.41 litres and range of 2.40 to 12.50 litres. Moisture content in food was not included in this analysis, but would increase the calculated fluid consumption rates.

The mean full-shift average fluid consumption rate was 0.8 litres per hour (0.27, 0.32 to 1.47).

3.6 Fatigue

3.6.1 Subjects

A summary of the anthropometric and body morphology and $\dot{V}O_{2\max}$ data of the subjects is shown in Table 7 page 93.

3.6.2 Environmental Conditions

As noted in section 2.6.3 page 94, environmental conditions were only measured in the heart rate studies. However, in the 2nd summer, both the heart rate and cycle ergometer studies were conducted on the same subjects on the same day, and were collected contemporaneously with the core temperature study.

Over both summers, a total of 350 environmental observations (refer to Table 14 for the aggregated data) were taken (excluding observations when workers were inside air-conditioned areas and therefore not under thermal stress).

Prior to aggregation, a comparison of both WBGT and TWL shows the average environmental conditions in the first summer were not significantly different

(WBGT: p=0.44; TWL: p=0.39) to the second summer, after the protocols had been changed. Fifteen observations (4 %) exceeded 32^0 WB.

Table 14 Environmental conditions in fatigue study in the first summer and in the second summer after changes to working-in-heat protocols. There was no statistically significant change in the thermal environment from one summer to the next.

	WBGT, ^{0} C		TWL, W.m^{-2}	
	1st summer	2nd summer	1st summer	2nd summer
n	164	186	164	186
Avg	30.78	30.94	178	174
Std Dev	1.729	2.144	41.7	44.9
Range	26.8-36.9	25.7-35.2	81-286	83-276
p	0.44		0.39	

3.6.3 Continuous Heart Rates

The heart rate study was conducted on 45 workers (all males). Anthropometric, body morphology and $\dot{V}O_{2\max}$ data are shown in Table 7 page 93.

A total of 71 shifts of data (Table 15 page 133 for aggregated data, Table 16 page 134 for each summers' data, Appendix G page 216 for individual data) were collected for an elapsed recording time of 693 hours. Some workers were tested twice, usually on consecutive shifts. Included in this elapsed time was 56 hours (8%) that was excluded from the analysis because the heart rate data-logging device failed to operate during that time, or produced occasional spurious data. Data points where the heart rate was greater than 225 bpm was the typical problem and these points were omitted. This occurred either because of interference from other strong radio signals in the workplace or for other reasons (see below). A new model of Polar^{TM} sports testers was released into the market between the studies, and this new model, used to collect data on the second summer, resulted in less lost or spurious data in the underground environment.

Only data sets with at least four hours of heart rate data (excluding missing or invalid data) were considered for further analysis.

Table 15 Analysis of continuous heart rate data for target group for both summers: 1st and 2^{nd}, after aggregation. Recording time shows the number of shifts, total recording time (hrs) and max, min and average recording time per shift. Remainder of columns indicate number of shifts during which this information was recorded, the total minutes, and max, min, average, std dev and % of time spent in these zones.

Aggregated data from both summers, before and after changes to protocols										
	Recording time, hours and hrs/shift	Avg heart rate, bpm	Highest 10 min heart rate, bpm	Highest 30 min heart rate, bpm	Heart rate < 60 bpm, mins	Heart rate 60-80 bpm, mins	Heart rate 80-100 bpm, mins	Heart rate 100-120 bpm, mins	Heart rate 120-140 bpm, mins	Heart rate > 140 bpm, mins
n, shifts	71	71	71	69	9	61	71	71	70	69
Totals	636.6				20	5564	14548	10952	4758	2782
Avg	9.0	102.7	141.7	129.1	2	91	205	154	68	40
Std Dev	2.3	12.7	19.5	20.6	1	98	101	83	58	56
Range	4.0-13.0	76.0-135.0	103.0-202.0	81.0-193.0	1-4	1-335	15-474	17-448	1-272	0300
% time in zone					0%	15%	38%	29%	12%	7%

Table 16 Analysis of continuous heart rate data for target group for both summers, prior to aggregation (continued next page):

Data in first summer, prior to change to working in heat protocols										
	Recording time, hours and hrs/shift	Avg heart rate, bpm	Highest 10 min heart rate, bpm	Highest 30 min heart rate, bpm	Heart rate < 60 bpm, mins	Heart rate 60-80 bpm, mins	Heart rate 80-100 bpm, mins	Heart rate 100-120 bpm, mins	Heart rate 120-140 bpm, mins	Heart rate > 140 bpm, mins
n, shifts	51	51	51	49	8	43	51	51	50	49
Totals	454.3				19	4192	9640	7740	3646	2187
Avg	8.9	103.3	142.6	129.1	2	97	189	152	73	45
Std Dev	2.4	13.8	20.9	33.5	1	105	102	86	65	63
Range	4.0-13.0	76.0-135.0	103.0-202.0	81.0-193.0	1-4	1-335	15-474	17-448	1-272	1-300
% time in zone					0%	15%	35%	28%	13%	8%

(Continued from previous page)

Data in second summer, after change to working in heat protocols										
	Recording time, hours and hrs/shift	Avg heart rate, bpm	Highest 10 min heart rate, bpm	Highest 30 min heart rate, bpm	Heart rate < 60 bpm, mins	Heart rate 60-80 bpm, mins	Heart rate 80-100 bpm, mins	Heart rate 100-120 bpm, mins	Heart rate 120-140 bpm, mins	Heart rate > 140 bpm, mins
n, shifts	20	20	20	20	1	18	20	20	20	19
Totals	182.3				1	1372	4908	3212	1112	595
Avg	9.1	101.2	139.4	129.0	1	76	245	161	56	31
Std Dev	2.3	9.4	15.7	15.9	0	79	89	79	36	36
Range	4.0-11.2	76.0-123.0	103.0-170.0	81.0-161.0	1-1	1-303	15-414	17-381	1-152	1-138
% time in zone					0%	13%	45%	29%	10%	5%
p: 1st to 2nd		0.53	0.53	0.98						

Elapsed recording time was typically an hour less than the typical values of 9.5 and 7.5 hours for 12 and 10-hour shifts respectively, as the monitoring equipment was set up on each individual after the start of the shift, and removed before the conclusion of the shift.

The full-shift average heart rate for the 51 sets of continuous heart rate data from the first summer of 103.3 bpm (13.8, 76-135) was not significantly differently (p=0.53) to the average of 101.2 bpm (9.4, 76-123) from the 20 sets of data from the second summer.

Likewise there was no significant change in the mean values of the highest 10 consecutive minute (p=0.53) and highest 30 consecutive minute (p=0.98) averages during the shifts, from pre- to post-change.

On this basis, the data was aggregated to form 71 sets of results as shown in Table 15 page 133.

3.6.4 Fatigue over the duration of the shift, measured using the cycle ergometer

3.6.4.1 Control Group

A negative (non-fatigued) control group of 15 workers (all males) working in the same operation in sedentary work in thermoneutral conditions was also tested over several shifts using the cycle ergometer protocol. This produced 32 paired sets of results (before and after shift). Nine of the 15 workers in the control group were underground workers (some of whom also participated in the target group of the cycle fatigue study) who were attending an unrelated, sedentary training session on the surface for the day of the test. 26 sets of paired data were obtained from these nine workers over approximately four weeks. The other 6 sets of paired data were from 6 office workers who habitually work in sedentary employment in thermoneutral conditions in the same operation..

A paired t-test was applied to the 32 sets of data for non-fatigued heart rates on the cycle ergometer before and after a working shift. The average increase in heart rate on the ergometer was 1.1 bpm (std dev: 6.3 bpm, range: -16 to 16). The end of test heart rate does not show a significant increase compared to the start of shift (p=0.16).

3.6.4.2 Target Group

The target group comprised 39 of the workers from the heart rate study. A total of 46 sets of data (before and after shift) were collected. Of these 46 sets, 24 sets also included cycle fatigue results collected at approximately mid shift, immediately prior to taking the main meal break.

The average increase in heart rate on the cycle ergometer from start to end of the shift for the 46 sets of data in the target group (Table 17 for aggregate data, Appendix H page 220 for individual data) was 4.4 bpm (8.9, -11 to 28). This is highly significant (p=0.0007).

For the subjects (n=24) tested at start, mid and end of shift, the increase in ergometer heart rates from start to end of shift was 4.1 bpm (8.9, -11 to 28), which was significant (p=0.02). The increase from shift-start to the main meal break was 7.9 bpm (11.6, -10 to 35), which is highly significant (p=0.001). There was actually a significant decrease (p=0.04) of 3.8 bpm (9.9, -24 to 15) in ergometer heart rates between mid-shift and end of shift. This suggests that the major component of fatigue in these workers was occurring in the first half of the shift.

Table 17 Cycle ergometer data for the target group

	All results			Paired results		
	Start	Mid	End	Start	Mid	End
n	47	24	46	24	24	24
Avg, bpm	126.6	136.3	131.2	128.3	136.3	132.5
Std Dev, bpm	13.05	15.13	11.98	14.78	15.13	13.61
Range, bpm	98-152	105-165	107-158	105.0-152.0	105.0-165.0	110.0-158.0

Note: *All results* is all ergometer data. *Paired results* is the sub-set of “all data” where paired sets of start, mid and end of shift data are available for the same individuals.

3.6.4.3 Continuous Heart Rates Versus Cycle Fatigue

Comparisons were made between continuous heart rate results and the cycle ergometer results. No significant linear regressions could be found in terms of the average, Highest-10 minute or 30-minute values compared to the cycle ergometer increase over the shift, or compared to the shift-ending ergometer value, or between the ratio of end to start of shift cycle ergometer values and the average heart rate. Resting heart rates were not taken so that comparisons involving cardiac reserve could not be prepared.

3.6.5 Blood Lactate

Lactic levels were measured at the earlobe within 30 minutes of the conclusion of physical work in the second continuous heart rate study. Of the 18 workers measured, only 2 exceeded 2 $mmol.l^{-1}$ (4 $mmol.l^{-1}$ is usually considered the normal lower indication of an oxygen debt, see page 70), six were recorded as being "low" (below reading level) and the average of all the data (including the two above 2 $mmol.l^{-1}$) was only 1.44 $mmol.l^{-1}$. Thus workers were working within their aerobic capacity.

Apart from physical damage to the heart rate monitors and the occasional removal of the data loggers during meal breaks for personal comfort, there were two other problems of significance encountered during this study:

- Occasional spurious high and low heart rate data (usually as single points, but occasionally as a series of a few consecutive points), especially in the first summer. Some data sets were more seriously affected than others for unknown reasons. Spurious data was ignored from the analysis.

- Slippage of the ECG sensor down the subject’s chest, resulting in unintentional loss of data for varying periods of time. Various methods were trialled with a view to preventing this occurring, with little sustained success. Much of the work undertaken by the target group is upper body work, which tends to promote slippage of the chest sensor.

Chapter 4 - Discussion

4.1 Heat Stress Indices

4.2 Thermal Work Limit

Table 18 shows typical TWLs over a range of conditions. It should be noted that in the past, it has not been practical to routinely measure the five environmental parameters required to evaluate TWL for each workplace each shift. This is one of the reasons why empirical indices such as WBGT have been popular – the technology has not been available to support more elaborate indices. However, a suitable, pocket-sized instrument is now available[8] with the necessary accuracy to measure the parameters and with an internal processor to perform the necessary calculations for the heat strain model.

Table 18 TWL Values at Various Environmental Conditions and Clothing Ensembles

MRT = DB+2 ^{0}C						MRT = DB						MRT = DB+3 ^{0}C					
Wind speed =0.2 m.s^{-1}						Wind speed =0.5 m.s^{-1}						Wind speed =1.5 m.s^{-1}					
Barometric Pressure = 101 kPa						Barometric Pressure = 115 kPa						Barometric Pressure = 80 kPa					
I_{cl} = 0.45, i_{cl}=0.45						I_{cl} = 0.69, i_{cl}=0.4						I_{cl} = 0.35, i_{cl}=0.45					
WB						WB						WB					
DB	**24**	**26**	**28**	**30**	**32**	DB	**24**	**26**	**28**	**30**	**32**	DB	**24**	**26**	**28**	**30**	**32**
34	175	157	136	114	n/p	**34**	181	161	140	118	n/p	**34**	288	260	229	193	154
36	170	151	131	109	n/p	**36**	176	156	136	113	n/p	**36**	282	254	222	187	148
38	164	145	125	103	n/p	**38**	171	152	131	109	n/p	**38**	276	248	216	181	141
40	158	140	120	n/p	n/p	**40**	166	147	126	104	n/p	**40**	270	242	210	174	135
42	152	134	114	n/p	n/p	**42**	161	142	122	n/p	n/p	**42**	264	235	203	167	128

MRT = mean radiant temperature, ^{0}C

DB = dry bulb temperature, ^{0}C

WB = wet bulb temperature, ^{0}C

I_{cl} = intrinsic clothing thermal resistance, clo

i_{cl} = clothing vapour permeation efficiency, dimensionless

n/p = Heat stress too extreme even for (continuous) light work. Permit required.

The valid range for TWL is from resting (60 W.m^{-2}) to 380 W.m^{-2}, as this is the range of experimental data collected by Wyndham. TWL is not valid where the dew point temperature of the ambient air is above the skin or clothing temperature. Finally, as the equations used to derive the heat transfer through clothing are not valid for subjects in encapsulating protective clothing (EPC), TWL cannot be assumed to be valid where impermeable clothing is used.

With respect to TWL, it must be emphasised that the recommended values of TWL do not require constant assessment of metabolic rates in the workplace, which will vary considerably between workplaces and over the course of a work shift. This means that persons untrained in assessing metabolic rates can supervise the protocol. Whilst TWL itself is valid for any worker, the TWL protocols are designed for workers who are well informed about working in heat, have control over their work rate, are healthy and are well hydrated. Self-pacing works well when it is formally incorporated in a protocol where workers have the mandate to self-pace, and when supervisors and management are supportive.[18]

Where work is not self-paced, TWL remains a useful tool for predicting thermal strain, particularly where work rates are well described. This applies for many sporting activities, or for military activities such as marching. In these situations, the closer the work rate comes to the TWL, the higher the strain on the individual and the higher the risk of heat illness.

TWL suffers from the same problem as most other heat stress indices in that environmental conditions need to be measured to assess the required actions under the protocols. However, by designing the accompanying protocols specifically for self-pacing, there is less emphasis needed on measuring environmental conditions, as workers are allowed to reduce their work rate as needed. In most circumstances, workers are not working near the maximum work rate for the particular environment and they recognise this themselves – no measurements are required. When they believe they are working close to one of the action levels, measurements are taken. This has proved quite practical.

Recommended guidelines for TWL action levels in industry with the corresponding interventions are provided in section 3.2 page 107. These are based on the hierarchy of safety controls, and include a range of engineering, procedural and personal protective equipment (PPE) interventions.

Whilst TWL does not require metabolic rates to be assessed for routine use, the index itself provides an estimate of the limiting metabolic rate from simple measurements of environmental conditions. Therefore, TWL is of benefit not only in assessing thermal stress directly, but also in allowing occupational hygienists and engineers to make quantitative assessments of the following types of commonly encountered problems.

- The loss of productivity due to thermal stress. For example, if the metabolic rate (work rate) for a particular type of work in an environment of low thermal stress is 180 W.m^{-2}, and assuming a "resting" metabolic rate of 60 W.m^{-2}, then the productivity when working in an environment with a TWL of 120 W.m^{-2} is given by:

  Productivity = (120 - 60) / (180 - 60) = 50%, where (120-60) is the residual work capacity (the working rate less the resting rate) in this environment and (180-60) is the residual work rate required for full productivity. Simple calculations of the cost of lost production and other economic impacts of environmental conditions can then be made.

- Using the same premises, work/rest cycles can be established.

- Indicative exposure times before reaching a limiting deep body core temperature can be estimated. Taking the above example, if work with an energy expenditure (metabolic rate) of 180 $W.m^{-2}$ is required in an environment with a TWL of 120 $W.m^{-2}$, then the heat storage is 60 $W.m^{-2}$ or 120 W using a conservative surface area per person of 2 m^2. If the typical worker has a mass of 80 kg, then the deep body core temperature will rise by about 60/3500 x 3600/80 = 0.77^0 C per hour, since the specific heat of the body is 3500 $J.(kg.K)^{-1}$. If the maximum acceptable deep body core temperature is (say) 38.2^0 C and work starts from a thermoneutral condition (deep body core temperature 37^0 C), then withdrawal would need to occur no longer than (38.2-37.0)/0.77 = 1.5 hours after work in these conditions commences. Clearly this calculation would only be a starting point and field checks would be needed to confirm practical exposure times.

- The cost benefit of installing cooling installations can be assessed. Because TWL is measured in $W.m^{-2}$, it can easily be compared to watts of refrigeration. The impact of localised cooling using various types of refrigeration can therefore be measured directly. For example, consider a workplace being ventilated with 10 $m^3.s^{-1}$ of air at 30^0 C WB, 40^0 C DB, 40^0 C Globe, 100 kPa barometric pressure and a wind speed of 0.2 $m.s^{-1}$. The initial TWL (with $I_{cl} = 0.35$ and $i_{cl} = 0.45$) is 110 $W.m^{-2}$ (withdrawal conditions for self-paced work). Local refrigeration of 100 kW(R) [kilowatts of refrigeration effect] is installed. Standard psychrometric equations can be used to calculate that temperatures in the work place will drop to 28.0^0 C WB and 31.4^0 C DB, which results in an increase in TWL to 158 $W.m^{-2}$. For conditions to be made acceptable for solitary, self-pacing, unacclimatised workers, the TWL would need to be improved further to 220 $W.m^{-2}$ (refer recommended guidelines in section 3.2 page 107). The capital and operating costs of this engineering intervention (refrigeration) can be directly evaluated against the cost benefit of improved productivity.

- The “free” cooling available as a result of increased local airflow. Using the above example, the TWL could have been increased to the same 158 $W.m^{-2}$ by increasing the wind speed over the skin from 0.2 to 0.7 $m.s^{-1}$ without any addition of refrigeration. For indoor work, this could probably be achieved by installation of a local electric or compressed air-operated fan or venturi air mover. This is not to say that increasing the wind speed over the skin is able to increase the TWL in all situations; typically, increasing the wind speed beyond 4 $m.s^{-1}$ provides little further benefit.

The serious and generally detrimental impact of clothing ensemble (clothing plus any additional PPE) on thermal stress, and particularly any loss of vapour permeability. When various hazards in the workplace are being evaluated and PPE or alternative protective clothing ensembles is a consideration, the effects on thermal stress of the proposed changes can therefore be easily evaluated, by adjusting the I_{cl} and i_{cl} values.

4.2.1 Use of Limiting Metabolic Rate to Compare Indices, Including TWL

From Figure 18 page 114, the following conclusions can be drawn:

- There is a wide range of “limiting” environmental conditions for identical metabolic rates and similar clothing ensembles and acclimatisation states. Table 19 page 145 summarises the maximum wet bulb temperature recommended for workers with a metabolic rate of 140 $W.m^2$ (a moderate work rate) according to ACGIH, TWL, ISO7933, USARIEM and CET. Maximum wet bulb temperatures exceeding 33^0 were not considered, as these are outside the range generally considered acceptable for continuous work, even light work, by industrial workers.

- ISO7933 appears to be insensitive to temperature, humidity and wind speed, at least at the nominated 140 $W.m^2$ metabolic rate.

- The converse approach is to examine the “limiting” metabolic rate for a particular environmental condition. Table 20 page 145 gives a comparison between the above four indices, at an identical 28^0 WB.

- Again, problems with some indices emerge when compared according to these criteria. ISO7933 appears to indicate that an increase in wind speed (from condition A to B, and from C to D in Table 20 page 145) results in a marginal reduction in the maximum metabolic rate, contrary to all the other indices. Moreover, ISO indicates that an increase in DB temperature, at a fixed WB (from condition C to A and from D to B above), allows a marginal increase in limiting metabolic rate, contrary to the other indices, and contrary to the finding from others that an increase in dry bulb temperature, with the wet bulb temperature and wind speed fixed, results in more severe thermal stress.[138] These issues with ISO7933 are probably related to the way the standard boosts wind speed as a function of metabolic rate.

- TWL and USARIEM are both sensitive to wind speed at these conditions, although TWL is more so; however, ACGIH and ISO7933 are insensitive to wind speed at these conditions.

- The “normal” (clothed) scale of Corrected Effective Temperature significantly underestimates thermal stress, compared to all other scales, under most conditions. Moreover, the slope of the CET index (limiting work rate versus WB) is much steeper than all the other indices. This indicates that CET is much more sensitive to changes in WB (and hence humidity) than are the other indices.

- There is a very wide range of acceptable limiting metabolic rates (with differences of up to 100 $W.m^2$ or 100%, after deducting resting metabolic rates, under identical environmental conditions).

Table 19 Comparison of maximum WB for selected heat stress indices at a fixed metabolic rate of 140 W.m^{-2} for four environments: high and low wind speeds and hot/humid and hot/dry conditions.

Hot, dry: DB=MRT=WB+10^0 C *Hot, humid: DB=MRT=WB+3^0 C*	Maximum WB for metabolic rate of 140 W.m^{-2}				
	ACGIH	TWL	ISO7933	USARIEM	CET
Hot, dry, 0.2 m.s^{-1} wind	25.2	27.5	27.5	31.4	29.0
Hot, dry, 3.0 m.s^{-1} wind	25.7	31.9	27.4	> 33.0	30.3
Hot, humid, 0.2 m.s^{-1} wind	27.6	28.9	27.5	32.4	31.0
Hot, humid, 3.0 m.s^{-1} wind	27.7	32.8	27.3	> 33.0	32.7

Table 20 Comparison of selected indices in terms of limiting metabolic rate for four environments, all at 28^0 WB: high and low wind speeds and hot/humid and hot/dry conditions.

Hot, dry: DB=MRT=WB+10^0 C *Hot, humid: DB=MRT=WB+3^0 C*		Maximum metabolic rate (W.m^2) for 28^0 WB [rounded to nearest 5 W.m^2]				
		ACGIH	TWL	ISO7933	USARIEM	CET
A	Hot, dry, 0.2 m.s^{-1} wind	75	135	135	195	175
B	Hot, dry, 3.0 m.s^{-1} wind	80	225	130	245	290
C	Hot, humid, 0.2 m.s^{-1} wind	130	150	130	225	>300
D	Hot, humid, 3.0 m.s^{-1} wind	135	240	125	265	>300

By using the thermal resistance and vapour permeation values for a "nude" body, the influence of different clothing ensemble treatments by the different indices can be removed, and a comparison of the underlying physiological models or assumptions can be made.

One weakness in using this method to compare indices is that the comparison can only be made at the limiting metabolic condition (in terms of thermal stress). However,

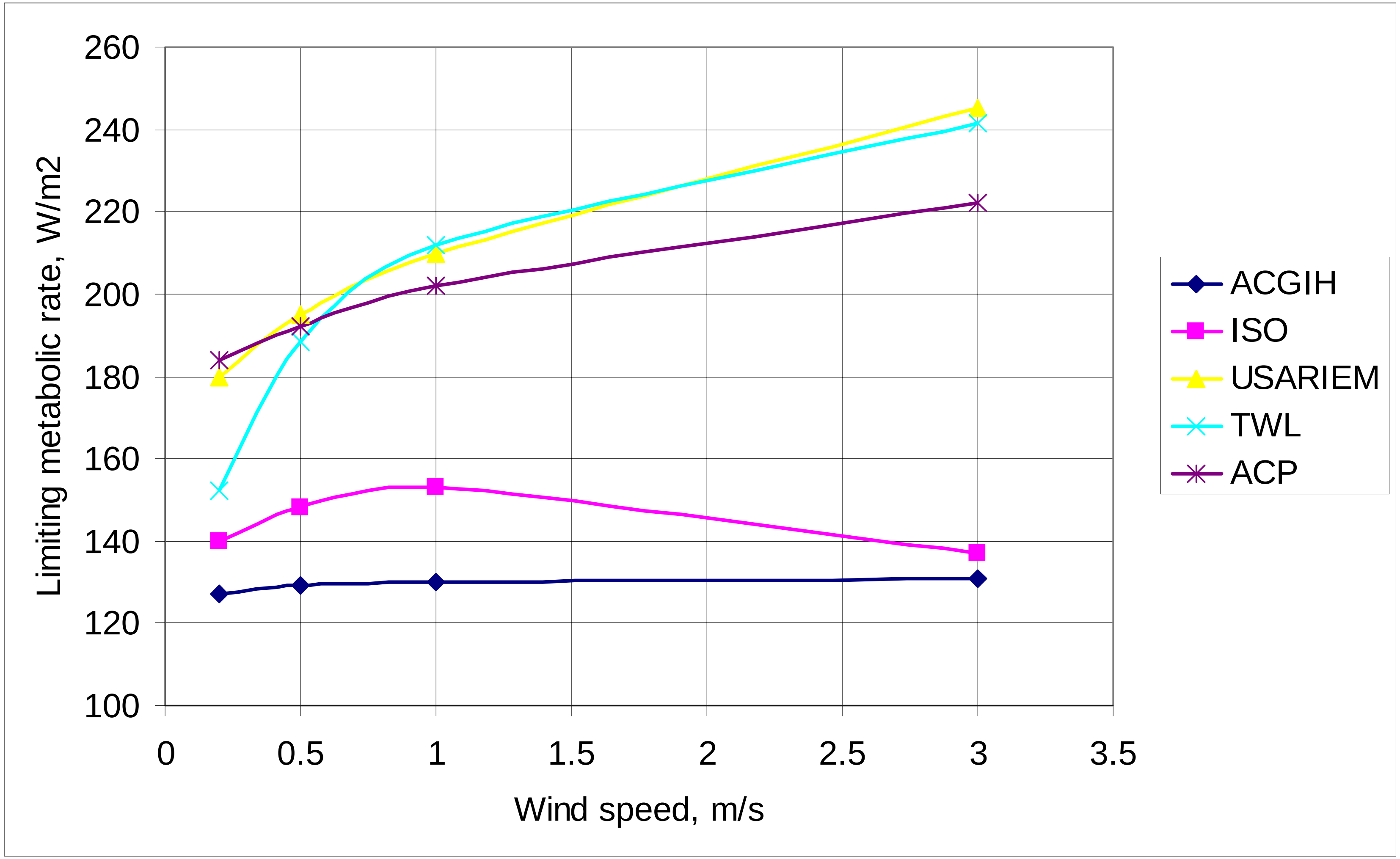
- Where the required work rate is lower than the limiting condition, an unlimited work cycle is possible, so that comparisons in this range are of less practical relevance,
- For conditions "worse than" the limiting condition, the method of comparison can be extended as shown below, and
- Even restricting the comparison to the point of limiting metabolic rate still gives an unlimited number of points for comparison, as there are effectively an unlimited number of possible combinations of environmental condition and clothing ensemble.

4.2.2 Using the Method for Sensitivity Studies

Often it is desirable to know how sensitive an index is to a particular parameter, such as wind speed. It is generally straightforward to plot how the index itself varies with wind speed, but a plot so produced cannot be compared directly with a similar sensitivity study using another index, as the parameters involved (WBGT, CET, etc) are not directly comparable. Using the limiting metabolic rate methodology, sensitivity studies of various indices can be directly compared. An example is given in Figure 29 page 148, where the sensitivity of selected indices to wind speed is given for a reference condition of 28^0 WB and 31^0 DB.

Not only does this chart confirm that the various indices produce very different recommended maximum metabolic rates for the same wind speed at identical environmental conditions, but it also indicates widely differing sensitivity (slope of the limiting metabolic rate versus wind speed curves) to increasing/decreasing wind speed. It also highlights the apparent anomaly with ISO, which indicates that increasing wind speed at this reference condition results in reduced ability to work.

Figure 29 Sensitivity of various indices to wind speed for "typical cotton summer uniforms", and condition of 28^0 WB, 31^0 DB, 31^0 MRT, 100 kPa barometric pressure.



Sensitivity studies of any environmental or clothing parameter, or acclimatisation state, using this method, are possible. Sensitivity studies to particular physiological limits are also possible, e.g. different maximum sweat rates or deep body core temperatures within a given model. The method is therefore flexible in application in terms of sensitivity studies across indices or protocols.

4.2.3 Extension of the Method to Conditions Beyond the Limiting Metabolic Rate

This methodology can be extended to the situation where a workplace with a formal work/rest cycle needs to be evaluated, i.e. where the actual metabolic rate required for the task exceeds the limiting metabolic rate.

Assume that when in the "rest" portion of the cycle, workers have a metabolic rate of MR_{rest}, and the environmental conditions are WL_{rest}. Further assume that in the "work" portion of the cycle, workers have a metabolic rate of MR_{work}, and the environmental conditions are WL_{work}, then for no net heat storage in the body, the time-weighted average metabolic heat gain from the work portion must not exceed the time metabolic heat loss in the rest portion. If the proportion of time spent in the "work" portion of the cycle is $T_{w\%}$, then,

$$T_{w\%}, \text{ x } (MR_{work} - WL_{work}) = (1- T_{w\%},) \text{ x } (WL_{rest} - MR_{rest}) \text{...........equation 1}$$

Or, by rearranging and solving for $T_{w\%}$,,

$$T_{w\%}, = 1 / [1+ (MR_{work} - WL_{work}) / (WL_{rest} - MR_{rest})] \text{ ....equation 2}$$

By constructing a limiting metabolic rate curve for the particular heat stress index, the theoretical working time per hour for a particular environmental and clothing condition (where the required work rate is beyond the limiting (continuous) metabolic rate) can be calculated using equation 2 above. This can then be compared to the actual work/rest cycle in existence in the workplace, or to the theoretical work/rest cycle using any other index. In addition, approximate actual exposure times prior to withdrawal (and recovery times) can be calculated, assuming an allowable core temperature increase and the average thermal capacity of body tissues.

4.3 Deep Body Core Temperature

For clarity, the standard deviations and ranges of values are listed in the tables only and are omitted from the text.

Neither the WBGT nor the TWL in the workplace had changed significantly from one summer to the next; it was concluded that the level of heat stress exposure had not changed.

The maximum and average core temperatures also had not changed significantly from one summer to the next; it was concluded that the new working-in-heat protocols had not changed the level of hyperthermia. The core temperature data was therefore pooled for further analysis.

In recommending safe core temperature limits from this study, it would be misleading to restrict this to the average upper values measured. For example, some workers were allocated jobs where they were under little thermal stress for the shift – their upper core temperature was low and this is supported by Table 10 page 116, where the highest core temperature recorded by one worker was only 37.7^0 C. As no worker reported symptoms of heat illness during the study and environmental conditions included a range of temperatures, not all workers reached their maximum safe individual core temperature during the shift. It is hypothesised that a realistic upper limit from this data is probably about one standard deviation above the measured group averages. However, alternate more conservative approaches might be to consider the safe limit as being the value that was *not* exceeded by 95% of workers, or to consider the safe limit to be the value that *was* exceeded by at least (say) 20 workers in the study, this being a significant number. The values based on one standard deviation above the average are reported in *italics* in the following discussion and comments regarding the alternate approaches also provided where relevant.

4.3.1 Control Group

The most significant feature of the control group is a 0.9^0 C *(1.2^0)* average core temperature rise during the working shift. As the control group was sedentary and thermally unstressed, this increase is probably due to diurnal variation in core temperature over this period. Note that this mean value is close to the ILO[129] recommended allowable core temperature rise for acclimatised workers of 1^0 C, with almost 50% of workers exceeding the ILO value without physical exertion or heat stress. In fact, as data logging for the control group on the first day of their two-day test did not start until mid-morning, this average of 0.9^0 C somewhat understates the true increase. The average of the four sets of day two data, which did capture the full diurnal increase from shift-start, was 1.0^0 C. Note that these values do not reflect the *full* 24-hour diurnal variation in core temperature (including the sleeping period), only the diurnal variation from about 6:30 am to the end of the working day (typically between 5 pm and 6 pm). The full diurnal variation was found to be larger than this as can be seen in Figure 21 page 121. Note that this particular subject went to considerable effort to not become thermally stressed during this control period. No exercise was performed and exposure to heat stress was avoided. The subject remained inside an air-conditioned office during work hours. Nevertheless, the magnitude and cyclical nature of the trace indicates the range of core temperatures that are incurred even for a sedentary person in thermoneutral conditions.

4.3.2 Target Group

Average maximum core temperature during the working shift was 38.3^0 *(38.7^0)*, which exceeds the ACGIH recommended value of 38.0^0 (although the 1998 Notification of Intended Change provides for a core temperature of 38.5^0 for well-screened, acclimatised workers). Two workers exceeded 39^0 C (being 39.4^0 and 39.5^0 respectively; one of which is shown in Figure 25 page 125. These figures are broadly in line with the findings of others, who have reported that the working core temperature upper limit for moderately fit industrial workers, prior to collapse or withdrawal, was in the range of 39.0^0 to 39.5^0 C.[93,21,126,130] Trained athletes have been found to continue without ill effects at core temperatures in excess of 40^0 C.[42,111,79] The fact that these data were measured on subjects in the ordinary course of their working activities, and without reporting any heat illness, questions the validity of using 38.0^0 as an absolute limit for occupational hyperthermia. However, if a safe limit was to be based on the 95th percentile from this study, the limit would be approximately 37.8^0 C, and if based on the safe level achieved by 20 workers, would be approximately 38.2^0 C, which are both within the most recently recommended ACGIH limits for screened and acclimatised workers.

The highest 10- and 30-consecutive minute averages, maximums and minimums were all very close to the one-minute (single reading) average, maximum and minimum values reached. This indicates that workers plateau near the maximum temperature for that shift and remain there for some time.

The average increase in core temperature (or the core temperature *working reserve*, defined hereafter as the maximum reached in the shift, less the minimum reached) was 1.4 ^{0} C *(1.9^0 C)*, compared to the ISO recommended maximum of 1.0^0 C for acclimatised workers. Note that 26 (68 %) of the 38 sets of data in the target group were for workers on 12 or 12.5 hour shifts, and of these 26 sets, 19 were for day shift. The average increase of 1.4^0 C is in accordance with the findings of Rastogi[105] who found an average core temperature increase of 2.2^0 F (1.2^0 C) for industrial workers, with one group averaging an increase of 2.5^0 F (1.4^0 C).

If gastrointestinal temperatures are in fact 0.5^0 C lower than oesophageal temperatures, then the "core" temperatures found in this study, which were already higher than the generally recommended values, would be even higher. This highlights the importance of defining when, where and how core temperatures are to be defined in setting future occupational limits.

The average heat storage (defined as the calculated maximum versus minimum heat content of the body during the shift) was 431 kJ *(594 kJ)* compared to the ISO recommended value of 389 kJ for standard acclimatised workers.

The average maximum increases in core temperature were 0.5^0 C *(0.7^0 C)* in 10 minutes, 0.8^0 C *(1.1^0 C)* in 30 minutes, and 0.9^0 C *(1.2^0 C)* in 60 minutes. The average maximum decline in core temperature for the three time periods were 0.5^0*(0.8^0 C)*, 0.7^0 *(1.0^0 C)* and 0.8^0 *(1.1^0 C)* respectively. Individual increases in core temperature of up to 1.3^0 C in 10 minutes, and up to 1.5^0 C in 30 minutes were recorded. The significance of the rate of increase or decrease in core temperature for industrial workers is not known, but several authors have speculated that the rate of increase in core temperature and/or the duration of the hyperthermia may be important factors in terms of developing heat illness in addition to the actual level of core temperature reached.[35,47]

The relatively rapid increase and decrease in core temperature could explain why intermittent rectal temperature measurements in the past during other field studies may not have caught the true maximum temperatures reached. Most laboratory studies, on the other hand, have used "steady-state" or slowly changing heat stress, which is not likely to reflect modern industrial work patterns.

The distribution of temperatures during the working shift indicated that temperatures above 38.2^0 C were only exceeded about 7% of the time. It was on this basis, and on the basis of other authorities (refer Literature Review), that the allowable limit for core temperature in the standard TWL formulation was set, somewhat arbitrarily, at 38.2^0 C. Temperatures over 38.8^0 C were infrequent to rare. Given the wide range of environmental conditions, body morphology, aerobic capacity and work rates in this study, this is strong evidence that workers are able to self-pace when they are properly trained and supported by their management. Acclimatised, self-paced workers are therefore unlikely to voluntarily exceed core temperatures of about 38.8^0 C.

The fact that the incidence of heat exhaustion and stroke is more prevalent in the military, where work is frequently externally paced (e.g. marching), also supports this conclusion.

It appears that authorities charged with responsibility for developing standards or advisory guidelines on occupational heat stress assume there is such a thing as a single measuring site for “deep body core temperature”, and also assume that such a measure has a single value rather than a range of values. This is certainly the case with the ACGIH TLV and ISO7933, which refer to, but do not define, “deep body temperature”.

One of the reasons several authorities have advised the adoption of the cautious limits of 38^0 C or an increase of 1^0 C, is that this limit is needed to cover the wide range of inter-individual variances. However, this has the effect of creating artificially restrictive limits if these are then used as ceiling values to trigger withdrawal of personnel not under medical surveillance. Where they are used to develop heat stress indices and protocols, this study shows they would lead to unnecessary conservatism for self-paced workers who have, by definition, the ability to reduce their work rate, or withdraw from conditions in which they are feeling unnecessarily stressed.

Given the exposure to very hot conditions in this workforce of about 2000 underground miners over a period of at least 50 years, it is perhaps surprising that there have been no recorded incidents of heat stroke, a conclusion which can be confidently made as a 24-hour medical clinic with attending occupational physicians is on site. It is most likely that the causes of this include the following:

- The workforce, and especially the target group who habitually work in the heat, is reasonably well-informed about the impacts of working-in-heat,

- The surface climate is hot and workers are at least partly acclimatised by living in this climate,

- Workers typically work by themselves, or with one or at most two regular co-workers. Older workers typically "mentor" new workers with advice about suitable work paces and rest pauses. This is unlike some other occupational settings where the work rate is externally paced.

- Work is typically conducted with no on-the-job supervision. Supervisors usually visit each work place twice each shift, for about 10 minutes each visit.

- The workforce is relatively unfit (compared to athletes). The fitness levels of the target group (all company employees) is shown in Table 5 page 79. Not all workers were tested, but a test of 469 contract employees joining the organisation for project work under similar levels of heat stress during this period had a measured $\dot{V}O_{2\max}$ of 39.0 $ml.kg^{-1}.min^{-1}$ (std dev 7.8 $ml.kg^{-1}.min^{-1}$) and a BMI of 25.9 (std dev 5.4), which are similar values to those in Table 5. Others[54,5,116] have found that relatively unfit workers are likely to suffer heat exhaustion that is self-limiting, resulting in voluntary withdrawal or collapse, before serious hyperthermia is incurred.

With respect to the last point, it is possible to *speculate* that:

- For externally paced work, it is reasonable to assume that fitter workers will be less at risk of heat illness than unfit workers, due to their higher efficiency and higher cardiovascular reserve;

- For self-paced work, it is possible that unfit workers may be at no greater risk of heat illness than fit workers, due to the potential for fitter workers to generate higher internal heat loads and hence higher core temperatures (i.e. greater levels of hyperthermia) with its associated risk of heat illness. This is also supported by Donoghue[32] who found no correlation between $\dot{V}O_{2\max}$ and the risk of heat illness in industrial workers.

Indications of the impact of lower core temperatures experienced by workers on night shift (due to normal circadian rhythm) can be seen in Figure 23 page 123. Note that the normal circadian peak occurs about 6 pm; however for this worker, the 6 pm value is about 36.7^0 C. It should also be noted that these workers only work two consecutive night shifts, so that this "inversion" of the normal 6 pm circadian value occurred at the end of only one night shift. This additional core temperature reserve at night compared to work during the day could help explain why others[31,24] have found that workers exposed to heat stress on day shift were statistically more likely to develop heat illness than workers on night shift. The threshold for sweat onset is also lower at night than during the day.[88] Note that the literature generally believes that many more than one or two shifts are required for the circadian clock to be re-set,[72] although at least the core temperature portion of the circadian clock appears to be re-set much more quickly than this in this study, based on the above data.

The close correlation between heart rate and core temperature, when under significant thermal stress, can be seen in the Figure 24 page 124 and Figure 25 page 125. However, as expected, this is not as pronounced when the stress is low (e.g. Figure 27 page 127). Moreover, the response is generally delayed with heart rate preceding core temperature (Figure 26 page 126). This confirms what others[65,115,82] have found as to heart rate being a reasonable indicator of overall physiological and psychological strain when imposed on a significant baseline, and opens the possibility of using widely-available ambulatory heart rate monitors to continually assess hyperthermia in industrial workers. However, such a possibility would need to be confirmed in further studies.

It should be noted that the widespread adoption of WBGT as an index of thermal stress was historically driven by two important factors:

- It was seen as a proxy for Corrected Effective Temperature,[97] which at the time (1957) was the most widely used heat stress index for occupational use, and

- It was able to be measured directly by an instrument that could be made sufficiently small and robust to be used in the field.

Neither of these assumptions is now true, with widespread recognition of weaknesses in both CET and WBGT as indices of thermal stress[104,57,82,105,69] and the development of microprocessor based instruments that can measure and compute more complex physiological models than the WBGT instruments.[8]

Apart from physical damage to the recorders and the occasional removal of the recorders during meal breaks, there were three other problems of significance encountered during this study:

- Interference from strong radio signals in the workplace environment and interference with other recorders in the area (the latter was only a problem at lunch breaks, as workers were scheduled so as to not be working near one another).

- Brief spurious low temperature readings due to the ingestion of large quantities of cold water, particularly in the first few hours after ingesting the pill. [This was also a problem with a control group of office workers, except that in their case, the problem was ingestion of hot drinks during these first few hours].

- Other spurious low temperature readings possibly due to the worker entering an air-conditioned environment when the pill was located in the intestine near the abdominal wall, particularly when covered with clothing saturated with sweat.

In the case of low temperature readings due to ingested fluids, the fall in temperature generally occurred rapidly, and as data below 36^0 C were excluded from the data set, had no significant effect on the aggregated results.

It was found that the core temperature pill would rise to a steady state temperature within 10 to 15 minutes of ingestion. Cold and hot drinks would affect the temperature reading for periods of up to 20 minutes at any time during the first few hours after ingestion of the pill.

Note that the principal source of heat strain for these workers is generally the environmental heat load, rather than an internally produced heat load due to sustained strenuous metabolic rates. This is a function of the concept of self-pacing; a cool environment can allow higher work rates (limited, however, by the aerobic capacity of the workers) and therefore a higher proportion of the heat strain to be generated by internal (endogenous) loads, but as the environmental heat stress increases, workers reduce their work rate and the balance shifts, with the environmental (exogenous) load now creating most of the heat strain. Internally generated heat loads must be transported by the cardiovascular system to the skin for rejection to the environment, whereas external heat loads can be rejected directly from the skin by evaporation of sweat, with substantially less strain on the cardiovascular system,[93,122,47] although the same sweat gland response is required as the overall heat rejection requirement from the surface of the skin is unchanged.

