A quantitative method for assessing

THE IMPACT OF ACCLIMATISATION

in the workplace

Rick Brake
Principal Consultant, Mine Ventilation Australia

Abstract

One of the important ways that humans cope with repeated exposure to heat stress is by physiological adaptation, a process known as *heat acclimatisation*. This paper identifies the issues of acclimatisation and de-acclimatisation that impact on fly-in, fly-out (FIFO) and local-domicile (LD) operations and proposes a model to obtain some quantitative indication of the impact of different types of rosters on FIFO and LD operations, as well as the impact of workers changing job type or returning from vacation or other work absences into hot conditions. Using the methodology, important differences can be seen in the acclimatisation status of workers domiciled locally, compared to those on a fly-in, fly-out roster, depending on the type of roster, their fly-out location and other factors.

Introduction

Excessive heat stress in the workplace can result in heat illness, poor safety, low productivity, poor morale and increased costs. It is therefore important to provide a ' holistic' approach to the management of heat stress in the workplace (Brake et al, 1998).

Symptoms of heat illness range from headache and nausea through vomiting and syncope to 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 organ damage. Heat exhaustion has been shown to have a clear clinical profile (Donoghue and Bates, 1999) and may well have been under-reported in many industries during periods of high ambient temperature.

One of the important ways that humans cope with repeated exposure to heat stress is by physiological adaptation, a process known as *heat acclimatisation*.

This adaptation is expressed in at least the following ways: an increase in circulating blood volume, an increase in sweat rate, a reduction in the time delay prior to the onset of sweating, a reduction in the sodium and other solute (salt) content of sweat, a reduction in both deep body core temperature and heart rate during the exposure, an increase in total body water and an increased resistance to sweat gland fatigue and hidromeiosis.

When exposed to heat, the thirst sensation of unacclimatised persons is also much weaker than that of acclimatised persons, predisposing unacclimatised persons to a much greater probability of dehydration, which is one of the most common causes of heat illness.

As an indication of the impact of acclimatisation on productivity alone, one study (Leithead and Lind, 1964) found that acclimatised workers are most *efficient* at about 27^0 ET, whereas unacclimatised workers are most efficient at about 18 to 21^0 ET. Other studies have found a 2^0 to 4^0 ET (or WBGT or WB, depending on the study) difference in the practical *maximum* working limit of acclimatised and unacclimatised workers (ACGIH, 1998; Ramsey and Beshir, 1997; Schutte et al, 1991).

If the heat adaptation process reaches completion, acclimatisation therefore produces quite profound reductions in the heat strain of humans exposed to identical levels of heat stress.

The physiological process of *heat* adaptation can be compared to that of *exercise* adaptation, as illustrated in Table 1.

These similarities should not be pressed beyond the fact that when the human body is exposed to certain types of stress, it can adapt, that the adaptation can lead to substantial benefits in terms of future exposures to that stressor and that there are similarities between the requirements needed to adapt to heat and exercise, and the results of the adaptation to each of these.

In an occupational context, a loss of heat

Stressor ->	Heat	Exercise
Name of adaptation process	Heat acclimatisation	Aerobic exercise
End point	' Heat acclimatised'	'Fit'
Time to reach end point	4 weeks plus	4 weeks plus
Frequency of each exposure	Daily (minimum about 4 times per week)	Daily (minimum about 4 times per week)
Intensity of each exposure	Sweating, preferably at least 50% skin wetness	Heart rate more than 40% of cardiac reserve
Duration of each exposure	30 to 120 minutes	Minimum 30 minutes

Table 1 Similarities between heat adaptation and exercise adaptation

acclimatisation (or inability to gain full acclimatisation) results in lower productivity, poor morale, and a much-increased risk of fatigue and more serious forms of heat illness.

Until recent times, industrial workers have usually been domiciled within a short distance of their place of employment, and have worked a repeating pattern consisting of typically five or six days at work, followed by a (short) rest of one or two days.

If their workplace subjected them to heat stress, they therefore reached a fully acclimatised state and retained this during their period of employment. In recognition of the importance of acclimatisation, some mines have introduced formal acclimatisation protocols.[1]

In more recent years, changes to this historical practice of housing workers on site can have a significant impact on the ability of workers to develop and then retain this important mechanism for coping with heat stress. Two of these changes include:

- Extended rosters, eg nine work days followed by five non-work days. However, some rosters are as long as four or six weeks of work followed by one or two weeks of non-work
- Fly-in, fly-out (FIFO) commuting.This refers to the practice of domiciling workers in one or more major regional towns (typically a large town with established facilities and sometimes a more temperature climate) and flying workers up to 1000km or more to a work site, frequently located in a much more severe climate.

It is clear from the above discussion that these new work arrangements may not allow workers to develop and retain the same degree of heat acclimatisation that they might have been able to in the past.

There is therefore a need for health and safety professionals who manage work sites with a significant heat stress exposure to be able to assess the impact on workers of the following sorts of situations:

- A new employee from a temperate climate commences at a workplace with a serious heat exposure and it is desired to know how long it will take for him to become as acclimatised as his colleagues
- An organisation is reviewing its roster arrangements and wants to examine the impact on safety and health of different combinations of days on and off, in terms of the likely changes in the acclimatisation levels of its workers
- An organisation is establishing a new facility in a remote area, which will be run as a FIFO operation, and needs to examine the impact of two or more different domicile locations on workers' acclimatisation
- An organisation wishes to examine the difference between the gain and loss of acclimatisation in summer versus winter, for various roster arrangements
- An organisation is considering transferring a worker into a job that has a significantly increased level of heat stress (either due to a hotter environment, more severe clothing requirement, or higher work rate) and wants to assess issues of acclimatisation
- An organisation is planning a major plant shutdown and refurbishment during the Christmas/New Year period and wants to examine the impact of contractors bringing in workers from temperate climates into work which involves significant heat stress
- An organisation wishes to assess the impact of loss of acclimatisation on a worker leaving the job in mid summer for a holiday in a cold climate.

There is currently no agreed 'index' for acclimatisation, nor any method of assessing any of the issues of acclimatisation such as those listed above.

This paper proposes a method of assessing, both quantitatively and qualitatively, acclimatisation in industrial workers.

Methodology

Substantial studies have been conducted into the effects of human heat acclimatisation, particularly on soldiers during and after WW2 (Adolf, 1947; McArdle et al, 1947), elite athletes and workers in some industries including mining.

A useful discussion on many features of human heat stress and acclimatisation is given in the International Labor Organisation *Encyclopaedia of Occupational Health and Safety* (ILO, 1998).

Whilst there are significant differences in individual responses to heat, the following is generally agreed about the overall human response (Leithead & Lind, 1964; ASHRAE, 2001; Gisolfi, 1987; Sawka et al, 1996):

- Humans cannot adapt to an unlimited level of heat stress; the end-point of heat adaptation is limited and at this point the human is ' fully acclimatised'
- The process involved in gaining acclimatisation takes four to six weeks, perhaps more, but most of the gain (typically about 70 percent occurs in the first seven days of continuous exposure. The most significant improvements,in fact occur in the first three days of exposure
- The key requirement to achieve acclimatisation is to be sweating. Exercise in itself will not result in any significant heat acclimatisation, although fit persons acclimatise faster than unfit persons.
- There are some differences between acclimatising to a hot, humid environment or a hot,dry environment, and between the acclimatisation of men and women, along with ethnic differences; however, for persons of working-age, these differences are minor compared to other risk factors relating to heat illness.
- Salt concentration in the sweat of unacclimatised persons is about 4g/litre, reducing to about 1g/l in acclimatised persons (the typical diet contains 10g/day salt). However, unacclimatised persons produce much less sweat (one to 1.5 times the evaporative heat loss[1]) than acclimatised persons (two to 2.5 times the evaporative heat loss). Unacclimatised persons may therefore need some salt supplementation during heat exposures (eg extra salt on meals) but additional salt intake should not be required for acclimatised persons.
- Humans need to be exposed to somewhere between 30 and 120 minutes of heat stress per day to commence and then continue the acclimatisation process through to its end-point.

- Humans adapt to the level of heat stress to which they are habitually exposed. Hence, a person can be ‘ 100% acclimatised’ (ie fully acclimatised) to the heat stress in his normal workplace, but much less than fully acclimatised to an environment of higher heat stress.
- The wide range of individual responses to heat stress reduces as persons acclimatise. The variation in heat tolerance of a well-acclimatised group is therefore much less than that of an unacclimatised group.
- The process involved in losing acclimatisation is more poorly understood (as it is generally of less consequence for athletes or soldiers than the process of gaining acclimatisation). The consensus is that it is roughly similar in duration to the gaining of acclimatisation, but most authorities agree that the loss in the first few days to a week of non-exposure is modest. However, for persons needing to be highly acclimatised, even two or three days of non-exposure could result in a significant loss of acclimatisation.

The challenges in understanding the impact of acclimatisation on work rosters are therefore:

- To develop an index of acclimatisation, preferably both an absolute and relative scale
- To determine the level of acclimatisation (‘end-point’ or full acclimatisation state) that could be reached by moderately fit and healthy humans in a particular environment
- To determine the residual level of acclimatisation retained when humans move into a less heat-stressful environment.

In terms of developing an index for acclimatisation, two important physiological parameters could potentially be used.

The first of these is deep body core temperature as this is the key determinant of hyperthermia, which in turn is strongly related to the development of heat illness. The second is sweat rate.

These two are also causally related; an increase in deep body core temperature promoting a range of important physiological responses (including vasodilation and an increase in heart rate), but the most externally-obvious of these possible indicators is sweating.

Sweat rate has some advantages over core temperature as a possible index. Whilst core temperature does *increase* when a human is exposed to heat stress, it subsequently *reduces* as an individual becomes acclimatised to that same environment.

Sweat rate increases on exposure to heat stress, and increases further as a human becomes acclimatised to that environment.

Furthermore, in some circumstances exercise may produce an increase in core temperature unaccompanied by either heat stress or any sweating (eg in an elite swimmer).

Finally, deep body core temperature is difficult to measure in a workplace, whereas sweat rate can be measured or estimated by using a mass balance and some simple field controls over the intake and release of fluids and solids.

Consider therefore a particular environment requiring a sweat rate of (say) 1.2 litres per hour from a highly-acclimatised group. If the maximum sustainable sweat rate from this same highly-acclimatised group was (say) 1.5 litres per hour, then this environment could be described as requiring an *absolute* acclimatisation level of 1.2/1.5 = 80%.

This assumes a nil sweat rate for the fully unacclimatised state, however, the choice of the ‘ zero point’ for an acclimatisation scale is not particularly important – it would simply mean that even an unacclimatised person has a positive residual acclimatisation value (ie ability to sweat) using such a scale.

Furthermore, with such a scheme it would then be possible to assess a group’s *relative* degree of acclimatisation. For example, assume the same highly-acclimatised group in a particular environment has a sweat rate response of 1.2 l/hr, and the unknown group exhibits a mean response of 0.8 l/hr, then the unknown group could be said to be 0.8/1.2 = 66% acclimatised (on a *relative* basis) to that environment.

For the purpose of this proposed model, an upper sweat rate of 1.5 litres per hour has been selected as the ‘100 percent absolute acclimatised’ value. This is based on the work of McArdle et al (1947) in many experiments (leading to the development of the Predicted Four-Hour Sweat Rate, or P_4SR scale), the work of Wyndham (1967) and also of others. Note that the only use of this assumed upper limit of 1.5 l/hr is to develop a ‘ percent absolute acclimatised’ scale and it is of little practical consequence otherwise. However, if a more conservative lower value was selected (e.g. 1 litre per hour), then some environments would result in highly acclimatised workers being ‘120 percent acclimatised’ (eg if they had a sustainable sweat rate of 1.2 litres per hour), which could be confusing.