4.4 Fluid Losses, Replacement and Hydration Status

4.4.1 Environmental Conditions

54% of workplace readings were above 30^0 WBGT and 83% were above 26.7^0 WBGT. Note that WBGT values of 30^0 and 26.7^0 are the ACGIH recommended limits for continuous work for acclimatised workers at light work and moderate work respectively.

On average, therefore, workers in this study were in very thermally stressful conditions (under ACGIH definitions). Workers in "hot jobs" ($>32^0$ C WBGT) were in even more extreme conditions.

Over ten million manshifts have been worked at this operation over the past 30 years in conditions where the WBGT exceeded 28^0 C without any recorded incidence of heat stroke.[59] As work in this operation includes both light and moderate rates, with periods of hard work, and work continues in conditions well above the ACGIH recommended values, it could be concluded that the probability of developing a life-threatening heat illness (stroke) under the ACGIH guidelines is exceedingly low for self-paced, acclimatised workers. The ACGIH guidelines are therefore too conservative and unlikely to be used, particularly in thermally stressful environments using self-paced, acclimatised workers.

4.4.2 Hydration Changes (hydration study 1)

As there is no statistical change in the mean specific gravity before, during or at the end of the working shift, it can be concluded that workers sweating under these substantial levels of thermal stress do have the ability to maintain their hydration state. This is at variance with some earlier studies that found that workers always dehydrated during a significant heat exposure. The explanation for this contrary finding is almost certainly the strong emphasis at this operation on workforce education and programmed drinking during the working shift.

Note also that over 60% of the workers in this study were commencing their shift insufficiently hydrated to be fit for work in hot conditions, using the definition used at this workplace of a specific gravity exceeding 1.0220.[19] However, whilst these workers were hypohydrated at the start of their shift, they were maintaining their hydration state during their shift.

4.4.2.1 Comparison with other workers at start of shift (hydration study 2)

The average specific gravity of this group prior to commencing their shift was 1.0225 (sd 0.0078, range 1.002-1.035), which confirmed that workers are substantially hypohydrated prior to starting work.

4.4.2.2 Comparison with "hot job" workers at end of shift (hydration study 3)

Those workers who worked in the most severe thermal stress (WBGT>32^0 C) did dehydrate during their shift, compared to workers at the start of their shift. The absolute increase is small (from 1.0225 to 1.0246); however, this could be affected by the time delay between exposure and measurement.

The main differences between the groups of workers in the main study (who did not dehydrate) and those in hydration study 3 (who did dehydrate) is that the workers in the main study were monitored regularly during their shift as to how much water they were drinking, and can therefore be assumed to be much more focussed on replacing fluids, compared to hydration study 3, where no fluid monitoring was conducted. This data does therefore tend to support the conclusion that there is some altered behaviour when workers' fluid consumption is being monitored.

4.4.3 Fluid Consumption study

These average and maximum fluid consumption rates are well in excess of values reported for workers in more temperate climates,[109] and the maximum values are well above those considered advisory by some sources (e.g. ISO7933[64]).

Virtually all the rehydration beverage was water, with relatively minor quantities of coffee, tea, cola soft drinks and sports drinks consumed. No carbonated drinks are able to be purchased in the workplace or lunch rooms and few workers bring soft drinks as part of their lunch. Some workers used the low-joule cordial flavouring provided by the employer.

Fluid consumption during meal breaks amounted to 31 litres, or 14% of the total fluid consumed. Duration of meal breaks as a proportion of exposure time was about 12%. The role of the meal breaks is therefore less important in maintaining fluid intake in these workers than has been found previously. Given the conclusion above, that these workers are, on average, not dehydrating during their working shift, the probable reasons for the relatively low consumption of fluids during the meal break are:

- The ad libitum availability of water "on the job" in personal water bottles,

- Water is cold and moderately palatable, with free access to cordial flavouring during the shift,
- Workers are informed about the need to drink small amounts frequently (the recommended value is 250 ml every 15 minutes) and in fact do so,
- It is also possible that these workers eat such large quantities of food at their meal breaks that it is uncomfortable for them to also drink large quantities of water.

The contrasting findings of Adolf[2] about the importance of the meal break in maintaining adequate fluid intake could possibly be explained by the above. In addition, Adolf's subjects (soldiers) were dehydrating during their exposures, whereas these workers, on average, were not.

It is important to recognise that whilst the meal break may not be crucial to the fluid intake of workers who are disciplined about program drinking during their heat exposure, it is crucial to their replacement of sodium and other necessary ions.[9]

Given that there was no net change in the hydration state of these workers over their shift, average sweat rates would not be significantly different to average fluid consumption rates. On this basis, five out of 39 workers (13%) exceeded a sweat rate of 1.04 l/hr. This implies that maximum sweat rates recommended under standards such as ISO7933[64] (1.04 litres per hour for acclimatised persons) are reasonable, although this rate can and will be safely exceeded by some workers. Note however, the curious comment in ISO7933's companion (and later) standard, ISO9886,[65] to the effect that the "maximum" sweat rate in ISO7933 is in fact a "minimum" for healthy persons under ISO9886.

It is on the basis of the above discussion, along with the findings from this study and from those of Wyndham's original work,[135] that a value of 1.2 litres per hour was selected, somewhat arbitrarily, as the upper limit for sweat rate in the standard TWL formulation.

4.5 Fatigue

4.5.1 Environmental Conditions

Conditions averaged 30.9^0 WBGT (std dev 2.0, range 25.7-36.9). Working conditions exceeded a WBGT of 30^0 C (the ACGIH[1] recommended maximum level for a continuous moderate work rate by acclimatised workers) for 66% of the exposure time. These conditions are clearly stressful according to ACGIH criteria.

4.5.2 Continuous Heart Rates

The mean and standard deviation of the pooled heart rate data was 103 and 13 bpm respectively. Approximately 14% of the working shifts resulted in a mean full-shift heart rate above 110 bpm. Less than 5% averaged over 120 bpm. A shift average of 120 bpm was also found to be a suitable maximum by Minard[83] and Rastogi[104] and is a more realistic upper limit for workers in this operation than a figure of 110 bpm.

On average, workers experienced a peak 10-minute heart rate of about 140 bpm and a peak 30-minute heart rate of about 130 bpm during their shifts. Heart rates in excess of 140 bpm were exceeded about 7% of the shift duration. These values confirm that excursions for significant periods above the recommended levels are frequent.

4.5.3 Cycle Fatigue

4.5.3.1 Control Group

The fact that there was no significant increase in heart rate on the cycle ergometer from start to end of shift for workers in sedentary work in thermoneutral conditions (defined as "non-fatigued" workers in this study) provides a baseline for evaluating the target group.

4.5.3.2 Target Group

The average increase in heart rate on the cycle ergometer from start to end of the shift for the 46 sets of data in the target group (Table 17 page 137) was 4.4 bpm (std dev 8.9, range -11 to 28). This is highly significant (p=0.0007). For precisely the same mechanical work output on the ergometer at the end of the shift, this group was clearly more fatigued compared to the non-fatigued control. The cause of this fatigue has not been demonstrated, and in particular, has not been partitioned between skeletal and cardiac muscle fatigue, or central fatigue.

The highly significant increase in heart rate from start to mid shift suggests that the major component of fatigue in these workers was occurring in the first half of the shift. Fatigue appeared to actually decrease from mid to end of shift. However, a “slowing down” period was frequently observed in workers prior to the end of the shift, and this may be reflected in these second-half results.

The fact that no correlations could be found between the continuous heart rate and cycle ergometer data could not be explained. However, given the wide range of age and $\dot{V}O_{2\max}$ in the subjects, comparisons on the basis of cardiac reserve might have produced a correlation.

Nevertheless, the cycle ergometer test, which does not require any data-logging device in the field, may be a useful test of the fatigue levels of groups of industrial workers, given that it produces a negative result in sedentary workers, and a positive result in manual workers.

4.5.4 Blood Lactate

The low lactate levels recorded at shift end suggest that work is being conducted within the aerobic capacity of workers (i.e. below the anaerobic threshold), and that this is not a cause of fatigue.

Chapter 5 - Conclusions and Recommendations

5.1 Heat Stress Indices

5.1.1 Thermal Work Limit

The Thermal Work Limit index has significant advantages over other commonly used thermal indices. It incorporates wind speed and has a single figure output. It does not have many of the internal inconsistencies found in other indices available to industry. It can also be used by hygienists and engineers to directly examine the impact of changed environmental conditions on heat stress and work productivity.

The protocols accompanying TWL have been developed especially for well-informed workers undertaking self-paced work. However, the index can also be used, where paced work is unavoidable, to give pacing guidelines (work/rest schedules) and can be used to trigger a formal Permitting system. Practical intervention levels and protocols have been developed to assist in the reduction of heat illness. These have been extended to take into account unacclimatised workers. TWL also allows cost calculations to be undertaken into lost productivity and the impact of possible engineering remedies to be evaluated directly. A method for calculating TWL is proposed, which is an original integration of data and theory published elsewhere, but which has been extensively tested in a workforce of 2000 persons exposed to significant thermal stress, located inside the Tropics.[18] TWL limits in the standard formulation are based on the Core temperature and Fluid loss studies conducted as part of this work, along with advice from other authorities (refer to the Literature review). TWL should only be used within the range from 60 $W.m^{-2}$ to about 380 $W.m^{-2}$.

5.1.2 Comparison of heat stress indices

Implicit or explicit in all heat stress indices is a metabolic rate, because metabolic rate (along with the state of acclimatisation) is a significant component of the human heat balance equation.

Any heat stress index can therefore be converted into a limiting (maximum) metabolic rate applicable to the particular environmental, clothing ensemble and acclimatisation state.

This limiting metabolic rate then allows all heat stress indices, and any combination of environmental and clothing parameters acceptable under that index, to be compared on an equivalent basis.

The confounding effects of different treatments of clothing parameters can be removed by using values for nude bodies in the comparisons.

Comparisons completed to date under this innovative approach indicate major differences between heat stress indices currently in use, and also internal inconsistencies within indices. These differences relate not just to the actual recommended limits for work, but also to the sensitivity of the respective indices to important parameters such as wind speed.

5.2 Deep Body Core Temperature

The gastrointestinal temperature-sensing radio-transmitting pill is an effective method of profiling the core temperature of workers in thermally stressful occupational settings. The gastrointestinal pill should ideally be swallowed two hours prior to the start of recording, to avoid problems due to the ingestion of cold or hot fluids.

The rapid increase and decrease in core temperatures suggests that previous data collected in occupational settings, which is almost always from intermittent measurements taken rectally, have probably failed to give a true picture of the maximums reached.

The range of core temperatures measured in this study highlights problems in existing guidelines where the place or method of measuring core temperature is not specified. Nor do current guidelines adequately take into account circadian variability.

The current limits advocated by ISO, ACGIH and others appear to be conservative compared to those actually experienced in heat acclimatised workers in this operation. In particular, the suggestion that a 1^0 C limit on the rise of core temperature due to exposure to heat is unlikely to be realistic, especially for workers on 12 hours shifts, where increases of 1^0 C in core temperature can be due to normal circadian rhythms alone. This finding is also in accordance with the findings of others.[122,130]

Note that the proposed revised upper limit of 38.5^0 C recommended by ACGIH for medically screened, acclimatised workers appears to be endorsed by this study, with workers in the target group spending very little time at temperatures exceeding this figure, although some brief excursions did occur. However, given that no worker developed heat illness during these exposures, the need for continuous medical surveillance during the exposure, as recommended by ACGIH, is unlikely to be warranted, at least for self-paced, well-informed workers.

This study suggests that workers can self-pace. This is based on the observation that the environment was frequently very stressful, with at least 15 environmental readings above 32^0 C WB, yet only a low proportion of time was spent with a core temperature above 38.2^0 C. If workers could not perceive they were over-heating or if their work was not self-paced, core temperatures higher than those found would be expected in these conditions.

The current ACGIH limits of a 26.7^0 C for moderate work rates and 30.0^0 C for light work rates are not supported by this study, with average workplace environmental conditions being substantially above these recommended values.

Shortening the working shift to avoid hyperthermia is unlikely to be necessary for self-paced workers. This can be deduced from the poor correlation between the "six hour job" (shortened shift) and the incidence of heat illness in the workforce.

Further work is required to determine whether it is the peak core temperature reached, the rate of increase in core temperature, or the duration of the temperature excursion that results in heat exhaustion and heat illness.

5.3 Fluid Losses, Replacement and Hydration Status

The conclusions from these studies are as follows:

Urinary specific gravity is a good screening test for hypohydration, probably the most serious risk factor for developing heat exhaustion in self-paced workers.

A combined dehydration and heat illness protocol has been developed, with recommended limits of urinary specific gravity for the start and end of a working shift.

A majority of workers started their shift in a hypohydrated state.

Where fluid rates were not monitored, workers in very stressful conditions (WBGT>32.0^0 C) dehydrated over the course of their shift, although the actual increase in urinary specific gravity was small (1.0225 to 1.0244).

Where workers were well informed and subject to monitoring, "involuntary dehydration" (if it is defined as an unavoidable dehydration during exposure to heat) did not occur. Whilst voluntary dehydration has been observed regularly in other settings, it is probably a function of poor access to water, workplace practices (particularly a lack of self-pacing), inadequate education, or insufficient quality or palatability of water, and is neither physiologically nor psychologically inevitable.

Standards for heat stress should not assume that workers are unable to avoid dehydration when exposed to heat, i.e. involuntary dehydration should not be implicit in heat stress standards.

Whilst a meal break is important to allow replacement of solutes lost in sweat, its role in fluid replacement per se for well-informed workers trained in the need for program drinking may be less than has been previously considered.

Fluid consumption rates (and hence, in circumstances where workers' hydration status is not changing, sweat rates) of up to 1.5 litres per hour occur in self-paced, acclimatised, industrial workers with typical rates varying between 0.5 and 1.1 litres per hour. There is a high variation in the preferred fluid intake, even for acclimatised workers with ad libitum access to water.

Education is vital if a workforce that is exposed to significant levels of thermal stress is to come to work euhydrated, and maintain their hydration state during their work shift. Paced fluid replacement (program drinking) rather than responding to the thirst sensation is critical to maintaining hydration levels when working under thermal stress.

5.4 Fatigue

A standardised cycle ergometer test at a fixed work rate before, during and after their shift is a simple method of assessing decrements in performance due to physical fatigue in groups of occupational workers.

Mine workers are undergoing fatigue during their shift, but it is mainly in the first half of their shift. It is interesting to note that recent studies have also found that the incidence of safety accidents is also highest in the portion of the working shift immediately prior to the meal break (i.e the portion of the shift found in this study to be leading to the greatest fatigue levels).

Most workers experienced mean heart rates during the shift that were lower than 110 bpm, with about 14% of workers having mean heart rates that were above 110 bpm; about 5% had mean heart rates exceeding 120 bpm.

Given that the environmental conditions were thermally very stressful, it is highly likely that these workers were self-pacing. This finding of self-pacing is also in accordance with other findings in occupational settings in the Western world.[34,82,130,128,23] However, Soule et al[116] found that self-pacing produced excessive deep body core temperatures when environmental conditions exceed 33.5^0 WB. Therefore, it is possible that self-pacing exists only within reasonable environmental conditions. This is also in accordance with Brake et al[19] who proposed that when work rates become excessively slow under a "self-pacing" protocol, that the increasing frustration levels and desire to complete the activity and escape the stress can result in a self-imposed excessive work rate, which can lead to hyperthermia. Therefore upper limits of thermal stress remain essential in a working-in-heat protocol even with self-paced workers.

There was no significant increase in average heart rate as a result of removing the "shortened shift" from the working in heat protocol. This further indicates that workers are "self-pacing" and that the fatigue levels found are not related, in this operation, to extending the duration of the heat exposure beyond six hours. This is also in accordance with the much earlier observation of Leithead and Lind[72] who stated:

> "It does not seem logical to suggest that if conditions are extreme for an exposure of 8 hours, then the duration of exposure should be reduced to 6 hours; it is probable that any acute heat disorder that may develop as a result of an 8-hour exposure will also occur during a 6 hour exposure. Therefore it is preferable to retain the 8-hour duration of exposure and to reduce the average rate of work by an appropriate amount".

In a self-paced context, this "reduction in the average rate of work" is self-imposed, rather than externally imposed.

Blood lactate levels were very low at the end of the shift, indicating no significant oxygen debt at shift-end and only a minor anaerobic contribution to metabolic rate.

5.5 Final summation

Overall, this thesis demonstrates significant weaknesses and inconsistencies in existing heat stress indices and their accompanying management protocols. It indicates the current literature has an inadequate and oversimplified understanding of the occupational limits on deep body core temperatures and sweat rates. It contradicts some key existing protocols that assume that workers cannot maintain their hydration state when exposed to significant levels of heat stress. Improved methods of measuring and managing heat stress using a new index called Thermal Work Limit have been developed. This “rational” index provides for variable clothing ensembles and gives a direct single value of the heat stress on a working human, in terms of the limiting metabolic rate for an acclimatised person in that environment. It has the ability to vary the maximum core temperature or sweat rate. Methodologies for assessing heat stress at non-limiting conditions, including the ability to calculate work-rest cycles, are developed. The index can also be used directly by hygienists or engineers who are charged with modifying the work environment.

Appendix A Howes ACP formulation (Visual Basic™ code)

```
Function fHstACPHowes(WB, DB, GlobeT, BaroP, WindSpeed, icloc, CalcType)
'  CalcType is the type of calculation:
'  1=ACP (physio), 2=ACP (eng), 3=PredSweatRate (litres/hr), 4=PredSweatRate
(W.m-2), 5=PredEvapRate (W.m-2),6=tSkin,7=tCore,8=tSigma
'  9=PredEvap/PredSweat (ie efficiency of sweating), 10=Emax (W.m-2),
11=CplusR (i.e. convective plus radiative heat transfer)
'  Note that all options 3 and above assume "engineering" type of calc
Dim Trad, Fcl, Rcl, Tskin, MHGR, hc, hr, h, Fcle, qconrad, kelvin, Eskin, E, qeu,
Sr, la, lasr, Fpcl, qevap, qevap1, cp, cpnx, cp1, dcp
Dim P1, z, B, MRT, cAbsZero, MaxSR
'  Note: for MIM formulation, icloc = 0.52
cAbsZero = 273.15
' GlobeT = DB ' under original Howes ACP, "trad=db"
'  icloc = 0.52 ' under original Howes ACP, icloc was fixed to 0.52
'  Check data validity
If WB > DB Then
   fHstACPHowes = -1
   Exit Function
End If
'  calculate MRT (trad) from GlobeT and DB using ISO7933 formula
If GlobeT = 0 Then
   Trad = DB
Else
   Trad = fPsyMRTfromGlobe(GlobeT, WindSpeed, 0.15, DB, 0.95) ' assume
Globe dia is 6" (0.15 m) and emissivity is 0.95 ASHRAE 14.26
End If
MHGR = 50 * (36 - WB)
Fcl = 0.95 + 0.39 * icloc   ' fcl is ratio of surface area of clothed body to nude
body
Rcl = 0.155 * icloc
If WindSpeed < 0.1 Then WindSpeed = 0.1 ' minimum convection current around
a hot human
MaxSR = 1.2
Do
   Tskin = 36.46055 - 0.00386917 * MHGR - 0.0000201111 * MHGR ^ 2
   hc = 0.858 * (BaroP * (0.72 - 0.003 * DB) * WindSpeed) ^ 0.6
   hr = 4.62 * 0.73 * ((1 + ((Tskin + Trad) / 546.3)) ^ 3) * (1 + 0.15 * icloc)
   h = hc + hr
   Fcle = (1 / h) / (Rcl + 1 / (Fcl * h))
   qconrad = h * (Tskin - DB) * Fcle
   kelvin = cAbsZero + Tskin
   Eskin = 100 * 10 ^ (28.59051 - 8.2 * Log(kelvin) / Log(10) + kelvin / 403.16 -
3142.3 / kelvin)
   E = fPsyVapPress(WB, DB, BaroP)
   qeu = (Eskin - E) * BaroP * (BaroP * (0.72 - 0.003 * DB) * WindSpeed) ^ 0.6
* 1363 / (BaroP - E) ^ 2
```

```
    Sr = 0.1 + 0.00575 * MHGR - 0.0000075 * MHGR ^ 2
    If Sr < 0.6 Then Sr = 0.6
    If Sr > MaxSR Then Sr = MaxSR
    la = 2501 - 2.383 * Tskin
    lasr = la * Sr / 6.48
    Fpcl = 1 / (1 + 0.155 * Fcl * hc * icloc)
    qeu = qeu * Fpcl * Fcl
    If lasr / qeu < 0.46 Then qevap1 = lasr
    If lasr / qeu < 0 Then qevap1 = qeu
    If lasr / qeu > 1.7 Then qevap1 = qeu
    If lasr / qeu > 0.46 And lasr / qeu < 1.7 Then qevap1 = lasr * Exp(-0.4127 *
(lasr / qeu - 0.46) ^ 1.168)
    qevap = qevap1
    cpnx = Int(WindSpeed) + 1
    cp = qconrad + qevap
    cp1 = (cp + cpnx * MHGR) / (cpnx + 1)
    dcp = Abs(MHGR - cp)
    If dcp > 0.01 Then MHGR = cp1
Loop Until dcp < 0.01
If cp < 60 Then cp = cp
Select Case CalcType
    Case 1
        fHstACPHowes = Application.WorksheetFunction.Max(cp, 60)
    Case 2
        fHstACPHowes = cp
    Case 3  ' pred sweat rate in l/hr
        fHstACPHowes = Sr
    Case 4  ' pred sweat rate in W.m-2
        fHstACPHowes = lasr
    Case 5
        fHstACPHowes = qevap1
    Case 6
        fHstACPHowes = Tskin
    Case 10
        fHstACPHowes = qeu
    Case 11
        fHstACPHowes = qconrad
    Case Else
        MsgBox "Error: calc type 7 or 8 or 9 not allowed"
        Exit Function
    End Select
End Function
```

Appendix B McPherson ACP formulation (Visual Basic$^{\text{TM}}$ code)

```
Function fHstACPMcP(WB, DB, Trad, BaroP, RelWindSpeed, icloc, icl, fr)
'   calculates the max met rate before skin temp reaches 36 deg, the McP criteria for excess thermal stress
'   for more explanation, refer to fACPMcPSkinTemp description below
'   icl = 0.45  for standard McP
'   fr = 0.73   for standard McP
Dim Tskin, MetRate, Br, Conv, Rad, Evap, tcl, tav, hr, esk, Lsk, E, he, W, MetRateCalc
Dim Rcl, Fcl, u, hc, Increment
If WB > DB Then
   fHstACPMcP = -1
   Exit Function
End If
Tskin = 36  ' Fixed limiting value of tskin according to McP
MetRate = 300 ' Initial guesstimate of metrate
Rcl = 0.155 * icloc ' where icloc = 0.7097 for Rcl =0.110 per McP p 614
Fcl = 1 + 0.3945 * icloc ' to get McP example p 614 to work to get fcl =1.28
u = (0.8 * RelWindSpeed) + 0.6
hc = 0.00878 * (BaroP * 1000) ^ 0.6 * u ^ 0.5
esk = fPsyVapPress(Tskin, Tskin, BaroP) * 1000
Lsk = fPsyLatentHeatEvapWater(Tskin) * 1000
E = fPsyVapPress(WB, DB, BaroP) * 1000
he = 0.0007 * hc * Lsk / (BaroP * 1000)
Conv = (Tskin - DB) / (Rcl + 1 / (Fcl * hc))
'   tskincorr = -0.009 * hc * (Tskin - DB) * (0.15 - Rcl / 0.15)
'   Tskin = Tskin - tskincorr + Rcl / 0.15
tcl = Tskin - Conv * Rcl
tav = (tcl + Trad) / 2 + 273.15
hr = 4 * 5.67 * 0.00000001 * tav ^ 3
Do
   Increment = Increment + 1
   Br = fBr(WB, DB, BaroP, MetRate)
   Rad = hr * fr * (tcl - Trad)
   W = fSweatFraction(WB, MetRate, Tskin)
   Evap = (W * he * (esk - E)) / (hc * Rcl / icl + 1 / Fcl)
   If Rad + Evap < 0 And W = 1 Then ' no solution will be possible, too much radiant load
      fHstACPMcP = -1
      Exit Function
   End If
   MetRateCalc = Br + Conv + Rad + Evap
   MetRate = Application.WorksheetFunction.Max((MetRate + MetRateCalc) / 2, 0)
Loop Until Abs((MetRateCalc - MetRate)) < 0.2 Or Increment = 100
fHstACPMcP = MetRateCalc
End Function
```

```
Function fHstACPMcPSkinTemp(WB, DB, Trad, BaroP, RelWindSpeed, MetRate, icloc, icl, fr, CalcType)
'  Derived from McP pp 608 ff
'  Calculates skintemp needed to sustain met rate
'  RelWindSpeed can be more or less than wind speed, depending on direction of body movement (with or against wind)
'  icloc is clothing ensemble insulation in clo
'  Trad is average radiant temp of surroundings in deg C
'  icl is vapour permeation efficiency (0 for impermeable, 1 for nude) (McP uses 0.45)
'  fr is posture factor (McP uses 0.73 for walking person)
'  CalcType is calctype
Dim MetRateTrial, Tskin, Ac
Dim Br, Con, Rad, Evap
Dim Rcl, Fcl, hc
Rcl = 0.155 * icloc ' where icloc = 0.7097 for Rcl =0.110 per McP p 614
Fcl = 1 + 0.3945 * icloc ' to get McP example p 614 to work to get fcl =1.28
icl = 0.45  ' see comments above
fr = 0.73   ' see comments above
Br = fBr(WB, DB, BaroP, MetRate)
Tskin = 24.85 + 0.322 * DB - 0.00165 * DB ^ 2  '   McP eqn 17.16
Do
   Con = fCon(DB, BaroP, Rcl, Fcl, hc, RelWindSpeed, Tskin)
   Rad = fRad(WB, DB, BaroP, Trad, Tskin, Con, Rcl, fr)
   Evap = fEvap(WB, DB, BaroP, MetRate, Tskin, hc, Rcl, Fcl, icl)
   MetRateTrial = Br + Con + Rad + Evap
   Ac = MetRate - MetRateTrial
   Tskin = Tskin + (0.02 * Ac)
Loop Until Ac < 0.2 ' continue to iterate until diff in met rate is less than 0.5 W/m2
fHstACPMcPSkinTemp = Tskin
If Tskin > 36 Then
   '  MsgBox "WARNING: skin temperature more than 36 deg is dangerous!"
End If
End Function
Private Function fBr(WB, DB, BaroP, MetRate) ' Breathing losses W/m2 from McP
'  MetRate is met rate in W/m2
'  This function is called only once in the McP ACP skin temp calculation, as it does not vary with skin temp
Dim Sout, Sin, Tex ' for breathing losses McP eqn 17.7
Tex = 32.6 + 0.066 * DB + 0.0002 * fPsyVapPress(WB, DB, BaroP)
Sin = fPsySigmaHeat(WB, DB, BaroP) * 1000
Sout = fPsySigmaHeat(Tex, Tex, BaroP) * 1000
fBr = 1.7 / 1000000 * MetRate * (Sout - Sin) '   Breathing losses in W/m2
End Function
Private Function fCon(DB, BaroP, Rcl, Fcl, hc, ur, Tskin) ' Convective losses W/m2 from McP
```

```
'   ur is relative speed between body and wind (can be more or less than wind
speed, depending on direction)
'   in addition to returning the conv heat loss, this fn also changes the global
variable, tskin and hc
Dim u, tskincorr, tskinact
u = (0.8 * ur) + 0.6
hc = 0.00878 * (BaroP * 1000) ^ 0.6 * u ^ 0.5
tskincorr = -0.009 * hc * (Tskin - DB) * (0.15 - Rcl / 0.15)
Tskin = Tskin - tskincorr + Rcl / 0.15
fCon = (Tskin - DB) / (Rcl + 1 / (Fcl * hc))
End Function
Private Function fRad(WB, DB, BaroP, Trad, Tskin, Con, Rcl, fr) ' Radiative
losses W/m2 from McP
'   tskin is skin temp, Con is convective loss, fr is posture factor
'   Trad is avg temp of surroundings
Dim tcl, tav, hr
tcl = Tskin - Con * Rcl
tav = (tcl + Trad) / 2 + 273.15
hr = 4 * 5.67 * 0.00000001 * tav ^ 3
fRad = hr * fr * (tcl - Trad)
End Function
Private Function fEvap(WB, DB, BaroP, MetRate, Tskin, hc, Rcl, Fcl, icl) '
Evaporative losses W/m2 from McP
Dim he, esk, Lsk, E, W
esk = fPsyVapPress(Tskin, Tskin, BaroP) * 1000
Lsk = fPsyLatentHeatEvapWater(Tskin) * 1000
E = fPsyVapPress(WB, DB, BaroP) * 1000
he = 0.0007 * hc * Lsk / (BaroP * 1000)
W = fSweatFraction(WB, MetRate, Tskin)
fEvap = (W * he * (esk - E)) / (hc * Rcl / icl + 1 / Fcl)
End Function
Private Function fSweatFraction(WB, MetRate, Tskin)
Dim A, B, C, D, SF, W
Select Case WB
   Case Is < 27.194 * Exp(-0.004 * MetRate)
      SF = 0.06
   Case Is > 33
      SF = 1#
   Case Else
      If MetRate > 200 Then
         A = -(0.0001781265 - 0.0000002544 * MetRate + 8.557743 / MetRate ^
2.218731)
         B = 0.012095 - 0.0000179735 * MetRate + 1063.187 / MetRate ^ 2.31927
         C = -(0.194294 - 0.0003279531 * MetRate + 46903 / MetRate ^ 2.44229)
         D = 0.998117 - 0.001816454 * MetRate + 924321 / MetRate ^ 2.651246
      Else
         A = -(0.0000397379 + 0.00000007075456 * MetRate + 17.880231 /
MetRate ^ 2.218441)
```

```
         B = 0.002369825 + 0.000003359426 * MetRate + 2211.1688 / MetRate ^
2.316119
         C = -(0.005682282 + 0.0000586905 * MetRate + 95583.18 / MetRate ^
2.437565)
         D = -0.321605 + 0.0007958265 * MetRate + 1875636 / MetRate ^
2.645912
      End If
      SF = Application.WorksheetFunction.Max(0.06, D + WB * (C + WB * (B +
WB * A)))
End Select
Select Case Tskin
   Case Is < 32.5
      fSweatFraction = SF
   Case Is > 38
      fSweatFraction = 1
   Case Else
      fSweatFraction = Application.WorksheetFunction.Min(1, SF + Sin((31.85 *
Tskin - 762) * 0.01745) * 0.5 + 0.5)
End Select
End Function
```

Appendix C TWL formulation (Visual Basic^{TM} code)

Note this formulation calculates the limiting metabolic rate (to the nearest 0.1^0 C on core temperature) that does not exceed the limits of core temperature and sweat rate provided by the user. If no solution is found within these constraints, then it has the option of finding the value of TWL that does have a solution, within the full range of experimental data.
Two formulations are presented. The first (***TWL Formulation I***) is for the standard TWL solution. The second (***TWL Formulation II***) is to use variable clothing insulation values, based on wind speed.

TWL Formulation I: Standard Formulation Of TWL

```
Function fHstTWLnew(WB, DB, GlobeT, BaroP, WindSpeed, Optional MRT =
0, _
   Optional Iclo = 0.35, Optional VapPerm = 0.45, Optional Posture = 0.73, _
   Optional SrMaxkgperhr = 1.2, Optional TcTarget = 38.2, Optional CalcType =
2)
   Dim LoopNumber, PrevSr
'  Function returns -1 if no solution possible.
'   Function returns 0 if solution found, but outside of user limits (e.g. on Sr,Tc,
etc)
'  CalcType is the type of calculation:
'  1=TWL (returns value of zero when TWL <80 OR DB>=45 OR WB>32,
'     or Srkgperhr>Srmaxkgperhr or Tc>TcTarget and limits wind speed to 4 m/s).
'  2=TWL (does not limit TWL, DB, WB or wind speed);
'     does not limit Tc to TcTarget (ltd to 39.5)
'     does not limit Sr to SrMaxkgperhr (ltd to 1.5)
'  3=sweat rate (litres/hr)
'  4=Ts
'  5=Tc
'  6=Tsigma
'  7=Sweat efficiency
'   -1    *** NOTE *** If function encounters an error, it returns value of -1
(negative 1).
'  This typically occurs in very hot, humid environmnents with low wind speed,or
very cold temps with high wind,
'    where no heat balance is possible within the range of physiological
relationships that are used,
'  or where psychrometric equations go out of range.
'   Note: valid range of TWL is > 100 W/m2. This range is not limited in this
program.
'  However, refer to additional comments below.
'  Tc is set to 37.6 to start.
'  Program tries to find a solution. If finds solution, and Tc=TcTarget, then returns
TWL, else 0 or -1.
'   If no solution, and calctype<>1, then increments Tc by 0.1 and looks for
solution.
```

```
'  Continues until Tc>39.5, when returns 0.
'  WB, DB, GlobeT in degrees C
'  MRT, Iclo, VapPerm,SrMaxkgperhr,TcTarget and CalcType are optional
'  Iclo is intrinsic clothing insulation in clo (1 clo = 0.155 m2.K/W)
'  VapPerm is clothing vapour permeation factor, (icl), dimensionless
'  WindSpeed in m/sec
On Error GoTo ErrorHandler2
If TcTarget >= 39.5 Then TcTarget = 39.5
Tc = 37.6   ' note: adds 0.1 at very start, hence true start value is 37.7
RelWind = Application.Max(WindSpeed, 0.2) ' Even in still conditions,
convection around body is a minimum
'       of about 0.2 m/s. If assumed as 0, then no convective heat transfer, which is
clearly not the case.
If (GlobeT = 0 Or GlobeT = "") And (MRT = 0 Or MRT = "") Then
   MRT = DB
ElseIf MRT = 0 Or MRT = "" Then
   MRT = fPsyMRTfromGlobe(GlobeT, RelWind, 0.15, DB, 0.95) ' assume
Globe dia is 6" (0.15 m) and emissivity is 0.95 ASHRAE 14.26
End If
Fcl = 1 + 0.3 * Iclo   ' fcl is ratio of surface area of clothed body to nude body,
ASHRAE F8.10 eqn 47
Rcl = 0.155 * Iclo ' Rcl is intrinsic clo insulation, without air boundary layer,
ASHRAE F8.8 eqn 41
Pair = fPsyVapPress(WB, DB, BaroP)      ' std equations to calculate vapour
pressures
If CalcType = 1 And RelWind > 4 Then '  limit RelWind for type 1 calc
   RelWind = 4 ' maximum RelWind, beyond this dust becomes serious problem
End If
'   Find the unique value of Ts which gives a heat balance, assuming unlimited
sweat rate,
'  skin wettedness of 1 and Tc as supplied
'  LoopNumber = 1
Do  ' set up loop to find heat balance
   PrevSr = SrKgPerHr
   Ts = fFindTsforQbal(WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm,
Posture)
   '  from this skin temp, calculate the actual met rate
   MRok = fQbalError(Ts, WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm,
Posture)
   tSigma = fTsigma(Tc, Ts)
   SrKgPerHr = fPhySweatRateCurve(tSigma) * cStdSurfArea
   MetRate = fPhyConductanceCurve(tSigma) * (Tc - Ts)
   Emax = 1 * Fpcl * Fcl * he * (Psatskin - Pair)
   LSREmax = 2430000 * (SrKgPerHr / 3600) / Emax
   Tc = Tc + 0.1    ' increment this here, else when the limits are found, the
reamining values will already be incremented
Loop Until (CalcType = 1 And Tc > TcTarget Or SrKgPerHr > SrMaxkgperhr) Or
_
```

```
   (CalcType <> 1 And Tc > TcTarget Or SrKgPerHr > SrMaxkgperhr And Ts <> -1 And Abs(MRok) < 1 And SrKgPerHr > 0.4 And LSREmax > 1.7 And MetRate > 60) _
   Or Tc > 39.5 _
   Or SrKgPerHr > 1.5
'  Hence stop once EITHER Calctype=1 with Tc > TcTarget and SrKgPerHr > SrMaxkgperhr) OR
'  (Ts <> 1 AND Met balance is OK AND Sr is high AND efficiency is low)
'  OR Tc or SrKgPerHr reach the absolute limits of 39.5 and 1.5
'  Reset values of Tc and Sr to those which were the last valid solution.
'  Note that this is the valid solution to the nearest 0.1 deg Tc below the 'invalid' solution
Tc = Tc - 0.1
SrKgPerHr = PrevSr
If Tc = 39.5 Or SrKgPerHr = 1.5 Then GoTo ErrorHandler2 ' Core temp too high, no solution
If tSigma > 39.5 Or tSigma < 35 Then GoTo ErrorHandler2  ' Problem: Try relaxing Tc or Sr constraints
If Ts < fPsyDewPt(WB, DB, BaroP) Then GoTo ErrorHandler2 ' Condensation on skin
If Abs(MRok) > 0.3 Then GoTo ErrorHandler2  ' Couldn't find solution, didn't get to end point
'  Add in component for respiration
MetRate = MetRate + 0.0014 * MetRate * (34 - DB) + 0.0173 * MetRate * (5.87 - Pair)
Select Case CalcType
Case 1  ' This is the case to be programmed into the HSM
   If DB >= 45 Or WB > 32 Or MetRate < 60 Or SrKgPerHr > SrMaxkgperhr Or Tc > TcTarget Then
         fHstTWLnew = 0
   Else
      fHstTWLnew = MetRate
   End If
Case 2
   fHstTWLnew = MetRate
Case 3  ' pred sweat rate in l/hr
   fHstTWLnew = SrKgPerHr
Case 4
   fHstTWLnew = Ts
Case 5
   fHstTWLnew = Tc
Case 6
   fHstTWLnew = tSigma
Case 7
   fHstTWLnew = Eskin / (2430000 * (SrKgPerHr / 3600))
Case Else
   fHstTWLnew = -1
End Select
```

```
Exit Function
ErrorHandler2:
   fHstTWLnew = -1
End Function
Function fTsigma(Tc, Ts)
   If Tc < Ts Then ' simple check to ensure programmer hasn't got values back to front
      fTsigma = -1
   Else
      fTsigma = 0.1 * Ts + 0.9 * Tc
   End If
End Function
Function fPhyConductanceCurve(tSigma)  ' Heat Flow Conductance parameter in W/(m2.degC)
fPhyConductanceCurve = 84 + 72 * Application.Tanh(1.3 * (tSigma - 37.9)) '0.70 + 0.64 * Application.Tanh(1.1 * (Tsigma - 37.9))
End Function
Function fPhySweatRateCurve(tSigma) ' Sweat rate in kg/m2/hr
fPhySweatRateCurve = 0.42 + 0.44 * Application.Tanh(1.16 * (tSigma - 37.4))   ' 0.74 + 0.74 * Application.Tanh(1.19 * (Tsigma - 37.5))
End Function
Function fFindTsforQbal(WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm, Posture) As Double
Dim ConvergenceLimit, Tolerence, Iteration, x0
Dim Oldxi, Newxi, Delta, Fxi, Fdashxi, Convergence
ConvergenceLimit = 0.00005
Tolerence = 0.01
'   set starting value for Delta
x0 = 35 '   set seed values of skin temp, for limiting condition, generally in range of 30 to 36 deg
Delta = 0.00001 * x0
Iteration = 1
Newxi = x0
Fdashxi = (fQbalError(Newxi + Delta, WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm, Posture) - fQbalError(Newxi, WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm, Posture)) / Delta
Do  ' iterate through this until acceptable convergence
   Oldxi = Newxi
   Newxi = Oldxi - fQbalError(Oldxi, WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm, Posture) / Fdashxi
   Delta = Oldxi - Newxi
   Fdashxi = (fQbalError(Newxi + Delta, WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm, Posture) - fQbalError(Newxi, WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm, Posture)) / Delta
   Iteration = Iteration + 1
Loop Until Iteration = 1000 _
   Or Abs((Newxi - Oldxi) / Oldxi) < ConvergenceLimit _
   Or Abs(Newxi - Oldxi) = 0 _
```

```
   And Abs(Oldxi) <> 0 _
   And fQbalError(Oldxi, WB, DB, BaroP, WindSpeed, MRT, Iclo, VapPerm,
Posture) < Tolerence
'  loop until iteration count is exceeded
'  OR relative change in skin temp is less than convergence (0.0005 or 0.02 deg
for ts of 35 deg)
'  OR skin temp doesn't change AND skin temp <> 0 AND QbalError is less than
tolerance (0.2 W/m2)
If Iteration = 1000 Then
   fFindTsforQbal = -1
Else
   fFindTsforQbal = Oldxi
End If
End Function
Private Function fQbalError(Ts, WB, DB, BaroP, WindSpeed, MRT, Iclo,
VapPerm, Posture)
'  calcualte difference between core to skin heat transfer and skin to env heat
transfer at this value of ts
'  assumes fully wet skin
   tSigma = fTsigma(Tc, Ts)
   Qcoretoskin = fPhyConductanceCurve(tSigma) * (Tc - Ts)
   Psatskin = fPsyVapPress(Ts, Ts, BaroP)  ' std equations to calculate vapour
pressures
   hr = 4.61 * Posture * (1 + (MRT + Ts) / (2 * cAbsZero)) ^ 3   'EESAM p 500
eqn 9
   hc = 0.608 * BaroP ^ 0.6 * RelWind ^ 0.6  'EESAM p 500 eqn 13
   h = hc + hr 'ASHRAE F8.3 eqn 9
   tOper = fPsyOperativeTemp(DB, MRT, hr, hc) 'ASHRAE eqn 8
   Fcle = Fcl / (1 + Fcl * h * Rcl)  'ASHRAE Table 2 "Sensible Heat Flow" last
eqn
   CplusR = Fcle * h * (Ts - tOper) ' CplusR is total heat loss (gain) from
breathing, convection & radiation
   he = 1587 * hc * BaroP / (BaroP - Pair) ^ 2   'EESAM p 501 eqn 17
   Recl = Rcl / (16.5 * VapPerm) 'ASHRAE Table 2 "Parameters relating sensible
and evaporative heat flows",
   Fpcl = 1 / (1 + Fcl * he * Recl) 'ASHRAE Table 2 "Evaporative heat flow" last
eqn
   Eskin = 1 * Fpcl * Fcl * he * (Psatskin - Pair)
   Qskintoenv = CplusR + Eskin
   fQbalError = Qskintoenv - Qcoretoskin
End Function
Function fPsyLatentHeatEvapWater(T)
fPsyLatentHeatEvapWater = (2502.5 - 2.386 * T)
End Function
Function fPsySpecificHeatWater(T)
fPsySpecificHeatWater = 4.2169 - T / 302.22 + T ^ 2 / 11002.4 - T ^ 3 / 1242331
End Function
Private Function fEnthalpyDryAirAtWB(WB, DB, BaroP)
```

```
fEnthalpyDryAirAtWB = 1.006 * WB
End Function
Private Function fEnthalpyWaterVapAtWB(WB)  ' BB 442 cubic eqn, OK from 0
to 67 deg C, H'wo, BB 454 step 2
fEnthalpyWaterVapAtWB = -0.00000662 * WB ^ 3 - 0.000194 * WB ^ 2 +
1.8375 * WB + 2500.83
End Function
Private Function fEnthalpyWaterVapAtDB(WB, DB, BaroP)
fEnthalpyWaterVapAtDB = -0.00000662 * DB ^ 3 - 0.000194 * DB ^ 2 + 1.8375
* DB + 2500.83
End Function
Function fPsyMoistCont(WB, DB, BaroP)
Dim Pws, ro
  Pws = 0.6105 * Exp(17.27 * WB / (237.3 + WB)) ' BB 454
  ro = cMw / cMa * ((cBBf * Pws) / (BaroP - cBBf * Pws)) 'BB 451
  fPsyMoistCont = (ro * (fEnthalpyWaterVapAtWB(WB) -
fEnthalpyLiquidWater(WB, DB, BaroP)) - (fEnthalpyDryAirAtDB(WB, DB,
BaroP) - fEnthalpyDryAirAtWB(WB, DB, BaroP))) /
(fEnthalpyWaterVapAtDB(WB, DB, BaroP) - fEnthalpyLiquidWater(WB, DB,
BaroP)) ' BB 454 step 3
End Function
Function fPsyVapPress(WB, DB, BaroP)  'ASHRAE eqn 6 p 6.2
Dim MoistContent
  MoistContent = fPsyMoistCont(WB, DB, BaroP)
  fPsyVapPress = MoistContent * BaroP / (cBBf * (cMw / cMa + MoistContent))
End Function
Function fPsyRelHum(WB, DB, BaroP)
Dim Pws
Pws = 0.6105 * Exp(17.27 * DB / (237.3 + DB))
fPsyRelHum = fPsyVapPress(WB, DB, BaroP) / Pws
End Function
Function fPsyMRTfromGlobe(GlobeT, RelWind, GlobeDia, DB, Emissivity)
If Emissivity = 0 Then Emissivity = 0.95   ' per ASHRAE 14.26
fPsyMRTfromGlobe = ((GlobeT + 273) ^ 4 + (110000000# * RelWind ^ 0.6) *
(GlobeT - DB) / (Emissivity * GlobeDia ^ 0.4)) ^ 0.25 - 273
End Function
Function fPsyDewPt(WB, DB, BaroP)
Dim X
X = Log(fPsyVapPress(WB, DB, BaroP) / 0.6105)
fPsyDewPt = 237.3 * X / (17.27 - X)
End Function
Private Function fEnthalpyDryAirAtDB(WB, DB, BaroP) ' ASHRAE eqn 30, p
6.9
fEnthalpyDryAirAtDB = 1.006 * DB
End Function
Function fPsyEnthalpy(WB, DB, BaroP) ' BB 454 step 7
' is enthalpy (kJ) per kg of dry air, with based value of zero at 0 deg C
```

```
fPsyEnthalpy = fEnthalpyDryAirAtDB(WB, DB, BaroP) + fPsyMoistCont(WB,
DB, BaroP) * fEnthalpyWaterVapAtDB(WB, DB, BaroP)
End Function
Function fPsySigmaHeat(WB, DB, BaroP) ' BB 454 step 8
' enthalpy of air less the enthalpy of the water vapour content associated with 1 kg
of dry air, calculated as if the water vapour was present as liquid water at the wet-
bulb temperature
fPsySigmaHeat = fPsyEnthalpy(WB, DB, BaroP) - fPsyMoistCont(WB, DB,
BaroP) * fEnthalpyLiquidWater(WB, DB, BaroP)
End Function
Private Function fEnthalpyLiquidWater(WB, DB, BaroP)  ' BB 443 cubic eqn,
OK from 0 to 67 deg C, H'wl, BB 454 step 2
'  Enthalpy of water (vapour or liquid) per unit mass of water vapour
'  Black book, p 443, cubic equation
'  valid temp range 0 to 67 deg C
fEnthalpyLiquidWater = 0.0000063 * WB ^ 3 - 0.000727 * WB ^ 2 + 4.2508 *
WB + 0.03
End Function
```