Once such a scale has been selected, it is then possible to describe the *rate* of gain or loss of acclimatisation in terms of that scale.

Figures 1a and 1b indicate the likely rates of gain and loss of acclimatisation, based on a general consensus within the literature; these curves are therefore subject to modification as further studies becomes available.

However, they are unlikely to change dramatically from the shapes shown and in any event, the purpose of this model is to identify basic trends and issues.

Broadly speaking, both the acclimatisation and de-acclimatisation processes are complete at about the 28-day mark, but the gaining of acclimatisation is faster, being about 70 percent complete after seven days of exposure, with the losing of acclimatisation being slower, showing a residual level of about 60 percent after seven days of non-exposure.

The following equations can be fitted using least-squares means to these curves (with $r^2 > 0.99$ in each case):

Where acclimatisation is being gained:

$$Ac(g) = \text{Tanh}(0.124 * D) \qquad \text{Equation 1}$$

Where: D is the day of exposure (first day being day 1)

Where acclimatisation is being lost:

Ac(l) = 0.9663 - (Tanh (0.06054 (D - 0.55626))) Equation 2

It is therefore assumed that any group of moderately fit and healthy workers will, if exposed to heat stress, acclimatise approximately along the curves shown with the end-point being the level that would be reached by a notional highly-acclimatised group.

To translate this into an effective model, it is necessary to know what the ' end-point' and 'starting point' of the acclimatisation process would be, in terms of the agreed acclimatisation index.

In terms of the heat-acclimatised end-point, we need to know the sweat rate response of a highly acclimatised group to any particular environment. A model of human thermoregulation has been recently described, which is based on the thermal work limit (TWL) index (Brake and Bates, 2002).

This model was based on detailed laboratory testing of highly acclimatised workers and, for any given work rate and set of environmental conditions (temperature, humidity, wind speed, radiant heat loads and clothing ensembles) will provide, amongst other parameters, the sweat rate and deep body core temperature response of such a group. The TWL model has therefore been used to predict the acclimatised end point.

The unacclimatised end-point is more poorly defined. It is likely that a person who retreated to an entirely air-conditioned environment in a tropical city for his off-duty break would retain no more acclimatisation than a similar person who retreated to a temperate city for his break. However, this is not normally the case. It is reasonable to assume that a worker returning to a tropical city in mid-summer will continue to experience the outdoor heat and a higher level of heat stress (and therefore of residual acclimatisation) than a similar person returning to a much more temperature city.

For the purposes of this model the ' residual acclimatisation state' has been assessed as follows: The residual state of acclimatisation is defined as the acclimatisation level (sweat rate) developed by a person at a work rate of 110 W/m^2 (ie a light work rate, typical of light gardening or a leisurely stroll, - the type of activity that most persons would experience even on their 'days off'). Whilst this is a somewhat arbitrary approach, it will be seen later that the actual level of this 'off-duty' acclimatisation state does not have a profound impact on the model and therefore errors in this value are unlikely to be of vital consequence for most workers.

In addition, there is little difference in the sweat response of acclimatised and unacclimatised persons to *low* levels of heat stress. However, there remains considerable work required to properly describe the unacclimatised state and therefore more adequately validate this proposed model.

Results and discussion

The methodology is best illustrated with some case studies. Table 2 describes the various work and off-work situations in the case studies:

Different domicile locations for FIFO operations:

Consider a person working in condition A, but who can be domiciled in either conditions E or H. If he is on a seven days on seven days off roster (' seven on seven off'), his acclimatisation state is shown graphically in Figure 2.

This chart indicates that the absolute acclimatisation level required at work is 66 percent but that he ranges from 43 percent to 59 percent due to his off-duty acclimatisation state being only 16 percent. In effect, on a relative basis, he cycles between being about 65 percent and 90 percent acclimatised compared to the ideal acclimatisation level for his work environment.

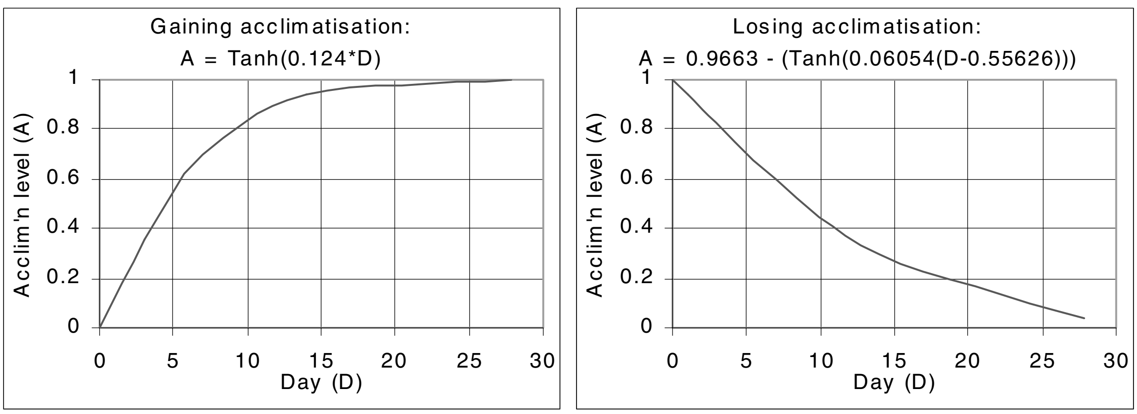
Note also that it takes at least two roster cycles for him to develop his long-term acclimatisation cycling pattern.

Clearly, the more time spent by a worker near the fully acclimatised state (for this environment), the less stressful the environment will become. In addition, the long-term health effects of workers continually 'acclimatising' and then 'de-acclimatising' (hereafter described as *acclimatisation cycling*) are not known, but it may be reasonable to assume, by analogy with exercise adaptation, that it is desirable to keep the 'range' (or 'spread') of this acclimatisation cycling to a smaller rather than a greater value.

Impact of holiday periods

Consider now a worker in environment A in the Southern hemisphere, who takes a four-week summer vacation into the Northern hemisphere winter in environment G. If he is on a four on four

Figure 1a and b. Process of gaining and losing acclimatisation



off roster, his acclimatisation state is shown in Figure 3.

It can be seen that, on returning to work, it takes him three roster cycles to achieve a 'steady state' acclimatisation pattern.

Impact of changing seasons on acclimatisation state

Consider a person working in winter conditions D, but domiciled in condition G. If he is on a seven on seven off roster, his acclimatisation state is shown in Figure 4. These conditions of 22^0 WB, 28^0 DB, a small radiant heat component and only low wind speed would be typical of many 'summer' conditions in temperate climates, and therefore also shows the low levels of acclimatisation required (and obtained) for workers in such conditions.

Impact of different 'panels' on roster design

Consider a worker in conditions A and F, but working either a four on four off roster, or a four week on one week off roster. His acclimatisation state is shown in Figure 5 and Figure 6.

Now assume the same worker was working a roster in which there were four separate panels, these being four on four off, seven on seven off, nine on five off, and five on two off. His state is shown in Figure 7. This illustrates the potential complexity of acclimatisation cycling in more complex rosters.

Impact of a worker changing work rate, temperature/humidity/wind speed or clothing

Consider a worker in environments A and F, working seven on seven off roster, who accepts a transfer into a job requiring a higher work rate (situation B). His acclimatisation state will be as shown in Figure 8.

If, however, his work rate remained as per his previous job but the environmental conditions in the new job were much poorer (situation C), then his acclimatisation state would be as shown in Figure 9. In this particular case, there is not a big difference between the results.

How long it takes for a new 'starter' to become as acclimatised as his colleagues

It can be seen from the above charts (eg Figure 5a) that it can take several roster cycles to obtain the long-term acclimatisation state possible under that roster.

It is important to note that an acclimatisation scale, whether based on core temperature or sweat rate, will not be linear.

It is obvious that an increase in deep body core temperature from 37.0 to 37.5^0 C will not result in the same strain on a human as an increase from 38.5^0 to 39.0^0 C – the first 0.5^0 C increase is well within the safe core temperature response of humans, the second is much closer to the point at which moderately fit and healthy industrial workers can be expected to suffer from collapse.

However, this non-linearity is true of most physiological parameters – the further the parameter moves from the central point, the more severe the strain.

Summary and conclusions

Acclimatisation is an important means by which

Table 2 Key parameters for workers in the case examples. In all cases, the vapour permeation of clothing was assumed to be 0.45 (dimensionless). The off-work clothing insulation of 0.33 is based on typical off-work shorts and shirt (clothing expected to be worn when off-work under low levels of heat stress); the at-work clothing insulation of 0.35 is based on typical dry values of 0.55 (short shirt, long trousers, boots, hard hat) reduced by 40% to account for the (sweat) saturation of clothing under these conditions

	A	B	C	D	E	F	G	H
	Underground miner at work, summer	As for A, but higher work rate	As for A, but hotter work	As for A, but winter	Home environ – tropical coastal location, summer	Home environ – temperate coastal loc, summer	Off-work environ – cold loc, winter	Home environ – cold loc, summer
WB, °C	28	28	28	22	26.7	20.4	6.0	17.8
DB, °C	36	36	36	26	31.0	32.9	12.0	25.0
GT, °C	38	38	38	28	33.0	34.9	14.0	27.0
WS, m/s	0.5	0.5	0.5	.5	2.0	2.0	2.0	2.0
BP, kPa	111	111	111	111	101	101	101	101
Clothing insulation, clo	0.35 (wet)	0.35 (wet)	0.35 (wet)	0.35 (wet)	0.33 (dry)	0.33 (dry)	0.33 (dry)	0.33 (dry)
Work rate (metabolic)	150	200	150	150	110	110	110	110
Sweat rate, litre/hr	0.99	1.45	1.32	0.28	0.24	0.21	0.02	0.10
Skin wetness, fraction	1.00	1.00	1.00	0.98	0.91	0.50	0.05	0.28
Core temp, °C	37.90	38.73	38.31	37.5	37.29	37.24	37.00	37.07
TWL (std), W/m^2	174	174	144	275	339	339	457	373

Note: WB = wet bulb temperature, DB = dry bulb temperature, GT = globe temperature, WS = wind speed, BP = barometric pressure.

workers in hot conditions reduce the heat strain on their bodies. A method has been proposed to provide a preliminary quantitative assessment of the impact of various rosters and work and domicile climates on the acclimatisation state of workers. It shows that, as is often described anecdotally by workers themselves, there are significant issues involved in acclimatising, de-acclimatising and re-acclimatising to the work environment, depending on the combination of heat stress and required metabolic rate at work, the roster, and the climate in the 'off-work' domiciled situation.

Further research needs to be undertaken to fully understand and to be able to quantitatively assess the impacts of acclimatisation (and loss of acclimatisation) in hot working environments in Australia.