TWL Formulation II: Thermal Insulation That Varies With Wind Speed

```
Function fHstTWLvar(WB, DB, GlobeT, BaroP, WindSpeed, Optional MRT = 0,
_
   Optional Icloc = 0.35, Optional CloVapPermEffic = 0.45, Optional Posture =
0.73, _
   Optional SrMaxkgperhr = 1.2, Optional TcTarget = 38.2, Optional CalcType =
2)
'  Calls fTWL but uses dynamic clo factors
Dim DynClo, DynVap, TWLtry, MetError, MetRate
MetRate = 200
Do
   DynClo = fHstDynCloFactors(WindSpeed, MetRate, icloc, CloVapPermEffic,
0, False, 0, 1)
   DynVap = fHstDynCloFactors(WindSpeed, MetRate, icloc, CloVapPermEffic,
0, False, 0, 2)
   TWLtry = fHstTWLnew(WB, DB, GlobeT, BaroP, WindSpeed, 0, DynClo,
DynVap)
   MetError = TWLtry - MetRate
   MetRate = (TWLtry + MetRate) / 2
Loop Until Abs(MetError) < 1
fHstTWLvar = MetRate
End
FunctionFunction fHstDynCloFactors(AbsVel, MetRate, IntrinsicClo,
StaticVapPerm, WalkSpeed, OmniDirectionalWalking,
WindDir0WindInBack180WindInFace, Type1Clo2Vap)
'  Uses Parsons et al Ann. occup. Hyg vol 43, No 5, pp 347-352, 1999
Dim ThetaR, Var, Hst, Iast, Iclst, Fcl, Itst, Wind, Walk, Itc, Itnc, Itdyn, Iadyn,
Icldyn, L, Itred, Imc, Imdyn
```

```
If WalkSpeed <> 0 Then
    If OmniDirectionalWalking Then
        If AbsVel >= WalkSpeed Then
            Var = AbsVel
        Else
            Var = WalkSpeed
        End If
    Else
        ThetaR = (Application.WorksheetFunction.pi() / 180) * WindDir0WindInBack180WindInFace
        Var = Abs(AbsVel - WalkSpeed * Cos(ThetaR))
    End If
Else
    WalkSpeed = 0.0052 * (MetRate - 58)
    If WalkSpeed > 0.7 Then
        WalkSpeed = 0.7
    End If
    Var = AbsVel
End If
Hst = 9
Iast = (1 / Hst) / 0.155
Iclst = StaticVapPerm
Fcl = 1 + 0.3 * Iclst
Itst = Iclst + Iast / Fcl
Wind = Var
Walk = WalkSpeed
If Wind > 3.5 Then Wind = 3.5
If Walk > 1.5 Then Walk = 1.5
Itc = Exp(0.043 - 0.398 * Wind + 0.066 * Wind ^ 2 - 0.378 * Walk + 0.094 * Walk ^ 2)
If Wind > 2 Then Wind = 2
If Walk > 1.2 Then Walk = 1.2
Itnc = Exp(0.126 - 0.899 * Wind + 0.246 * Wind ^ 2 - 0.313 * Walk + 0.097 * Walk ^ 2)
If IntrinsicClo <= 0.6 Then Itc = ((0.6 - IntrinsicClo) / 0.6) * Itnc + (IntrinsicClo / 0.6) * Itc
If Itc > 1 Then Itc = 1
If Itnc > 1 Then Itnc = 1
Itdyn = Itst * Itc
Iadyn = Itnc * Iast
Icldyn = Itdyn - Iadyn / Fcl
L = 16.7
Itred = 1 - Itc
Imc = (1# + 1.3 * Itred + 2.6 * Itred ^ 2)
Imdyn = StaticVapPerm * Imc
If Imdyn > 0.9 Then Imdyn = 0.9
If Type1Clo2Vap = 0 Then
    fHstDynCloFactors = Icldyn
```

```
Else
   fHstDynCloFactors = Imdyn
End If
End Function
```

Appendix D Anthropometric, body morphology, $\dot{V}O_{2\max}$ and working shift data for all target subjects (for summarized data, refer to Table 1). No data available for control group subjects. Note that *not* all subjects participated in every experiment. Summary results for subjects who participated in each study are provided separately.

Code	Age, years	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$ ml.kg^{-1}.min^{-1}	Nominal Shift Length
ADA10M8	48	175	90	29.4		12
AGL13J9	25	196	125	32.5	37.7	10
AMC03M8	35	180	86	26.5	47.4	12
ARU04M8	32	187	93	26.6		12.5
BCA28J9	39	173	93	31.1	31.3	12
BCO17M8	30	178	85	26.8		10
BDO20M8	40	173	84	28.1	33	12
BLO31M8	48	170	65	22.5		10
BRE15J9	30	182	92	27.8		10
BRO19J9	38	178	72	22.7	35.8	12
CBU06A8	38	190	112	31.0		12
CGA13M8	29	178	80	25.2	46.8	12
CLI13J9	35	188	80	22.6		10
CMU03A8	35	147.3	75	34.6		12
CSU10A8	29	184	94	27.8	44.4	12
DAR23J9	28	173	76	25.4	41.2	12
DIS09J9	36	182	80	24.2	32.8	12
DJO28J9	21	175	74	24.2	56.3	12
DKE23J9	33	189	108	30.2	35.2	12
GHA09A8	38	178	121	38.2		12

Code	Age, years	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$ ml.kg^{-1}.min^{-1}	Nominal Shift Length
GRI15J9	25	188	108	30.6		10
HSC09A8	40	183	96	28.7		12
JHA04M8	39	192	102	27.7	37	12.5
JHU10A8	36	176	95	30.7	32.4	12
JLA06M8	26	180	99	30.6		10
JTA07M8	47	165	65	23.9	38.1	10
KHU03M8	33	174	74	24.4		12
KHU17J9	34	174	75	24.8	39.5	12
LBE23J9	29	183	103	30.8	37.7	12
LNE13M8	36	163	79	29.7	31.1	12
LWE06F8						10
MCA19J9	30	178	73	23.0	50.6	12
MDU17M8	37	178	80	25.2		10
MNO03M8	37	183	95	28.4	40	12.5
MPA18J9	31	173	74	24.7	52.5	10
RCL20M8	51	188	96	27.2		10
RSM04M8	33	173	88	29.4		12
RSV19J9	25	183	95	28.4	37.8	12
SFA13J9	28	183	74	22.1		10
SSM20M8	39	175	83	27.1	36.4	12
SWA09J9	35	184	120	35.4	28	12
TAN10M8	24	170	90	31.1	42	12
THA28J9	52	175	90	29.4		12
TMA17M8	37	169	68	23.8	38	10
WAG02A8	36	170	70	24.2		10

Code	Age, years	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$ ml.kg^{-1}.min^{-1}	Nominal Shift Length
WSH17J9	41	180	86	26.5	33.2	12

Appendix E ‘Hourly’ data on environmental conditions, Rating of Perceived Exertion (RPE), Fluid consumption, Urinary specific gravity and Tympanic temperatures. Summary results for subjects in each study are provided in each separate section of the thesis text.

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
ADA10M8	10/3 9:10 am	27.6	35.0	35.0	0.2	145	30.1						
ADA10M8	10/3 9:17 am	27.5	38.3	38.3	0.6	184	30.8	drilling - 1/2hr			2.4		
ADA10M8	10/3 10:50 am	28.1	39.2	39.2	0.5	167	31.6	waiting for equip.		2.0		1.020	
ADA10M8	10/3 11:00 am	28.0	39.4	39.4	0.5	167	31.6	crib		5.0			
ADA10M8	10/3 12:40 pm	27.7	38.1	38.1	1.6	215	30.8	1/2 - heavy lifting		1.0	4.5	1.025	
ADA10M8	10/3 2:15 pm	24.6	31.0	31.5	0.3	202	26.8						
ADA10M8	10/3 3:15 pm												
ADA10M8	10/3 3:45 pm	28.4	37.5	37.5	0.2	130	31.5						
ADA10M8												1.023	
ADA11M8	11/3 9:30 pm	28.7	38.1	38.3	0.5	160	31.7			6.0			
ADA11M8	11/3 11:00 pm	27.4	37.9	38.1	0.6	185	30.7			6.0			
ADA11M8	11/3 12:50 pm	28.3	38.2	38.2	0.5	166	31.4			6.0			
ADA11M8	11/3 3:30 am	23.1	29.8	30.1	0.3	221	25.4	crib					
ADA11M8	11/3 4:40 am	28.2	38.1	38.1	0.2	130	31.5			8.0			
ADA11M8	11/3 6:50 am									8.0			
AMC03M8	3/3 11:00 am	30.8	38.4	38.4	0.6	136	33.1	charging		5.0	3	1.03	37.3
AMC03M8	3/3 12:30 pm	29.4	37.4	37.4	0.8	169	31.8	charging		6.0	1		

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
AMC03M8	3/3 1:35 pm	28.7	38.2	38.2	4.9	222	31.4	toyota		1.0	0.5		
AMC03M8	3/3 2:55 pm	21.9	27.4	27.7	0.2	216	23.9	crib			0.4	1.03	36.0
AMC03M8	3/3 5:12 pm	30.5	35.6	35.6	0.5	141	32.1	charging		6.0	2		
AMC03M8	3/3 6:42 pm	28.6	38.4	38.4	1.2	192	31.5	charging (easy part)		3.0	0.5	1.03	36.7
ARU04M8	4/3 10:00 am	23.4	35.2	39.0	5.5	287	27.5			1.0	0.4	1.01	
ARU04M8	4/3 12:15 pm	30.0	39.6	39.6	1.1	164	32.9	mucking unit, clean-up		2.0	0.8		37.2
ARU04M8	4/3 1:15 pm	25.0	32.9	35.4	0.6	215	28.0	was grouting before crib. Crib: 1pm - 2.15pm		2.0	1	1.03	
ARU04M8	4/3 6:10 pm	20.0	25.0		0.2	238	16.8	mucking unit, a/c cab		1.2			
ARU04M8	4/3 6:50 pm	27.4	38.5	38.5	0.3	155	31.0	charging unit		5.0	1	1.03	37.3
ARU05M8	5/3 10:30 am	26.9	37.4	37.4	0.8	206	30.1			4.0			
ARU05M8	5/3 11:30 am	25.8	36.7	36.9	0.8	221	29.2			4.0			36.7
ARU05M8	5/3 12:40 pm	20.7	28.4	29.7	0.4	257	23.5						36.9
ARU05M8	5/3 2:10 pm	25.5	36.7	36.7	1.2	241	28.8			3.0			
ARU05M8	5/3 3:00 pm	24.4	36.2	36.3	3.8	286	27.8			4.0			
ARU05M8	5/3 4:35 pm	25.4	36.8	36.8	0.6	215	28.9			4.0			36.8
ARU05M8	5/3 6:25 pm	25.6	36.9	36.9	0.5	204	29.1			4.0			
BCO17M8	17/3 9:50 am	24.8	35.5	35.6	0.7	231	28.1			3.0	1	1.03	
BCO17M8	17/3 10:50 am	24.2	35.3	35.3	1.2	260	27.5			5.0	1.6		
BCO17M8	17/3 12:00 pm	26.1	36.5	36.6	0.1	155	30.0			5.0	0.8	1.02	
BCO17M8	17/3 12:30 pm	20.0	28.1	28.8	1.1	310	22.6	crib		1.0	1		

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
BCO17M8	17/3 2:00 pm	24.6	36.4	36.5	1.3	255	28.1			1.0	0.8	1.03	
BCO17M8	17/3 3:45 pm	24.2	36.1	36.2	1.9	273	27.7			6.0			
BDO20M8	20/3 9:30 am	30.1	36.5	36.8	0.5	143	32.2			5.5	0.8	1.01	
BDO20M8	20/3 10:30 am	30.7	36.8	36.8	0.5	135	32.6			2.0	0.7		37.7
BDO20M8	20/3 12:00 pm	29.5	37.5	37.5	0.4	143	32.0			5.0	0.83		37.4
BDO20M8	20/3 2:00 pm	27.3	37.5	37.5	0.6	189	30.5			5.0	1.25		37.7
BDO20M8	20/3 3:15 pm	16.6	24.4	24.8	0.5	312	19.2	crib			0.25		37.3
BDO20M8	20/3 5:30 pm	29.1	36.9	36.9	0.3	139	31.6				0.75		37.8
BDO20M8	20/3 6:40 pm	29.1	36.8	36.8	0.4	150	31.5			5.0			37.7
BDO20M8	20/3 6:40 pm									5.0			
BDO21M8	21/3 10:00 am	27.9	35.4	35.4	0.4	169	30.3			1.0			37.4
BDO21M8	21/3 10:45 am	28.9	37.1	37.1	0.3	141	31.6						
BDO21M8	21/3 11:00 am	31.3	38.4	38.4	0.2	94	33.7			2.0			37.7
BDO21M8	21/3 1:20 pm	28.7	37.4	37.4	0.2	127	31.6			3.0			37.4
BDO21M8	21/3 3:15 pm	17.3	25.9	29.1	0.5	293	20.7	crib					
BDO21M8	21/3 4:45 pm	29.0	38.3	38.3	0.7	168	31.9			5.0			37.0
BDO21M8	21/3 5:30 pm	26.9	37.1	37.2	2.1	236	29.9			5.0			37.0
BDO21M8													
CBU13M8	13/3 9:20 pm	27.1	36.1	36.1	0.3	165	30.0			6.5	1.2	1.01	
CBU13M8	13/3 11:00 pm	27.6	40.1	40.1	0.5	171	31.5			6.0	1		Broken Tymp

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
CBU13M8	14/3 12:35 am	25.8	36.9	39.2	1.6	233	29.5			6.0	2.5		
CBU13M8	14/3 3:15 am	25.3	38.3	38.9	1.0	230	29.3			6.0	2.4	1.01	
CBU13M8	14/3 4:30 am	24.7	31.1	32.7	0.6	228	27.0						
CBU13M8	14/3 5:10 am	29.0	38.9	38.9	0.4	147	32.1			7.0	1	1.01	
CBU13M8	14/3 6:30 am	26.5	37.2	37.3	0.5	192	29.9			7.0			
CGA13M8	13/3 9:35 am	29.3	37.8	37.8	0.2	119	32.1			7.0	0.4	1.03	
CGA13M8	13/3 11:25 am	26.4	37.9	38.9	1.9	234	30.0			7.0	2		
CGA13M8	13/3 2:00 pm	30.4	39.1	39.1	0.2	103	33.3	Hot Job		8.0	1.5		
CGA13M8	13/3 3:15 pm	17.0	24.7	25.7	1.4	333	19.5	crib			0.8	1.03	
CGA13M8	13/3 4:00 pm	31.1	36.5	36.5	0.3	114	32.8			7.5	2		
CGA13M8	13/3 5:15 pm	31.6	39.1	39.1	1.1	137	33.9			7.5	0.5	1.03	
CLI05F8	5/2 9:20 am	31.1	36.7	36.7	0.2	101	33.0						
CLI05F8	5/2 10:30 am	29.4	37.2	37.2	0.7	165	31.8			5.0			
CLI05F8	5/2 11:30 am	29.8	37.9	37.9	0.8	161	32.3			0.0			
CLI05F8	5/2 12:30 pm	22.7	27.5	27.8	0.2	209	24.4	Crib		2.0			
CLI05F8	5/2 1:30 pm	30.5	36.9	36.9	0.3	121	32.6			7.0			
CLI05F8	5/2 2:30 pm	30.0	37.4	37.4	0.5	144	32.3			8.0			
CLI05F8	5/2 3:30 pm	28.7	38.0	38.3	1.1	187	31.6			8.0			
CLI05F8	5/2 4:30 pm	28.5	37.3	37.3	0.4	157	31.3			2.0		1.01	
GRI06M8	6/3 11:00 am	28.7	33.6	33.6	0.8	188	30.2	gear picked up, pump/bucketed, bricks		7.0	1	1.02	36.4
GRI06M8	7/3 12:15 pm	19.6	29.0	30.2	0.4	266	22.9	crib (12.00 - 12.30)		1.0	2	1.03	36.0
GRI06M8	7/3 1:50 pm	28.6	34.2	34.2	3.3	227	30.2	laying bricks		8.0	1.2		
GRI06M8	7/3 3:15 pm	27.8	33.6	34.0	1.3	215	29.6	laying bricks		7.0	1.6		36.2

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
GRI06M8	7/3 4:30 pm	28.4	33.9	34.0	3.3	230	30.0	laying bricks		7.0	1.2	1.03	
GRI08M8	7/3 9:55 am	19.8	30.6	33.8	1.1	297	23.7			1.0			
GRI08M8	7/311:15 am	32.4	35.9	35.9	1.9	140	33.4			7.0			36.8
GRI08M8	7/31:13 pm	36.6	37.5	37.5	5.5	81	36.9			8.0			36.6
HSC10M8	10/3 9:10 pm	27.6	35.0	35.0	0.2	145	30.1			1.0	1.2		
HSC10M8	10/3 9:17 pm	27.5	38.3	38.3	0.6	184	30.8			1.0	0.8		
HSC10M8	10/3 10:33 pm	27.2	38.4	38.4	0.8	199	30.6			3.0	0.8		
HSC10M8	10/3 11:55 pm	28.7	38.9	38.9	0.6	166	31.9			3.0	0.6		
HSC10M8	11/3 1:45 am	29.8	40.0	40.0	0.4	133	33.0			3.0	0.7		
HSC10M8	11/3 3:15 am	24.6	31.0	31.5	0.3	202	26.8	crib			0.8	1.03	
HSC10M8	11/3 4:25 am	30.3	37.6	37.6	0.7	150	32.5			3.0			
HSC10M8	11/3 6:00 am	29.2	38.7	38.7	0.6	159	32.1			3.0			
HSC11M8	11/3 10:50 am	30.3	38.6	38.6	0.3	120	33.0			5.0			
HSC11M8	11/3 10:50 am	29.4	39.2	39.2	0.4	140	32.5			5.0			
HSC11M8	11/3 1:30 pm	29.6	39.6	39.6	0.4	137	32.8			6.0			
HSC11M8	11/3 3:30 pm	23.1	29.8	30.1	0.3	221	25.4	crib	1				
HSC11M8	11/3 4:30 pm	30.1	37.5	37.5	0.6	149	32.4			8.5			
JHA04M8	4/3 10:15 am	27.5	38.8	38.8	0.4	166	31.1	Driving - tamrock, mucker		3.0	1	1.02	
JHA04M8	4/3 11:55 am	28.0	39.6	39.6	0.8	185	31.5	Cleaning lifters (hoses)		6.0	3		36.5
JHA04M8	4/3 1:55 pm	21.0	36.8	36.8	0.6	263	25.9			5.0	3.5		36.8
JHA04M8	4/3 4:00 pm	20.6	30.9	32.9	0.8	282	24.1	crib		2.0	1.5		
JHA04M8	4/3 4:40 pm							driving and drilling (no air		2.0	1.5		

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
								conditioning)					
JHA04M8	4/3 6:00 pm	29.5	38.6	38.6	0.4	141	32.4						
JHA04M8	4/3 6:10 pm	28.1	40.0	40.0	0.4	156	31.9	charging		8.0	1.2	1.01	36.6
JHA05M8	4/3 10:00 am	27.7	37.3	37.3	0.6	184	30.7			7.0			
JHA05M8	4/3 11:08 am	26.0	37.4	37.0	1.0	228	29.4			4.0			36.3
JHA05M8	4/3 1:35 pm	26.6	35.0	35.0	0.8	215	29.2			4.0			
JHA05M8	4/3 2:53 pm	26.1	35.5	36.3	1.2	231	29.1			4.0			
JHA05M8	4/3 4:10 pm	21.7	36.3	36.6	0.6	255	26.3			5.0			36.4
JHA05M8	4/3 5:45 pm	20.7	28.4	29.7	0.4	257	23.5						
JHA05M8	4/3 7:00 pm	28.0	38.6	38.6	0.8	187	31.2			2.0			35.4
JLA06M8	7/3 11:15 am	19.6	28.8	31.7	0.5	270	23.1			1.0	2	1.02	36.3
JLA06M8	7/3 12:15 pm	19.6	29.0	30.2	0.4	266	22.9	crib		7.0	1	1.02	36.1
JLA06M8	7/3 1:40 pm	28.3	34.0	34.1	0.7	188	30.1			1.0	1		
JLA06M8	7/3 2:00 pm	19.6	28.8	31.7	0.5	270	23.1	A/C			1		
JLA06M8	7/3 2:40 pm	28.0	34.0	33.9	1.2	212	29.8			8.0	1	1.03	
JLA06M8	7/3 3:00 pm	18.7	28.5	32.7	0.5	272	22.7	A/C		1.0			
JLA06M8	7/3 4:00 pm	28.0	33.9	34.1	1.3	213	29.8						
JLA06M8	7/3 4:30 pm	28.4	33.4	33.5	0.9	197	29.9			8.0			36.3
JLA08M8	8/3 9:45 am	28.1	35.3	35.3	1.4	211	30.2			4.0			
JLA08M8	8/3 11:00 am	31.6	35.4	35.4	1.0	143	32.7			7.0			36.2
JLA08M8	8/3 12:40 pm									7.0			
JLA08M8	8/3 1:30 pm	29.1	34.2	34.2	0.7	177	30.7			4.0			36.1
JTA06M8	7/3 11:00 am	28.7	33.6	33.6	0.8	188	30.2			7.0		1.02	36.9
JTA06M8	7/3 12:15 pm	19.6	29.0	15.0	0.4	324	19.9	crib			1.5	1.03	36.1
JTA06M8	7/3 1:55 pm	28.3	34.0	34.1	0.7	188	30.1			7.0	0.8		
JTA06M8	7/3 3:15 pm	28.0	33.9	34.1	1.3	213	29.8			7.0	1.6		36.2

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
JTA06M8	7/3 4:30 pm	28.4	33.4	33.5	0.9	197	29.9			7.0	1.6	1.03	
KHU03M8	3/3 9:47 am	27.2	37.5	37.5	0.9	206	30.3	change location		5.0	0.4	1.02	
KHU03M8	3/3 11:27 am	26.8	37.6	37.6	0.3	165	30.3	jacking cables		8.0	1.2		36.5
KHU03M8	3/3 12:54 pm	25.9	36.6	36.6	0.4	191	29.3	jacking cables		8.0	1.2		
KHU03M8	3/3 2:40 pm	21.4	28 .1	28.8	0.2	- 1	#VALUE!	plating rebar (until 2pm) (blocks in ceiling)	crib	8.0	1.2	1.03	36.4
KHU03M8	3/3 5:30 pm	29.0	38.0	38.0	0.9	178	31.7	grouting (hasn't stopped since crib)		10.0	1.5		
KHU03M8	3/3 6:17 pm	28.5	37.4	37.4	0.1	129	31.7	grouting		10.0	1.25	1.03	37.2
LNE13M8											0.8	1.02	
LNE13M8											2.8		
LNE13M8											2.8		
LNE13M8												1.03	
LNE13M8											2.9		
LNE13M8											3.2	1.03	
LWE06F8	6/2 9:20 am	31.1	36.7	36.7	0.2	101	33.0		Worked with CLI all day				
LWE06F8	6/2 10:30 am	29.4	37.2	37.2	0.7	165	31.8						
LWE06F8	6/2 11:30 am	29.8	37.9	37.9	0.8	161	32.3						
LWE06F8	6/2 12:30 pm	22.7	27.5	27.8	0.2	209	24.4	Crib					
LWE06F8	6/2 1:30 pm	30.5	36.9	36.9	0.3	121	32.6						
LWE06F8	6/2 2:30 pm	30.0	37.4	37.4	0.5	144	32.3						
LWE06F8	6/2 3:30 pm	28.7	38.0	38.3	1.1	187	31.6						
LWE06F8	6/2 4:30 pm	28.5	37.3	37.3	0.4	157	31.3						
MDU17M8	17/3 9:50 am	25.2	34.5	34.5	0.4	204	28.2			1.0	0.4	1.03	
MDU17M8	17/3 11:00	25.3	35.6	35.6	0.4	200	28.6			8.0	1.6		

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
	am												
MDU17M8	17/3 12:30 pm	20.0	28.1	28.8	1.1	310	22.6	crib		8.0	0.8	1.02	
MDU17M8	17/3 1:15 pm	31.0	36.0	36.0	0.6	138	32.5			2.0			
MDU17M8	17/3 1:50 pm	27.9	36.9	36.9	0.6	182	30.7			2.0	1.2		
MDU17M8	17/3 2:50 pm	25.6	36.3	36.3	0.6	213	28.9			7.0	1.6	1.03	
MDU17M8	17/3 4:25 pm	25.8	36.4	36.4	0.4	192	29.2			8.0			
MNO03M8	3/3 12:13 pm									2.5			36.2
MNO03M8	3/3 1:17 pm	25.3	34.7	35.3	1.3	247	28.2			2.5			36.5
RCL20M8	20/3 9:45 am	26.8	36.2	26.2	0.5	242	27.7	30% toyota. 30% walking. 40% bolts (level = 3)			1.2	1.03	
RCL20M8	20/3 10:45 am	25.4	36.2	36.2	0.3	184	28.9	drilling		1.0	1.4		37.8
RCL20M8	20/3 12:00 pm	24.9	36.1	36.1	0.6	222	28.4				1	1.02	
RCL20M8	20/3 12:30 pm	21.0	32.9	32.9	0.3	234	25.0	crib					37.1
RCL20M8	20/3 1:50 pm	26.2	36.6	36.6	0.5	197	29.5			8.0	1.6		38.0
RCL20M8	20/3 3:50 pm	28.0	36.3	36.3	0.4	166	30.6			8.0	1.4	1.01	37.8
RCL20M8	20/3 5:10 pm	25.4	36.8	36.8	0.6	215	28.9			8.0			37.5
RCL21M8	21/3 10:30 am	26.8	37.7	37.7	1.5	228	30.0			8.0			
RCL21M8	21/3 12:00 pm									6.0			
RCL21M8	21/3 12:30 pm	20.3	31.1	32.2	0.3	239	24.1	crib					

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
RSM04M8	4/3 10:00 am	29.7	38.4	38.4	0.4	138	32.5			6.0	1.5	1.01	
RSM04M8	4/3 11:35 am	30.0	39.6	39.6	1.1	164	32.9	chasing gear before, 3/4hr ground support		8.0	1.75		36.9
RSM04M8	4/3 12:30 pm	27.5	38.8	38.8	0.4	166	31.1	ground support, pushing bolts				1.02	
RSM04M8	4/3 1:30 pm	25.0	32.9	35.4	0.6	215	28.0	cribtime			1		
RSM04M8	4/3 4:00 pm	27.2	38.9	38.9	0.4	170	30.9	pushing cables for 1/2 hr (2.30-3.00), waiting		4.0	1		
RSM04M8	4/3 6:35 pm	26.3	38.0	38.1	0.5	192	30.0	mixing cement, pushing cables, grouting		6.0	2	1.03	36.7
RSM05M8	5/3 9:30 am	27.1	37.2	37.2	0.4	175	30.3			4.0			
RSM05M8	5/3 10:46 am	26.2	37.7	37.7	0.9	219	29.7			4.0			36.4
RSM05M8	5/3 12:00 pm									1.0			36.1
RSM05M8	5/3 12:45 pm	20.7	28.4	29.7	0.4	257	23.5			4.0			
RSM05M8	5/3 2:10 pm												
RSM05M8	5/3 3:00 pm	24.4	36.2	36.3	3.8	286	27.8			5.0			
RSM05M8	5/3 4:35 pm	25.4	36.8	36.8	0.6	215	28.9			7.0			37.1
RSM05M8	5/3 6:25 pm	25.6	36.9	36.9	0.5	204	29.1			6.0			
RSM05M8													
SSM20M8	20/3 10:00 am	30.8	37.1	37.1	0.3	117	32.8				2.9	1.02	
SSM20M8	20/3 11:25 am	29.2	36.5	36.5	0.4	150	31.5			6.0	1.8		38.1
SSM20M8	20/3 1:00 pm	28.1	35.4	35.4	0.6	183	30.4			5.0	0.38	1.02	37.3
SSM20M8	20/3 3:15 pm	20.6	30.6	31.8	0.7	281	23.9	crib					36.7
SSM20M8	20/3 4:25 pm	27.8	35.6	35.6	0.7	192	30.2			1.0	1.8	1.02	37.0
SSM20M8	20/3 6:00 pm	27.5	35.9	36.1	0.7	195	30.1			7.0			37.2

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
SSM21M8	21/3 11:00 am	28.3	37.1	37.1	0.8	186	31.0			1.0			37.5
SSM21M8	21/3 1:30 pm	28.9	37.1	37.1	0.3	141	31.6			7.0			37.6
SSM21M8	21/3 3:15 pm	17.3	25.9	29.1	0.5	293	20.7	crib					
SSM21M8	21/3 4:45 pm	29.0	38.3	38.3	0.2	121	32.1			6.0			37.3
SSM21M8	21/3 5:00 pm	26.9	37.1	37.2	2.1	236	29.9			6.0			
TAN10M8	10/3 9:50 pm	28.5	36.5	37.0	2.7	216	30.9			3.0	1.4		
TAN10M8	11/3 12:10 am	27.9	38.5	38.6	0.5	170	31.2			1.0	1		
TAN10M8	11/3 1:05 am	30.8	41.3	41.3	0.5	123	34.1			5.0	1		
TAN10M8	11/3 2:00 am	28.6	39.8	39.8	0.5	158	32.1						
TAN10M8	11/3 3:15 am	24.6	31.0	31.5	0.3	202	26.8	CRIB		2.0	2		
TAN10M8	11/3 5:00 am	32.6	37.5	37.5	0.2	84	34.2			2.0			
TAN10M8	11/3 6:45 am	30.0	36.5	36.8	0.5	145	32.1			2.0			
TAN11M8	11/3 9:30 pm	31.1	38.2	38.2	0.3	110	33.4						
TAN11M8	11/3 10:00 pm	30.2	38.9	38.9	0.4	130	32.9			3.0			
TAN11M8	11/3 11:30 pm	31.0	38.3	38.3	0.4	120	33.3			6.0			
TAN11M8	11/3 12:00 am	27.5	37.1	38.1	0.9	197	30.6			2.0			
TAN11M8	11/3 1:15 am	29.3	38.3	38.3	0.4	144	32.1			4.0			
TAN11M8	11/3 3:30 am	23.1	29.8	30.1	0.3	221	25.4	crib					

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
	11/3 4:00 am	31.3	37.7	37.7	0.4	118	33.3						
TAN11M8	11/3 5:00 am	27.2	37.0	37.5	0.7	195	30.3			5.0			
TAN11M8	11/3 5:15 am	28.4	36.6	36.6	0.4	160	31.0						
TAN11M8	11/3 6:40 am	27.8	36.8	36.8	0.4	167	30.7			5.0			
TMA17M8	17/3 10:00 am	24.2	35.7	35.7	1.3	262	27.6			4.0	0.5		
TMA17M8	17/3 11:00 am	24.0	35.7	35.7	1.2	262	27.5			4.0	1	1.02	
TMA17M8	17/3 12:00 pm	26.1	36.5	36.6	0.1	155	30.0			6.0	0.5		
TMA17M8	17/3 12:30 pm	20.0	28.1	28.8	1.1	310	22.6	crib				1.03	
TMA17M8	17/3 2:00 pm	24.6	36.4	36.5	1.3	255	28.1			4.0	3	1.03	
TMA17M8	17/3 3:45 pm	24.2	36.1	36.2	1.9	273	27.7			6.0			
TMA17M8													
TMA17M8													
AGL13J9	13/1 8:45 am	22.8	25.9	25.9	0.1	213	24.0				0		37.4
AGL13J9	13/1 10:10 am	30.2	37.0	37.0	6.5	201	32.2			1.0	0.3		37.3
AGL13J9	13/1 11:10 am	28.6	35.7	35.7	6.7	235	30.6			1.0	0.6		37.2
AGL13J9	13/1 11:50	20.3	29.7	29.7	0.5	275	23.3	start crib		1.0	0.38		37.0

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
	am												
AGL13J9	13/1 12:43 pm	20.4	23.8	23.8	0.4	275	21.5	end crib		1.0	0.6		37.3
AGL13J9	13/1 1:50 pm	33.7	38.0	38.0	0.4	83	35.1			9.0	0.9		38.3
AGL13J9	13/1 2:51 pm	32.7	37.9	37.9	0.5	101	34.3			3.0	0.6		38.1
AGL13J9	13/1 4:35 pm	24.4	33.0	33.0	0.3	202	27.2			1.0			37.1
BCA28J9	28/1 8:40 am	31.4	35.1	35.1	0.2	102	32.6				1.2		37.5
BCA28J9	28/1 10:35 am	29.4	39.4	37.2	7.0	226	31.8			2.0			36.9
BCA28J9	28/1 11:48 am	33.0	38.1	38.1	3.1	130	34.5			5.0			37.2
BCA28J9	28/1 12:29 pm	30.4	36.7	36.9	6.4	197	32.3	MIA		7.0			
BCA28J9	28/1 1:34 pm	30.4	36.7	36.9	6.4	197	32.3	MIA		6.0	1.2		
BCA28J9	28/1 2:40 pm	21.8	27.5	28.3	0.5	262	23.8	crib		3.0	1.5		37.0
BCA28J9	28/1 3:50 pm	21.9	25.8	26.0	0.5	267	23.2	crib		1.0	0.5		37.5
BCA28J9	28/1 5:00 pm	32.4	36.7	36.7	3.6	148	33.7			3.0	0.75		37.5
BCA28J9	28/1 5:50 pm	29.9	38.3	38.3	2.1	184	32.4			5.0	0.9		37.4
BCA28J9	28/1 6:50 pm	29.9	36.5	37.9	7.0	200	32.1				1.5		
BCA28J9	28/1 7:30 pm	29.2	34.1	34.1	0.1	130	31.0			2.0	3		37.6
BRE15J9	15/1 8:37 am	23.0	26.9	26.9	0.2	209	24.3				0.3		37.2
BRE15J9	15/1 9:56 am	31.0	40.0	40.0	0.6	129	33.8			2.0	0		37.7
BRE15J9	15/1 10:58 am	29.9	39.1	39.1	0.7	153	32.7			2.0	0.6		37.5
BRE15J9	15/1 12:00 pm	20.6	28.1	39.5	0.5	219	25.3	start crib		5.0			37.2

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
BRE15J9	15/1 12:50 pm	20.7	25.0	25.3	0.3	254	22.2	end crib		1.0			37.2
BRE15J9	15/1 1:30 pm	31.3	37.7	37.7	0.4	118	33.3				0.3		37.9
BRE15J9	15/1 1:54 pm	28.9	36.0	36.8	1.0	182	31.2			4.0	0.3		
BRE15J9	15/1 2:50 pm	29.6	28.9	38.9	0.9	131	31.4			5.0	0.3		37.8
BRE15J9	15/1 3:53 pm	29.3	38.5	38.5	1.0	175	32.1			6.0	0.6		37.8
BRE15J9	15/1 4:45 pm	26.7	32.9	32.9	0.1	159	29.0						37.6
BRE15J9	19/1 8:45 am	28.2	32.1	32.1	0.1	146	29.6						36.9
BRE15J9	19/1 9:46 am	25.9	34.5	35.7	0.6	207	28.8			1.0			37.2
BRE15J9	19/1 10:57 am	24.6	34.4	34.8	2.4	276	27.5			5.0			37.2
BRO19J9	19/1 11:52 am	24.5	34.9	36.2	2.1	268	27.8			5.0	0.6		37.0
BRO19J9	19/1 12:47 pm	24.9	35.1	35.2	1.3	254	28.0			5.0	0.3		37.1
BRO19J9	19/1 1:50 pm	23.9	34.8	35.6	2.3	280	27.2	start crib		5.0	1.2		37.0
BRO19J9	19/1 3:20 pm	20.4	24.6	25.3	0.4	270	21.9	end crib		1.0	0.9		36.7
BRO19J9	19/1 4:29 pm	25.4	33.7	33.7	0.5	214	28.0			3.5	0.25		37.7
BRO19J9	19/1 5:53 pm	29.9	37.3	37.3	0.3	128	32.3			8.0			38.1
BRO19J9	19/1 6:38 pm	33.2	39.1	39.1	0.9	103	35.0			2.0	1.2		37.1
BRO19J9	19/1 7:20 pm	27.1	34.5	34.5	0.1	151	29.8				1.35		36.9
CBU09J9	9/1 8:00 am	25.2	26.7	26.7	0.2	190	25.7				2		37.5
CBU09J9	9/1 10:55 am	30.4	38.5	38.5	0.1	105	33.3			7.0	2		37.2
CBU09J9	9/1 12:00 pm	28.2	38.7	38.7	0.4	158	31.5			7.0	0.5		38.1
CBU09J9	9/1 1:00 pm	19.1	28.3	31.9	1.6	316	22.5			6.0	0.5		37.2
CBU09J9	9/1 2:40 pm	30.6	36.9	36.9	1.0	157	32.5	crib		0.0	0.5		37.4