Figure 2 Case study for worker A domiciled in conditions E or H

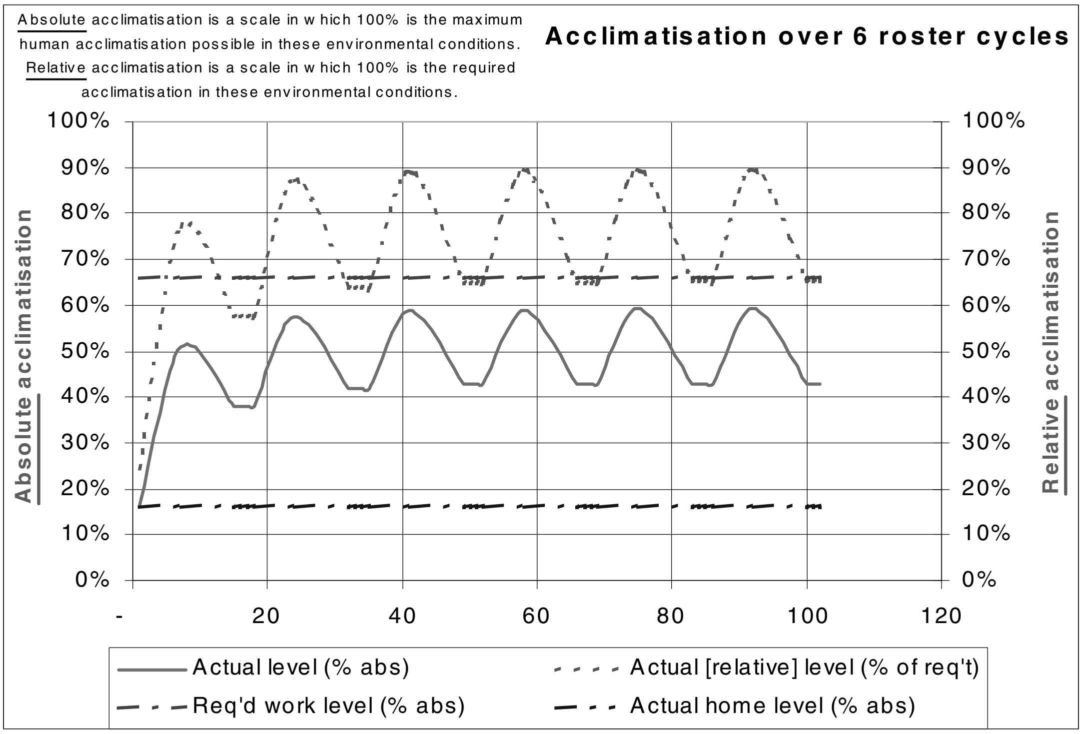
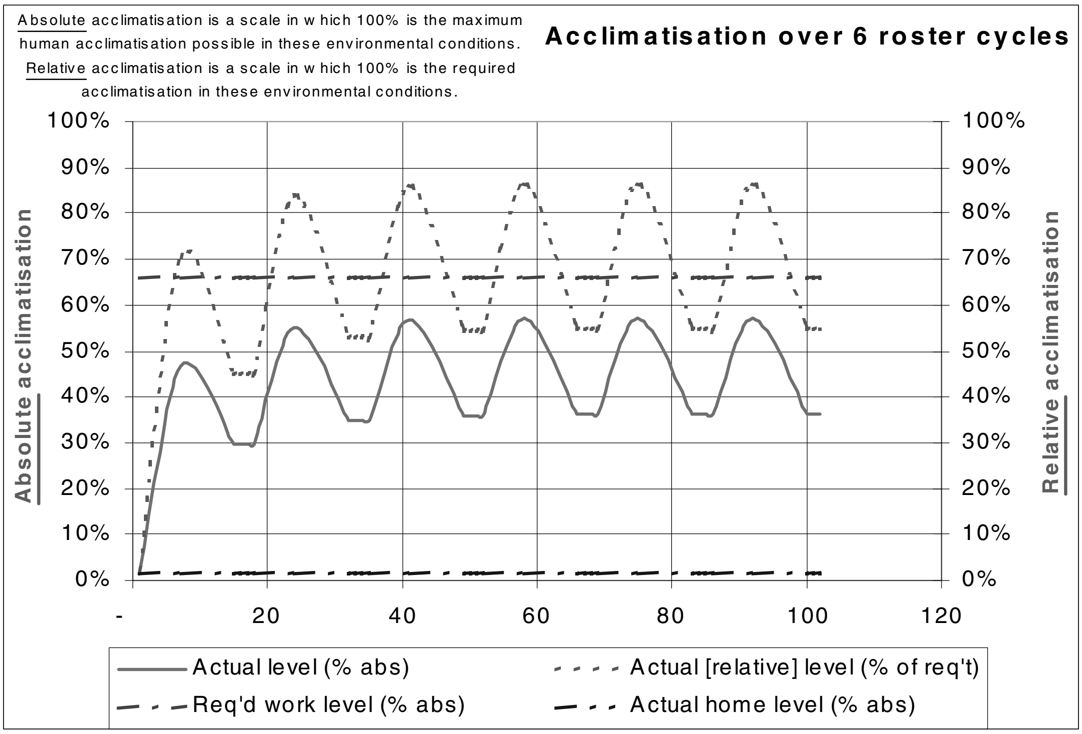


Figure 3 Case study for worker A taking 4 week holiday in conditions G



It can also be seen that the ' residual level of acclimatisation', under this scale, for most climates in summer is not dramatically different (typically ranging between 0.2 l/hr and 0.3 l/hr, a difference of only 0.1 l/hr, refer to situations D to F) and that this therefore does not impact dramatically on the ' acclimatisation cycling' for those workers under significant levels of heat stress (where sweat rates are invariably more than 0.7 l/hr). Where work is not being carried out under such high levels of heat stress (e.g. required sweat rates of only 0.3 to 0.4 l/hr), then an error of 0.1 l/hr in the 'non-working' acclimatisation state will have a much higher relative impact. However, the problems of losing and gaining acclimatisation are also of less significance for such workers. This is particularly true since even unacclimatised workers can safely sweat at rates of up to at least 0.6 l/hr.

Figure 4 Case study for worker D domiciled in conditions G

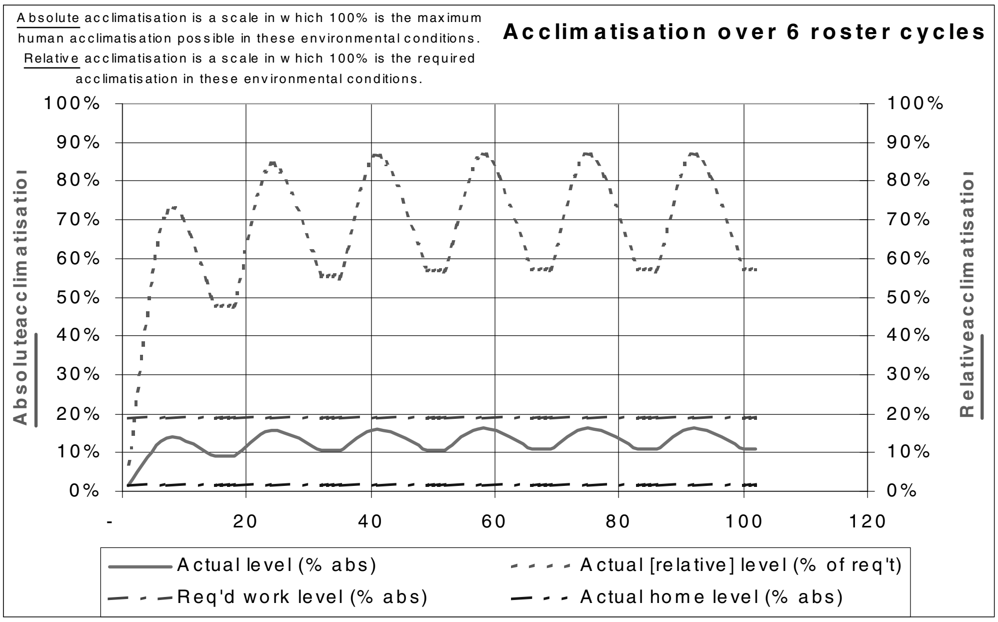


Figure 5 Case study for worker A on 4 day on – 4 day off roster

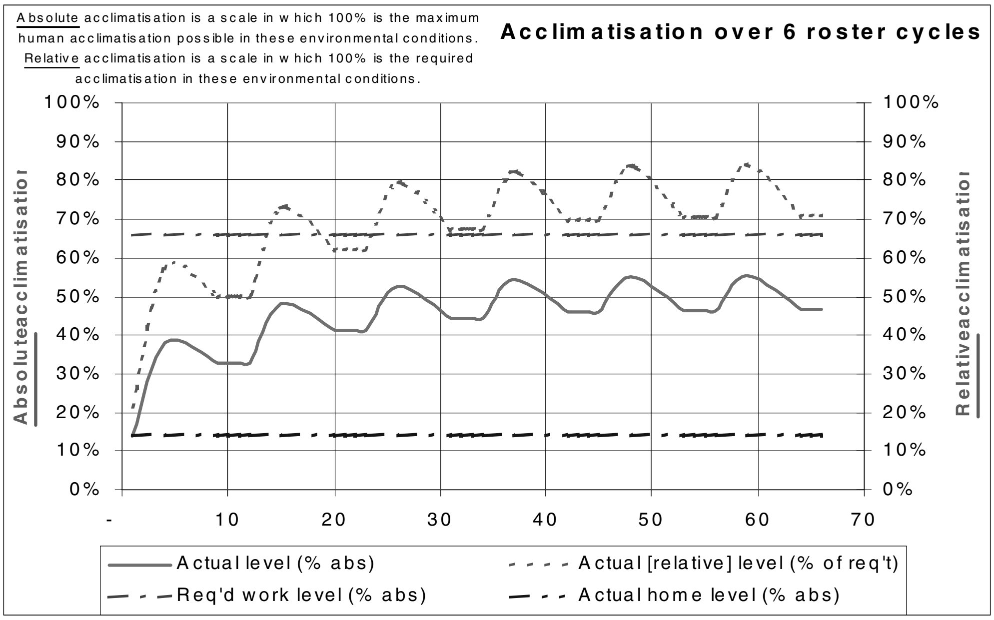


Figure 6 Case study for worker A on 4 week on – 4 week off roster

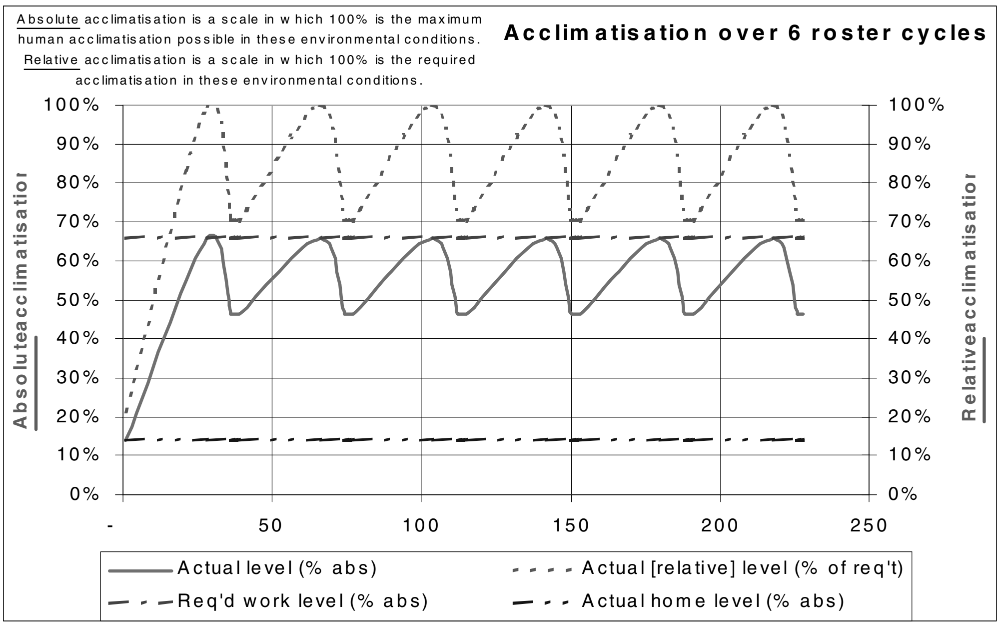


Figure 7 Case study for worker A and F, working 7 day on – 7 day off roster, transferring into situation B