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
CBU09J9	9/1 3:40 pm	30.4	36.3	36.3	2.3	182	32.1			6.0			37.6
CBU09J9	9/1 4:40 pm	30.4	36.7	36.9	2.3	180	32.3			7.0			37.3
CBU09J9	9/1 5:41 pm	30.4	36.7	36.7	2.2	180	32.3			6.0	0.5		37.5
CBU09J9	9/1 6:55 pm	31.3	37.3	37.3	0.9	141	33.1			10.0	1		38.2
CBU09J9	9/1 7:30 pm	24.8	32.1	33.2	0.3	195	27.4				1		37.6
CLI13J9	13/1 8:45 am	22.8	25.9	25.9	0.1	213	24.0				0.6		37.6
CLI13J9	13/1 9:59 am	30.1	35.6	35.6	0.3	130	31.9			1.0	0.6		37.7
CLI13J9	13/1 10:56 am	30.2	35.7	35.7	0.4	138	31.9			1.0	0.3		37.7
CLI13J9	13/1 11:50 am	20.3	27.1	29.7	0.5	268	23.0	start crib		1.0	0.38		37.0
CLI13J9	13/1 12:42 pm	30.4	23.7	23.8	0.4	162	28.3	end crib		1.0	0.6		36.7
CLI13J9	13/1 1:37 pm	30.4	38.5	38.5	1.6	169	32.8			3.0			38.2
CLI13J9	13/1 2:39 pm	28.9	38.9	38.9	0.9	177	31.9			3.0	0.9		37.5
CLI13J9	13/1 3:37 pm	29.4	39.0	39.0	0.6	156	32.4			3.0	0.9		37.7
CLI13J9	13/1 4:35 pm	24.4	31.9	33.0	0.3	199	27.1						37.1
CLI13J9	0/1 9:00 am	27.2	31.2	31.2	0.1	159	28.7				0.6		37.8
CLI13J9	0/1 10:00 am	28.1	36.1	36.1	0.9	196	30.5			2.0	0.6		38.0
CLI13J9	0/1 11:00 am	27.5	36.9	37.3	0.9	200	30.4			4.0	0.3		38.1
CLI13J9	0/1 11:50 am	19.9	24.5	25.7	0.3	257	21.7	start crib		3.0	0.38		37.3
CLI13J9	0/1 12:30 pm	20.9	25.1	25.6	0.6	285	22.3	end crib		1.0	0.6		37.6
CLI13J9	0/1 1:39 pm	29.0	35.1	35.1	0.1	130	31.2			3.0			38.2
CLI13J9	0/1 2:39 pm	27.4	35.7	35.7	1.3	219	29.9			4.0	0.9		38.0
CLI13J9	0/1 3:30 pm	27.2	36.0	36.0	1.6	228	29.8			4.5	0.9		37.8
CLI13J9	0/1 4:30 pm	28.2	36.9	36.9	1.0	196	30.8			2.0			37.8

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
CLI13J9	0/1 5:30 pm	26.7	34.5	34.5	0.1	155	29.6						37.4
DAR23J9	23/1 8:50 am	31.3	35.2	35.2	0.1	103	32.7				0.6		37.4
DAR23J9	23/1 10:00 am	30.4	37.7	37.7	5.1	192	32.5			1.0			37.3
DAR23J9	0/1 11:07 am							Gone to surface for 1st aid		1.0			37.4
DAR23J9	0/1 12:07 pm							Gone to surface for 1st aid	MIA				
DAR23J9	23/1 1:15 pm	24.1	33.0	34.4	0.7	238	27.1	crib	MIA	1.0			
DAR23J9	0/1 1:27 pm												37.2
DAR23J9	23/1 3:02 pm	23.9	31.8	32.4	0.5	232	26.5	crib		1.0	0.9		37.2
DAR23J9	23/1 4:00 pm	28.8	37.3	38.1	4.9	218	31.4			1.0			37.6
DAR23J9	23/1 5:10 pm	31.0	38.7	38.8	0.3	110	33.5			1.0	0.9		37.5
DAR23J9	23/1 6:24 pm	29.7	37.6	37.6	5.6	207	32.0			1.0	1.2		37.6
DAR23J9	23/1 7:30 pm	28.7	36.3	36.3	0.4	157	31.1				0.9		37.3
DIS09J9	9/1 8:00 am	25.2	26.7	26.7	0.2	190	25.7				1		37.3
DIS09J9	9/1 10:00 am	30.3	37.4	37.4	0.8	155	32.5			4.0	2		37.1
DIS09J9	9/1 11:24 am	29.7	37.7	37.7	1.6	183	32.1			5.5	0.5		36.9
DIS09J9	9/1 12:21 pm	30.9	38.4	38.4	1.5	158	33.1			7.0	1		37.4
DIS09J9	9/1 1:54 pm	25.4	33.6	34.9	0.6	215	28.2	crib		7.0	0.38		36.7
DIS09J9	9/1 2:56 pm	25.6	33.4	36.1	1.1	229	28.5	crib		0.0	0.5		36.5
DIS09J9	9/1 4:00 pm	21.9	30.8	35.8	0.5	233	25.7			1.5			36.4
DIS09J9	9/1 5:00 pm	23.6	32.7	34.7	0.6	235	26.8			2.0	0.5		36.1
DIS09J9	9/1 6:23 pm	21.9	31.4	36.3	0.7	248	25.8			2.0			35.5
DIS09J9	9/1 7:30 pm	24.8	32.1	33.2	0.3	195	27.4				2		36.8
DJO28J9	28/1 8:40 am	31.4	35.1	35.1	0.2	102	32.6				1.2		37.1
DJO28J9	28/1 10:08	31.3	39.0	39.0	1.5	149	33.6			1.0			37.3

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
	am												
DJO28J9	28/1 11:07 am	23.9	32.0	36.7	1.1	243	27.3			1.0			37.0
DJO28J9	28/1 12:12 pm	30.7	37.4	37.8	7.0	188	32.7			1.0	1.2		37.3
DJO28J9	0/1 1:36 pm									3.0			37.2
DJO28J9	28/1 2:40 pm	21.8	27.5	28.3	0.5	262	23.8	start crib		2.0	0.6		36.4
DJO28J9	28/1 3:50 pm	21.9	25.8	26.0	0.5	267	23.2	end crib		1.0	0.3		36.7
DJO28J9	28/1 5:00 pm	32.4	36.7	26.7	3.6	214	31.7			3.0	0.5		37.6
DJO28J9	28/1 6:17 pm	29.7	39.0	39.0	1.7	181	32.5			5.0	0.6		37.2
DJO28J9	28/1 6:50 pm	29.9	36.5	37.9	7.0	200	32.1				0.6		
DJO28J9	28/1 7:30 pm	29.2	34.1	34.1	0.1	130	31.0			5.0	0.6		37.3
DKE23J9	23/1 8:50 am	31.3	35.2	35.2	0.1	103	32.7						37.7
DKE23J9	23/1 10:00 am	30.7	39.0	39.0	0.6	136	33.3			1.0			37.5
DKE23J9	23/1 11:00 am	29.0	37.8	37.8	0.4	149	31.8			1.0			37.5
DKE23J9	23/1 12:12 pm	29.7	40.3	40.3	0.6	148	33.0			5.0			37.8
DKE23J9	23/1 1:07 pm	28.5	38.9	38.9	0.8	179	31.7			1.0	1.2		37.5
DKE23J9	23/1 1:47 pm	23.9	31.8	32.4	0.5	232	26.5	start crib		2.0	1.5		37.0
DKE23J9	23/1 3:02 pm	25.0	31.3	31.3	0.5	224	27.0	end crib		1.0	1.2		37.2
DKE23J9	23/1 4:00 pm	33.3	39.5	39.5	1.5	109	35.2			3.0	2.7		38.2
DKE23J9	23/1 5:01 pm	30.7	40.3	40.3	1.9	163	33.5			4.0	0.5		38.1
DKE23J9	23/1 6:01 pm	31.9	36.5	36.5	0.3	103	33.4			2.0	0.9		37.7
DKE23J9	23/1 6:40 pm	30.0	37.4	37.4	1.6	179	32.2			1.0	1.8		37.7

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
DKE23J9	23/1 7:30 pm	28.7	36.3	36.3	0.4	157	31.1				2.1		37.5
GRI15J9	15/1 8:37 am	23.0	26.9	26.9	0.2	209	24.3				0		36.3
GRI15J9	15/1 10:20 am	26.3	34.6	36.2	0.8	211	29.2			1.0	0		36.2
GRI15J9	15/1 11:14 am	25.7	31.7	32.8	2.3	262	27.7			1.0			36.8
GRI15J9	15/1 12:00 pm	20.6	28.1	39.5	0.5	219	25.3	start crib		1.0	0		36.4
GRI15J9	15/1 12:50 pm	20.7	25.0	25.3	0.3	254	22.2	end crib		1.0			36.4
GRI15J9	15/1 1:50 pm	31.3	37.7	37.7	0.4	118	33.3			4.0	0.6		37.3
GRI15J9	15/1 1:50 pm	28.9	36.0	36.8	1.0	182	31.2			4.0	0.9		
GRI15J9	15/1 3:05 pm	32.6	38.0	38.0	1.8	130	34.2			6.0	0.6		37.4
GRI15J9	15/1 4:05 pm	30.7	37.3	37.3	6.7	191	32.6			1.0	0.9		37.2
GRI15J9	15/1 4:45 pm	26.7	32.9	32.9	0.1	159	29.0						37.0
KHU17J9	17/1 8:30 am	29.0	31.1	31.1	0.1	140	29.8				0.3		37.1
KHU17J9	17/1 10:10 am	25.8	35.2	35.2	0.7	220	28.7			4.0	0.6		37.1
KHU17J9	17/1 11:08 am	25.4	34.5	34.2	0.5	214	28.2			7.0			36.9
KHU17J9	17/1 12:19 pm	25.0	35.5	35.5	1.4	255	28.1			6.0			36.8
KHU17J9	17/1 1:05 pm	24.4	34.6	35.3	1.4	261	27.6			6.0	1.8		36.9
KHU17J9	17/1 2:00 pm	21.1	28.7	29.9	0.8	285	23.7	start crib		6.0	0		36.2
KHU17J9	17/1 3:12 pm	20.7	24.8	34.9	0.4	221	24.0	end crib		1.0	0		36.8
KHU17J9	17/1 4:20 pm	23.5	34.1	35.0	2.5	288	26.8			7.0	0.75		37.1

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
KHU17J9	17/1 5:28 pm	23.6	35.0	35.5	1.1	262	27.1			7.0	0.3		37.2
KHU17J9	17/1 7:20 pm	26.4	33.8	33.8	0.1	160	29.1				0.9		36.8
LBE23J9	23/1 8:50 am	31.3	35.2	35.2	0.3	115	32.6				0.4		37.4
LBE23J9	23/1 9:51 am	31.8	35.9	35.9	0.3	106	33.1			1.0			37.4
LBE23J9	23/1 10:49 am	32.3	37.7	37.7	0.4	102	34.0			4.0			37.8
LBE23J9	23/1 12:00 pm	31.6	39.6	39.6	0.9	131	34.0			3.0			38.0
LBE23J9	23/1 1:00 pm	31.2	39.6	39.6	1.2	145	33.7			3.0			37.7
LBE23J9	23/1 1:47 pm	23.9	31.8	32.4	0.5	232	26.5	start crib		4.0	0.5		37.1
LBE23J9	23/1 3:02 pm	25.0	31.3	31.3	0.5	224	27.0	end crib		1.0	2		37.3
LBE23J9	23/1 4:11 pm	29.9	38.6	38.6	0.9	162	32.5			4.0	1.5		37.7
LBE23J9	23/1 5:10 pm	31.0	38.7	38.6	0.3	111	33.5			5.0	0.38		37.5
LBE23J9	23/1 6:10 pm	31.1	37.5	37.5	0.7	137	33.1			1.0	0.5		
LBE23J9	23/1 6:50 pm	28.9	37.9	37.9	0.8	175	31.6			3.0	0.5		
LBE23J9	23/1 7:30 pm	28.7	36.3	36.3	0.4	157	31.1				1.5		
MCA19J9	19/1 8:45 am	28.2	32.1	32.1	0.1	146	29.6						37.3
MCA19J9	19/1 9:46 am	25.9	34.5	35.7	0.6	207	28.8			1.0			37.3
MCA19J9	19/1 10:57 am	24.6	34.5	34.8	2.4	276	27.5			5.0			37.2
MCA19J9	19/1 11:52 am	24.5	34.9	36.2	2.1	268	27.8			5.0			37.2
MCA19J9	19/1 12:47 pm	24.9	35.1	35.2	1.3	254	28.0			5.0			37.2
MCA19J9	19/1 1:50 pm	23.9	34.8	35.6	2.3	280	27.2	start crib		5.0			37.2
MCA19J9	19/1 3:30 pm	20.4	24.6	25.3	0.4	270	21.9	end crib		1.0			36.9

Code	Time	WB, ⁰ C	DB, ⁰ C	GT, ⁰ C	Wind, $m.s^{-1}$	TWL, $W.m^{-2}$	WBGT, ⁰ C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ⁰ C
MCA19J9	19/1 5:00 pm	29.3	40.2	40.2	0.5	148	32.7			5.0			37.7
MCA19J9	19/1 6:05 pm	27.1	37.7	37.7	3.3	243	30.2			8.0			37.9
MCA19J9	19/1 6:49 pm	27.2	37.8	37.8	2.1	231	30.3			6.0			37.7
MCA19J9	19/1 7:20 pm	27.1	34.5	34.5	0.1	151	29.8						37.5
MPA18J9	18/1 9:00 am	27.2	31.2	31.2	0.1	159	28.7				0.3		37.4
MPA18J9	18/1 10:00 am	28.1	36.1	36.1	0.9	196	30.5			2.0	0.9		37.9
MPA18J9	18/1 11:00 am	27.5	36.9	37.3	0.9	200	30.4			4.0	0.9		37.8
MPA18J9	18/1 11:50 am	19.9	24.5	25.7	0.3	257	21.7	start crib		3.0			36.7
MPA18J9	18/1 12:30 pm	20.9	25.1	25.6	0.6	285	22.3	end crib		1.0	0.6		37.2
MPA18J9	18/1 1:39 pm	29.0	35.1	35.1	1.0	188	30.8			3.0	0.9		37.5
MPA18J9	18/1 2:39 pm	27.4	35.7	35.7	1.3	219	29.9			5.0	0.6		37.7
MPA18J9	18/1 3:30 pm	27.2	36.0	36.0	1.6	228	29.8			3.0			37.4
MPA18J9	18/1 4:30 pm	28.2	36.9	36.9	1.0	196	30.8			2.0			37.2
MPA18J9	18/1 5:30 pm	26.7	34.5	34.5	0.1	155	29.6				0.6		37.6
RSV19J9	19/1 8:45 am	28.2	32.1	32.1	0.1	146	29.6						37.3
RSV19J9	19/1 9:34 am	29.8	37.0	37.0	0.9	167	32.0			1.0			37.4
RSV19J9	19/1 10:38 am	26.7	37.3	33.7	0.8	228	29.2			7.0			37.8
RSV19J9	19/1 11:39 am	26.4	37.6	37.6	1.2	227	29.8			5.0			37.5
RSV19J9	19/1 12:31 pm	25.6	37.2	37.2	1.2	238	29.1			5.0	0.6		37.6

Code	Time	WB, ⁰ C	DB, ⁰ C	GT, ⁰ C	Wind, $m.s^{-1}$	TWL, $W.m^{-2}$	WBGT, ⁰ C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ⁰ C
RSV19J9	19/1 1:35 pm	26.4	37.5	37.5	0.5	193	29.9			4.0	3.6		37.8
RSV19J9	19/1 2:30 pm	20.9	27.5	29.6	0.4	253	23.5			4.0	1.2		
RSV19J9	19/1 3:20 pm	20.4	24.6	25.3	0.4	270	21.9	end crib		1.0	0.9		36.8
RSV19J9	19/1 4:41 pm	27.0	36.8	26.8	1.0	266	28.0			2.0	0.3		37.5
RSV19J9	19/1 5:46 pm	24.8	36.1	36.1	1.7	263	28.1			2.0	0.6		37.4
RSV19J9	19/1 7:20 pm	27.1	34.5	34.5	0.1	151	29.8				0.6		37.0
SFA13J9	13/1 8:45 am	22.8	25.9	25.9	0.1	213	24.0				0.3		37.1
SFA13J9	13/1 10:10 am	30.2	37.0	37.0	6.5	201	32.2			1.0	0.3		37.3
SFA13J9	13/1 11:10 am	28.6	35.7	35.7	6.7	235	30.6			1.0	0.3		37.1
SFA13J9	13/1 11:50 am	20.3	29.7	29.7	0.5	275	23.3	start crib		1.0	0.38		36.8
SFA13J9	13/1 12:43 pm	20.3	23.8	23.8	0.4	276	21.4	end crib		1.0	0.6		37.0
SFA13J9	13/1 1:50 pm	33.7	38.0	38.0	0.4	83	35.1			8.0	0.9		38.8
SFA13J9	13/1 2:51 pm	32.7	37.9	37.9	0.5	101	34.3			3.0	0.3		38.1
SFA13J9	13/1 4:34 pm	24.4	33.0	33.0	0.3	202	27.2			1.0			36.9
SFA18J9	18/1 9:00 am	27.2	31.2	31.2	0.1	159	28.7						37.4
SFA18J9		31.2	37.5	37.5	0.2	98	33.3						
SFA18J9	18/1 10:11 am	29.9	36.4	36.4	1.0	170	31.9			5.0			38.5
SFA18J9	18/1 11:09 am	29.4	37.5	37.5	0.2	119	32.1			4.0			37.4
SFA18J9	18/1 11:50 am	19.9	34.5	25.7	0.3	280	23.0						

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
SFA18J9	18/1 12:30 pm	20.9	25.1	25.6	0.6	285	22.3	end crib		1.0			37.2
SFA18J9	18/1 1:32 pm	30.0	31.6	31.6	0.3	141	30.5			3.0			37.7
SFA18J9	18/1 2:29 pm	27.5	34.1	34.2	2.0	233	29.5			2.0			36.9
SFA18J9	18/1 3:30 pm	27.6	33.9	35.3	3.3	236	29.7			3.0			36.9
SFA18J9	18/1 4:30 pm	26.9	34.1	35.5	2.4	239	29.3			1.0			37.2
SFA18J9	18/1 5:30 pm	26.7	34.5	34.5	0.1	155	29.6						37.3
SWA09J9	9/1 8:00 am	25.2	26.7	26.7	0.2	190	25.7						37.5
SWA09J9	9/1 10:06 am	30.3	37.4	37.4	0.8	155	32.5			4.0			37.3
SWA09J9	9/1 11:24 am	29.7	37.6	37.7	1.6	183	32.1			5.5			36.9
SWA09J9	9/1 12:21 pm	30.9	38.4	38.4	1.5	158	33.1			5.5			37.3
SWA09J9	9/1 1:38 pm	31.4	38.0	38.0	1.5	150	33.4			8.0			37.5
SWA09J9	9/1 2:57 pm	25.6	33.4	36.1	1.1	229	28.5	crib		8.0			36.8
SWA09J9	9/1 4:11 pm	30.9	37.8	37.8	1.2	154	33.0	crib		0.0			
SWA09J9	9/1 5:12 pm	31.1	37.7	37.7	1.3	153	33.1			7.0			37.4
SWA09J9	9/1 6:34 pm	30.3	37.3	37.3	1.0	161	32.4			8.0			37.7
SWA09J9	9/1 7:30 pm	24.8	32.1	33.2	0.3	195	27.4						37.3
TAN17J9	17/1 8:30 am	29.0	31.1	31.1	0.1	140	29.8				2		36.8
TAN17J9	17/1 9:54 am	25.3	33.6	33.7	1.2	250	27.8			3.0			36.3
TAN17J9	17/1 10:50 am	29.3	36.2	36.2	1.4	190	31.4			3.0			36.4
TAN17J9	17/1 12:00 pm	25.1	34.5	34.5	1.9	265	27.9			3.0	0.3		35.9
TAN17J9	17/1 1:41 pm	28.5	37.3	37.3	0.2	129	31.5			5.0	1		37.0
TAN17J9	17/1 3:12 pm	20.7	24.8	34.9	0.4	221	24.0	end crib		1.0	0.5		37.0
TAN17J9	17/1 4:08 pm	29.8	35.9	35.9	0.3	133	31.8			2.0	0.6		37.1

Code	Time	WB, ^{0}C	DB, ^{0}C	GT, ^{0}C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0}C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0}C
TAN17J9	17/1 5:05 pm	28.3	39.1	39.1	2.1	210	31.5			4.0	0.3		36.7
TAN17J9	17/1 6:05 pm	28.9	38.4	38.4	0.2	122	32.1			5.0	0.5		37.2
TAN17J9	17/1 7:20 pm	26.4	33.8	33.8	0.1	160	29.1				0.9		37.1
THA28J9	28/1 8:40 am	31.4	35.1	35.1	0.2	102	32.6				0.9		37.1
THA28J9	28/1 9:55 am	32.4	38.8	38.8	1.4	127	34.3			1.0			37.2
THA28J9	28/1 10:52 am	29.5	38.0	38.0	0.4	142	32.2			2.0			37.3
THA28J9	28/1 11:56 am	29.6	38.3	38.3	0.9	167	32.2			1.0			37.2
THA28J9	28/1 12:57 pm	28.6	36.6	36.6	0.2	130	31.3			6.0	0.6		37.3
THA28J9	28/1 2:40 pm	21.8	27.5	28.3	0.5	262	23.8	start crib		3.0	1.5		37.3
THA28J9	28/1 3:50 pm	21.9	25.8	26.0	0.5	267	23.2	end crib		1.0	0.5		37.4
THA28J9	28/1 4:55 pm	29.5	34.7	34.7	0.5	158	31.1			5.5	0.5		37.6
THA28J9	28/1 6:03 pm	28.3	37.9	37.9	0.5	167	31.3			1.0	0.25		37.1
THA28J9	28/1 6:50 pm	29.9	36.5	37.9	7.0	200	32.1				0.5		
THA28J9	28/1 7:30 pm	29.2	34.1	34.1	0.1	130	31.0			1.0	3		37.2
WSH17J9	17/1 8:30 am	29.0	31.1	31.1	0.1	140	29.8				1.5		37.2
WSH17J9	17/1 10:18 am	27.0	34.4	34.6	1.1	221	29.3			5.0	1.5		37.4
WSH17J9	17/1 11:20 am	32.0	38.5	38.5	0.7	120	34.0			5.0	1		37.5
WSH17J9	17/1 12:30 pm	29.9	37.6	37.6	1.3	174	32.2			7.0	0.3		37.2
WSH17J9	17/1 1:20 pm	29.3	37.3	37.5	0.5	154	31.8			7.0	0.65		37.2
WSH17J9	17/1 2:17 pm	21.1	28.7	29.9	0.8	285	23.7	start crib		1.0	0.75		36.9

Code	Time	WB, ^{0} C	DB, ^{0} C	GT, ^{0} C	Wind, m.s^{-1}	TWL, W.m^{-2}	WBGT, ^{0} C	Activity	Comment	Borg (1-10)	Fluid, litre	SG	Tym, ^{0} C
WSH17J9	17/1 3:12 pm	20.7	24.8	24.9	0.4	270	22.0	end crib		1.0	0.3		37.1
WSH17J9	17/1 4:30 pm	26.8	35.7	35.7	0.4	182	29.6			1.0			37.3
WSH17J9	17/1 5:34 pm	26.7	36.7	36.7	0.3	168	30.0			2.0			37.1
WSH17J9	17/1 7:20 pm	26.4	33.8	33.8	0.1	160	29.1				0.6		37.4

Appendix F Continuous core temperature values for target groups. Temperatures (^{0} C) recorded every minute. CtPts is elapsed recording time, CtBadMissing is data missing or out of bounds (mins), CtDataHrs is data used in study (converted to hours). CtMax, CtMin and CtAvg are maximum, minimum and average values for the shift. Hi10Ct, Hi30Ct are highest consecutive 10- and 30-minute averages for the shift. TempRise is the difference between CtMin and CtMax. MaxStorage is the calculated heat storage based on thermal capacity of body tissue (3.49 kJ.^{0} C^{-1}.kg^{-1}, refer ASHRAE[3]). Hi10Inc, Hi10Dec to Hi60Inc, Hi60Dec are the highest 10-minute increase and decrease, highest 30-minute increase and decrease, and highest 60-minute increase and decrease in core temperature. Remaining columns are the number of minutes spent in specific core temperature zones (e.g. Ct360-370) is time spent between 36.0 and 37.0^0 C. "No data" indicates data collection mal-functioned, or a minimum of four hours recording time was not achieved.

Code	Ct DataHrs	CtPts	CtMax	CtMin	CtAvg	Hi10Ct	Hi30Ct	Temp Rise	Max Storage	Hi 10Inc	Hi 10Dec	Hi 30Inc	Hi 30Dec	Hi 60Inc	Hi 60Dec	Ct360-370	Ct370-376	Ct376-382	Ct382-388	Ct388-394	Ct394-400	CtBad-Missing	Ct comment
CST26M8	7.3	499	37.5	36.5	36.6	37.2	37.2	1.0		0.5	-0.3	0.5	-0.4	0.5	-0.4	278	160					61	
DMO24M8	8.9	561	37.6	36.8	37.1	37.5	37.4	0.8		0.4	-0.4	0.5	-0.5	0.6	-0.5	142	381	6	5			27	
DMO25M8	7.0	441	36.9	36.0	36.9	36.9	36.9	0.9		0.3	-0.1	0.4	-0.1	0.4	-0.3	141						20	
GHA26M8	5.4	331	37.8	36.9	37.5	37.7	37.7	0.9		0.5	-0.3	0.8	-0.3	0.8	-0.4	4	272	45				10	
GHA27M8	8.6	516	37.8	36.7	37.3	37.8	37.7	1.1		0.4	-0.3	0.5	-0.4	0.7	-0.4	20	472	24					
GXU25M8	9.5	576	37.6	36.8	37.3	37.6	37.6	0.8		0.4	-0.2	0.5	-0.4	0.5	-0.4	202	7	20				4	
RBR06M8	10.8	661	37.9	36.7	37.3	37.8	37.8	1.2	306.0	0.7	-0.5	0.8	-0.5	0.8	-0.5	71	55					15	
RBR07M8	11.0	661	37.5	36.4	37.1	37.5	37.5	1.1	280.0	0.2	-0.3	0.5	-0.4	0.8	-0.7	195							
SML24M8	8.5	534	37.9	36.5	36.9	37.1	37.1	0.6		0.3	-0.4	0.4	-0.4	0.5	-0.4	441	5	2				25	
SML25M8	10.3	662	37.5	36.1	36.5	36.8	36.8	0.8		0.2	-0.1	0.3	-0.3	0.4	-0.3	617						45	
ADA10M8	11.6	754	38.5		37.8	38.4	38.2									27	129	527	13			58	
ADA11M8	11.9	724	38.6	37.3	37.8	38.6	38.6	1.3	408.0	0.3	-0.3	0.7	-0.5	1.0	-0.8		267	366	79			12	
AMC03M8	12.2	742	39.0	37.0	38.0	38.9	38.8	2.0	600.0	0.8	-0.7	0.9	-0.7	1.1	-0.9	52	84	322	265	11		8	
ARU04M8																							No data
ARU05M8																							No data
BCO17M8	9.5	595	37.8	37.1	37.4	37.7	37.7	0.7	208.0	0.4	-0.3	0.4	-0.5	0.4	-0.5	41	511	18				25	
BDO20M8	10.4	757	37.9	37.2	37.2	37.9	37.9	0.7	208.0	0.4	-0.3	0.4	-0.5	0.4	-0.5	141	403	78				135	
BDO21M8	8.1	618	37.9		37.5	37.9	37.8									421	197	78				135	
CBU13M8	11.1	790	38.1	36.8	37.3	38.1	38.0	1.3	508.0	1.0	-0.6	1.2	-1.0	1.2	-1.0	153	441	74				122	
CGA13M8	5.9	666	38.2		37.2	38.1	38.0									135	158	62				311	

Code	Ct DataHrs	CtPts	CtMax	CtMin	CtAvg	Hi10Ct	Hi30Ct	Temp Rise	Max Storage	Hi 10Inc	Hi 10Dec	Hi 30Inc	Hi 30Dec	Hi 60Inc	Hi 60Dec	Ct360-370	Ct370-376	Ct376-382	Ct382-388	Ct388-394	Ct394-400	CtBad-Missing	Ct comment
CLI05F8	9.8	618	39.4	37.1	37.9	39.3	39.3	2.3	682.0	0.5	-0.8	1.4	-1.0	1.5	-1.4	178	207	108	63			28	
GRI07M8	11.9	721	38.7	37.2	38.6	38.5	38.5	1.5		0.5	-0.9	0.6	-1.2	1.1	-1.2	195	434	72				10	
GRI08M8																							
HSC10M8	8.0	501	38.2	36.9	37.6	38.1	38.0	1.3	436.0	0.6	-0.5	0.9	-0.7	0.9	-0.9	42	186	254				19	
HSC11M8																							No data
JHA04M8																							No data
JHA05M8																							No data
JLA06M8																							No data
JLA08M8																							No data
JTA07M8	8.4	555	38.1	36.7	37.3	38.1	38.1	1.4	318.0	0.5	-0.3	1.1	-0.7	1.4	-0.8	144	272	87				52	
KHU03M8	11.3	694	38.6	36.6	37.6	38.6	38.4	2.0	516.0	0.7	-0.5	1.0	-0.6	1.4	-0.6	60	403	139	75			17	
LNE13M8	11.7	733	38.8	36.9	38.0	38.7	38.6	1.9	524.0	1.2	-1.2	1.5	-1.2	1.5	-1.2	36	73	407	227			30	
LWE06F8	9.8	622	38.9	37.0	37.8	38.9	38.7	1.9		0.6	-0.9	1.1	-1.3	1.5	-1.4	32	285	154	114	5		32	
MDU17M8	9.9	618	38.5	37.0	37.8	38.5	38.4	1.5	419.0	0.3	-0.6	0.7	-0.9	1.2	-1.1	34	177	274	107			26	
MNO03M8																							No data
RCL20M8	11.0	712	38.2	36.7	37.5	38.2	38.1	1.5	503.0	0.6	-0.5	1.0	-0.7	1.1	-0.7	39	287	336				50	
RCL21M8																							No data
RSM04M8																							No data
RSM05M8	12.4	757	39.5	37.7	38.9	39.4	39.4	1.8	553.0	0.4	-0.2	0.5	-0.3	0.7	-0.4			55	212	476	1	13	
SSM20M8	12.5	776	38.4	36.8	37.5	38.4	38.4	1.6	464.0	0.5	-0.7	0.7	-1.1	0.9	-1.3	74	475	164	34			29	
SSM21M8																							No data
TAN10M8	13.1	813	37.9	36.8	37.3	37.9	37.9	1.1	345.0	0.4	-0.5	0.5	-0.5	0.6	-0.6	149	544	82				29	
TAN11M8	12.8	805	37.7	36.0	37.0	37.7	37.5	1.7	534.0	0.6	-0.8	0.8	-0.8	1.0	-0.9	377	400	6				38	
TMA17M8	8.6	602	37.9	37.2	37.3	37.9	37.9	0.7	166.0	0.3	-0.4	0.5	-0.4	0.5	-0.6	143	220	151				88	
AGL13J9	6.0	427	38.5	36.4	37.7	38.5	38.4	2.2	942.0	1.3	-0.4	1.3	-0.6	1.4	-0.7	49	226	42				69	
BCA28J9	10.9	662	38.1	37.0	37.6	38.1	38.0	1.1	347.0	0.4	-0.4	0.7	-0.7	0.8	-0.7	351	294					6	
BRE15J9	7.5	482	38.6	37.0	37.7	38.3	38.3	1.6	523.0	0.7	-0.6	1.3	-0.7	1.3	-0.8	123	248	37				32	
BRO19J9	10.8	680	38.0	36.8	37.5	38.0	37.9	1.2	299.0	0.7	-0.5	0.9	-0.5	0.9	-0.5	389	228					30	
CBU09J9	9.2	559	38.8	37.4	38.0	38.8	38.6	1.4	555.0	0.8	-0.8	0.8	-1.0	0.8	-1.0	101	338	111				8	
CLI13J9	7.2	435	38.0	36.8	37.6	37.9	37.9	1.2	365.0	0.6	-1.0	0.6	-1.0	0.8	-1.0	226	202					3	
CLI18J9																							No data

Code	Ct DataHrs	CtPts	CtMax	CtMin	CtAvg	Hi10Ct	Hi30Ct	Temp Rise	Max Storage	Hi 10Inc	Hi 10Dec	Hi 30Inc	Hi 30Dec	Hi 60Inc	Hi 60Dec	Ct360-370	Ct370-376	Ct376-382	Ct382-388	Ct388-394	Ct394-400	CtBad-Missing	Ct comment
DAR23J9	10.7	649	37.8	36.9	37.3	37.7	37.7	0.9	228.0	0.5	-0.4	0.6	-0.4	0.6	-0.4	569	35					5	
DIS09J9	10.1	659	38.6	36.3	37.3	38.6	38.5	2.3	651.0	0.6	-0.5	0.8	-0.9	1.1	-1.4	309	123	34				55	
DJO28J9																							
DKE23J9	8.4	673	38.5	37.3	37.7	38.5	38.4	1.2	460.0	0.3	-0.5	0.6	-0.6	0.9	-0.7	113	283	62				172	
GRI15J9																							No data
KHU17J9	10.3	674	38.2	37.0	37.4	38.1	38.1	1.2	317.0	0.3	-0.3	0.6	-0.4	0.8	-0.6	282	217					57	
LBE23J9	9.9	676	38.1	36.9	37.5	38.0	38.0	1.2	439.0	0.5	-0.4	0.7	-0.4	0.7	-0.7	343	206					81	
MCA19J9																							No data
MPA18J9																							No data
RSV19J9	10.7	669	38.2	37.3	37.8	38.2	38.1	0.9	308.0	0.4	-0.6	0.7	-0.8	0.8	-0.8	89	539	3				29	
SFA13J9																							No data
SFA18J9	7.1	533	37.8	36.2	37.2	37.8	37.8	1.6	408.0	0.6	-1.0	1.1	-1.0	1.1	-1.0	232	42					106	
SWA09J9																							No data
TAN17J9	11.0	684	38.4	37.2	37.5	38.3	38.3	1.1	355.0	0.3	-0.3	0.4	-0.5	0.8	-0.7	358	184	31				25	
THA28J9	10.4	626	37.9	36.9	37.5	37.8	37.7	0.9		0.4	-0.4	0.6	-0.4	0.6	-0.4	491	109					4	
WSH17J9	6.1	547	38.3	37.6	37.9	38.2	38.1	0.7	207.0	0.2	-0.1	0.3	-0.3	0.3	-0.3		361	5				181	

Appendix G Continuous heart rate data for target groups. Heart rates recorded every minute. HrPts is elapsed recording time, HrBadMissing is data missing or out of bounds (mins), HrDataHrs is data used in study (converted to hours). HrAvg is average value for the shift. Hi10Hr, Hi30Hr are highest consecutive 10- and 30-minute averages for the shift. Remaining columns are the number of minutes spent in specific heart rate zones (e.g. Hr80-100) is time spent between 80 and 100 bpm. "No data" indicates data collection mal-functioned, or a minimum of four hours recording time was not achieved.

Code	HrDataHrs	HrPts	HrAvg	Hi10Hr	Hi30Hr	Hr<60	Hr60-80	Hr80-100	Hr100-120	Hr120-140	Hr>140	HrBad-Missing	Hr Comment
ADA10M8	11.4	737	96	121	112		12	474	179	20		52	
ADA11M8	11.4	777	93	143	134		177	336	126	35	10	93	
AMC03M8	12.6	900	110	148	145		54	218	245	174	66	143	
ARU04M8	12.8	779	128	172	167			33	289	272	176	9	
ARU05M8	6.6	402	102	123	116		23	165	158	44	3	9	
BCO17M8	9.9	603	98	124	115		24	363	164	35	5	12	
BDO20M8	12.6	763	100	150	141		62	411	171	68	42	9	
BDO21M8	8.0	524	96	133	121		60	268	100	42	9	45	
CBU13M8	12.6	839	98	142	133		160	226	304	60	8	81	
CGA13M8	9.9	673	97	133	112		160	226	304	60	8	81	
CLI05F8	10.3	652	130	202	193		4	163	163	66	222	34	
GRI07M8	4.0	246	127	153	147		1	22	62	93	62	6	
GRI08M8	4.5	484	109	147	141	2	16	90	81	55	28	212	
HSC10M8	4.1	260	94	123	108		23	158	46	16	7	17	
HSC11M8	8.9	556	88	128	122		245	144	109	31	11	22	
JHA04M8	12.4	785	109	153	139		21	262	285	131	46	40	
JHA05M8	10.5	699	102	157	129		34	354	131	68	40	72	
JLA06M8	9.4	595	114	162	159		55	153	128	117	113	29	
JLA08M8	5.8	357	125	154	149			46	113	99	89	10	
JTA07M8	5.3	337	102	146	140	4	86	57	79	74	19	18	

Code	HrDataHrs	HrPts	HrAvg	Hi10Hr	Hi30Hr	Hr<60	Hr60-80	Hr80-100	Hr100-120	Hr120-140	Hr>140	HrBad-Missing	Hr Comment
KHU03M8	9.1	766	120	181	160	4	34	129	155	80	146	218	
LNE13M8	12.5	808	116	172	162			75	448	168	57	60	
LWE06F8	7.1	583	113	167		1	29	153	104	48	93	155	
MDU17M8	8.4	595	83	124	111		284	129	73	15	2	92	
MNO03M8													Not 4 hrs
RCL20M8	9.5	605	85	114	106		256	227	86		1	35	
RCL21M8													No recording
RSM04M8	13.0	785	135	175	171		3	15	190	272	300	5	
RSM05M8	12.2	751	117	146	140		1	113	312	264	43	18	
SSM20M8	10.1	690	115	158	153		14	211	138	134	109	84	
SSM21M8													Not 4 hrs
TAN10M8	11.5	774	85	118	98		335	252	87	14	3	83	
TAN11M8	10.7	727	87	135	122		314	206	89	22	13	83	
TMA17M8	8.5	598	115	145	132		2	128	199	126	56	87	
AGL13J9	4.6	293	89	142	133		132	87	29	17	12	16	
BCA28J9	11.0	659	85	139	126		303	268	66	17	5		
BRE15J9													Not 4 hrs
BRO19J9	10.6	671	103	147	130		16	314	231	64	13	33	
CBU09J9													Not 4 hrs
CLI13J9	8.0	516	100	122	114		27	249	157	40	7	36	
CLI18J9	8.8	526	123	170	161			99	200	89	138		
DAR23J9	11.1	666	93	129	119	1	121	388	113	30	12	1	
DIS09J9	11.0	672	100	133	127		90	304	159	81	25	13	
DJO28J9	9.2	631	97	135	112		72	309	125	27	20	78	

Code	HrDataHrs	HrPts	HrAvg	Hi10Hr	Hi30Hr	Hr<60	Hr60-80	Hr80-100	Hr100-120	Hr120-140	Hr>140	HrBad-Missing	Hr Comment
DKE23J9	10.9	671	100	137	131		86	274	196	80	20	15	
GRI15J9	8.2	497	96	137	122		54	286	106	30	15	6	
KHU17J9	10.9	670	96	130	121		112	307	173	52	10	16	
LBE23J9	10.9	676	104	142	127		38	274	243	75	23	20	
MCA19J9	11.2	691	94	134	126		212	253	121	72	13	20	
MPA18J9	8.7	524	115	164	152		3	138	222	88	73		
RSV19J9	10.8	668	111	144	136		6	212	228	152	49	21	
SFA13J9													Not 4 hrs
SFA18J9	8.8	530	106	165	153		23	251	127	78	46	5	
SWA09J9	4.4	274	98	116	106		26	139	79	15	4	11	
TAN17J9	4.3	418	115	161	157		4	187	155	72	100	163	
THA28J9	9.7	624	93	118	108		47	414	101	9	10	43	
WSH17J9	9.3	677	105	122	118			155	381	24		117	
ADA09A8	6.8	436	111	145	124			89	245	49	26	27	
AMC03A8													Not 4 hrs
ARU05A8	12.0	722	121	168	158			68	346	209	94	5	
BDO07A8	6.7	410	87	111	97		131	231	36	2	1	9	
BLO31M8													No recording
BRO07A8	8.5	570	98	121	112	1	40	287	138	39	4	61	
CBU06A8	8.7	566	86	118	111		256	169	74	15	6	46	
CLI30M8													Not 4 hrs
CMU03A8	8.2	544	98	180	130	2	125	192	85	42	45	53	
CSU10A8	8.8	613	98	162			85	266	111	27	38	86	
DIS05A8	9.9	609	105	154	130			282	173	97	29	18	

Code	HrDataHrs	HrPts	HrAvg	Hi10Hr	Hi30Hr	Hr<60	Hr60-80	Hr80-100	Hr100-120	Hr120-140	Hr>140	HrBad-Missing	Hr Comment
GHA09A8	8.3	543	127	168	159			32	208	105	152	46	
HSC09A8													No recording
JHU05M8	7.5	589	81	110	81		270	126	47	4	2	140	
JHU10A8	7.8	599	109	142	127		3	174	185	92	12	133	
JLA31M8	7.3	474	100	125	114		20	230	144	40	2	38	
JTA02A8	5.5	346	102	146	140	4	89	63	79	74	19	18	
LNE06A8	8.8	571	94	126	104		51	336	115	21	2	46	
MNO03A8	9.0	553	108	135	129			202	224	104	8	15	
MPA30M8	7.3	461	105	143	127	1	12	182	168	56	18	24	
RCL02A8	7.2	444	76	103	86		332	79	17	1	0	15	
SSM07A8	8.5	542	104	130	115		1	222	241	40	6	32	
SWA06A8	9.0	571	93	134	125		150	222	115	47	4	33	
TMA31M8	7.5	461	106	141	124			208	153	71	18	11	
WAG02A8	7.8	468	90	132	114		138	241	64	17	8	0	

Appendix H Cycle ergometer steady state heart rate and end of shift lactic acid values for target groups

Code	Heart rate, start of shift test, bpm	Heart rate, mid shift test, bpm	Heart rate, end of shift test, bpm	Lactic Value end of shift, mmol.l^{-1}
AGL13J9	116		107	2.2
BCA28J9	109		124	low
BRE15J9	120		132	0.8
BRO19J9	124		129	low
CBU09J9	115		136	
CLI13J9	135		138	0.8
CLI18J9				0.8
DAR23J9	131		127	low
DIS09J9	143		132	
DJO28J9	114		125	1.5
DKE23J9	135		135	1
GRI15J9	117		118	3.1
KHU17J9	137		131	low
LBE23J9	123		123	low
MCA19J9	130		124	1.2
MPA18J9	133		141	low
RSV19J9	144		144	1.2
SFA13J9	122		126	1.2
SFA18J9	126		145	
SWA09J9	127		143	
TAN17J9	127		136	0.8
THA28J9	98		110	2
WSH17J9	127		132	low
ADA09A8	125	146	138	

Code	Heart rate, start of shift test, bpm	Heart rate, mid shift test, bpm	Heart rate, end of shift test, bpm	Lactic Value end of shift, mmol.l^{-1}
AMC03A8	115			
ARU05A8	114	130	125	
BDO07A8	114	117	118	
BLO31M8	150	140	145	
BRO07A8	126	130	126	
CBU06A8	110	120	112	
CLI30M8	150	146	143	
CMU03A8	125	160	145	
CSU10A8	112	132	116	
DIS05A8	145	163	142	
GHA09A8	140	165	141	
HSC09A8	110	125	112	
JHU05M8	115	116	116	
JHU10A8	140	149	156	
JLA31M8	132	125	125	
JTA02A8	134	132	132	
LNE06A8	130	141	135	
MNO03A8	133	130	137	
MPA30M8	113	128	141	
RCL02A8	105	105	110	
SSM07A8	128	136	130	
SWA06A8	125	140	135	
TMA31M8	152	151	141	
WAG02A8	152	143	158	

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Published and Accepted Papers

Deep Body Core Temperatures in Industrial Workers Under Thermal Stress

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To date, no field study has continuously monitored the deep body core temperatures of industrial workers. A program to continuously measure deep body core temperatures in 36 industrial workers working 10-, 12-, and 12.5-hour day and nightshifts in a hot, deep, underground mine in the Tropics was conducted. No heat illness occurred in these workers during the study. Miniaturized radio-transponders ("pills") taken orally were used to measure temperature during the transit time in the gastrointestinal tract. Commonly recommended limits for industrial hyperthermia are 38.0°C, or an increase of + 1 °C. The results showed that miners regularly exceeded these limits in terms of maximum deep body core temperature (average, 38.3°C; standard deviation, 0.4°C), maximum temperature rise (1.4°C, 0.4°C), and maximum heat storage (431 kJ, 163 kJ) without reporting any symptoms of heat illness. A significant component of the observed elevated core temperatures was attributable to the normal circadian rhythm, which was measured at 0.9°C (standard deviation, 0.2°C). Evidence was found that workers "self-pace" when under thermal stress. (J Occup Environ Med. 2002; 44:125–135)

Excessive heat strain in the workplace can lead to a continuum of medical conditions, with symptoms ranging from headache and nausea to vomiting, syncope, and more severe central nervous system disturbances. The most severe form of heat illness is heat stroke, which, if untreated or sufficiently severe, can lead to death and frequently leads to permanent tissue damage. One subclass of heat illness (heat exhaustion) has been shown to have a clear clinical profile' and is relatively common in the mining industry. This condition may well have been underreported in other industries during periods of high ambient temperature. The principal pathophysiological factor responsible for heat illness is hyperthermia, due to an extreme environment (high ambient temperatures), high metabolic loads (strenuous physical work), a reduction in heat rejection capability (vapor barrier or heavily insulating protective clothing) or any combination of these. In addition, it can be hypothesized that the rate of increase in deep body core temperature is an additional potential factor in the development of heat illness.[2,3] Circulatory insufficiency, which results from an excessive call on cardiac output to transport heat from the deep body core to the skin, and dehydration due to inadequate replacement of fluids lost in sweat, are factors that frequently lead to hyperthermia and, possibly, heat exhaustion. To date, no major field study has been conducted to continuously document the actual core temperature of workers in hostile environ-

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ments. Such a study would better define the relationship between environmental heat stress and the physiological strain on the worker. In addition, it would allow the validation of currently recommended limits for the prevention of occupational hyperthermia.

These recommend limits generally fall into one of three categories:

- Limiting (maximum) deep body core temperature, with a typical limit being 38°C or 38.5°C.[4–10]
- Limiting (maximum) increase in deep body core temperature, with a typical limit being 1°C.[4,5]
- Limiting (maximum) heat storage in the body, with a typical limit being 60 watts/hour/meter^2 for acclimatized workers (50 watts/hour/meter^2 for unacclimatized workers).[11,12] These figures translate to 389 kJ and 324 kJ of heat storage, respectively, for "standard" individuals with 1.8 m^2 skin surface area.

Frequently, these governing authorities advise evaluating the thermal stress by using two or more of these criteria and using the most conservative as the relevant limit. Some of these indices are extremely difficult to monitor as prescribed. For example, to administer a workplace using the IS07933 standard, a range of environmental parameters must be monitored continuously near each worker, an assessment of metabolic rates and clothing ensemble (including personal protection equipment) is required, and exposure limits and times must be calculated and then weighted to find the overall allowable exposure.

Apart from the technical difficulties, there are a number of other complications in measuring and setting limits for industrial hyperthermia.

- In practice, the temperature of the important deep tissues in the body of any particular individual at any given time varies within about a 0.5°C range, even when at rest in thermoneutral conditions (conditions of no heat strain).[13] The temperature can be estimated by a number of methods, including sublingual, tympanic, rectal, esophageal, and gastrointestinal. There is no broad acceptance of a single superior site within the body as defining, from a physiological point of view, a critical "core" temperature.[14–18] However, because of the crucial role of the blood in collecting heat from the core and transmitting it to the skin, where the heat can be rejected, esophageal temperature (measured at about the level of the heart) is considered a very close indicator of the temperature of blood leaving the heart and is, therefore, probably the most valid single indicator of deep body core temperature. Unfortunately, esophageal temperature can be safely measured only in a laboratory.
- Even when unstressed, the "average" temperature of deep body tissues can differ by up to 1°C for different individuals, indicating that a range rather than a single set value exists for humans.[13,19]
- There is a daily (circadian) rhythmicity, which includes temperature, for virtually every organ of the body.[20] The "average" deep body core temperature can vary diurnally by 1°C or more for any individual,[14,18] even when unstressed and in thermoneutral conditions. For resting, thermoneutral conditions, deep body core temperature is at its lowest at about 4 AM and at its highest at about 6 PM. This daily variability has practical consequences when attempting to set limits for night-shift workers or workers on extended shifts.
- There is also a periodic change of about 0.5°C in the overall deep body core temperature associated with menstrual periods.[21,14,18]

In the past, most information about deep body core temperatures has been obtained using rectal thermometers or transducers. For safety reasons associated with manual handling and mobile workers, this has effectively prevented the continuous measurement of core temperatures in actual work environments; the insertion of rectal probes also generally meets with strong resistance from workers. Therefore, the rectal measurements that have been taken intermittently in field studies are unlikely to have captured the full temperature response in the body, particularly when environmental conditions or work rates have varied significantly with time.

For this reason, only modest amounts of reliable information on continuous temperatures are available from field studies. Extrapolation of laboratory work to occupational settings is generally prone to some error and uncertainty because of the very different environments involved, the artificial nature of the laboratory setting, and the interaction of the experimenter with the subject.[22]

Improved information on deep body core temperatures of occupational workers in their work environment would, therefore, assist significantly with the development of appropriate heat stress indices and protocols. The information needed for these decisions can be grouped as follows:

- What upper values of core temperature are reached regularly and safely in a typical thermally stressful workplace where workers are self-pacing?
- What is the time duration over which elevated core temperatures prevail?
- What is the rate at which core temperatures increase and decrease?
- Is heat exhaustion likely to be related to hyperthermia, or to something else, eg, hypohydration?
- What is a safe and realistic core temperature increase for workers on 12-hour shifts when the workday comprises a significant proportion of their overall circadian cycle?

Background and Methods

This article reports a field investigation to measure the deep body core temperatures (hereafter "core temperatures") using gastrointestinal pills with radio-transponders to investigate the above questions and make recommendations.

All subjects were industrial workers habitually exposed to heat stress in a hot, deep underground mine located in the Tropics and were therefore considered to be acclimatized. All in the target group worked 10-, 12-, or 12.5hour shifts.

The clothing ensemble consisted of long cotton trousers and short or long sleeved shirts, safety boots, safety helmet, and eye protection. Where the environment was dusty or noisy, a face respirator or noise protection was also worn. On occasion, elbow-length impermeable gloves, a rubber apron, and a visor clipped to the safety helmet were worn. However, the workforce was highly mobile, and some work was conducted from within air-conditioned cabins of mobile equipment. Therefore, not all work was performed in hot conditions or was physically strenuous. All lunch breaks were taken in air-conditioned lunchrooms.

Because all workplaces were at a vertical depth of between 1000 m and 1600 m below the surface, and because of the considerable thermal damping effect as air traveled from the surface to the worksites, no significant change in environmental conditions occurred in the workplace between day and night.

The study was conducted over two summers, with a major change to the existing working-in-heat protocols occurring between the summers. The earlier protocol relied heavily on the shortening of the work shift to 6 hours when environmental conditions exceeded approximately 32°C wet bulb globe temperature for more than 2 hours. The shortened shift had been in operation since 1942. The new protocol removed the short shift, increasing exposure times to 12 hours and instituting a graduated management response based on a new thermal stress index called Thermal Work Limit.[23] The experiments were designed, in part, to ensure that the introduction of the new protocols and longer shift lengths did not compromise the workers' health.

The workers were all relatively well informed about the issues related to working in heat, and they worked mostly in self-paced arrangements. No cases of heat stroke had been reported to the 24-hour on-site medical clinic during over 10 million work shifts at temperatures exceeding 28°C wet bulb temperature and 36°C dry bulb temperature from 1966 to 1997.[24] Workers are not generally subject to any regular form of health screen, apart from a preemployment medical and ongoing chest radiographs and blood-lead testing. With self-pacing, the work rate reduces as workplace temperatures increase; therefore, hyperthermia in a self-paced setting is generally due to exposure to extreme thermal environments (exogenous heat) rather than high metabolic loads (endogenous heat). There are significant physiological differences between internal and external heat loads. Internally generated heat loads must be transported by the cardiovascular System to the skin for rejection to the environment, whereas external heat loads can be rejected directly from the skin by evaporation of sweat, with substantially less strain on the cardiovascular system.[17,25,26]

Although mild-to-moderate forms of heat illness do occur in this context,[1,27] none of the participating workers developed heat illness during the course of the study. The fact that such a large number of work shifts have been worked in extreme conditions without a recorded case of heat stroke also indicates that the risk of serious heat illness is low.

Core temperature monitoring equipment consisted of CorTemp temperature-sensing pills (HTI Technologies, St. Petersburg, FL), each with an in-built miniature radio transmitter, and BCTM ambulatory data recorders (PED [Personal Electronic Devices], Inc, Wellesley, MA). The lo-mm-long pills transmit the temperature of the surrounding tissues for their transit time in the gastrointestinal tract, typically 24 to 48 hours, and are not recovered. The manufacturer's reported accuracy of the pill is ±0.05°C. Each pill is individually calibrated during manufacture and can be set, in the field, to transmit the temperature at an interval between 5 seconds and 1 minute (1 minute in this study). Gastrointestinal temperature is considered to be more closely related to rectal temperature than to esophageal temperature[28] and, therefore, is likely to be about 0.5°C below the temperature of blood leaving the heart and diffusing through the body core.[29] However, rectal temperatures have the advantage of being directly comparable with numerous historical studies, which invariably measured core temperatures rectally.

The study was conducted on 36 male workers, who comprised the target group. All participants gave their written, informed consent to a series of studies that had ethics committee approval. The target group was selected from the rest of the workforce on the basis of highest relative exposures to environmental heat and highest relative work rates.

A control group of six office workers (all male, all day shift), working in the same operation but in sedentary jobs in an air-conditioned office (typically 24°C, 50% relative humidity), was also tested. They were heat-unacclimatized in comparison with the target group.

Because of the travel time required to get from the surface to the workplace and back again, the actual work time on the job was typically 7.5 hours for 10 hour shifts and 9 hours for 12 hour shifts. Workers on 10-hour shifts took one meal break per shift; those on the longer shifts took two meal breaks per shift.

Environmental conditions were measured at each workplace approximately every 60 minutes using a Heat Stress Meter,[30] which provided digital readouts of ventilated wet bulb temperature, dry bulb temperature, wind speed, globe temperattire, calculated mean radiant temperature, barometric pressure and wet bulb globe temperature (WBGT). WBGT was evaluated in accordance with the guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH).[4]

Core temperature data were collected on day shift, night shift, and, for some individuals, for work conducted over 2 consecutive day or night shifts, along with "recovery/resting" core temperatures between shifts. For each individual shift, and for the aggregated data, the following was calculated:

- maximum, minimum, and average shift values, and highest 10 and 30 consecutive minute averages
- duration of time spent in the following core temperature zones ("C): 36 to 37, 37 to 37.6, 37.6 to 38.2, 38.2 to 38.8, 38.8 to 39.4, 39.4 to 40
- core temperature rise during the shift (defined as the difference between maximum and minimum temperatures during the shift)
- calculated maximum heat storage in the body (defined as the temperature rise multiplied by the average thermal capacity of body tissue multiplied by the body weight)
- highest 10-, 30-, and 60-minute temperature increase and decrease during the shift, which indicated the rate at which the body underwent thermal strain, and the rate at which the strain attenuated, respectively.

TABLE1
Target Group*

	Age (yrs)	Height (cm)	Weight (kg)	BMI	$\dot{V}O_{2max}$ (mL/kg/min)
n	31	31	32	38	19
Max	52	198	125	33	47.4
Min	24	163	65	23	31.1
Avg	35.4	179.4	88.8	27.5	37.7
SD	7.56	8.36	13.96	2.77	4.67

* BMI, body mass index; i/O,,,,, maximum oxygen consumption, SD, standard deviation.

TABLE 2
Environmental Conditions in the First and Second Summers, After Changes to Working-in-Heat Protocols*

	WBGT ("C)		TWL (watts/mete?)	
	1st Summer	2nd Summer	1st Summer	2nd Summer
n	164	186	164	186
Avg	30.78	30.94	178	174
SD	1.729	2.144	41.7	44.9
Max	36.9	35.2	286	276
Min	26.8	25.7	81	83

* WBGT, wet bulb globe temperature; TWL, Thermal Work Limit; SD, standard deviation.

Only data sets with more than 4 hours of core temperature data were considered in the analyses. All statistical tests were based on the unpaired, two-tailed *t* test, assuming equal variances, unless otherwise noted.

Results

A summary of the anthropometric, body structure, and maximum oxygen consumption ($\dot{V}O_{2max}$) data of the subjects in the target group is shown in Table 1.

A total of 350 environmental observations (Table 2) were taken (excluding observations when workers were inside air-conditioned areas and therefore not under thermal stress). The average workplace WBGT temperature in the first summer with the former protocols was not significantly different (WBGT: $P = 0.38$; Thermal Work Limit: $P = 0.44$) to that of the second summer with the revised protocols. Fifteen observations (4%) exceeded 32" wet bulb temperature.

A total of 38 sets of core temperature data were obtained from the target group, comprising 22 sets from the first summer and 16 from the second summer. The two sets of data were compared on the basis of average and maximum shift values over the two summers.

The average shift value (± standard deviation [SD] and range) for the first summer was 38.4°C (SD, 0.50°C; range, 37.7" to 39.5°C), and for the second summer, 38.2°C (SD, 0.31°C; range, 37.8" to 38.8°C); the difference was not significant ($P = 0.26$).

The maximum shift value for the first summer was 37.65°C (SD, 0.45°C; range, 37.0" to 38.9°C), and for the second summer, 37.58°C (SD, 0.22°C; range, 37.2" to 38.0°C); the difference was not significant ($P = 0.55$).

The total recorded time over the 38 shifts was 413 hours. Gaps in the record set, or invalid data, constituted a total of 35 hours, or 9% of the total elapsed time.

The results for the pooled core temperature data from both summers are summarized in Table 3 for the target group and Table 4 for the control group.

Figures 1 and 2 show core temperature traces for shiftworkers in the target group, whereas Fig 3 shows a trace for an office worker in the control group. Note some examples of gaps in the data set.

Discussion

For clarity, the SDs and ranges of values are listed in either the tables or the text but not both. Neither the WBGT nor the Thermal Work Limit in the workplace changed significantly from one summer to the next; it was concluded that the level of

TABLE 3

Deep Body Core Temperature of 36 Male, Underground Miners (the Target Group) Measured Continuously Over 38 Shifts*

	Max °C†	Min °C	Avg °C	Highest 10 Consecutive Mins (avg, °C)	Highest 30 Consecutive Mins (avg, °C)	Max Temp Increase Over Shift (°C)	Max Heat Storage Over Shift (kJ)	Highest 10-Min Increase (°C)	Highest 10-Min Decrease (°C)	Highest 30-Min Increase (°C)	Highest 30-Min Decrease (°C)	Highest 60-Min Increase (°C)	Highest 60-Min Decrease (°C)	
n	38	35	38	38	38	35	32	35	35	35	35	35	35	
Max	39.5	37.7	38.9	39.4	39.4	2.3	942	1.3	−0.1	1.5	−0.3	1.5	−0.3	
Min	37.7	36.0	37.0	37.7	37.5	0.7	166	0.2	−1.2	0.3	−1.3	0.3	−1.4	
Avg	38.3	36.9	37.6	38.3	38.2	1.4	431	0.5	−0.5	0.8	−0.7	0.9	−0.8	
SD	0.4	0.4	0.4	0.4	0.4	0.5	163	0.2	0.3	0.3	0.3	0.3	0.3	
Temperature range (°C)								36.0–37.0	37.0–37.6	37.6–38.2	38.2–38.8	38.8–39.4	39.4–40.0	>40.0
% of time								29	43	18	5	2	0	0

* The thermal capacity of the body,[12] used to calculate the maximum heat storage, is taken as $3.49\ kJ^{0}C^{-1} \cdot kg^{-1}$.

† For example, the intersection of the Max column and the Max row is the highest core temperature recorded on any shift in the study. The intersection of the Max column and the Avg row indicates the average over all data sets of the maximum individual core temperatures recorded during each shift in the study. The intersection of the Max column and the Min row indicates the lowest single maximum core temperature reached on any shift during the study, etc.

heat stress exposure had not changed.

The maximum and average core temperatures also had not changed significantly from one summer to the next; it was concluded that the new working-in-heat protocols had not changed the level of hyperthermia. The core temperature data was therefore pooled for further analysis.

When recommending safe core temperature limits from this study, it would be misleading to consider only the average upper values measured. For example, some workers were allocated jobs in which they were under little thermal stress for the shift (their upper core temperature was low); this is supported by Table 3, which shows that the highest core temperature recorded by one worker was only 37.7% Because no worker reported symptoms of heat illness during the study and environmental conditions included a range of temperatures, not all workers reached their maximum safe individual core temperature during the shift. It is hypothesized that a realistic upper limit from this data is probably about 1 SD above the measured group averages. However, more conservative approaches might be to consider the safe limit as being the value that was *not* exceeded by 95% of workers, or to consider the safe limit to be the value that was exceeded by at least (for example) 20 workers. The values based on 1 SD above the average are reported in italics in the following discussion, and comments regarding the alternate approaches are provided when relevant.

Control Group

The most significant feature of the control group is a 0.9°C (1.2”) average core temperature increase during the work shift. Because the control group was sedentary and thermally unstressed, this increase was probably caused by diurnal variation in core temperature over this period, This value was close to the International Labour Organisation[31] recom-

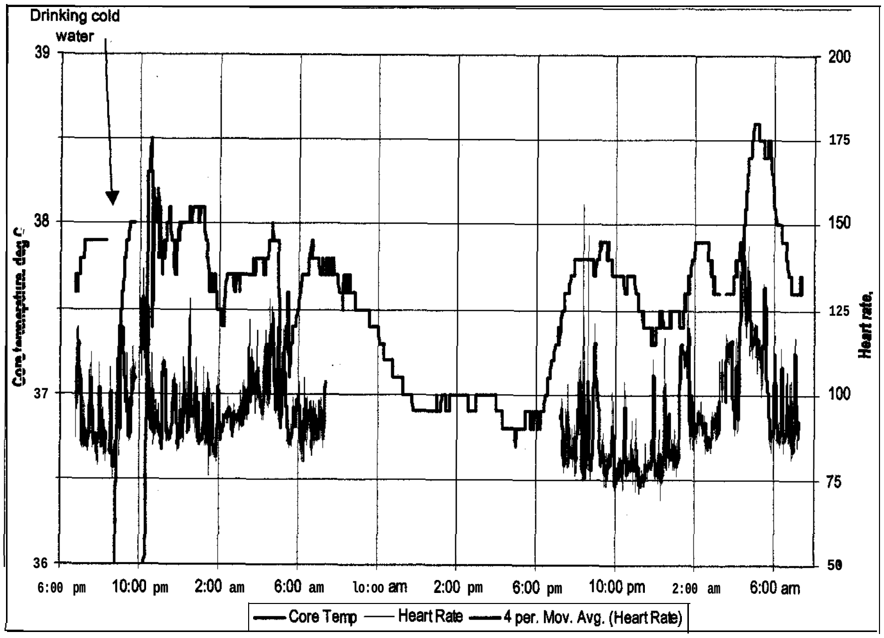

Fig. 1. Core temperature ("C), heart rate (bpm), and (trailing) 4-minute moving average heart rate for subject working two consecutive 12-hour night shifts. Note the drinking of cold water after 8 AM.

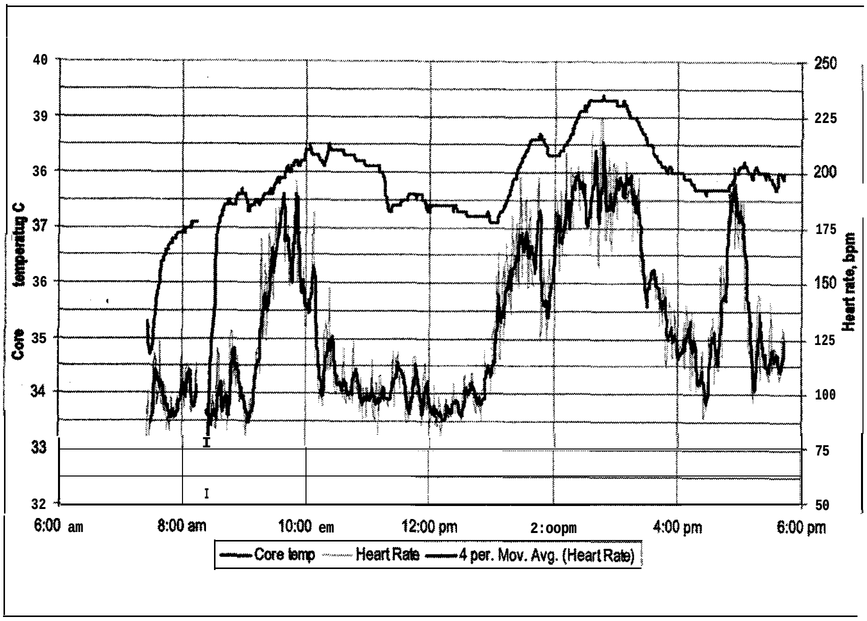

Fig. 2. Core temperature ("C), heart rate (bpm), and (trailing) 4-minute moving average heart rate for subject working lo-hour day shift. Note the drinking of cold water after 8 AM.

mended core temperature rise for acclimatized workers of 1°C, with almost 50% of workers exceeding the International Labour Organisation value without physical exertion or heat stress. Note that these values do not reflect the *full* 24-hour diurnal variation in core temperature (including the sleeping period), but rather only diurnal variation from about 6:30 AM to the end of the workday (typically between 5 PM and 6 PM). The full diurnal variation was found to be larger than this, as can be seen in Figs. 1 and 3. If the 24-hour circadian rhythm increase by itself

TABLE 4

Deep Body Core Temperature of a Control Group of 10 Male Mine Workers, All Employed in Sedentary Work in Air-Conditioned Offices, Measured Continuously*

	Max °C†	Min °C	Avg °C	Highest 10 Consecutive Mins (avg °C)	Highest 30 Consecutive Mins (avg °C)	Max Temp Increase Over Shift (°C)	Highest 10-Min Increase (°C)	Highest 10-Min Decrease (°C)	Highest 30-Min Increase (°C)	Highest 30-Min Decrease (°C)	Highest 60-Min Increase (°C)	Highest 60-Min Decrease (°C)
n	10	10	10	10	10	10	10	10	10	10	10	10
Max	37.9	36.9	37.5	37.8	37.8	1.2	0.7	−0.1	0.8	−0.1	0.8	−0.3
Min	36.9	36.0	36.5	36.8	36.8	0.6	0.2	−0.5	0.3	−0.5	0.4	−0.7
Avg	37.6	36.5	37.1	37.4	37.4	0.9	0.4	−0.3	0.5	−0.4	0.6	−0.4
SD	0.3	0.3	0.3	0.4	0.4	0.2	0.2	0.1	0.2	0.1	0.2	0.1

* This group wore the core temperature monitor day and night for up to 3 days and 2 nights (see Fig. 3). Ten sets of "day shift" results were obtained, comprising six sets on the first day, and four sets on the second day. The control subjects were not weighed, so heat storage figures were not calculated for this group.

† For description of the row and column headings, refer to Table 3.

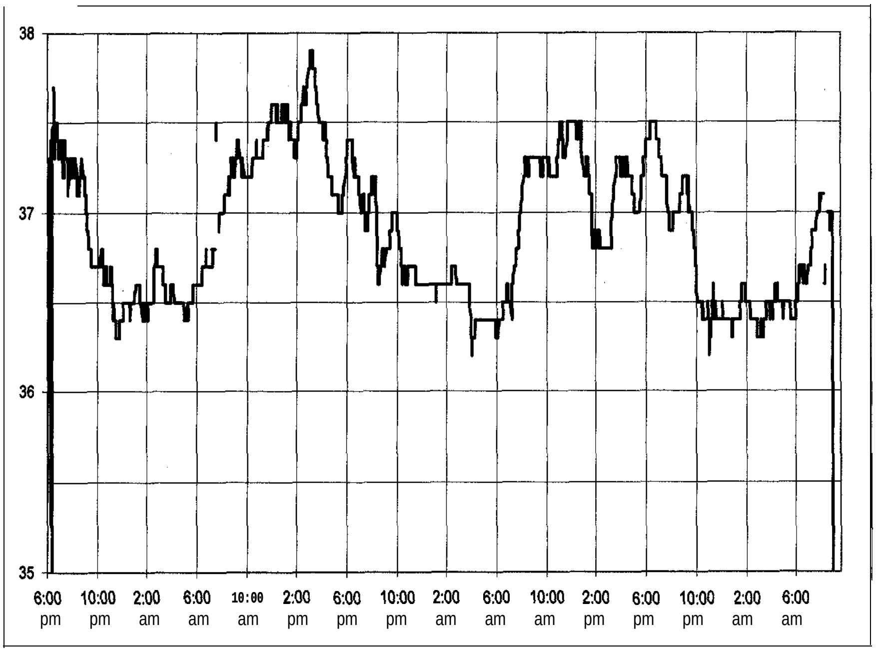

Fig. 3. Core temperature (°C) data for control group (non-stressed) subject. Recording period covers 3 nights and 2 days.

can meet or exceed the allowable core temperature increase due to thermal stress, then it is likely that the recommended allowable increases are too low, certainly for 12-hour shift workers.

Target Group

The average body mass index (27.5) of the target group (Table 1) is in the middle of the "overweight" range of 25 to 30 kg/m^2 as designated by the World Health Organization.[32] The average $\dot{V}O_{2max}$ (37.7 mL/kg/min) is outside the normal range (39 to 48 mL/kg/min) for non-athletes aged 30 to 39 years.[33] The target group was typical of industrial workers in this operation. A test of 469 contract employees joining the organization for project work under similar levels of heat stress during this period had a measured $\dot{V}O_{2max}$ of 39.0 mL/kg/min (SD, 7.8 mL/kg/min) and a body mass index of 25.9 (SD, 5.4).

The average maximum core temperature during the shift was 38.3" (38.7°), which exceeds the ACGIH recommended value of 38.0" (although the 2000 TLVs provide for a core temperature of 38.5" for medically selected, acclimatized workers). Two workers exceeded 39°C (being 39.4" and 39.5°, respectively; one is shown in Fig 2). These figures are broadly in line with the findings of others, who have reported the core temperature limit for moderately fit industrial workers, prior to collapse or withdrawal, as being in the range of 39.0" to 39.5°C[26,32–36] Trained athletes have been found to continue without ill effects at core temperatures in excess of 40°C.[37–39] The fact that these data were measured on workers with a wide range of age, body mass index, and $\dot{V}O_{2max}$ in the ordinary course of their work activities, and who reported no heat illness, questions the validity of using 38.0°C as an absolute limit for industrial workers. However, if a safe limit were to be based on the 5th percentile from this study, the limit would be approximately 37.8°C; if based on the safe level achieved by 20 workers, it would be approximately 38.2°C. Both limits are within the most recently recommended ACGIH limits for screened and acclimatized workers.

The highest 10- and 30-consecutive-minute averages, maximums, and minimums were all very close to the l-minute (single reading) values. This indicates that workers plateau near the maximum temperature for that shift and remain there for some time.

The average increase in core temperature (or the core temperature working ***reserve,*** defined here as the maximum reached in the shift minus the minimum reached) was 1.4°C (1.9°C), compared with the IS0 recommended maximum of 1.0°C for acclimatized workers. Note that 26 (68%) of the 38 sets were for workers on 12- or 12.5hour shifts; of these 26 sets, 19 were for the day shift. The average increase of 1.4°C is in accordance with the findings of Rastogi et al,[40] who found an average core temperature increase of 2.2°F (1.2°C) for industrial workers, with one group averaging an increase of 2.5°F (1.4°C).

If gastrointestinal temperatures are, in fact, 0.5°C lower than esophageal temperatures, then the "core" temperatures found in this study, which were already higher than the generally recommended values, would be even higher. This highlights the importance of defining when, where, and how core temperatures are to be defined in setting future occupational limits.

The average heat storage (defined as the calculated maximum minus minimum heat content of the body during the shift) was 431 kJ (594 *kJ)* compared with the IS0 recommended value of 389 kJ for acclimatized workers.

The average maximum increase in core temperature was 0.5°C (0.7°C) in 10 minutes, 0.8°C (1.1°C) in 30 minutes, and 0.9°C (1.2°C) in 60 minutes. The average maximum decline in core temperature for the three time periods were 0.5" (0.8°C), 0.7" (1.0°C), and 0.8" (1.1°C), respectively. Individual increases in core temperature of up to 1.3°C in 10 minutes, and up to 1.5°C in 30 minutes, were recorded. The significance of the rate of increase or decrease in core temperature for industrial workers is not known, but it has been speculated that the rate of increase and/or the duration of the hyperthermia may be important factors in developing heat illness, in addition to the actual core temperature reached.[2]

The relatively rapid increase and decrease in core temperature could explain why intermittent rectal temperature measurements in the past during other field studies might not have caught the true maximum temperatures reached. Most laboratory studies, on the other hand, have used "steady-state" or slowly changing heat stress, which is not likely to reflect modern industrial work patterns.

The distribution of temperatures during the work shift indicated that temperatures above 38.2°C were only exceeded about 7% of the time. Temperatures over 38.8°C were infrequent to rare. Acclimatized, self-paced workers are therefore unlikely to voluntarily exceed core temperatures of about 38.8°C. Given the wide range of environmental conditions, body structure, aerobic capacity, and work rates in this study, this is strong evidence that workers are able to self-pace when they are properly trained and supported by their management. The fact that the incidence of heat exhaustion and stroke is more prevalent in the military, in which work is frequently externally paced, also supports this conclusion.

It also seems that authorities charged with responsibility for developing standards or advisory guidelines on occupational heat stress assume that a single measuring site for "deep body core temperature" exists, and that this measure has a single value rather than a range of values. This is certainly the case with the ACGIH TLV and IS0 7933, which refer to, but do not define, "deep body temperature."

One of the reasons several authorities have advised the adoption of the cautious limits of 38°C or an increase of 1°C is that this modest limit is needed to cover the wide range of interindividual variances. However, artificially restrictive limits are created if these limits are then used as ceiling values to trigger withdrawal of personnel under medical surveillance. Where these limits are used to develop heat stress indices and protocols, this study shows that they would lead to unnecessary conservatism for self-paced workers who have, by definition, the ability to reduce their work rate or to withdraw from conditions when they feel unnecessarily stressed.

Given the exposure to very hot conditions in this workforce of about 2000 underground miners over a period of at least 50 years, it is perhaps surprising that there have been no recorded incidents of heat stroke, a conclusion that can be made with reasonable confidence, as a 24-hour medical clinic with attending occupational physicians is on-site. The most likely reasons for this record include the following:

- The workforce, especially the target group that habitually works in the heat, is reasonably well-educated about the affects of working in heat.
- The surface climate is hot, and workers are at least partly acclimatized by living in this climate.
- Workers typically work by themselves or with one, or at most two, regular coworkers. Older workers typically "mentor" new workers with advice about suitable work paces and breaks. This situation differs from occupational settings in which the work rate is externally paced.
- Because of the geographical spread of workers, work is typically conducted with no on-the-job supervision. Supervisors usually visit each workplace twice each shift, for about 10 minutes each visit.
- The workforce is relatively unfit (compared with athletes). Others have found that relatively unfit workers are likely to suffer heat exhaustion that is self-limiting, resulting in voluntary withdrawal or collapse, before serious hyperthermia is incurred.[41–43]

It should not be concluded from the above that this industrial operation is inefficient. Productivity is within good practice levels of other similar operations in the Western world. Workers are well paid, and there is a production-based incentive component (typically about 25%) in their earnings.

Indications of the impact of lower core temperatures experienced by workers on night shift (due to normal circadian rhythm) can be seen Fig. 1. This additional core temperature reserve at night compared with daytime work could help explain why Donoghue et al' and Cabanac[44] found that workers exposed to heat stress on day shifts were statistically more likely to develop heat illness than workers on night shifts. The threshold for sweat onset is also lower at night than during the day.[45]

Note that 26 of the 38 data sets from the target group were from workers on 12- or 12.5-hour shifts. This roster requires only two 12-hour night shifts to be worked, so that the resetting of the circadian clock would not occur to any significant extent over the course of this roster.[46] If subjects worked long rosters of consecutive night shifts, then the circadian clock would reset and the natural increase in core temperature working reserve at night would no longer exist.

The close correlation between heart rate and core temperature, when under thermal stress, can be seen in the Figs. 1 and 2. This confirms what others[16,47,48] have found as to heart rate being a reasonable indicator of overall physiological and psychological strain, and it opens the possibility of using widely available ambulatory heart rate monitors to continually assess hyperthermia in industrial workers.

It should be noted that the widespread adoption of WBGT as an index of thermal stress was historically driven by two important factors:

- It was seen as a proxy for Corrected Effective Temperature, which at its inception (1957) was the most widely used heat stress index for occupational use.[17]
- It could be measured directly by an instrument that could be made sufficiently small and robust to be used in the field.

Neither of these assumptions is now true, with widespread recognition of weaknesses in both Corrected Effective Temperature and WBGT as indices of thermal stress,[40,48–51] and the development of microprocessor-based instruments that can measure and compute more complex physiological models than the WBGT instruments.[30]

Note that the principal source of heat strain for these workers is the environmental heat load rather than an internally produced heat load due to heavy metabolic rates. As discussed earlier, this follows from the nature of self-pacing; a cool environment can allow higher work rates and therefore a higher proportion of the heat strain to be generated by internal (endogenous) loads, but as the environmental heat stress increases, self-paced workers reduce their work rates and the balance shifts, with the environmental (exogenous) load now creating most of the heat strain. Internally generated heat loads must be transported by the cardiovascular system to the skin for rejection to the environment, whereas external heat loads can be rejected directly from the skin by evaporation of sweat with substantially less strain on the cardiovascular system,[2,18,26,52] although the same sweat gland response is required as the overall heat rejection requirement from the surface of the skin is unchanged.

Conclusions and Recommendations

The gastrointestinal temperature-sensing radio-transmitting pill is an effective method of profiling the core temperature of workers in difficult occupational settings.

The rapid increase and decrease in core temperatures suggests that previous data collected in occupational settings, which are almost always from intermittent measurements taken rectally, have probably failed to give a true picture of the maximum limits reached.

The range of core temperatures measured highlights problems in existing guidelines in which neither the location nor method of measuring core temperature is specified. Moreover, current guidelines do not adequately account for circadian variability.

The current limits advocated by ISO, ACGIH, and others are possibly conservative compared with those actually experienced in heat acclimatized workers in this operation. In particular, the suggestion that a 1°C limit on the rise of core temperature due to exposure to heat is unlikely to be practical, especially for workers on 12-hour shifts, in which increases of 1°C in core temperature can be due to normal circadian rhythms alone. This is in accordance with the findings of others.[18,53]

The proposed revised upper limit of 38.5 recommended by ACGIH for medically screened, acclimatized workers seems to be endorsed by this study, with workers in the target group spending very little time at temperatures exceeding this figure, although some brief excursions did occur. However, given that no worker developed heat illness during these exposures, the need for continuous medical surveillance during the exposure, as recommended by ACGIH, is unlikely to be warranted, at least for self-paced, well-informed workers.

Workers can self-pace, as seen by the fact that this environment was frequently very stressful, with an average WBGT of 31.9°C. Nevertheless, only 7% of the time was spent with core temperatures above 38.2°C.

When workers are both educated and encouraged to self-pace, it is likely that a higher upper limit on core temperature would not result in significant heat illness problems. When workers are unable or not permitted to self-pace (eg, some military personnel), limits based on much more conservative values may be required to account for interindividual differences.

The current ACGIH limits of a 26.7°C WBGT for moderate work rates and 30.0°C WBGT for light work rates are not supported by this study, with average workplace environmental conditions being substantially above these recommended values.

Shortening the working shift to avoid hyperthermia is unlikely to be necessary for self-paced workers.

Further work is required to determine whether it is the peak core temperature reached, the rate of increase in core temperature, or the duration of the temperature excursion that results in heat exhaustion and heat illness.

It is important to recognize< that this study was conducted on acclimatized workers who were reasonably well educated about the affects of working in heat and had a measure of control over their pace of work during their work shifts. Moreover, the principal source of heat stress for these workers was generally environmental heat load rather than an internally produced heat load due to sustained strenuous metabolic rates.

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Fluid Losses and Hydration Status of Industrial Workers under Thermal Stress Working Extended Shifts

D J Brake and G P Bates

Abstract

Objectives

A field investigation to examine the fluid consumption, sweat rates and changes in the hydration state of industrial workers on extended (10, 12 and 12.5 hour) shifts under significant levels of thermal stress (WBGT>32^0 C) was conducted on 39 male underground miners.

The purpose was to assess whether workers under significant thermal stress necessarily dehydrated during their exposure and whether 'involuntary dehydration' was inevitable, as supported by ISO9866 and other authorities. Other objectives were to quantify sweat rates against recommended occupational limits, to develop a dehydration protocol to assist with managing heat exposures and to understand the role of meal breaks on extended shifts in terms of fluid replacement.

Methods

Urinary specific gravity was measured before, during and at the completion of the working shift. Environmental conditions were measured hourly during the shift. Fluid replacement was measured during the working periods and during the meal breaks.

Results

Average environmental conditions were severe (WBGT 30.9^0 C, sd 2.0^0 C, range 25.7-35.2^0 C). Fluid intake averaged 0.8 l/h during exposure (sd 0.3 l/h, range 0.3-1.5 l/h). Average urinary specific gravity at start-, mid- and end of shift was 1.0251, 1.0248 and 1.0254 respectively; the differences between start and mid-shift, mid and end-shift, and start and end-shift were not significant. However, a majority of workers were coming to work in a moderately hypohydrated state (urinary specific gravity avg 1.024, std dev 0.0059).

A combined dehydration and heat illness protocol was developed. Urinary specific gravity limits of 1.022 for start of shift and 1.030 for end of shift were selected; workers exceeding these values were not allowed into the workplace (if the start of shift limit was exceeded) or re-tested prior to their next working shift (if the end of shift limit was exceeded). A target of 1.015 as a euhydrated state for start of shift was adopted for workforce education.

Conclusions

This study found that "involuntary dehydration" did not occur in well-informed workers, which has implications for heat stress standards that do not make provision for full fluid replacement during heat exposure. Fluid replacement during meal breaks was not significantly elevated above fluid replacement rates during work time, with implications for the duration and spacing of meal breaks on long shifts. Testing of urinary specific gravity was found to be a good indication of hydration status and a practical method of improving workforce awareness and understanding of this important risk factor. Approximately 10 000 dehydration tests have been conducted under the dehydration protocol in a workforce of 2 000 persons exposed to thermal stress and has proved practical and reliable.

Key words

fluid replacement, sweat rate, dehydration, hypohydration, heat stress

Summary box:

- A combined dehydration and heat illness protocol has been developed, with recommended limits of urinary specific gravity for the start and end of a working shift.
- A majority of workers started their shift in a hypohydrated state.
- Where workers were well-informed and subject to monitoring, "involuntary dehydration" (if it is defined as a physiologically unavoidable dehydration during exposure to heat) did not occur. Whilst voluntary dehydration (inadequate or delayed thirst response) has been observed regularly in other settings, it is probably a function of poor access to water, workplace practices (particularly

a lack of self-pacing), inadequate education, or insufficient quality or palatability of water, and is neither physiologically nor psychologically inevitable.

- Whilst a meal break is important when working in heat in terms of replacing solutes lost in sweat, its role in fluid replacement for well-educated workers trained in the need for program drinking during the heat exposure may be less than has been previously considered.
- Fluid consumption rates (and hence, in circumstances where workers' hydration status is not changing, sweat rates) of up to 1.5 litres per hour occur in self-paced, acclimatised, industrial workers with typical rates varying between 0.5 and 1.1 litres per hour.

Policy implications

- Education is vital if a workforce that is exposed to significant levels of thermal stress is to come to work euhydrated, and maintain their hydration state during their work shift. Paced fluid replacement (program drinking) rather than responding to the thirst sensation is critical to maintaining hydration levels when working under thermal stress.
- Standards for occupational heat stress should not assume that workers are unable to avoid dehydration when exposed to heat, i.e. involuntary dehydration should not be implicit in heat stress standards.

Introduction

This study reports a field investigation to examine the hydration status and fluid replacement in industrial shiftworkers. All subjects were miners employed in the hottest of four deep, underground mines located within 20 km of each other well inside the tropics in northern Australia. The workers were all on 10, 12 or 12.5 hour shifts. The climatic profile [1] for the city in which these workers live consists of near-maximum summer temperatures of 41.5^0 C dry bulb (DB) and 25^0 C wet bulb (WB). The near-minimum winter temperature is 3.5^0 C DB.

The objectives of the study were:

- To determine whether workers dehydrated during their shift.
- To measure fluid consumption during the working shift.
- To estimate sweat rates during the working shift, and assess these against currently published occupational limits.
- To examine the role of the meal break in overall fluid replacement during the working shift.

The target group within the workforce were those workers most exposed to severe thermal environmental conditions. They are acclimatised and work hardened and are generally well-informed about the importance of drinking water. A personal 4-litre water bottle is a compulsory component of their PPE (personal protective equipment). The employer at this operation provides low-joule cordial essence (flavouring) at no cost, and some workers add this to their drinking water. All subjects in the study were drawn from the target group.

Approximately 2 000 persons work underground at these mines providing a 24-hour, 363-day coverage. As the underground workplaces are widely dispersed, workers are typically visited by their supervisor twice per shift for approximately 10 minutes per visit.