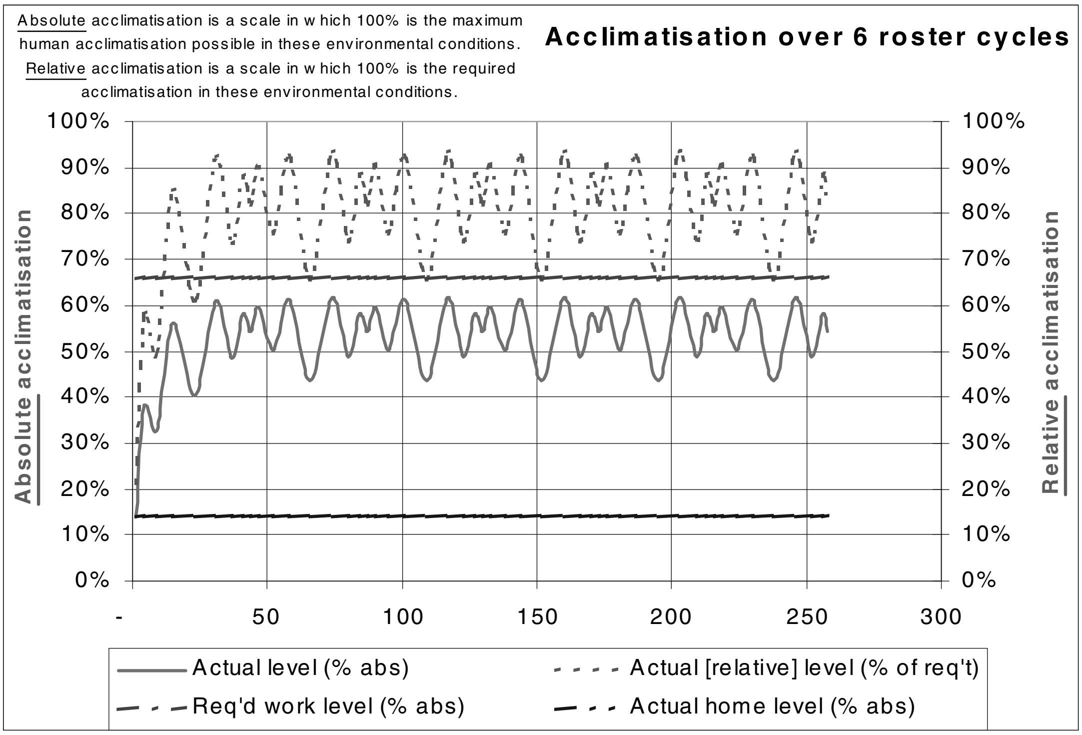
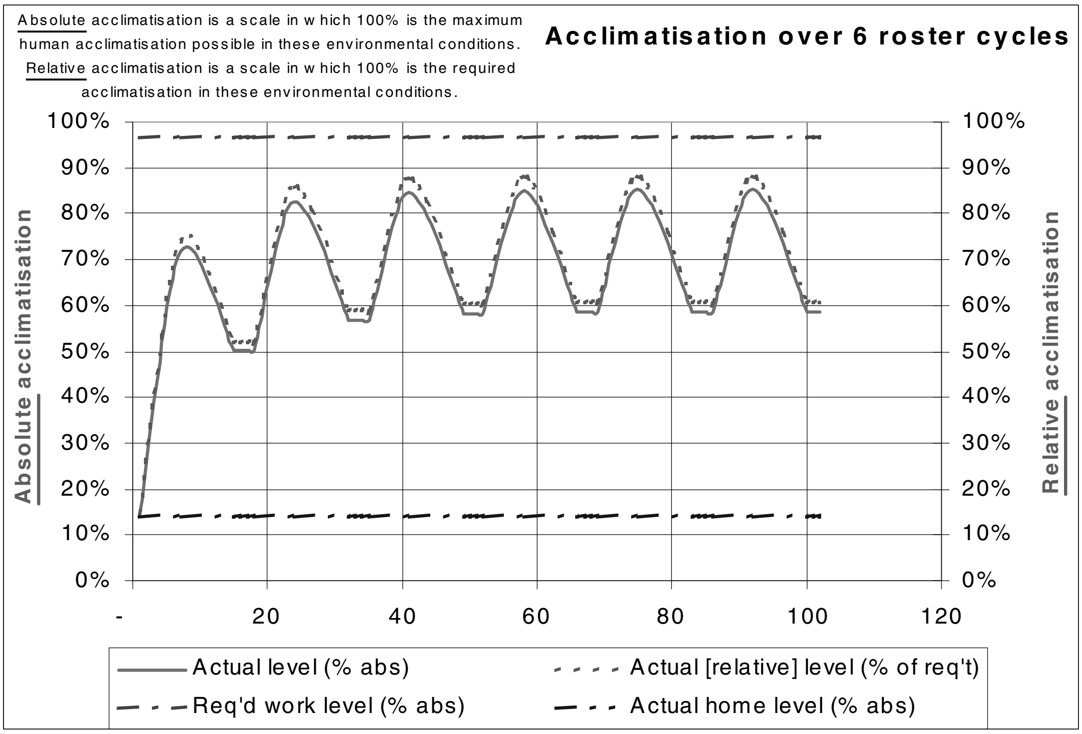


Figure 8 Case study for worker A and F, working 7 day on – 7 day off roster, transferring into situation B