In addition to the heat and humidity in the environment, these workers must cope with poor illumination, dust, noise and broken ground. Compulsory mine workers' uniforms consist of long cotton trousers and short or long sleeved shirts, safety boots, safety helmet, eye protection, heavy safety belt, cap lamp and cap lamp battery. Where the environment is dusty or noisy, a face respirator or noise protection must also be worn. Some activities involve cement grout or other chemical agents, and these require wearing elbow-length impermeable gloves, a rubber apron, and a visor clipped to the safety helmet. However, the workforce is highly mobile, and some work is conducted from within air-conditioned cabins of mobile equipment. Not all work was in extreme conditions or was physically strenuous. Lunch breaks are all taken in air-conditioned underground lunchrooms.

As these workplaces are at a depth of between 1 000 m and 1 800 m below surface, there is no significant change in temperatures in the workplace between day and night due to the thermal damping that occurs in the long intake airways between the surface and the workplace. Furthermore, autocompression (the increase in air temperature as it descends a shaft due solely to conversion of potential energy into heat) adds about 6^0 C DB and 4^0 C WB per 1 000 m of vertical depth.[2] This temperature increase, along with the diminished effects of changing surface seasons due to the distance to the workplace, means that exposures to elevated levels of heat stress occur throughout the year, although they are less frequent and less extreme in winter. An analysis of the incidence of heat illness with respect to surface temperatures at this operation has recently been completed.[3]

Dehydration is known to produce a wide range of physical, mental and psychological decrements in performance,[4-9] and has been implicated in 50% of all heat stroke cases in South African miners.[10] Therefore the ability of industrial workers to replace fluid lost in sweat is crucial when designing protocols for working in heat, and particularly in the design of protocols for extended shifts.

In this regard, there is disagreement in the literature about acceptable sweat rates for industrial workers. Whilst sweat rates of 1.5 to 2.5 l/h have been demonstrated over short periods (with peaks of 3 l/h),[11-12] acceptable figures for a working shift are generally considered to be lower. ISO 7933[13] and Belding and Hatch[14] advocate a limit of 1.04 and 1.0 l/h respectively for acclimatised persons, although ISO 9886[15] curiously states that "There is no limit applicable concerning the maximum sweat rate: the values…adopted in ISO 7933…must be considered not as maximum values but rather as minimal values that can be exceeded by most subjects in good physical conditions". Nunneley[16] reports that humans can sweat indefinitely at rates of 1.5 to 2.0 l/h, whilst McArdle[17] recommended a limit of 4.5 l over 4 hours. This relatively wide range of acceptable sweat rates is in part related to the wide range of views on acceptable skin wettedness, with ISO 7933 accepting a fully wet skin (1.0 wettedness) for acclimatised workers over extended periods, but Azer[18] recommending a maximum skin wettedness of 0.5 for similar, fully acclimatised persons. A much higher sweat rate is required to maintain a fully-wet skin than a 50% wet skin.[13,19]

Various authors have found that fluid replacement when under thermal stress is only ½ to $^2/_3$ of the fluid loss.[4,10,20] This observation has subsequently been endorsed as an unavoidable water deficit in thermal stress standards such as ISO 7933 (which does not provide for a fluid replacement term in its formulation). It therefore has a major impact on allowable exposure times in hot conditions with high sweat rates.

This fluid deficit has been attributed to two phenomena.

The first is "voluntary dehydration", in which persons dehydrate while under thermal stress despite having access to plentiful supplies of palatable water. Adolf[4] attributed this to an inadequate thirst response, i.e. the thirst response is delayed and/or insufficient to provide for adequate fluid replacement. Other authors have found that the thirst sensation does not begin until about 1% to 2% of body weight[0] or 2% of total body water[21] has been lost. There is still disagreement as to whether the thirst response is inadequate or merely delayed or both.[21,22]

The second phenomenon is rather confusingly called "involuntary dehydration". It refers to the fact that during the dehydration process (or once hypohydrated), the rate of fluid retention (or rate of rehydration), even when the fluid intake exceeds the sweat rate, is governed largely by the ability to replace the solutes lost in sweat, principally sodium.[23-26]

Other authors have found and described a condition called "sweat gland fatigue".[27,19,5,4] Its pathogenesis remains unclear [28]; however, it has been implicated in reductions in sweat rates of up to 50% after continuous exposures of four hours.[29,30] Sweat gland fatigue should not be confused with hidromeiosis, which is a localised reduction in sweat rate; several mechanisms have been proposed for this but the most probable is that localised swelling (hydration) of the stratum corneum results in mechanical obstruction of the sweat duct.[28,31,19]

A further issue for review in this study was to examine the importance of the meal break in maintaining the hydration state. Early authors such as Adolf[4] found that the meal break had an important role in rehydration. He found that the ingestion of food during a meal break stimulated the thirst response and led to the intake of additional fluids, which he found essential to restoring total body water. With the trend towards longer (e.g. 12-hour) shifts, the number of meal breaks and their location within the working shift and duration could be more significant than on traditional 8-hour shifts.

A combined "dehydration and heat illness protocol" (Figure 1) and other management procedures were introduced at this operation immediately prior to and during these studies.[33] Figure 1 superseded an earlier protocol that included a Fantus test.[32] These protocols introduced a new heat stress index[34] and a more pro-active approach to the management of heat stress, heat illness and dehydration in the workplace than had previously been the case. Hydration status was estimated from urinary specific gravity, which is considered to be an important indicator of the absolute hydration status of the body and of relative changes in hydration status over time, although it does not mimic body water loss in a perfectly linear relationship,[35] and may be in error where the subject is experiencing diuresis due to alcohol or caffeine intake, or is taking vitamin supplements or some drugs.

Pure water has a specific gravity of 1.000 (dimensionless), whilst the maximum concentrating capacity of the renal system is about 1.050. In this study, a dehydrated state was considered to be a specific gravity > 1.030, based on the criterion used by the Australian Pathology Association. A euhydrated state was considered to be < 1.015, based on work by Donoghue et al[0] and the fact that 1.015 is one standard deviation below the average start-of-shift value found for workers in this study. However, Armstrong et al[35] reported that a euhydrated state is a specific gravity of 1.004 ± 0.002, using a carefully controlled protocol to ensure euhydration in 9 male athletes; this is well outside the range of 1.015 to 1.024 considered to be "normal" by Reaburn and Coutts.[36] Armstrong's definition of euhydration as being a fully-hydrated condition (i.e. no nett body water deficit), is different to the more common usage of the term as being a normally-hydrated condition. Further work is needed to fully define euhydration in an occupational setting.

Figure 1 shows that workers under significant levels of thermal stress were tested at the end of shift, and if their specific gravity exceeded 1.030, were required to re-present and have a specific gravity not exceeding 1.022 prior to commencing their next shift. The value of 1.022 was an arbitrary value approximately half-way between a euhydrated (1.015) and dehydrated (1.030) state.

Methods

Subjects

All participants gave their written informed consent to a series of studies that was authorised by management, their Labour unions, and the supervising organisation's ethics committee on human experimentation.

The workers in these mines were all relatively well informed about the issues of working in heat, and in particular about the need for self-pacing and for fluid replacement. Workers were not generally subject to any regular form of medical assessment, apart from a pre-employment health screen. No worker in the study reported heat illness and all workers were engaged in their ordinary work activities.[37]

Sub-maximal $\dot{V}O_{2\,\max}$ (aerobic capacity) was measured using the Astrand and Rodahl protocol.

Studies

The main study measured the hydration state of 39 male workers most exposed to heat stress before, at the mid-point, and at the end of their shift. The environmental conditions in which they were working and their fluid intake was also measured or estimated regularly during the shift.

For comparison purposes, the specific gravity of a sample of 64 workers prior to commencing their work shift was also measured. No further interaction was had with these workers.

The end-of-shift specific gravity of all workers (n = 546) who were working in such extreme environments that their shift length had been reduced to six-hours duration (locally called a "hot job") was also collected over a period of approximately 12 months. Temperatures in a "hot job" had to exceed a WBGT of approximately 32^0 to 33^0 C; the actual values were based on an adaptation of the Predicted 4-hour sweat rate (P_4SR).[38] If work continued in these conditions for at least two hours, the shift duration was reduced to 6 hours (which includes a meal break). The maximum exposure time to heat stress under a "hot job" would be 4 hours.

Part of the reason for the comparison studies was to ensure that workers who were studied in the main study did not modify their behaviour, compared to workers who were not monitored during their work shift.

Urinary specific gravity

Urinary specific gravity was measured using a handheld, optical refractometer (Atago Uricon-NE) at the start, mid (just before the meal break [called "crib"]) and end of shift.

Environmental conditions

Environmental conditions were measured at each workplace approximately every 60 to 90 minutes using a Heat Stress Meter,[39] which provides digital readouts of ventilated wet bulb temperature (WB), dry bulb temperature (DB), wind speed, globe temperature, calculated mean radiant temperature, barometric pressure and Wet bulb globe temperature (WBGT). Sling (whirling) psychrometers and vane anemometers were also used to obtain redundant measurements of the most important environmental parameters in these workplaces: WB, DB and wind speed. WBGT was evaluated in accordance with ACGIH guidelines.[40] Thermal Work Limit (TWL) values[34] were calculated assuming a barometric pressure of 110 kPa (an approximate average barometric pressure for the workplaces, about 1 000 metres below sea level; TWL is not highly sensitive to small changes in barometric pressure).

Fluid Consumption

Fluid consumption was estimated by allocating a separate 4-litre water bottle to each worker participating in the study. The cup on each water bottle had a capacity of 400 ml. Each worker was visited approximately every 60 to 90 minutes and the water consumption estimated from the cups drunk and checked against water levels in the bottle.

The heat stress exposure hours were obtained by deducting 3.5 hours from a 12- or 12.5-hour shift, and 2.5 hours from a 10-hour shift. This is based on prior internal reviews that showed that for a shift with one meal ("crib") break, workers lose 2.5 hours in travelling underground to their crib room, getting instructions from their supervisor, getting to the job, returning to the crib room for lunch, returning to the workplace after crib, and returning to the hoisting shaft before the end of the shift to get back to the surface by shift end.

For 12-hour shifts, workers take two 30-minute meal breaks per shift, so that exposure time is 3.5 hours less than nominal work duration. Workers on 10-hour shifts have one 30-minute break per shift. Crib breaks may be taken at any time convenient to the workers.

An additional 30 minutes was typically lost at the start and end of each subject's shift, for administrative reasons associated with the test protocol. Therefore fluid consumption rates calculated as litres per hour in this study may be somewhat conservative.

The main study provided pairs of data (before-mid shift, mid-end shift, before-end shift) and the differences were assessed using the paired, two-tailed student's T test assuming equal variances. For the other tests, paired data was not available so the unpaired, one-tailed student's T test assuming equal variances was used.

Results

Subjects

A summary of the anthropometric and body morphology data and $\dot{V}O_{2\,\max}$ for the subjects in the main study is shown in Table 1.

Environmental conditions

Environmental conditions for the main study were measured at each workplace approximately every 60 to 90 minutes, with 233 sets of readings taken in total. Of these 233 sets, 46 observations were in the cribroom or inside air-conditioned mobile equipment cabins, leaving 187 sets from thermally exposed workplaces (Table 2). The unweighted average of these 187 sets was 28.4^0 C WB, 36.2^0 C DB, 36.3^0 C globe temperature, 1.1 m/s wind speed, 30.9^0 C WBGT and a TWL of 175 W/m^2.

Hydration

The main study

The start, mid and end of shift urinary specific gravity values were measured for 39 workers over 39shifts. 9 of these shifts were 10-hour duration and 30 shifts were 12-hour duration. The results are summarised in Table 3 and Figure 2. There is no significant difference in the means of the paired sets of specific gravity values, either between start and mid shift (p=0.81), between mid and end of shift (p=0.70), or between start and end of shift (p=0.85).

Comparison with other workers at start of shift

The average urinary specific gravity of the separate group of workers (n = 64) prior to going underground was 1.0225 (sd 0.0078, range 1.0020-1.0350). 9% of this group came to work with a specific gravity exceeding 1.0300 and a total of 56% had a specific gravity exceeding 1.0220, these being the allowable end- and start-of-shift limits under the Dehydration protocol.

Comparison with "hot job" workers at end of shift

The average specific gravity at the end of shift for all workers (n = 546) who worked in "hot job" conditions over the previous 12 months was 1.0244 (sd 0.0067, range 1.0020-1.0360). None of these workers reported symptoms of heat illness. For these individuals, specific gravity was checked on the surface rather than underground and this could be between 30 minutes and two hours after the completion of the heat exposure, so that some workers in this study would have rehydrated to some extent prior to providing their urine samples.

The average end-of-shift specific gravity of these workers (n = 546) was significantly higher (p=0.019) than the start-of-shift specific gravity of the group of workers (n = 64) prior to commencing work. However, the absolute increase (1.0220 to 1.0244) was small.

Fluid consumption

The fluid consumed during the working shift was monitored and recorded in detail for 39 workers over 39 shifts with a total nominal shift duration of 444 hours (comprising 23 x 12 hour shifts, 3 x 12.5 hour shifts and 13 x 10 hour shifts). Estimated exposure time was 320 hours (72% of nominal work time). The remaining time was spent getting to and from the workplace, and having meal breaks, etc.

The average fluid consumption per shift was 6.48 litres (over this mix of different shift lengths) with a standard deviation of 2.41 litres and range of 2.40 to 12.50 litres. Moisture content in food was not included in this analysis, but would increase the calculated fluid consumption rates.

The mean full-shift average fluid consumption rate was 0.8 litres per hour (sd 0.27,range 0.32-1.47).

Discussion

Subjects

The average BMI (27.5) of the target group is in the middle of the “overweight” range of 25 to 30 kg/m^2 as designated by the World Health Organisation.^{0} The average $\dot{V}O_{2\max}$ (39.0 ml/kg/min) is at the lower limit of the normal range (39-48 ml/kg/min) for non-athletes aged 30 to 39 years.[42] The target group was typical of industrial workers at this operation. A test of 469 contract employees joining the organisation for project work under similar levels of heat stress during this period had a measured $\dot{V}O_{2\max}$ of 39.0 ml/kg/min (std dev 7.8 ml/kg/min) and a BMI of 25.9 (std dev 5.4).

Environmental conditions

54% of workplace readings were above 30^0 WBGT and 83% were above 26.7^0 WBGT. Note that WBGT values of 30^0 and 26.7^0 are the ACGIH[40] recommended limits for continuous work for acclimatised workers at light work and moderate work respectively. On average, therefore, workers in this study were in very thermally stressful conditions. Workers in “hot jobs” (>32^0 C WBGT) were in even more extreme conditions.

Over ten million manshifts have been worked at this operation over the past 30 years in conditions exceeding 28^0 C WB without any recorded incidence of heat stroke.[43] As work in this operation includes both light and moderate rates, with periods of hard work, and work continues in conditions well above the ACGIH recommended values, it could be concluded that the probability of developing a life-threatening heat illness (stroke) under the ACGIH guidelines is very low for self-paced, acclimatised workers.

Hydration Changes

As there is no statistical change in the mean specific gravity before, during or at the end of the working shift, it can be concluded that workers sweating under these substantial levels of thermal stress do have the ability to maintain their hydration state. Note that these results do not support voluntary or involuntary dehydration. This varying conclusion is supported by Donoghue et al[3] who found that serum sodium levels were within the normal range both for workers at this operation who developed heat illness and for those who did not. The explanation for this contrary findings is almost certainly the strong emphasis at this operation on workforce education, self-pacing and programmed drinking during the working shift.

Note also that over 60% of the workers in this study were commencing their shift insufficiently hydrated to be fit for work in hot conditions, using the definition at this workplace of a specific gravity exceeding 1.0220.[33] However, whilst these workers were hypohydrated at the start of their shift, they were non-dehydrating during their shift.

Comparison with other workers at start of shift

The average specific gravity of this group prior to commencing their shift was 1.0225 (sd 0.0078, range 1.002-1.035) which confirmed that workers are substantially hypohydrated prior to starting work.

Comparison with "hot job" workers at end of shift

Those workers who worked in the most severe thermal stress (WBGT>32^0 C) did dehydrate during their shift, compared to workers at the start of their shift. The absolute increase is small (from 1.0225 to 1.0246); however, this could be affected by the time delay between exposure and measurement

The main differences between the groups of workers in the main study (Table 1) and the comparison studies, is that the workers in the main study were monitored regularly during their shift as to how much water they were drinking, and can therefore be assumed to be much more focussed on replacing fluids, compared to the comparison studies, where no fluid monitoring was conducted. This data does therefore tend to support the conclusion that there is some altered behaviour when workers' fluid consumption is being monitored.

Fluid consumption

These average and maximum fluid consumption rates are well in excess of values reported for workers in more temperate climates,[12] and the maximum values are well above those considered advisory by some sources.[13]

Virtually all the rehydration beverage was water, with relatively minor quantities of coffee, tea, cola soft drinks and sports drinks consumed. No carbonated drinks are able to be purchased in the workplace or lunch rooms and few workers bring soft drinks as part of their lunch. Some workers used the low-joule cordial flavouring provided by the employer.

Over the 39 shifts, fluid consumption during meal breaks amounted to 31 litres, or 14% of the total fluid consumed. Duration of meal breaks (60 mins) as a proportion of exposure time was approximately 12%. The role of the meal breaks is therefore less important in maintaining fluid intake in these workers than has been found previously. Given the conclusion above that these workers are, on average, not dehydrating during their working shift, the probable reasons for the relatively low consumption of fluids during the meal break are:

- The ad libitum availability of water "on the job" in personal water bottles,
- Water is cold and moderately palatable, with free access to cordial flavouring,
- Workers are educated about the need to drink small amounts frequently (the recommended value during their induction and annual refresher training is 250 ml every 15 minutes).

The findings of Adolf[4] and others about the importance of the meal break in maintaining adequate fluid intake could possibly be explained by the above. In addition, Adolf's subjects (soldiers) were dehydrating during their exposures, whereas these workers, on average, were not. It is important to recognise that whilst the meal break may not be crucial to the fluid intake of workers who are disciplined about program drinking during their heat exposure, it is crucial to their replacement of sodium and other osmols.[44]

Given that there was no net change in the hydration state of these workers over their shift, average sweat rates would not be significantly different to average fluid consumption rates. On this basis, five out of 39 workers (13%) exceeded a sweat rate of 1.04 l/hr. This implies that the allowable sweat rates recommended under standards such as ISO7933 (1.04 litres per hour for acclimatised persons) are reasonable, although this rate can and will be safely exceeded by some workers, which is in accordance with the comments in ISO 9886.

Conclusions and Recommendations

The conclusions from these studies are as follows:

- Urinary specific gravity is a good screening test for hypohydration, the most serious risk factor for developing heat exhaustion in self-paced workers.
- A combined dehydration and heat illness protocol has been developed, with recommended limits of urinary specific gravity for the start and end of a working shift.
- A majority of workers started their shift in a hypohydrated state.
- Education is vital if a workforce that is exposed to significant levels of thermal stress is to come to work euhydrated, and maintain their hydration state during their work shift. Paced fluid replacement (program drinking) rather than responding to the thirst sensation is critical to maintaining hydration levels when working under thermal stress.

- Where fluid rates were not monitored, workers in very stressful conditions (WBGT>32.0^0 C) dehydrated over the course of their shift, although the actual increase in urinary specific gravity was small (1.0225 to 1.0244).
- Where workers were well-informed and subject to monitoring, "involuntary dehydration" (if it is defined as a physiologically unavoidable dehydration during exposure to heat) did not occur. Whilst voluntary dehydration (inadequate or delayed thirst response) has been observed regularly in other settings, it is probably a function of poor access to water, workplace practices (particularly a lack of self-pacing), inadequate education, or insufficient quality or palatability of water, and is neither physiologically nor psychologically inevitable.
- Standards for heat stress should not assume that workers are unable to avoid dehydration when exposed to heat, i.e. involuntary dehydration should not be implicit in heat stress standards.
- Whilst a meal break is important when working in heat, in terms of replacing solutes lost in sweat, its role in fluid replacement for well-educated workers trained in the need for program drinking during the heat exposure may be less than has been previously considered.
- Fluid consumption rates (and hence, in circumstances where workers' hydration status is not changing, sweat rates) of up to 1.5 litres per hour occur in self-paced, acclimatised, industrial workers with typical rates varying between 0.5 and 1.1 litres per hour.

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Table 1, Anthropometric and body morphology for the 39 workers in the main study

Name	Age, yrs	Height, cm	Weight, kg	BMI	$\dot{V}O_{2\max}$, ml/kg/min
n	39	38	38	37	18
Avg	35	178	88	27.9	39.1
Std dev	8	9	16	4.0	7.7
Range	21-52	147-196	65-125	22.1-38.2	28.0-56.3

Table 2 Environmental conditions for the workers in the main study

	WB	DB	GT	Wind	WBGT	TWL
	0 C	0 C	0 C	m/s	0 C	W/m2
n	187	187	187	187	187	187
Avg	28.4	36.2	36.3	1.1	30.9	175
Std dev	2.2	2.6	2.8	1.6	2.0	42
Range	24.2-33.7	23.7-41.3	23.8-41.3	0.1-7.0	25.7-35.2	83-268

Table 3 Urinary specific gravity data from the main study

	S.G. Start of shift	S.G. Mid-shift	S.G. End of shift
n	39	39	39
Avg	1.0252	1.0248	1.0254
Std dev	0.00533	0.00533	0.00686
Range	1.012-1.035	1.009-1.035	1.006-1.035
p value	Start to mid=0.85	Mid to end=0.70	Start to end=0.85

Figure 1 Dehydration and Heat Illness Protocol used in workplace. “S.G.” is urinary specific gravity measured using hand refractometer.

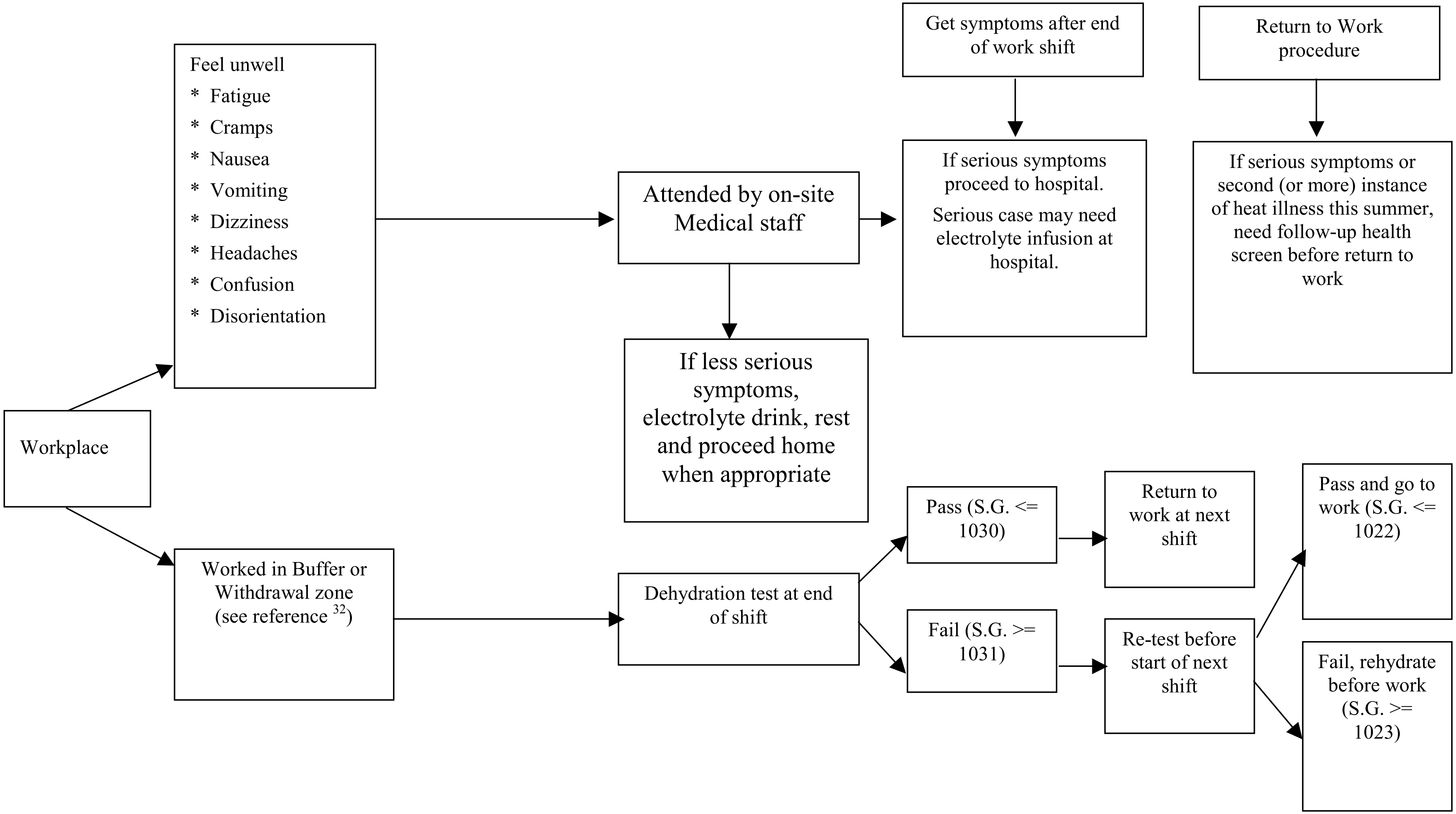
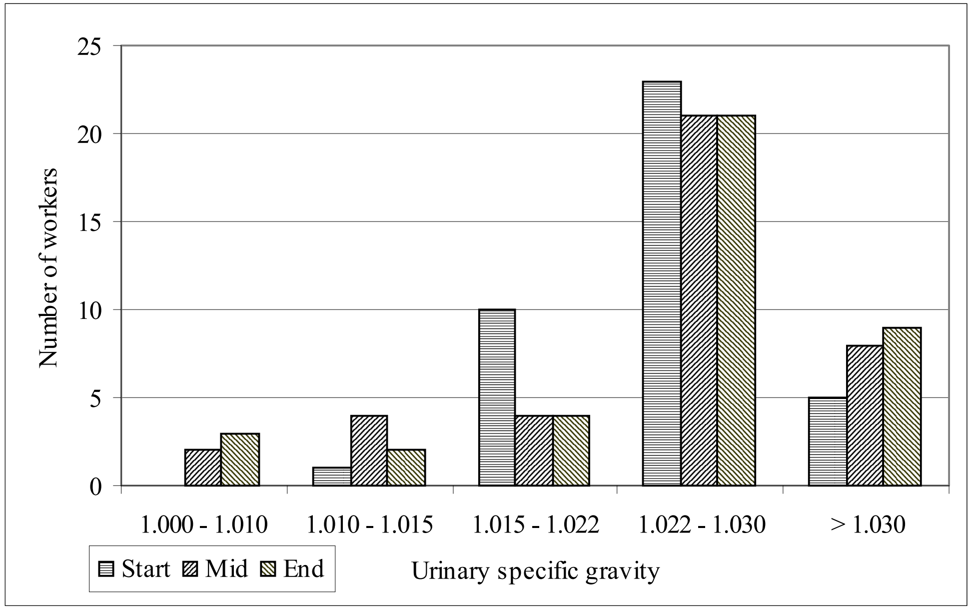


Figure 2 Urinary specific gravity of 39 workers working in very thermally stress conditions at start, middle and end of shift



Fatigue in industrial workers under thermal stress on extended shift lengths

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A field investigation to examine the fatigue levels in industrial workers working extended (10, 12 and 12.5 h) shifts under significant levels of thermal stress was conducted on 45 male underground miners. Studies were conducted both before and after a major change to the working-in-heat protocol used at the operation. Prior to the change, shortened (6 h) shifts had been used when thermal conditions exceeded certain values. This reduced shift length was removed and replaced with other protocols. Heart rates were continuously monitored, and a cycle ergometer was also used to assess cardiovascular fatigue over the shift. Average heart rates, as well as highest 10 and 30 min averages, and heart rate durations within various bands were analysed. No worker reported heat illness during the study. Results showed that removing the shortened shift did not increase the fatigue levels. Workers did experience fatigue, but this occurred in the first half of the shift. Evidence was found that these workers practised self-pacing.

Key words: Extended hours; fatigue; heart rate; industrial worker; shift work; thermal stress.

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Introduction

Fatigue is a general term used to describe a wide variety of conditions [1]. Acute fatigue can be divided into mental fatigue, due to mental overload or underload (associated with monotony and boredom), and physical fatigue. Physical fatigue has been noted in heat exhaustion and attributed to several possible physiological disturbances: hyperthermia [2], circulatory strain due to excessive call on cardiac output to deal with hyperthermia and/or reduced circulating volume due to dehydration [3], sweat gland fatigue [4], depleted muscular glycogen concentration [5] and muscle soreness due to overuse [6].

Work rate is directly proportional to $\dot{V}O_2$. In terms of physical fatigue, several authors have found that endurance is not limited if work rate does not exceed 33–50% of $\dot{V}O_{2max}$ [7–9]. This is the aerobic capacity (defined as the $\dot{V}O_2$ at which no significant oxygen debt accumulates [10]) or the anaerobic threshold [11]. Most humans' aerobic capacity is about that of a brisk walk ($\dot{V}O_2$ of 1 l/min, or 5 kcal/min). However, $\dot{V}O_{2max}$ is not generally limited by respiratory or cardiovascular function, but by the exercise capacity of the musculature [6]. Its value will therefore vary depending on which muscle group is being used in its assessment, and whether the exercise is dynamic or static [12].

Whilst $\dot{V}O_2$ is difficult to measure directly in an occupational setting, % $\dot{V}O_{2max}$ is known to be approximately equivalent to % cardiac reserve [11]. As % cardiac reserve is a function of working and resting heart rates only, and resting heart rates do not change for a particular individual, changes in working heart rates serve as a good approximation for changes in work rates and changes in $\dot{V}O_2$. Whilst heart rate is known to be affected by both physical and psychological factors, it is a good index of strain if an appreciable stress is already imposed as a baseline [13].

In this regard, Minard [14] found that impaired performance for an industrial worker did not occur until the mean heart rate over a full shift was 120 beats/min or higher, with the World Health Organization (WHO) recommending a lower figure of 110 beats/min whilst allowing brief excursions above 120 beats/min for acclimatized, fit persons [15]. ISO9886 recommends an

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increase in heart rate due to thermal strain to not exceed 30 beats/min with an absolute limit from all causes to not exceed the individual's maximum heart rate less 20 beats/min [16].

Except for new workers or new activities, muscle soreness is unlikely to be a cause of physical fatigue unless it involves excessively repetitive or forceful activities, as work hardening (muscle hypertrophy) results in rapid adaptation to job requirements [12].

Heavy exercise is known to result in a decline in pH due to an accumulation of lactate in the muscle cells, which can result in fatigue [17]. Blood lactate has also been found to be an indicator of decreased muscle blood flow [18]. A level of ~4 mmol/l in arterial blood is considered to indicate the anaerobic threshold [19].

Heat exhaustion is a form of thermal fatigue. It is generally defined as a circulatory deficiency due to water or salt depletion. It is characterized by thirst, weakness, fatigue, dizziness, anxiety, oliguria, tachycardia and moderate hyperthermia [20], weakness, inability to continue work and frontal headaches [21]. It has recently been described in an occupational setting [22].

Adolf [23] also described a condition he called dehydration exhaustion. This was not associated with hyperthermia, and related to non-working (resting) subjects exposed to hot environments who gradually dehydrated to the point of total exhaustion, i.e. a survival situation. Its onset was at 12% or more hypohydration. This is not a level of dehydration likely to be encountered in an occupational setting, except in extended emergency entrapment or rescue situations.

Dehydration and hyperthermia have both been found to result independently in decrements in mental performance [24], and especially attention overload [25]. Mental and physical decrements in performance have been associated with hypohydration of as little as 2% total body water [26], with pronounced effects at 4% [3,27]. Fatigue due to hyperthermia has been associated with a deep body temperature of as low as 38°C [20,28], with most persons suffering fatigue at deep body temperatures exceeding 38.5°C [29].

Hypohydration also results in muscle fatigue [30]. Both hyperthermia and dehydration are known to result in cardiovascular strain [29,31], and hence manifest as an increase in heart rate.

Background

This study reports a field investigation to examine the fatigue levels in industrial shift workers under considerable thermal stress, both before and after the introduction of a major change to the working-in-heat (WIH) protocols under which the workforce had been working for in excess of 30 years. All workers were employed on 10, 12 or 12.5 h shifts in a hot, deep, underground mine located well inside the tropics in northern Australia. The prior WIH protocol was based on a variation [32] of the Predicted Four Hour Sweat Rate [33], and provided for a 6 h shift when thermal conditions exceeded a wet bulb globe temperature (WBGT) of ~32.5°C, considered an extreme heat stress under American Conference of Governmental Industrial Hygienists (ACGIH) guidelines [34]. The 6 h shift itself had been in use for 56 years. A shortened shift length is a very common method of reducing the risk of heat illness in British and Continental mines, but is rarely practised in Australia or South Africa. The new protocol was based on a new heat stress index called the Thermal Work Limit (TWL) [35], and removed the 6 h working shift, irrespective of the thermal conditions in the workplace, and replaced it with a different method of managing environmental extremes [35–37], predicated on the workforce being able to self-pace, being well informed about the various issues of WIH, and with progressive management interventions (including withdrawal of workers) at increasing levels of heat stress, depending on the state of acclimatization and hydration; however, it did not provide for a reduced shift length.

All workers were drawn from a target group of those most exposed to severe thermal environmental conditions and gave their written informed consent to a series of studies that was authorized by management, their labour unions, and Curtin University's ethics committee on human experimentation.

In addition to the heat and humidity in the environment, these workers must cope with poor illumination, dust, noise and broken ground. Their uniforms consist of long cotton trousers and short- or long-sleeved shirts, safety boots, helmet and eye protection. The workforce is highly mobile, and some work was conducted from within air-conditioned cabins of mobile equipment. Therefore, not all work was in extreme conditions or physically strenuous. Lunch breaks were all taken in air-conditioned underground lunchrooms.

Work rates have been measured previously [32] and found to be generally low (e.g. driving machinery, <120 W/m^2) to moderate (laying bricks, <200 W/m^2), with short periods of heavy work (shovelling, <400 W/m^2), and to vary between workers, between shifts and even over the course of each shift. This is also consistent with the observed heart rates. Workers are heat acclimatized and work hardened to the conditions in which they work. They are not generally subject to any regular form of health assessment, apart from a pre-employment medical screen.

No worker reported heat illness during this study, although heat illness is experienced in this workplace and has recently been described [22,37].

The urinary specific gravity (hydration state) of the workers was also measured before, during and at the end of each shift during the study. On average, there was no change in hydration state [38].

The objectives of this study were to determine: (i) whether the changes in protocols resulted in a change in heart rates during the working shift; (ii) whether the elicited heart rates exceeded advisory levels; and (iii) if fatigue was occurring, whether it was related to shift length.

Method

The investigation was conducted over two consecutive summers, before and after changes to the WIH protocols.

In aggregate, the fatigue results consist of the following:

- Pre- and post-intervention heart rates recorded continuously using Polar^{TM} ECG-type sports heart rate recorders (hereafter called the 'continuous heart rate' studies).
- Pre- and post-intervention steady-state heart rates collected on a cycle ergometer pedalling at 50 r.p.m. at 100 W under a standardized test at the start and end of each shift (and at the middle of each shift for one series of tests) (hereafter called the 'cycle fatigue results'). All ergometer tests were performed underground at a hot location near the lunchroom. Heart rates typically plateaued after 3–6 min. This test was effectively a measure of $\dot{V}O_2$ using the Åstrand Rodahl protocol.
- Blood lactate measured at the earlobe immediately at the conclusion of the shift, collected in the post-intervention continuous heart rate study only.
- Pre- and post-intervention environmental conditions measured approximately every 60–90 min, including psychrometric wet and dry bulb temperatures, globe temperature, WBGT, wind speed and barometric pressure.
- Anthropometric data, body morphology and $\dot{V}O_{2max}$ data on subjects.

A negative (non-fatigued) control group of 15 workers (all males) working in the same operation in sedentary work in thermoneutral conditions was also tested over several shifts using the cycle ergometer protocol. This produced 32 paired sets of results (before and after shift), with nine workers (26 paired sets) being underground workers and the other six workers (six paired sets) being office workers.

Data were collected on both day and night shifts.

Heart rate data were analysed in the following manner: for each individual shift, and for the aggregated data, the following statistics were calculated: average heart rate, highest 10 consecutive minute average heart rate, highest 30 consecutive minute average heart rate and time spent in the following heart rate zones: <60 beats/min, 60–80 beats/min, 80–100 beats/min, 100–120 beats/min, 120–140 beats/min and >140 beats/min.

The difference in continuous heart rates before and after the change in protocols was tested using the unpaired, two-tailed Student's *t*-test assuming equal variances. The cycle ergometer results were tested using the paired, one-tailed Student's *t*-test, with the null hypothesis being that heart rates did not increase during the work shift. Results are reported as (mean, SD, range) or (SD, range).

Results

Environmental

A total of 350 environmental observations were taken over both summers (excluding observations inside air-conditioned areas). The WBGT in the first summer averaged 30.8°C (1.7, 26.8–36.9), compared with 30.9°C in the second summer (2.1, 25.7–35.2), which was not significant ($P = 0.44$). Comparisons using the TWL index also showed no significant change between the summers.

Continuous heart rates

Over the two summers, continuous heart rates were measured on 45 workers (all males) over 71 shifts (Table 1). The body mass index (BMI) of the target group averaged 27.9 (4.0, 22.1–38.1), which is in the middle of the 'overweight' range of 25–30 kg/m^2 as designated by the WHO [39]. The $\dot{V}O_{2max}$ of the target group averaged 39.1 ml/kg/min (7.7, 28.0–56.3), and is at the lower limit of the normal range (39–48 ml/kg/min) for non-athletes aged 30–39 years [40]. The target group was typical of industrial workers at this operation. A test of 469 contract employees joining the organization for project work under similar levels of heat stress during this period had a measured $\dot{V}O_{2max}$ of 39.0 ml/kg/min (SD = 7.8 ml/kg/min) and a BMI of 25.9 (SD = 5.4).

The full-shift average heart rate for the 51 sets of continuous heart rate data from the first summer of 103.6 beats/min (13.9, 76–135) was not significantly differently ($P = 0.53$) to the average of 101.2 beats/min (9.4, 76–123) from the 20 sets of data from the second summer. Likewise, there was no significant change in the mean values of the highest 10 consecutive minute ($P = 0.53$) and highest 30 consecutive minute ($P = 0.98$) averages during the shifts, from pre- to post-change. On this basis, the data were pooled to form 71 sets of results, also shown in Table 1.

Cycle fatigue

Control group

A paired *t*-test was applied to the 32 sets of data in the cycle ergometer control group. The average increase in heart rate on the ergometer was 1.1 beats/min (SD = 6.3 beats/min, range = –16 to 16). The end of

Table 1. Continuous heart rate data

Period of study	*Shift average heart rate (beats/min)*	*Highest 10 min heart rate (beats/min)*	*Highest 30 min heart rate (beats/min)*	*Heart rate <60 beats/min (% of time)*	*Heart rate 60–80 beats/min (% of time)*	*Heart rate 80–100 beats/min (% of time)*	*Heart rate 100–120 beats/min (% of time)*	*Heart rate 120–140 beats/min (% of time)*	*Heart rate >140 beats/min (% of time)*
Data from first summer, before changes to protocols									
Mean	103.6	143.1	129.7	0	15	35	29	14	8
SD	13.9	20.9	22.5	0	20	17	13	10	10
Range	76–135	103–202	81–193	0–1	0–77	2–69	4–60	0–39	0–38
Data from second summer, after changes to protocols									
Mean	101.2	139.4	129.0	0	14	46	30	10	7
SD	9.4	15.7	15.9	N/a	14	15	7	10	14
Range	76–123	103–170	81–161	0–0	0–48	2–73	4–68	0–28	0–39
Combined data from both summers									
Mean	102.9	142.1	129.5	0	14	38	29	13	7
SD	12.8	19.6	20.7	0	18	17	13	9	10
Range	76–135	103–202	81–193	0–1	0–77	2–73	4–68	0–39	0–39
P, 1st to 2nd summer	0.53	0.53	0.98						

shift heart rate does not show any significant increase compared with the start of shift ($P = 0.16$).

Target group

The cycle ergometer target group comprised 39 of the workers from the continuous heart rate study. A total of 46 sets of data (before and after shift) were collected. Of these 46 sets, 24 also included cycle fatigue results collected at approximately mid-shift, immediately prior to taking the main meal break.

The average increase in heart rate on the cycle ergometer from the start to the end of the shift for the 46 sets of data in the target group (Table 2) was 4.6 beats/min (8.9, –11 to 28). This is highly significant ($P = 0.0007$).

For the subjects ($n = 24$) tested at the start, the middle and the end of the shift, the increase in ergometer heart rates from the start to the end of the shift was 4.2 beats/min (8.9, –11 to 28), which was significant ($P = 0.02$). The increase from the shift start to the main meal break of 8.0 beats/min (11.6, –10 to 35) was highly significant ($P = 0.001$). There was actually a significant decrease ($P = 0.04$) of 3.8 beats/min (9.9, –24 to 15) in ergometer heart rate between the middle and the end of the shift in both day and night shifts.

Continuous heart rates versus cycle fatigue

Comparisons were made between continuous heart rate results and the cycle ergometer results. No significant linear regressions could be found in terms of the average, highest 10 min or highest 30 min values compared with the cycle ergometer increase over the shift, or compared with the shift-ending ergometer value, or between the ratio of the end to the start of the shift cycle ergometer values and the average heart rate during the shift. Resting heart rates were not taken, so comparisons involving cardiac reserve could not be prepared.

Lactate

Lactate levels were measured within 30 min of the conclusion of physical work in the second summer. Of the 18 workers measured, only two exceeded 2 mmol/l, six were recorded as being 'low' (below reading level) and the average of all the data (including the two above 2 mmol/l) was only 1.44 mmol/l.

Discussion

Environmental

The average environment did not change between summers, and over both summers averaged 30.9° WBGT (2.0, 25.7–36.9). Environmental conditions exceeded a WBGT of 30°C (the ACGIH [34] recommended maximum level for a continuous moderate work rate by acclimatized workers) for 66% of the exposure time. Under the ACGIH guidelines, these conditions are clearly stressful.

Continuous heart rate

The mean ± SD of the pooled heart rate data was 103 ± 13 beats/min. Approximately 14% of the work-

Table 2. Steady-state heart rate data from cycle ergometer tests over the working shift, as an indicator of fatigue

	Ergometer data from all subjects			*Ergometer data from individuals who completed each of the start, middle and end of shift tests*		
	Start	*Middle*	*End*	*Start*	*Middle*	*End*
n	47	24	46	24	24	24
Mean heart rate (beats/min)	126.6	136.3	131.2	128.3	136.3	132.5
SD (beats/min)	13.05	15.13	11.98	14.78	15.13	13.61
Range (beats/min)	98–152	105–165	107–158	105.0–152.0	105.0–165.0	110.0–158.0

Some subjects only completed cycle ergometer tests at the start and end of the shift; other subjects also completed a test at mid-shift immediately prior to their lunch break.

ing shifts resulted in a mean full-shift heart rate >110 beats/min. Less than 5% averaged >120 beats/min. A shift average for industrial workers of 120 beats/min was also found to be a suitable maximum by Minard [14] and the WHO [39], and is probably a realistic upper limit for an average heart rate over a full shift.

On average, workers experienced a peak 10 min heart rate of ~140 beats/min and a peak 30 min heart rate of ~130 beats/min during their shifts. Heart rates in excess of 140 beats/min exceeded ~7% of the shift duration. These values confirm that excursions above the recommended levels for significant periods are frequent.

Cycle fatigue

Control group

The fact that there was no significant increase in heart rate on the cycle ergometer from the start to the end of the shift for workers in sedentary work in thermoneutral conditions (defined as 'non-fatigued' workers in this study) provides a baseline for evaluating the target group.

Target group

The average increase in heart rate on the set-work cycle ergometer from the start to the end of the shift for the target group (Table 2) was 4.6 beats/min, which was highly significant (P = 0.0007). For precisely the same mechanical work output on the ergometer at the end of the shift, this group was clearly more fatigued compared with the non-fatigued control group. The cause of this fatigue has not been demonstrated and, in particular, has not been partitioned between skeletal and cardiac muscle fatigue or central fatigue.

The highly significant increase (P = 0.001) in heart rate (8.0 beats/min) from the start to mid-shift suggests that the major component of fatigue in these workers was occurring in the first half of the shift, i.e. when the workers were 'fresh'. Fatigue appeared actually to decrease from the middle to the end of the shift. However, a 'slow down' period of 2–3 h was frequently observed in workers prior to the end of these long 12 h shifts, and this may be reflected in these second-half results. This is consistent with anecdotal evidence that there may be reduced productivity [41] from self-paced, manual workers in the last few hours of an extended (12 h) shift, although there appear to be other significant factors as well [42].

The fact that no correlations could be found between the continuous heart rate and cycle ergometer data could not be explained. However, given the wide range of age and $\dot{V}O_{2\max}$ in the subjects, comparisons on the basis of cardiac reserve, age or some other basis might have produced a correlation.

Nevertheless, the cycle ergometer test, which does not require any data-logging device in the field, may be a useful test of the fatigue levels of groups of industrial workers, given that it produced a negative result in the non-fatigued control group and a positive result in the target group.

Note that neither the continuous heart rate nor the cycle fatigue data have been correlated to BMI or $\dot{V}O_{2\max}$. However, it has been reported from a different study of the same operation over the same period that BMI was a significant risk factor in developing heat illness but $\dot{V}O_{2\max}$ was not significant [43].

Lactate

The low lactate levels recorded at shift end suggest that work is being conducted within the aerobic capacity of workers, and that this is not a cause of fatigue.

Conclusions and recommendations

Mine workers under thermal stress are undergoing fatigue during their shift, as evidenced by repeating a cycle ergometer test at a fixed work rate before, during and after their shift, but not necessarily to dangerous levels.

Most workers experienced mean heart rates during the shift that were lower than the 110 beats/min recommended by some authorities, with ~14% of workers having mean heart rates that were >110 beats/min; ~5% had mean heart rates >120 beats/min.

Given that the environmental conditions were on average very thermally stressful (WBGT = 30.8°), it is highly likely that these workers were self-pacing. This finding of self-pacing is also in accordance with other findings in occupational settings in the Western world [11,26,43–46]. However, Soule *et al.* [47] found that self-pacing produced excessive deep body core temperatures when environmental conditions exceed 33.5° wet bulb. Therefore, it is possible that self-pacing exists only within reasonable environmental conditions. This is also in accordance with Brake *et al.* [36], who proposed that when work rates become excessively slow under a 'self-pacing' protocol, the increasing frustration levels and desire to complete the activity and escape the stress can result in a self-imposed excessive work rate, which can lead to hyperthermia. Therefore, upper limits of thermal stress remain essential in a WIH protocol, even with self-paced and well-educated workers. The inability to self-pace is probably a significant reason why heat stress and stroke are more common in military settings.

There was no significant increase in average heart rate as a result of removing the 'shortened shift' from the WIH protocol. This further indicates that workers are 'self-pacing' and that the fatigue levels found are not related, in this operation, to extending the duration of the heat exposure beyond 6 h. This is also in accordance with the much earlier observation of Leithead and Lind [13], who stated:

> It does not seem logical to suggest that if conditions are extreme for an exposure of 8 hours, then the duration of exposure should be reduced to 6 hours; it is probable that any acute heat disorder that may develop as a result of an 8-hour exposure will also occur during a 6-hour exposure. Therefore it is preferable to retain the 8-hour duration of exposure and to reduce the average rate of work by an appropriate amount.

In a self-paced context, this 'reduction in the average rate of work' is self-imposed, rather than externally imposed.

Blood lactate levels were very low at the end of the shift, indicating no significant oxygen debt at shift end and only a minor anaerobic contribution to metabolic rate.

It is important to recognize that this study was conducted on non-dehydrating, acclimatized workers who are reasonably well educated about the impacts of working in heat and have a measure of control over their pace of work during the course of their shift. Moreover, the principal source of heat stress for these workers is generally the environmental heat load, rather than an internally produced heat load due to sustained strenuous metabolic rates.

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limiting Metabolic Rate (Thermal Work Limit) as an Index of Thermal Stress

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The development of a rational heat stress index called thermal work limit (TWL) is presented. TWL is defined as the limiting (or maximum) sustainable metabolic rate that euhydrated, acclimatized individuals can maintain in a specific thermal environment, within a safe deep body core temperature ($< 38.20°C$) and sweat rate (< 1.2 kg/hr^{-1}). The index has been developed using published experimental studies of human heat transfer, and established heat and moisture transfer equations through clothing. Clothing parameters can be varied and the protocol can be extended to unacclimatized workers. The index is designed specifically for self-paced workers and does not rely on estimation of actual metabolic rates, a process that is difficult and subject to considerable error. The index has been introduced into several large industrial operations located well inside the tropics, resulting in a substantial and sustained fall in the incidence of heat illness. Guidelines for TWL are proposed along with recommended interventions. TWL has application to professionals from both the human and engineering sciences, as it allows not only thermal strain to be evaluated, but also the productivity decrement due to heat (seen as a reduced sustainable metabolic rate) and the impact of various strategies such as improved local ventilation or refrigeration to be quantitatively assessed.

Keywords Heat, Stress, Strain, Index, Limit, Work Rate, Self-Pacing

Thermal stress, with its attendant problems of heat illness, safety incidents. lowered productivity, poor morale, and higher costs, affects **many** industrial operations. Over the past 80 years, many heat stress indices have been developed to assist with the management of these problems. Some of these have been developed for particular industries and the majority are empirically derived. More recently, attempts have been made to develop so-called “rational” heat stress indices. These attempt to model some central physiological parameter that indicates thermal strain on the body (e.g., deep body core temperature, sweat rate, or heart rate) and provide a recommended limit. Empirical heat stress indices frequently have little validity outside the narrow range of conditions for which they were designed, and are often revised “in-house” to fit particular circumstances. Problems with a rational heat stress index, such as ISO 7933,(1) become evident when it is introduced into a workplace where workers are mobile and work at varying tasks and metabolic rates during their work shift.

“Externally paced work” has been traditional in many industries and countries. However, the increasing degree of mechanization of heavy tasks and the “duty of care” style of legislation that has now become common are resulting in better-informed workers and in redesigned jobs that do promote self-pacing for persons under considerable heat stress.

In this article, self-paced workers are defined as those who can and do regulate their own work rate, are not subject to excessive peer or supervisor pressure or monetary incentives, and are well educated about the issues of working in heat and the importance of self-pacing. The “environment” is defined as the full combination of factors outside the worker that lead to heat stress: air temperature and humidity, radiant heat, wind speed, barometric pressure, and clothing.

The need for a heat stress index designed primarily for self-paced workers has led to the development of the thermal work limit (TWL). TWL is defined as the limiting (or maximum) sustainable metabolic rate that euhydrated, acclimatized individuals can maintain in a specific thermal environment within safe limits of both deep body core temperature ($< 38.20°C$) and sweat rate (< 1.2 kg/hr^{-1}).

TWL and its accompanying management protocols(2–3) have been introduced into several industrial operations where workers are subject to thermal stress. Approximately 1400 persons work in these locations with over 10 million man-shifts being worked between 1965 and 1995 at wet bulb temperatures in **excess** of 28°C.(4) There has been **a significant** reduction *in* heat illness since the introduction of TWL.(5) The previous heat management protocol (used from 1942 to 1996) was based on the Predicted Four Hour Sweat Rate and involved a reduction in the shift length from 8 to 6 hours when the environmental conditions exceeded a certain threshold. With the introduction of 12-hour shifts in the operations, the cost and productivity loss of a shortened shift was severe. The introduction of new protocols allowing full shifts to be worked has therefore improved the productivity, as well as the safety, of the operations.

Most existing heat stress indices have significant shortcomings, being technically flawed, inappropriate, impractical, or poorly applied.(6–9) Typical problems include:

- Many indices require the metabolic rate to be assessed and then propose a time exposure limit or a work/rest cycle. However, the most common adaptations to working in hot environments are behavioral ones: reduction of the work rate (and thus of the considerable metabolic heat generated)(10–12) and removal of clothing. Parsons(13) noted that the realistic accuracy in estimating metabolic rate is only ± 50 percent. Job tasks are also becoming more varied due to increasing mechanization and "multi-skilling" of the workforce. Combined with the trend toward longer working hours (e.g., 12-hour shifts), it is common for work rates to vary significantly during a shift, and for workers to move frequently from one location to another (with potentially very different levels of thermal stress). It could therefore be argued that indices that require estimation of metabolic rates from observations are not very practical and are. prone to considerable error.
- Some indices do not explicitly take wind speed over the skin into account. This includes the widely used WBGT (wet bulb globe temperature), originally developed as a proxy for the corrected effective temperature (CET). WBGT uses the natural wet bulb temperature, which is relatively insensitive to wind speed; however, CET, from which WBGT was derived, is quite sensitive to wind speed. In addition, the natural wet bulb used to calculate WBGT is not generally shielded, so it will be insensitive to wind speed but quite sensitive to high radiant heat loads, such as solar radiation.

It is difficult to have a simple, practical measure of (heat) acclimatization. However, acclimatization is known to be an important adaptation to working in heat. A robust protocol needs to provide for this. Some protocols such as the American Conference of Governmental Industrial Hygienists (ACGIH®) threshold limit value (TLV®)(14) (using WBGT) have adopted various corrections in an attempt to take acclimatization into account; however, many indices do not provide advice for both acclimatized and unacclimatized states.

Other problems exist with rational indices such as ISO 7933,(15) especially when applied to hot, humid environments with low wind speeds. These problems include:

- An adjustment is frequently made within the index formulation to increase the relative wind speed (between body surface and the air) when the actual wind speed is low. This is justified, firstly, on the basis of step rest experiments, which indicate that at low wind speeds, an artificial air movement is induced over the skin by virtue of the work rate of the body, including arms and legs. This is not always the case, for example, in underground mines, where the metabolic work is sometimes produced by arm or upper body movements alone (not whole body) or is sometimes done against gravity. In these cases, work can be mainly isometric muscle contraction. When under extreme thermal stress, static muscle work can be as demanding as dynamic muscle work but may produce little induced air movement over the skin. From the authors' observations of self-paced workers in thermally stressful situations, it is not valid and may even be dangerous to justify an increased relative wind speed on this basis. Secondly, it is based on the minimum convection currents that are set up between a "hot" body and the fluid environment (in this case the ambient air) around that body. This is an acceptable use of minimum wind speeds and is supported by many authors. Refer to literature reviews by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE)(16) and Hólmer.(17)
- The assumption that the intrinsic clothing insulation (I_{cl}) and vapour permeation efficiency (i_{cl}) of the clothing ensemble do not change as thermal conditions change. Clearly, under thermal stress, workers sweat profusely and their clothing becomes saturated. This reduces the intrinsic clothing insulation, as most of the thermal resistance to dry heat in clothing comes from the air trapped between the clothing and the skin, and within the cloth fibers. The thermal conductivity of water is 20 times that of air, which largely accounts for the reduction in insulation of wet clothes. Some of these problems have been recognized and are currently being addressed in the European research project on heat stress and the proposal for revision of ISO 7933.(6,7,17)
- The absence of a fluid replacement term in the ISO protocol is a weakness. ISO assumes that fluid replacement will not match sweat loss during the working shift, probably because this phenomenon of "voluntary dehydration" has been reported by many authors.(18,19) However, workplaces have been observed where workers are careful to replace the fluids they are losing(20) and do not build up a water deficit.
- The ISO model is based on an overall "average" thermal strain value for a shift, even when different stress conditions exist during the shift. This is a problem as it does not use the "ending" values from one work segment as the "starting" values for the next or check that limiting physiological criteria are not exceeded during each segment. Averaging values over a shift may or may not be a weakness in practice, but is inconsistent in a protocol that is intended to provide advice on either external

pacing (mandatory work/rest cycles) or the duration of exposure, and which simultaneously sets up limits in terms of heat storage (deep body core temperature) and sweat rate.

The thermal work limit algorithm builds on work originated by Mitchell **and** Whillier,(21) who developed **an index** “specific cooling power,” which subsequently became known as “air coaling power” (ACP). The original formulation of ACP used a fixed mea” ski” temperature. Stewart and Van Rensburg(22) the” proposed a method involving variable mean ski” temperatures, but did not consider the effects of clothing. McPherson(23) later proposed a more general formulation for a range of thermal environments, including comfort and limiting conditions, but used limiting values that were relevant to hot, humid conditions.

With its units of watts per square meter and its measurement of maximum sustainable metabolic rate, TWL is a convenient measure for both occupational health practitioners and environmental engineers, as it allows direct comparison between limiting metabolic rates and environmental conditions. This allows the impact of engineering controls and other interventions (e.g., changed clothing) to be assessed directly. This article describes the formulation of TWL and the resulting limits and interventions and shows how the index can be extendedto unacclimatized workers.

METHODS

The basic purpose **of** the thermal work limit index is to calculate the maximum metabolic rate, in watts of metabolic heat per square meter of body surface area, that can be continuously expended in a particular thermal environment, while remaining within safe physiological limits. With TWL, the higher the “umber, the higher the sustainable work rate (in terms of thermal stress). The foundation of the TWL algorithm is **derived** from the work discussed below.

Wyndham(24) conducted a number of experiments measuring physiological conductance (the blood-borne Row of heat’ to the skin) along with steady-state deep body core **and** mean skin temperatures for a range of environmental conditions and metabolic rates. Complex equations were developed for these relationships. Later, Cabanac(25) reported that physiological conductance is a function of the thermoregulatory signal,. defined as the weighted average of the deep body core and mean ski” temperatures where the deep body core temperature is weighted at 90 percent and the mea” skin temperature is weighted at 10 percent.Wyndham’s original data plotted against the thermoregulatory signal is shown in Figure 1.

The limiting deep body core temperature in the standard TWL formulation is 38.2°C, although this is adjustable. The acceptable range for the thermoregulatory signal in the model is from 36°C to 39.5°C, based on Wyndham’s experimental data.(24) For heat to flow from the deep body core to the ski”, **the** maximum mean skin temperature cannot exceed the deep **body core temperature**, and in practice is usually more than 1°C cooler than the deep body core temperature. This is true even under light work when higher skin temperatures may still be sufficient to remove the relatively low levels of metabolic heat. Continuous heavy work requires a larger gap between deep body core and mean skin temperatures for the larger amount of heat generated to flow from core to skin.‘”

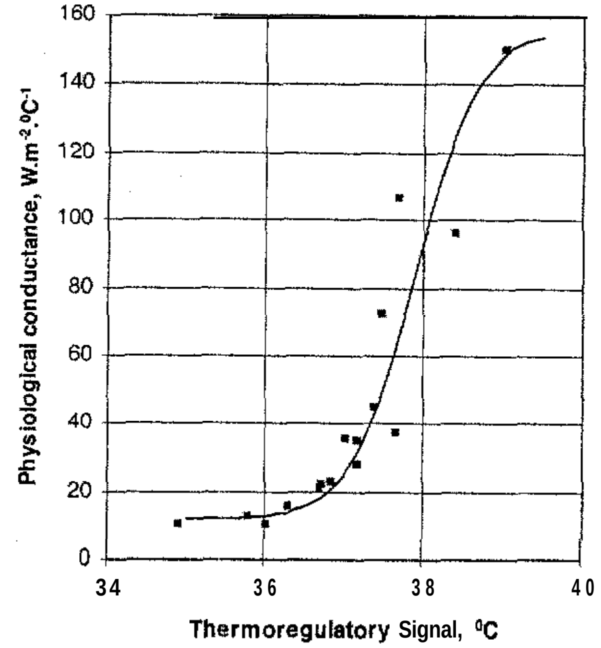

FIGURE 1
Relationship between physiological conductance (blood-borne heat transfer) from deep **body core to** skin **and** thennoregulatory signal. t_Σ, where $t_\Sigma = 0.1t_{skin} + 0.9t_{core}$ (data from Wyndham).(24)

Wyndham(24) also measured sweat rates, plotted in Figure 2, against the same thermoregulatory signal. In the standard TWL formulation, maximum sweat rate (which is adjustable) is restricted to 0.67 $kg/m^{-2}/hr^{-1}$ (1.2 liters per hour for a standard person), which is within the steep (responsive) region of the sweat rate curve. It is well within reported sustainable limits of about 0.83 $kg/m^{-2}/hr^{-1}$ (1.5 liters per hour) noted for acclimatized workers by Taylor,(26) **and is** also close to the original P_4SR limit of 4.5 liters over four hours recommended by McArdle.(27) The corresponding ISO 7933 sweat rate limit is 1.04 liters per hour, although ISO 9886(28) comments that the 1.04 liter per hour limit in ISO 1933 “must be considered not as (a) maximum value but as (a) minimal value that can **be exceeded by most** subjects in good physical condition.”

Following from the definition of the psychrometric dew point temperature (the temperature at which moisture condenses from the air), the minimum possible mean skin temperature cannot **be** lower than the ambient dew point temperature if evaporation from the skin to the ambient environment is to occur. It is also necessary to establish the proportion of the sweat produced that actually results in evaporation and cooling.

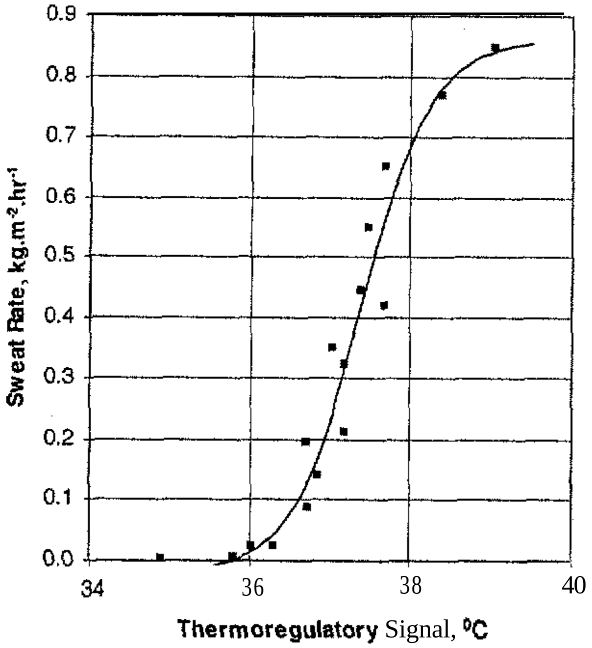

FIGURE 2

Relationship between sweat rate and thermoregulatory signal, t_Σ, where $t_\Sigma = 0.1t_{skin} + 0.9t_{core}$ (data from Wyndham).[24]

The evaporation rate from the skin clearly cannot exceed that of a fully wet body in the same circumstances. However, even when the skin is only partly wet, not all the sweat produced is evaporated This is because dripping commences well before the skin is fully wet, and the onset of dripping has been shown to be a function of the evaporative ability of the environment (Figure 3). This figure (redrawn from Stewart[34]) shows experimental data derived by Galimidi and Stewart[29] along with the original theoretical curve for skin wettedness derived by Kerslake.[30] In this figure:

- λ is the latent heat of evaporation of sweat (kJ/kg^{-1}) and S_r is the sweat rate (kg/hr^{-1}/m^{-2}); therefore λS_r is the sweat rate using the units of W/m^{-2} (after conversion of hours to seconds).
- E is the actual evaporation **rate** of **sweat** (W/m^{-2}) **under** these conditions and E_{max} is the maximum possible evaporation rate (W/m^{-2}) from a fully wet skin under these conditions.
- The Y-axis ($E/\lambda S_r$) is the ratio of the actual evaporation rate to the actual sweat rate and is a measure of the efficiency of sweating as a cooling mechanism **in** this condition; the maximum Y value is 1.0, at which point all the sweat produced is being evaporated.
- The X-axis ($\lambda S_r/E_{max}$) is the ratio of the actual sweat rate to the maximum possible evaporation rate from a fully wet skin in this environment, and is therefore a measure of **the** capacity of the environment to evaporate the sweat produced; where x-values exceed 1.0, sweat rates exceed the maximum possible evaporation **rate** in this environment.
- The product of any particular x-value and y-value on the solid line of this curve is $E/\lambda S_r$ × (h&/E,,,) = E/E_{max} = w (definedas the skin *wettedness*). Skin wettedness values greater than unity are not possible.

Galimidi and Stewart[29] and Kerslake[30] identified two reasons why sweat drips from the body before the skin *is* fully wet. Firstly, the evaporative heat transfer coefficient varies over the body, so that areas with low coefficients are unable to evaporate all the sweat being produced and start to drip, while areas with high coefficients are still able to evaporate all the sweat produced. Secondly, some regions of the skin produce more sweat than others.

The experimental data in Figure 3 shows that a fully wet skin (w = 1) only occurs when the actual sweat rate is about 170 percent (x-value = 1.1, y-value = 1/1.7 = 0.6) of the maximum evaporation rate possible in the environment, at which point about 60 percent of the sweat is evaporating. It also shows that dripping of sweat from the skin starts when the skin surface is just under 50 percent wetted (x-value = 0.46 and $E/\lambda S_r$ falls **below** 1.0).

The efficiency of sweating therefore falls into three distinct zones:

- Zone A, where the evaporating ability of the environment is high, no sweat drips, the efficiency of sweating is therefore 100 percent. and the skin is not fully

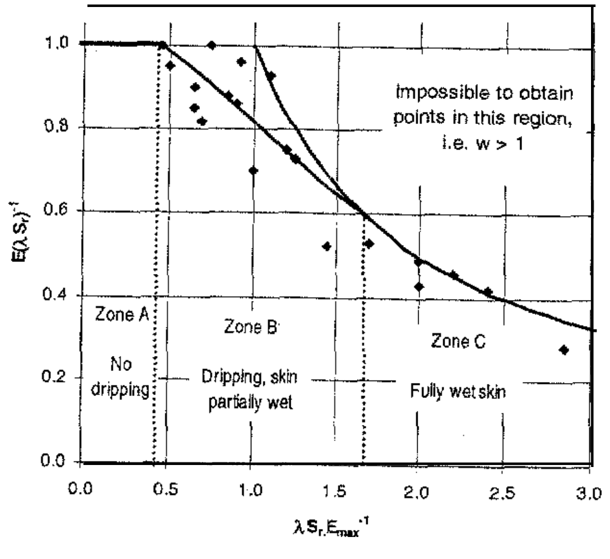

FIGURE 3

Comparison between predicted and observed relationships for evaporative cooling of an essentially nude male (redrawn from Stewart).[28]

- Zone B, where dripping occurs but the skin is not fully wet, and
- Zone C, where the evaporating ability of the environment is low compared to the sweat rate, the skin is fully wet, and dripping occurs.

By deriving mathematical equations for these various relationships, and combining these with standard equations for heat exchange and psychrometric properties, including the influence of clothing, the maximum (limiting) metabolic rate to ensure a deep body core temperature and sweat rate remain within nominated safe upper limits can he calculated. These equations are detailed in Appendix 1.

The valid range for TWL is from resting (60 W/m^{-2}) to 380 W/m^{-2}, as this is the range of experimental data collected by Wyndham. TWL is not valid where the dew point temperature of the ambient air is above the skin or clothing temperature. Finally, as the equations used to derive the heat transfer through clothing are not valid for subjects in encapsulating protective clothing (EPC), TWL cannot be assumed to be valid where impermeable clothing is used.

DISCUSSION AND PRACTICAL APPLICATIONS

It is emphasized that the recommended values of TWL do not require constant assessment of metabolic rates in the workplace, which will vary considerably between workplaces and over the course of a work shift. This means that persons untrained in assessing metabolic rates can supervise the protocol. TWL is designed for workers who are well educated about working in heat, have control over their work rate, are healthy, and are well hydrated. Self-pacing works well when it is formally incorporated in a protocol where workers have the mandate to self-pace, and when supervisors and management are supportive.(5)

TWL suffers from the same problem as most other heat stress indices in that environmental conditions need to be measured to assess the required actions under the protocols. However, by using an index that is designed specifically for self-pacing, there is less emphasis needed on measuring environmental conditions, as workers are allowed to reduce their work rate as needed. In most circumstances, workers are not working near the maximum work rate for the particular environment and they recognize this themselves-no measurements are required. When they believe they are working close to one of the limits, measurements are taken. This has proved quite practical.

Recommended guidelines for TWL limits with the corresponding interventions are provided in Appendix 2. These are based on the hierarchy of safety controls, and include a range of engineering. procedural, and personal protective equipment (PPE) interventions.

While TWL does not require metabolic rates to be assessed for routine use, the index itself provides an estimate of the limiting metabolic rate from simple measurements of environmental conditions. Therefore, TWL is of benefit not only in assessing thermal stress directly, but also in allowing occupational hygienists and engineers to make quantitative assessments of the following types of commonly encountered problems.

- The loss of productivity due to thermal stress. For example, if the metabolic rate (work rate) for a particular type of work in an environment of low thermal stress is 180 W/m^{-2}, and assuming a "resting" metabolic rate of 60 W/m^{-2}, then the productivity when working in an environment with a TWL of 120 W/m^{-2} is given by: Productivity $= (120-60)/(180-60) = 50\%$, where (120–60) is the residual work capacity (the workingrate less the resting rate) in this environment and (180–60) is the residual work rate required for full productivity. Simple calculations of the cost of lost production and other economic impacts of environmental conditions can then be made.
- Using the same premises, work/rest cycles can be established.
- Indicative exposure times before reaching a limiting deep body core temperature can be estimated. Taking the above example, if work with an energy expenditure (metabolic rate) of 180 W/m^{-2} is required in an environment with a TWL of 120 W/m^{-2}, then the heat storage is 60 W/m^{-2} or 120 W, using a conservative surface area per person of 2 m^2. If the typical worker has a mass of 80 kg. then the deep body core temperature will rise by about $60/3{,}500 \times 3{,}600/80 = 0.77°C$ per hour, since the specific heat of the body is 3,500 $J/(kg/K)^{-1}$. If the maximum acceptable deep body core temperature is (say) 38.2°C and work starts from a cool condition (deep body core temperature 37°C), then withdrawal would need to occur no longer than $(38.2-37.0)/0.77 = 1.5$ hours after work in these conditions commences. Clearly this calculation wouldonly be a starting point and fieldchecks would be needed to confirm practical exposure times.
- The cost benefit of installing cooling installations can be assessed. Because TWL is measured in W/m^{-2}, it can easily be compared to watts of refrigeration. The impact of localized cooling using various types of refrigeration can therefore be measured directly. For example, consider a workplace being ventilated with 10 m^3/s^{-1} of air at 30°C WB, 40°C DB, 40°C Globe, 100 kPa barometric pressure, and a wind speed of 0.2 m/s^{-1}. The initial TWL (with $I_{cl} = 0.35$ and $i_{cl} = 0.45$) is 110 W/m^{-2} (withdrawal conditions for self-paced work, refer to Appendix 2). Local refrigeration of 100 kW(R) (kilowatts of refrigeration effect) is installed. Standard psychrometric equations can be used to calculate that temperatures in the workplace will drop to 28.0°C WB and 31.4°C DB, which results in an increase in TWL to 158 W/m^{-2}. For conditions to be made acceptable for solitary, self-pacing, unacclimatized workers, the TWL would need to be improved

TABLE I

TWL values at various environmental conditions and clothing ensembles

MRT = DB + 2°C						MRT = DB						MRT = DB + 3°C					
Wind speed = 0.2 m/s^{-1} Barometric pressure = 101 kPa I_{cl} = 0.45, i_{cl} = 0.45						Wind speed = 0.5 m/s^{-1} Barometric pressure = 115 kPa I_{cl} = 0.69, i_{cl} = 0.4						Wind speed = 1.5 m/s^{-1} Barometric pressure = 80 kPa I_{cl} = 0.35, i_{cl} = 0.45					
	WB						WB						WB				
DB	24	26	28	30	32	DB	24	26	28	30	32	DB	24	26	28	30	32
34	175	157	136	114	n/p	34	181	161	140	118	n/p	34	288	260	229	193	154
36	170	151	131	109	nip	36	176	156	136	113	n/p	36	282	254	222	187	148
38	164	145	125	103	n/p	38	171	152	131	109	n/p	38	276	248	216	181	141
40	158	140	120	n/p	n/p	40	166	147	126	104	n/p	40	270	242	210	174	135
42	152	134	114	n/p	n/p	42	161	142	122	n/p	n/p	42	264	235	203	167	128

MRT = mean radiant temperature, °C; DB = dry bulb temperature, °C; WB = wet bulb temperature, "C; I,, = intrinsic clothing thermal resistance, clo; i_{cl} = clothing vapor permeation efficiency, dimensionless: n/p = heat stress too extreme even for (continuous) light work. Permit required.

further to 220 W/m^{-2} (refer to Appendix 2). The capital and operating costs of this engineering intervention (refrigeration) can be directly evaluated against the cost benefit of improved productivity.

- The "free" cooling available as a result of increased local air flow. Using the above example, the TWL could have been increased to the same 158 W/m^{-2} by increasing the wind speed over the skin from 0.2 to 0.7 m/s-' without any addition of refrigeration. For indoor work, this could probably he achieved by installation of a local electric or compressed air-operated fan or venturi air mover. This is-not to say that increasing the wind speed over the skin is able to increase the TWL in all situations; typically, increasing the wind speed beyond 4 m/s^{-1} provides little further benefit.
- The serious and generally detrimental impact of clothing ensemble (clothing plus any additional PPE) on thermal stress. and particularly any loss of vapor permeability; when various hazards in the workplace are being evaluated and PPE or alternative protective clothing ensembles is a consideration. the effects on thermal stress of the proposed changes can therefore he easily evaluated by adjusting the I_{cl} and i_{cl} values.

Table I shows typical TWLs over a range of conditions. In the past, it has not been practical to routinely measure the five environmental parameters required to evaluate TWL for each workplace each shift. This is one of the reasons why empirical indices such as WBGT have been popular-the technology has not been available to support more elaborate indices. However, a suitable pocket-sized instrument is now available[(32)] with the necessary accuracy to measure the parameters and with an internal processor to perform the necessary calculations for the heat strain model

CONCLUSIONS

Thermal work limit has advantages over other available indices where well-informed workers are undertaking self-paced work. The index can also he used, where paced work is unavoidable, to give realistic pacing guidelines (work/rest schedules) and can he used to trigger a formal permitting system. Practical intervention levels and protocols have been developed to assist in the reduction of heat illness. These have been extended to take into account unacclimatized workers. TWL also allows cost calculations to be undertaken into lost productivity and the impact of possible engineering remedies to be evaluated directly. A method for calculating TWL is proposed, which integrates data and theory published elsewhere, but which has been extensively tested in several hot industrial workplaces inside the tropics, TWL should only be used within the environmental conditions for which this data is valid (metabolic rates from 60 W/m^{-2} to about 380 W/m^{-2}).

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APPENDIX 1 DERIVATION OF TWL

Unless otherwise noted, in this appendix all references to ASHRAE (American Society of Heating, Refrigeration and Air-Conditioning Engineers) are to the reference text: 1997 *Fundamentals* SI edition, chapter 8, Thermal Comfort.(16) All references to EESAM are to: *Environmental Engineering in South African* Mines, 1989, chapter 20, Fundamentals of Human Heat Stress.(34) All temperatures are degrees Celsius.

In the TWL protocol. formulas for convection, radiation, and evaporation were derived from Stewart,(22,33,34) who derived them from Mitchell and Whillier's(21) work. Mitchell took "about a thousand measurements of each of radiation and convection spanning the complete range of temperature, wind speed,, and humidity experienced underground." Mitchell's values were all derived from mine workers in a climate laboratory wearing shorts only. Formulas for clothing correction are derived from ASHRAE.

The experimental data collected by Wyndham(24) has a range from resting (60 W/m^{-2}) to about 380 W/m^{-2}. These rates were sustained over three consecutive hours. The typical aerobic capacity ($\dot{V}O_{2max}$) of modern industrial workers is 30 to 50 $ml/kg^{-1}/min^{-1}$. Assuming a sustainable rate without fatigue at 33% of $\dot{V}O_{2max}$, this corresponds to a metabolic rate of 130 to 215 W/m^{-2} for a standard person (70 kg, 1.8 m^2). Given that TWL is defined as the sustainable metabolic rate under limiting conditions, the primary range of interest is, therefore, from light work (100 W/m^{-2}) to about 215 W/m^{-2}, although the experimental data is valid from 60 to 380 W/m^{-2}.

Ignoring heat loss via conduction (which is only significant for a worker in contact with a hot surface such as hot solids or liquids), the heat balance equation for humans and other homeotherms is as follows:

$$M - W = C + R + E + B + S_{sk} + S_c \qquad \text{[ASHRAE Eq. 1]}$$

Where W = rate of mechanical work accomplished
C = rate of heat loss from skin due to convection
R = rate of heat loss from skin due to radiation
E = rate of total evaporative heat loss from the skin
B = rate of convective and evaporative heat loss from respiration
S_{sk} = rate of heat storage in skin compartment
S_c = rate of heat storage in deep body core compartment

Note that the units for each term are W/m^{-2}.

By definition, for steady-state conditions, both S terms must be zero.

As the maximum useful mechanical work done by a human is of the order of 20 to 24 percent of the metabolic rate and is often zero in occupational settings, the W term is usually assumed to be zero, which is generally a conservative position to adopt. Note, however, that where negative work is done (i.e., work is done on the human body by an outside force, for example, a worker lowering a heavy object against gravity), the W term becomes negative and adds to the metabolic heat that must be dissipated by the body. Therefore, assuming W to be zero is nor the "worst case" scenario in all circumstances.

Heat losses due to respiration are given by the following formula:

$$B = 0.0014\,M\,(34 - t_a) + 0.0173\,M\,(5.87 - p_a) \qquad \text{[ASHRAE Eq. 26]}$$

where t_a = dry bulb temperature of ambient air in degrees C
p_a = partial water vapor pressure in ambient air in kPa

Note that in all ambient environmental conditions (except the extreme cold), air leaves the lungs in a saturated condition. For ambient dry bulb temperatures in the 30°C to 45°C range and ambient humidity in the 40 to 100 percent range, the range of heat losses due to breathing is 2 to 10 W/m^{-2}.

Losses from radiation for an essentially nude person can be given by the following relationship:

$$R = h_r f_r (t_{skin} - t_{rad}) \text{ in } W/m^{-2} \qquad \text{[EESAM Eq. 8]}$$

where

$$h_r = 4.61\,[1 + (t_{rad} + t_{skin})/546]^3,\ W/m^2/K^{-1} \qquad \text{[EESAM Eq. 9]}$$

f_r = posture factor (dimensionless), typically 0.73 for a standing person (ASHRAE Eq. 35).
t_{rad} = mean radiant temperature in degrees C

The radiant heat transfer coefficient, h_r, is a function of the difference in mean skin and mean radiant temperatures. As the difference between these two temperatures is generally small, the variation in h_r is also generally small. For example, over the range of dry bulb and globe temperatures from 22°C to 34°C and wind speeds from 0 to 4 m/s^{-1} (t_{rad} is a function of both globe temperature and wind speed), h_r varies within the small range of 5 to 6 $W/(m^2/C)^{-1}$, which is in accordance with *ASHRAE 1997* Fundamentals, Chapter 8, Eq. 35.

Losses from convection for an essentially nude person can be given by the following relationship:

$$C = h_c (t_{skin} - t_a) \text{ in } W/m^{-2} \qquad \text{[EESAM Eq. 11]}$$

where

$$h_c = 0.608\ P^{0.6} V^{0.6},\ W/m^2/K^{-1} \qquad \text{[EESAM Eq. 13]}$$

where P = the ambient barometric pressure in kPa
V = the wind speed over the skin in m/s^{-1}

In the TWL formulation, wind speed has a minimum value of 0.2 m/s^{-1}, which is about the minimum ("natural") convection current between *a* hot body and surrounding air (*ASHRAE 1997 Fundamentals,* Chapter 8, Table VI). Under TWL, wind speed is also limited to 4 m/s^{-1}. While a wind speed greater than 4 m/s^{-1} does have some further minor impact on convection and evaporation, it also tends to lift dust and other particles off surfaces, which can create separate hygiene problems.

The convective heat transfer coefficient, h_c, is a function of barometric pressure and wind speed only, not of temperatures. Over the range of wind speeds from 0 to 4 m/s^{-1}, h_c varies from 3.7 to 22 $W/(m^2/C)^{-1}$. For low wind speeds, the resulting values of h_c are very similar to those from ASHRAE Table VI, last equation, but do become more conservative compared to ASHRAE at higher wind speeds.

These formulations of h_c assume a reasonably uniform skin temperature. This will be true when the subject is working at the limiting condition, but will not be true for submaximal work in cool conditions, where the skin temperature of the extremities is typically much cooler than that of the trunk. As TWL is at the limiting condition, an assumption of uniform skin temperature is reasonable.

Clothing affects the sensible (C + R) and evaporative (E) heat losses. Sensible heat losses can be corrected using the process outlined in *ASHRAE 1997 Fundamentals*. Chapter 8.

$h = h_r + h_c$ in $W/(m^2/K)^{-1}$ [ASHRAE Eq. 9]

$f_{cl} = 1.0 + 0.3\ I_{cl}$, dimensionless [ASHRAE Eq. 47]

$t_{oper} = (h_r t_{rad} + h_c t_a)/(h_r + h_c)$ in degrees C [ASHRAE Eq. 8]

where t_{oper} = the operative temperature

$R_{cl} = 0.155\ I_{cl}$ in $(m^2/K)/W^{-1}$ [ASHRAE Eq. 411

where I_{cl} is the intrinsic clothing thermal resistance in clo units Do not confuse I_{cl} with i_{cl}, the clothing vapor permeation efficiency (refer later). Despite the potential confusion, these are the most commonly accepted abbreviations for these quite different parameters (ASHRAE).

$F_{cle} = f_{cl}/(1 + f_{cl} h R_{cl})$, dimensionless
ASHRAE Table II Sensible *Heat* Flow last equation

$C + R = F_{cle} h(t_{skin} - t_{oper})$
ASHRAE Table III Sensible *Heat* Lass third equation

Note that for a nude body, I,, = 0 and hence $F_{cle} = 1$, resulting in $C + R = h(t_{skin} - t_{oper})$.

There is a complex and generally inadequately understood interaction between clothing ventilation, wind penetration, moisture content, the "pumping action" due to physical work (itself partly dependent on the nature of the work and the body parts in motion), and the thermal insulation of clothing ensembles, among other factors. Real data is best obtained by the use of sweating, moving mannequins, and these are rare. Further experimental and theoretical work is currently being conducted (e.g., the European research project on heat stress and the proposal for revision of ISO 7933(6,7,17)) to better establish the impact of wetness and wind speed on dry and evaporative heat losses. These revised approaches can be incorporated into TWL as consensus develops in these areas. Note, however, that the use of a highly sophisticated clothing model may result in a complicated and poorly understood heat stress index that may be prone to misinterpretation and error.

The evaporative heat transfer coefficient for an essentially nude person, $h_e(W/m^{-2}/K^{-1})$, is given by the following relationship:

$h_e = 1587 h_c P/(P - p_a)^2$ [EESAM Eq. 17]

where P and p_a are the barometric and water vapor pressure in the ambient air, respectively, in kPa. Note that, since p_a is much less than P, and P is approximately equal to 100, this formula is **almost** identical to ASHRAE equation 27, i.e., $h_e = 16.5\ h_c$. It can further be seen that in typical conditions, h_e will be about 16 times the value of h_c, which in turn is 3 to 6 times the value of b,, illustrating the point that evaporative heat transfer is the main mechanism for heat loss when under thermal stress.

Adjustments to allow for clothing can follow the ASHRAE approach:

$R_{ecl} = R_{cl}/(LR\ i_{cl})$, dimensionless ASHRAE Table II *Parameters Relating Sensible and Evaporative Heat Flows*, first equation

where i_{cl} is the "clothing vapor permeation efficiency, the ratio of the actual evaporative heat flow capability through the clothing to the sensible heat flow capability as compared to the Lewis Ratio" (ASHRAE Table I text). For dry indoor clothing, i_{cl} is typically about 0.35 to 0.45 (ASHRAE Table VII), while for light cotton clothing with reasonable wicking properties, may be higher but cannot exceed 1.0 (the value if evaporative heat transfer through the clothing is unimpeded). LR is the Lewis Ratio and for typical conditions has the value of 16.5 (ASHRAE equation 27).

$F_{pcl} = 1/(1 + f_{cl} h_e R_{ecl})$, dimensionless
ASHRAE Table II *Evaporative* Heat *Flow*, last equation

where F_{pcl} is the "permeation efficiency, the ratio of the actual evaporative heat loss to that of a nude body at the same conditions, including an adjustment for the increase in surface area due to clothing" (ASHRAE Table I text).

The actual heat transfer from the evaporation of sweat off the skin, E_{sk} (W/m^{-2}), is:

$E_{sk} = w F_{pcl} f_{cl} h_e (p_s - p_a)$
ASHRAE Table III *Evaporative Heat Loss*, third equation

where p_s = saturated water vapor pressure at the mean skin temperature in kPa, and
w = skin wettedness

The maximum possible value of E_{sk} (E_{max}) is when the skin is fully wet (w = 1). Fully wet skin is not possible for a full work shift; however, healthy acclimatized individuals can maintain fully wet skin for several hours. *In* the context of self-paced work where workers can withdraw when stressed and who take a meal break approximately every four hours, the assumption of fully wet skin is a reasonable maximum value for the design of a limiting (maximum) allowable level. It is also the limit adopted by ISO for acclimatized persons.

Note that for a nude body $I_{cl} = 0$, hence $R_{cl} = 0$ and $R_{ecl} = 0$. Thus, as expected, the vapor permeation efficiency, i_{cl}, becomes increasingly less significant as fewer clothes are worn. Further, For a nude body, $F_{pcl} = 1$ and $E_{sk} = w h_e (p_s - p_a)$.

The heat transfer from the deep body core to the skin, H (W/m-*), must equal the heat losses from the skin to the ambient environment via radiation, conduction, and evaporation. This "core-to-skin" transfer can be expressed as:

$H = K_{cs}(t_{core} - t_{skin})$ [EESAM Eq. 23] where K_{cs} is the physiological conductance from deep body core to skin, in $W/(m^2/K)^{-1}$.

This requires the physiological conductance, K_{cs}, to be determined. K_{cs} is a function of both deep body core and mean skin temperatures as shown in Figure 1 where the thermoregulatory signal, t_Σ, is given by:

$$t_\Sigma = 0.1\ t_{skin} + 0.9\ t_{core} \qquad \text{Cabanac}^{(25)}$$

The physiological conductance, K_{cs} $(W/m^{-2}/K^{-1})$, can then be satisfactorily described by:

$$K_{cs} = 84 + 72\ \tanh[1.3\ (t_\Sigma - 37.9)]$$

curve fitted to Figure 1

where tanh is the hyperbolic tan value.

Sweat rate, S_r $(kg/m^{-2}/hr^{-1})$, is also a function of the thermoregulatory signal as shown in Figure 2. This curve can be adequately described by:

$$S_r = 0.42 + 0.44\ \tanh[1.16\,(t_\Sigma - 37.4)]$$

curve fitted to Figure 2

The latent heat of evaporation of sweat, λ, is given by:

$$\lambda = 2430\ kJ/kg^{-1}\ @\ 30°C \qquad \text{[ASHRAE Eq. 14]}$$

From Figure 3, the actual evaporation rate, E, in W/m^{-2}, is given by:

For $\lambda S_r/E_{max} < 0.46$ $\quad E = \lambda S_r$

For $0.46 \leq \lambda S_r/E_{max} \leq 1.7$ $\quad E = \lambda S_r \exp[-0.4127 \times (1.8\lambda S_r/E_{max} - 0.46)^{1.168}]$

For $\lambda S_r/E_{max} > 1.7$ $\quad E = E_{max}$

For a heat balance in the body,

$H = E_{sk}$ (heat flow core to skin equals heat flow skin to environment), and

$M = H + B$ (metabolic heat production equals heat flow core to skin + heat flow via respiration) The thermal work limit (TWL) for a person in this environment is then given by:

$TWL = M$

In summary, the above equations provide the heat flow from "skin to environment" due to convection, radiation, and respiration, skin wettedness, maximum evaporation rate and efficiency of sweating, heat flow from "core to skin," heat flow due to respiration, and sweat rate. There will then be a unique mean skin temperature and metabolic rate that provides a heat balance. This can be solved by iteration, at which point the body is in thermal equilibrium with the environment.

TABLE II

Recommended TWL limits and interventions for self-paced work

TWL limit (W/m^{-2})	Name of limit/zone	Interventions
<115 (or DB > 44°C or WB > 32°C)	Withdrawal	• No ordinary work allowed • Work only allowed in a safety emergency or to rectify environmental conditions • Permit to work in heat must be completed and authorized by manager beforehand • Dehydration test at end of shift • Personal water bottle (4-liter capacity) must be on the job at all times
115 to 140	Buffer	• Rectify ventilation or redeploy workers if possible • No person to work alone • No unacclimatized person to work • If work does continue, a corrective action request must be completed and signed by the manager within 48 hrs • Wind speed must be increased to at least 0.5 m/s^{-1} • Dehydration test at end of shift • Personal water bottle (4-liter capacity) must be on the job at all times
140 to 220	Acclimatization	• Acclimatized persons allowed to work, but not alone • Personal water bottle (4-liter capacity) must be on the job at all times
>220	Unrestricted	• No limits on work due to thermal stress

The resulting interactive desktop version of the TWL model, developed in Microsoft Excel using Visual Basic for Applications, is available from the authors at mvamail@tpg.com.au.

APPENDIX 2 RECOMMENDED GUIDELINES FOR TWL PROTOCOLS

Table II provides guidelines that have been introduced into several workforces with a large number of employees exposed to thermally stressful environments. Brake, Donoghue, and Bates(2) and Donoghue, Sinclair, and Bates(3) provided more details on some of these interventions, such as the health screen. acclimatization protocol, and dehydration tests.

The purpose of these protocols is primarily to ensure that management attention and progressively more serious intervention occurs at various threshold points.

The TWL value of 115 W/m^{-2} for the "withdrawal" limit (the trigger limit beyond which persons are withdraw" from the environment) was selected because 115 W/m^{-2} is an approximate metabolic rate for light work. When even light work is not continuously possible for acclimatized workers, they should be withdrawn for three reasons: 1) There is little practical benefit in keeping workers in such conditions, as productivity is excessively low; 2) if even light work is not continuously sustainable, a formal work-rest cycle should be initiated, and this probably requires supervision to positively ensure the employer's "duty of care" is met; and 3) because productivity is so low, workers frequently become frustrated and there is a danger that they will not continue to self-pace, which could result in hyperthermia.

It is important to recognize that work can still be undertaken when the TWL is less than 115 W/m^{-2}, but it is not conducted on a self-paced, self-supervised basis; a formal permitting system with prior management approval is required. Because TWL is quite sensitive to wind speed, it is sometimes possible to improve the air flow over the skin and continue work (i.e., move out of the withdrawal zone) without changing the temperature or humidity.

Workers are also withdraw" (or subject to a permit system) whenever the dry bulb temperature exceeds 44°C. irrespective of the TWL, as this temperature is close to the skin temperature at which several authors have found exposed skin discomfort or burning to commence.(13,17) Short exposures at ambient temperatures above 44°C can be tolerated, but continuous exposure to temperatures in excess of this is undesirable, especially under high wind speeds, where the insulation value of the air layer (the only protection for exposed ski") reduces to almost zero.

Workers are also withdrawn (or subject to a permit system) when the wet bulb temperature exceeds 32°C, irrespective of the TWL. This is because relatively small errors in measuring the individual environmental parameters can generate errors up to 20 W/m^{-2} in the calculated limiting metabolic rate under certain conditions. This is not a problem for self-paced work in "cooler" conditions (e.g.. 200 W/m^{-2}), as there is considerable latitude for the work rate to be adjusted downward. However. in hot conditions (e.g., 120 W/m^{-2}), the work pace may already be very slow and it would be difficult to adjust it downward any further without taking regular rest pauses. Clearly, a relative error of 20 W/m-* at a low TWL is much larger than at a high TWL, and the potential adverse consequences of the error are more severe. The additional limit of the wet bulb temperature was chosen because it has the strongest single influence on TWL and can be measured quite accurately. The wet bulb limit does not replace the TWL limit but adds a further "backstop" to the TWL values. The value of 32°C WB was chosen as it has historically been considered to be an upper limit for continuous light work.

The limit of 140 W/m^{-2} for the "buffer" limit was selected for two reasons. Firstly, it is desirable to have a graded response to increasing levels of heat stress, to avoid workers working in "near-withdrawal" conditions for several consecutive shifts. The buffer limit does this by providing a zone of 25 W/m^{-2} (about 1°C to 1.5°C Wet Bulb) up against the "withdrawal" limit. Unacclimatized workers are not allowed to work in the buffer zone. The acclimatization period lasts for the first 7 calendar days back at work after being away for more than 14 days. Also, by requiring a "Corrective Action Request" to be completed when work is carried out in buffer zone conditions, it ensures that environmental engineering defects arc noted and generally corrected before conditions approach withdrawal. A system of written corrective action requests is crucial to ensure defects in the workplace environmental conditions are recognized and rectified promptly.

The limit of 220 W/m^{-2} for the "acclimatization" limit was selected because virtually all of the approximately 130 cases of heat illness(3) found during the summer of 1997/1998 in one large underground mining operation in the tropics, which comprised workers with a wide variation of heat exposure and acclimatization, occurred where the TWL was less than about 220 W/m^{-2}. This limit (typically 26°C WB, 35°C DB and globe, 0.5 m/s^{-1} wind speed and 100 kP$_a$, or 28.7°C WBGT) can be compared to the "safe" condition for unacclimatized workers in summer uniforms doing light work (27.0°C WBGT), as indicated in ACGIH guidelines.

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A Valid Method for Comparing Rational and Empirical Heat Stress Indices

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No single heat stress index has gained universal acceptance within the past 20 years, despite extensive research. It is currently difficult to directly and quantitatively compare the many rational and empirical indices that are available, which results in confusion and a reluctance to change to a different index. A method is developed using the concept of *limiting metabolic rate*, which allows virtually all heat stress indices to be compared with one another. Because all occupational heat stress indices are based, explicitly or implicitly, on the human heat balance equation, a unique value of metabolic rate can be found that just allows an unrestricted work/rest cycle in particular environmental conditions. A comparison using this methodology shows that there are very large differences between the recommended limits under the various indices, even for similar populations of acclimatized workers.

Keywords: heat stress; standard; index; comparison

INTRODUCTION

There have probably been in excess of 60 heat stress indices developed since Houghton and Yagloglou formulated the Effective Temperature scale as an index of thermal comfort in 1923, many of which are still in use today (Parsons, 1993). These typically fall into one of two broad categories.

- *Empirical indices*. These have been developed from field experiments and the heat stress limits are generally expressed in terms of some environmental parameter, not a physiological parameter. Examples include the Effective Temperature (Basic and Normal), Corrected Effective Temperature, Oxford Index, Kata Thermometer, Wet Bulb, Wet Bulb Globe Temperature (WBGT) Index and others. Empirical indices can be subdivided into those that are in use in only one location, area, industry or employer and those that are more widely employed.
- *Rational indices*. These include indices that predict sweat rate (Belding and Hatch, 1955) or predicted 4 h sweat rate (McArdle *et al.*, 1947; International Organization for Standardization, 1989), those that predict 'core' temperature or core temperature increase (ISO 7933), those that predict heart rate (Fuller and Brouha, 1966) and those that predict a combination of two or more of these physiological parameters. Rational indices can be sub-divided into those that are *predictive* (i.e. measure environmental conditions and predict thermal strain for a population accordingly) and those that are essentially *reactive* (i.e. those that measure thermal strain for an individual and react accordingly). Reactive indices typically monitor a vital sign associated with heat strain in an individual and advise action depending on the result, whereas the intention of predictive indices is to estimate heat strain in a population or sub-population when exposed to particular levels of heat stress.

One of the intriguing and complicating issues of heat stress is that, unlike most other physical or chemical agents in the occupational environment, heat is a natural stressor and man, as a homeotherm, is generally well-adapted to deal with heat. Belding (1976) noted some time ago that '...man's adaptations to heat exposure are so well developed (and when naked his adaptations to cold stress are so poor) that he must be classed as a tropical animal'. Sawka *et al.* (1996) also noted that 'Humans are tropical animals because:

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- They rely on physiological thermoregulation in the heat but behavioural thermoregulation (adjustments) in the cold;
- The thermoneutral ambient temperature for nude humans and the temperature necessary for undisturbed sleep are relatively high (approximately 27°C);
- Humans demonstrate substantial heat acclimatisation but only modest cold acclimatisation.'

The number of heat stress indices developed over the years, the lack of broad acceptance of any single index (Mack and Nadel, 1996; Hansen, 1999), the recognized shortcomings of the most common index in use, the WBGT (Rastogi *et al.*, 1992) and the fact that heat is a naturally occurring stressor all reinforce the problems of managing heat stress, especially in an occupational setting.

To these fundamental issues are added the problems of clothing, which affects convective, evaporative and radiative heat transfer, and acclimatization.

Clothing thermal properties, which have generally been established using laboratory techniques at nil air flow and using 'dry' fabrics, are also known to be significantly affected by wind speed and clothing wetness (Lotens and Havenith, 1994; Havenith *et al.*, 1999; Holmér, 1999). This latter factor will be significant when a worker is sweating, as his clothing rapidly becomes wet and, at least in hot, humid environments, saturated.

Acclimatization, as alluded to above by Belding and Sawka, is another factor that impacts significantly on the thermal strain produced by equivalent levels of environmental stress (Leithead and Lind, 1964; Gisolfi, 1987).

Further, most indices are used to predict whether continuous work is possible or some sort of work/rest cycle is required under particular conditions. Where a comparison is made between two indices and both indicate continuous work is possible, the investigator has no simple means to know just how close each of the indices is to requiring a work/rest cycle. In other words, the indices may give the condition a 'simple pass' when the investigator really wants to have a 'graded pass'.

One tool that is therefore lacking in the current literature is a valid, quantitative means to compare the wide range of heat stress indices in use. Such a tool would allow a more informed discussion of the relative merits and quantitative impact of the various indices. It would make it substantially easier for regulators, hygienists, engineers, occupational physicians and operational managers to consider changing heat stress indices. This paper develops a method to compare most heat stress indices.

METHODS

For human thermoregulation, the heat balance equation is expressed (American Society of Heating, Refrigeration and Air-conditioning Engineers, 1997; Stitt, 1993) as:

$$M - W = Q_{sk} + Q_{res} + F + S \qquad (1)$$

where M is the metabolic rate (W/m^2), W is the external (mechanical, useful) work rate (W/m^2), Q_{sk} is heat loss through the skin (W/m^2), Q_{res} is heat loss through respiration (W/m^2), F is heat loss due to fluid ingestion (W/m^2) and S is the heat storage in the body (W/m^2). The units of all terms in equation (1) are W/m^2, where W is the metabolic rate in watts and m^2 is the skin surface area (for a 'standard' person this is usually taken to be 1.8 m^2).

Under most circumstances, the W term in equation (1) is small and is generally ignored because it is small, because it cannot be estimated with accuracy in the field and because doing so usually adds a degree of conservatism to the estimate of the amount of heat that must be lost via the skin and respiration. However, in some circumstances (e.g. manually lowering heavy objects), the W term is actually negative, as the useful work done resisting gravity becomes an additional heat load on the body.

The F term in equation (1) is generally overlooked by most authorities. However, for a person under thermal stress drinking 1 l/h water at 12°C and this being absorbed into the body at (say) 38°C, the net cooling effect is 30 W, or 17 W/m^2 for a standard person. This is substantially greater than the typical heat losses due to respiration and can be a significant proportion (>10%) of the total heat exchange when conducting light work (e.g. 115 W/m^2) under very thermally stressful circumstances. When making comparisons between heat stress indices, F can be considered to be 0, as no index to date takes this term specifically into account.

The purpose of most heat stress indices is to develop a guideline for safe work under particular environmental conditions. For *continuous* work to be safe in a particular environment, the core temperature must plateau at a safe level, i.e. the S term in equation (1) (heat storage in the body) must be 0. In the absence of cooling, body tissues cannot absorb large amounts of heat. A 70 kg person working at 140 W/m^2 could only sustain 16 min before the deep body tissues had increased by 1°C. Alternatively, for an increase in deep body tissue of 1°C over 4 h, the heat absorbed in the body itself is 9 W/m^2 for a standard person, insufficient to accommodate even resting metabolism.

As all heat stress indices are based, either explicitly or implicitly, on the heat balance equation, it is clear that every heat stress index will therefore have a maximum metabolic rate at which continuous work (under a given environmental condition) is regarded as safe by that index. This is the *limiting* (or maximum) metabolic rate predicted as being safe for the particular environmental and clothing conditions. This limiting metabolic rate is usually expressed in W/m^2.

At this limiting condition (with $W = 0$, $F = 0$ and $S = 0$),

$$M = Q_{\mathrm{sk}} + Q_{\mathrm{res}} \qquad (2)$$

Thus, the metabolic heat generated is just equal to the heat lost by the body. Ignoring the effects of fatigue and assuming that the hydration state is maintained, equation (2) describes the maximum metabolic rate that can be sustained without any rest pauses (i.e. without a formal work/rest cycle) in this particular environment wearing a nominated clothing ensemble.

By solving for this 'limiting' rate under a particular set of environmental conditions (combination of temperature, humidity, wind speed and barometric pressure), clothing parameters and acclimatization state, each index can be compared with the other.

Example using the ACGIH index

The *1998 TLVs and BEIs: threshold limit values for chemical substances and physical agents* (American Conference of Government Industrial Hygienists, 1998) has been used for this example (rather than the 2000 edition) as it provides a curve relating metabolic rate for an unlimited work cycle to its recommended heat stress index, the Wet Bulb Globe Temperature (WBGT). The 2000 edition provides qualitative guidance on metabolic rates only.

For outdoor work with a radiant heat load, the WBGT is defined as follows:

$$\mathrm{WBGT} = 0.7 \times \mathrm{NWB} + 0.2 \times \mathrm{GT} + 0.1 \times \mathrm{DB} \qquad (3)$$

where NWB is the natural wet bulb temperature, GT is the globe temperature and DB is the dry bulb temperature.

The recommended threshold limit values (TLVs) for acclimatized and unacclimatized workers are given in figure 1 of the 1998 Heat Stress TLV.

Standard curve fitting techniques (MS Excel linear regression functions) show that the ACGIH curves can be expressed by the following equations, with regression coefficients (r^2) better than 0.9995:

$$\mathrm{WBGT}_{\mathrm{max,\ acclimatized}} = 125.63 - 76 \times \mathrm{Met}^{0.04418} \qquad (4)$$

$$\mathrm{WBGT}_{\mathrm{max,\ unacclimatized}} = 70.91 - 22.04 \times \mathrm{Met}^{0.1317} \qquad (5)$$

where Met is the metabolic rate (W) and $\mathrm{WBGT}_{\mathrm{max}}$ is the maximum wet bulb globe temperature (°C) for either acclimatized or unacclimatized persons.

These can be transposed as:

$$\mathrm{Met}_{\mathrm{max,\ acclimatized}} = [(125.63 - \mathrm{WBGT})/76]^{22.634} \qquad (6)$$

$$\mathrm{Met}_{\mathrm{max,\ unacclimatized}} = [(70.91 - \mathrm{WBGT})/22.04]^{7.592} \qquad (7)$$

By then selecting any particular values of natural wet bulb, dry bulb and globe temperatures, the corresponding WBGT and ACGIH limiting metabolic rates can be calculated.

Extension to other heat stress indices

Using a similar process (see Appendix), the limiting metabolic rates for the following heat stress indices were evaluated.

- International Standards Organization (ISO) 7933, using a clothing thermal insulation value of 0.6 clo and a 0.7 posture factor (the proportion of the body surface exposed to radiation) and the limits applicable to the 'acclimatization, danger' criteria.
- ACGIH, using 'summer work uniform, 0.6 clo'.
- United States Army Research Institute for Environmental Medicine (USARIEM) (Pandolf *et al.*, 1986), using 'trousers and T-shirt clothing insulation and vapour permeation constants, Itc = 0.94, Itvc = –0.30, Imc = 0.61, Imvc = 0.38'.
- Air cooling power, or ACP (McPherson, 1992), using 0.55 clo (0.085°C m^2/W), 0.45 clothing vapour permeation efficiency (the ability of the clothing to pass water vapour) and a 0.7 posture factor.
- Corrected effective temperature (Houghton and Yagloglou, 1923; Bedford, 1946) with limits for industrial work from Wyndham, Lind and Nielsen and the World Health Organization as cited in Weiner (1972) (see also Appendix).
- Thermal work limit, or TWL (Brake and Bates, 2002), using 0.35 clo, 0.45 vapour permeation ratio and a 0.73 posture factor. The lower clo value is justified by the authors because this index is expressly written for 'limiting' self-pacing conditions and assumes that clothing will generally be saturated with sweat and because the thermal conductivity of water is some 20 times that of air (which is the main insulator in dry summer clothing).

The reason that different clothing properties and posture factors are used in the comparisons is that these are the values recommended by the respective authors for similar applications (acclimatized industrial workers wearing cotton shirt and cotton long trousers). Therefore, some of the variation seen in the above comparisons will be due to different recommended clothing properties for similar clothing ensembles. Some of the variation will also be due to the use of different allowed physiological limits and hence different 'factors of safety'. For example, the USARIEM model allows an upper limit for deep body core temperature of 38.5°C for continuous work and 39.0°C for a one-off exposure, whereas the ISO and ACGIH restrict this to 38.0°C and TWL is restricted to 38.2°C. Likewise, the USARIEM model has no limit on sweat rates (merely predicting these, resulting in sweat rates of up to 2.4 l/h), TWL is restricted to 1.2 l/h and ISO is restricted to 1.04 l/h. Higher upper limits can have a significant impact on acceptable metabolic heat generation under certain environmental conditions. Other differences may be due to different environmental limits. For example, consider a true wind speed of 0.2 m/s. The ISO would increase this by 0.7 m/s to 0.9 m/s at a metabolic rate of 180 W/m^2 (the increase in wind speed being justified by body movement associated with the metabolic rate), which will significantly lift the calculated evaporative cooling at low actual wind speeds, whereas TWL would restrict this wind speed to 0.2 m/s, which will drop evaporative cooling significantly and, hence, the limiting metabolic rate at low wind speeds. For the same true wind speed of 0.2 m/s, one index is basing its limiting metabolic rate on a wind speed of 0.9 m/s, whereas the other bases its limiting metabolic rate on a wind speed of 0.2 m/s. It is also important to recognize that each of the heat stress indices selected for these comparisons has been subject to varying degrees of validation.

RESULTS AND DISCUSSION

Figures 1 and 2 show comparisons of several heat stress indices for acclimatized workers wearing typical industrial cotton clothing (shirt, long trousers, safety helmet and safety boots). In these figures DB is the dry bulb temperature (°C), WB is the wet bulb temperature (°C) and MRT is the mean radiant temperature (°C). Figure 1 shows hot, dry conditions, defined here arbitrarily as DB = MRT = WB + 10°C, for wind speeds of 0.2, 0.5, 1.0 and 3.0 m/s, and Fig. 2 shows hot, humid conditions, defined here arbitrarily as DB = MRT = WB + 3°C, for wind speeds of 0.2, 0.5, 1.0 and 3.0 m/s.

Each chart shows the limiting metabolic rate recommended under the particular index as a function of wet bulb temperature.

Superimposed on these charts is an arbitrary metabolic rate of 140 W/m^2.

From these charts the following conclusions can be drawn.

- There is a wide range of 'limiting' environmental conditions for identical metabolic rates and similar clothing ensembles and acclimatization states. Table 1 summarizes the maximum wet bulb temperature recommended for workers with a metabolic rate of 140 W/m^2 (a moderate work rate) according to ACGIH, TWL, ISO 7933, USARIEM and CET.
- ISO 7933 appears to be insensitive to temperature, humidity and wind speed, at least at the nominated 140 W/m^2 metabolic rate.

The converse approach is to examine the 'limiting' metabolic rate for a particular environmental condition. Table 2 gives a comparison between the above four indices, at an identical 28°C WB.

- Again, problems with some indices emerge when compared according to these criteria. ISO 7933 appears to indicate that an increase in wind speed (from condition A to B and from C to D above) results in a marginal reduction in the maximum metabolic rate, contrary to all the other indices. Moreover, ISO indicates that an increase in DB temperature, at a fixed WB (from condition C to A and from D to B above), allows a marginal increase in limiting metabolic rate, contrary to the other indices and contrary to the findings of others that an increase in dry bulb temperature, with the wet bulb temperature and wind speed fixed, results in more severe thermal stress (Wyndham *et al.*, 1965).
- TWL, ACP, CET and USARIEM are all sensitive to wind speed under these conditions, although TWL is perhaps the most so; however, ACGIH and ISO 7933 are insensitive to wind speed under these conditions. TWL and USARIEM values are relatively close at higher wind speeds, but diverge at lower wind speeds. This could be explained in part by the fact that USARIEM assumes that the metabolic heat at low wind speeds is produced from dynamic muscle work (arm and leg work) which elevates wind speed over the skin; whereas TWL assumes that metabolic heat can be produced by static muscle work, which produces little increase in wind speed over the skin.
- The 'basic' (shorts only) scale of CET underestimates thermal stress, compared to the other scales, particularly under hot, humid conditions (see also Appendix). Moreover, the slope of the CET index is steeper than all the other indices. This steeper slope is probably related to the fact that CET was developed from instantaneous appreciations of warmth, whereas all the other indices are predicated on steady-state heat exposures.
- There is a very wide range of acceptable limiting metabolic rates (with differences of up to 100 W/m^2 or 100%, after deducting resting metabolic rates) under identical environmental conditions.

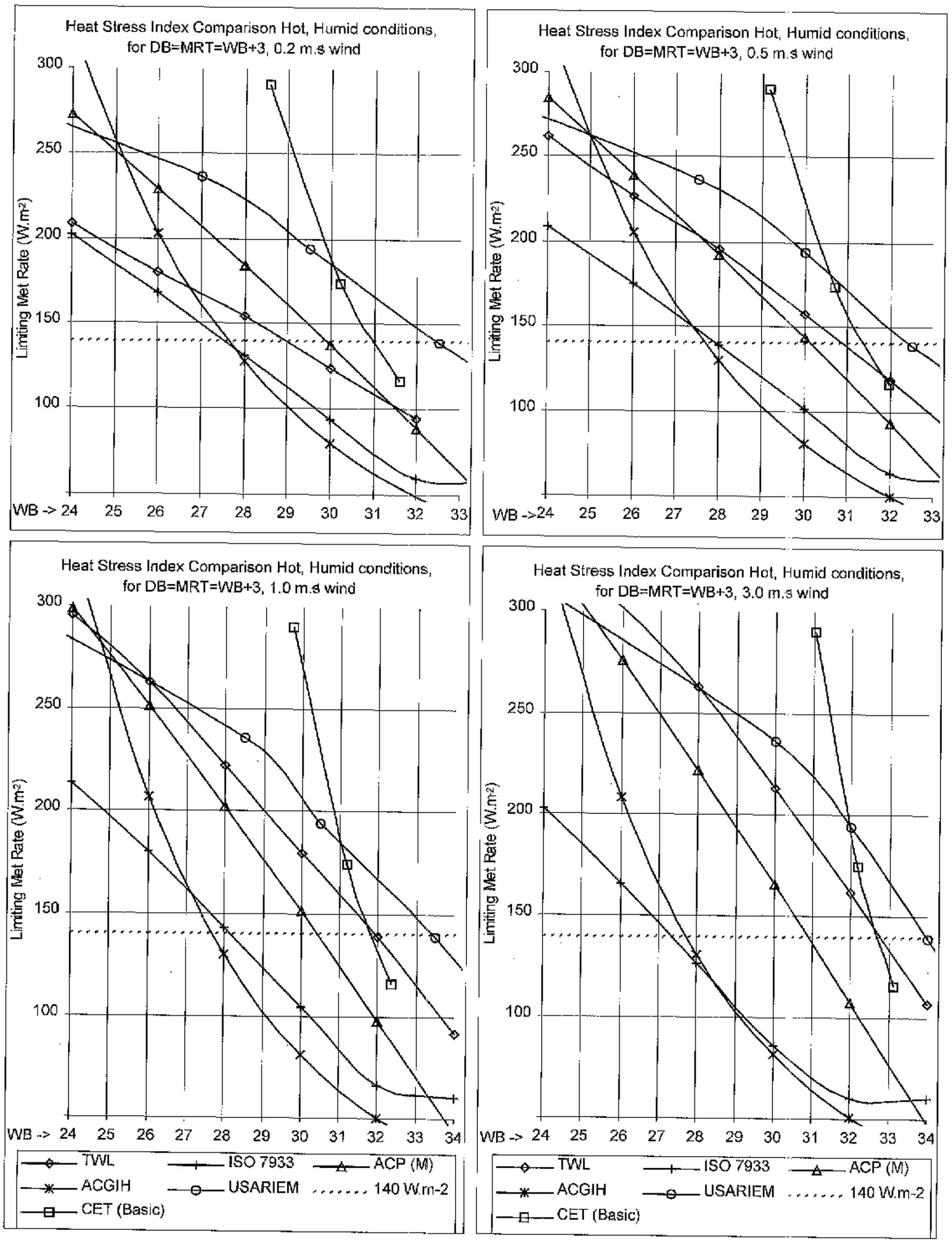

Fig. 1. Comparison using limiting metabolic rate of several heat stress indices under hot dry conditions (DB = MRT = WB + 10°C) for four wind speeds. An arbitrary metabolic rate of 140 W/m^2 is superimposed for comparison purposes.

By using the thermal resistance and vapour permeation values for a 'nude' body, the influence of different clothing ensemble treatments in the different indices can be removed and a comparison of the underlying physiological models or assumptions can be made.

Recently, substantial work has been undertaken on the use of 'dynamic' (rather than 'static') clothing values (Holmér, 1999). These differences can also be investigated using this approach.

One weakness in using this method to compare indices is that the comparison can only be made at the

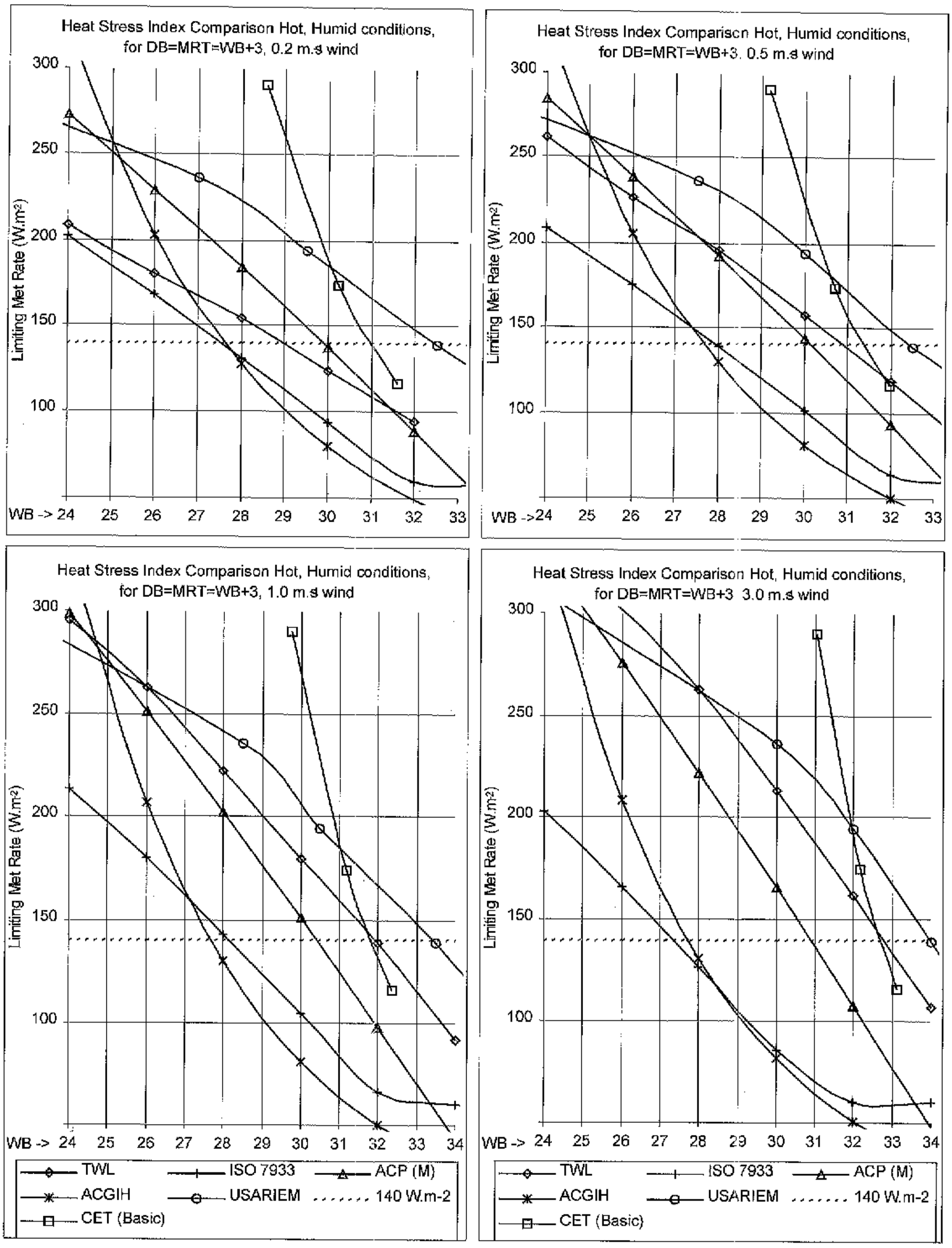

Fig. 2. Comparison using limiting metabolic rate of several heat stress indices under hot humid conditions (DB = MRT = WB + 3°C) for four wind speeds. An arbitrary metabolic rate of 140 W/m^2 is superimposed for comparison purposes.

limiting metabolic condition (in terms of thermal stress). However,

- where the required work rate is lower than the limiting condition, an unlimited work cycle is possible, so that comparisons in this range are of less practical relevance;
- for conditions 'worse than' the limiting condition, the method of comparison can be extended as shown below;

Table 1. Comparison of selected heat stress indices at a fixed metabolic rate of 140 W/m^2

	Maximum WB for metabolic rate of 140 W/m^2					
	ACGIH	TWL	ACP (M)	ISO 7933	USARIEM	CET
Hot, dry, 0.2 m/s wind	25.2	27.5	28.6	27.5	31.4	29.0
Hot, dry, 3.0 m/s wind	25.7	32.0	29.7	27.4	33.4	30.3
Hot, humid, 0.2 m/s wind	27.6	29.0	29.9	27.5	32.4	31.0
Hot, humid, 3.0 m/s wind	27.7	32.9	30.9	27.3	34.0	32.7

Hot, dry, dry bulb = mean radiant temperature = wet bulb + 10°C; hot, humid, dry bulb = mean radiant temperature = wet bulb + 3°C.

Table 2. Comparison of selected indices in terms of limiting metabolic rate (W/m^2)

		Maximum metabolic rate (W/m^2) for 28°C WB[a]					
		ACGIH	TWL	ACP (M)	ISO 7933	USARIEM	CET
Hot, dry, 0.2 m/s wind	A	75	132	153	135	195	175
Hot, dry, 3.0 m/s wind	B	80	243	188	130	245	290
Hot, humid, 0.2 m/s wind	C	130	154	185	130	225	>300
Hot, humid, 3.0 m/s wind	D	135	263	222	125	265	>300

Hot, dry, dry bulb = mean radiant temperature = wet bulb + 10°C; hot, humid, dry bulb = mean radiant temperature = wet bulb + 3°C.

[a] Rounded to nearest 5 W/m^2.

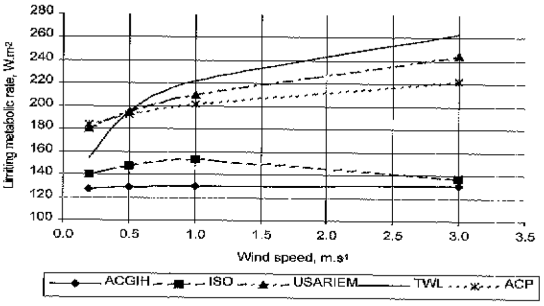

Fig. 3. Comparison of selected heat stress indices according to wind speed using limiting metabolic rate for environmental conditions 28°C wet bulb, 31°C dry bulb, 31°C mean radiant temperature and 100 kPa barometric pressure.

- even restricting the comparison to the point of limiting metabolic rate still gives an unlimited number of points for comparison, as there are effectively an unlimited number of possible combinations of environmental condition and clothing ensemble.

Using the method for sensitivity studies

Often it is desirable to know how sensitive an index is to a particular parameter, such as wind speed. It is generally straightforward to plot how the index itself varies with wind speed, but a plot so produced cannot be compared directly with a similar sensitivity study using another index, as the parameters involved (WBGT, CET, etc) are not directly comparable. Using the limiting metabolic rate methodology, sensitivity studies of various indices can be directly compared. An example is given in Fig. 3, where the sensitivity of selected indices to wind speed is given for a reference condition of 28°C WB and 31°C DB.

Not only does this chart confirm that the various indices produce very different recommended maximum metabolic rates for the same wind speed under identical environmental conditions, it also indicates widely differing sensitivities (slope of the limiting metabolic rate versus wind speed curves) to increasing/decreasing wind speed. It also highlights the apparent anomaly with the ISO, which indicates that increasing wind speed under this reference condition results in a reduced ability to work.

Sensitivity studies of any environmental or clothing parameter or acclimatization state are possible using this method. Sensitivity studies to particular physiological limits are also possible, e.g. different maximum sweat rates or deep body core temperatures within a given model. The method is therefore flexible in application in terms of sensitivity studies across indices or protocols.

Extension of the method to conditions beyond the limiting metabolic rate

This methodology can be extended to the situation where a workplace with a formal work/rest cycle needs to be evaluated, i.e. where the actual metabolic rate required for the task exceeds the limiting metabolic rate.

Assume that when in the 'rest' portion of the cycle, workers have an actual metabolic rate of MR_{rest}, with a limiting metabolic rate under those environmental conditions of WL_{rest}. Further assume that in the 'work' portion of the cycle, workers have an actual metabolic rate of MR_{work}, with a limiting metabolic rate under these environmental conditions of WL_{work}. Then for no net heat storage in the body, the time-weighted average metabolic heat gain from the work portion must not exceed the time-weighted average metabolic heat loss in the rest portion. If the proportion of time spent in the 'work' portion of the cycle is $T_{w\%}$, then,

$$T_{w\%} \times (MR_{work} - WL_{work}) = (1 - T_{w\%}) \times (WL_{rest} - MR_{rest}) \quad (8)$$

where all terms apart from $T_{w\%}$ are in W/m^2. Or, by rearranging and solving for $T_{w\%}$,

$$T_{w\%} = 1/[1 + (MR_{work} - WL_{work})/(WL_{rest} - MR_{rest})] \quad (9)$$

By constructing a limiting metabolic rate curve for the particular heat stress index, the theoretical working time per hour for a particular environmental and clothing condition [where the required work rate is beyond the limiting (continuous) metabolic rate] can be calculated using equation (9) and compared to the actual work/rest cycle in existence in the workplace or to the theoretical work/rest cycle using any other index. In addition, approximate actual exposure times prior to withdrawal (and recovery times) can be calculated, assuming an allowable core temperature increase and the average thermal capacity of body tissues.

CONCLUSIONS

All heat stress indices are based on some parameter [sweat rate, heart rate, core temperature, or environmental condition (WB, WBGT)]. Each index then develops 'limits' for work under this index, expressed in terms of the same parameter.

Implicit or explicit in all heat stress indices is a metabolic rate, because metabolic rate (along with the state of acclimatization) is a significant component of the human heat balance equation.

Any heat stress index can therefore be converted into a limiting (maximum) metabolic rate applicable to the particular environmental, clothing ensemble and acclimatization state.

This limiting metabolic rate then allows all heat stress indices, and any combination of environmental and clothing parameters acceptable under that index, to be compared on an equivalent basis.

The confounding effects of different treatments of clothing parameters can be removed by using values for nude bodies in the comparisons.

Comparisons completed to date on this basis indicate major differences between heat stress indices currently in use and also internal inconsistencies within indices. These differences relate not just to the actual recommended limits for work, but also to the sensitivity of the respective indices to important parameters such as wind speed.

APPENDIX

ISO 7933

ISO 7933 limiting metabolic rate was found by calculating the unique value of metabolic rate at which the rate of heat storage was nil for acclimatized persons, using the ISO heat balance equations, recommended limits for acclimatized persons and 0.6 and 0.7 for clothing thermal insulation and 'body area fraction exposed', respectively.

USARIEM

USARIEM limiting metabolic rate was found by finding the highest value of the target parameter (e.g. wet bulb temperature) for which work was continuously possible (work/rest cycle = 60 min/h) whilst holding the other environmental parameters constant. These limiting WB temperatures were then plotted over the range of metabolic rates and environmental conditions of interest and interpolated for the actual condition of interest.

The USARIEM limiting data for trousers, long-sleeved shirt, safety helmet and safety boots (Itc = 0.94, Itvc = –0.30, Imc = 0.61, Imvc = 0.38) are summarized in Table 3.

Corrected effective temperature (CET)

CET values were found directly from charts of CET. Table 4 gives the acceptable upper limits for continuous work in terms of CET (Weiner, 1972). The resulting values of maximum wet bulb tempera-

Table 3. USARIEM limiting wet bulb temperatures (°C)

Metabolic rate (W)	0.2 m/s	0.5 m/s	1.0 m/s	3.0 m/s
Hot, humid[a]				
100	>36.0	>36.0	>36.0	>36.0
150	35.0	36.0	36.0	36.0
250	32.5	32.5	33.5	34.0
350	29.5	30.0	30.5	32.0
425	27.0	27.5	28.5	30.0
600	16.5	17.5	19.0	22.0
Hot, dry[b]				
100	>36.0	>36.0	>36.0	>36.0
150	35.0	35.0	35.0	35.5
250	31.5	32.0	32.5	33.5
350	28.0	28.5	29.5	31.0
425	25.5	26.0	27.0	29.0
600	12.5	13.0	15.5	17.5

[a] Maximum WB (°C) for unlimited work cycle for dry bulb = mean radiant temperature = wet bulb + 3°C.

[b] Maximum WB (°C) for unlimited work cycle for dry bulb = mean radiant temperature = wet bulb + 10°C.

Table 4. Corrected effective temperature (CET) limiting values according to Weiner (1972)

Description of work	Metabolic rate (kcal/m^2/h)	Metabolic rate (W/m^2)	Acclimatized limit (°CET)	Unacclimatized limit (°CET)
Light work	100	116	32.0	30.0
Moderate work	150	174	30.6	28.0
Hard work	250	290	28.9	26.5

Table 5. Corrected effective temperature (CET) limiting wet bulb temperatures (°C)

		Metabolic rate (W/m^2)	Maximum wet bulb temperature for wind speed (m/s)			
			0.2	0.5	1.0	3.0
Hot, humid[a]						
Light work	32.0° CET	116	31.6	32.0	32.3	33.1
Moderate work	30.6° CET	174	30.6	30.6	30.6	30.6
Hard work	28.9° CET	290	30.2	30.7	31.2	32.2
Hot, dry[b]						
Light work	32.0° CET	116	28.9	28.9	28.9	28.9
Mod work	30.6° CET	174	28.6	29.1	29.8	31.0
Hard work	28.9° CET	290	32.0	32.0	32.0	32.0

[a] Dry bulb = mean radiant temperature = wet bulb + 3°C.
[b] Dry bulb = mean radiant temperature = wet bulb + 10°C.

tures, based on the basic scale of corrected effective temperature, were then read from the CET charts and are shown in Table 5. These values were then plotted and interpolated for the conditions of interest (i.e. 140 W/m^2 or 28°C WB).

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