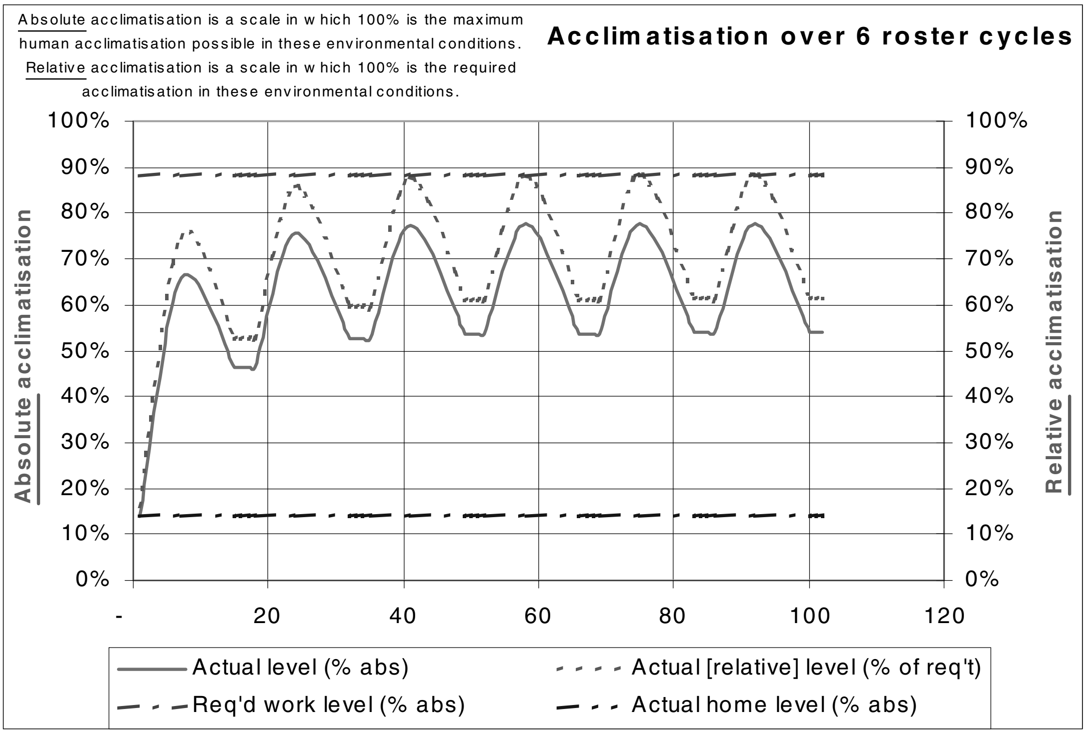


Notes

1 An acclimatisation protocol was introduced into South African mines in 1925, after the first deaths from heat stroke in 1923. A two-stage acclimatisation process was introduced in 1953, with surface acclimatisation starting in 1960. In 1974 the acclimatisation process was reduced from a maximum of eight days to 5 days, with a Heat Tolerance test introduced in 1977 and microclimate acclimatisation introduced in 1982. In recent years, the South Africans have gone almost ‘ full circle’ with most acclimatisation now being ‘on the job’ supplemented by a 30 minute ‘heat tolerance test’ on surface prior to initial exposure. However, levels of heat exposure and work rates are much higher in South African mines than are generally found in Australia (Kielblock and Schutte, 1991)

2 When a human becomes thermally stressed, he starts to sweat. The evaporation of sweat from the skin produces most of the cooling needed to avoid the body over-heating. However, the body produces ‘ surplus’ sweat for a variety of reasons (which drips off or remains on the skin). Humans who are poorly acclimatised produce much *less* sweat than those who are well-acclimatised.

Figure 9 Case study for worker A on 4 week on – 4 week off roster



References

1 Adolf E F, 1947. Physiology of Man in the Desert. p 146, 220, 272. Interscience Publishers.

2 American Conference of Government Industrial Hygienists: Thermal Stress. In: Threshold Limit Values for Hazards in the Environment, pp. 170-182. ACGIH, Cincinnati, OH (1998).

3 American Society of Heating, Refrigeration and Air-conditioning Engineers: ASHRAE Fundamentals (SI edition), pp. 8.1–8.28. ASHRAE, Atlanta, GA (1997).

4 Brake DJ and Bates GP, 2002. Limiting work rate (Thermal Work Limit) as an index of thermal stress.

5 Journal of Applied Occupational and Environmental Health (ACGIH). Vol 13(3):176-186, March.

6 Brake, D J, Donoghue, M D and Bates G P. A New Generation of Health and Safety Protocols for Working in Heat. Proc 1998 Qld Mining Ind Occ Health and Safety Conf. Yeppoon, 1998, pp. 91-100. Qld Mining Council, Brisbane (1998).

7 Gisolfi, C V 1987. Influence of acclimatization and training on heat tolerance and physical endurance proc Heat Stress – Physical Exertion and Environment 1st world conference on heat stress, physical exertion and environment, Syd, Aust, ed Hales J R S and Richards D A B, pp 355-366.

8 Donoghue A M., Sinclair M J, Bates G P, 2000. Heat exhaustion in a deep underground metalliferous mine. Occupational and Environmental Medicine. (57):165-174.
International Labour Organisation, 1998.

9 Encyclopaedia of Occupational Health and Safety. Stellman J M (ed). Chp 42 Heat and Cold. Geneva.
Kielblock A J and Schutte P C, 1991. Heat Stress Management – a comprehensive guideline. 1st ed. Chamber of Mines Research Organisation. Johannesburg.

10 Leithhead C S and Lind A R, 1964. *Heat Stress and Heat Disorders*, p87, 132, (Cassell: London)
McArdle B, Dunham W, Holling H E, Ladell W S S, Scott J W, Thomson M L and Weiner J S, 1947. The prediction of the physiological effects of warm and hot environments, Medical Research Council, London, RNP Rep 47/391.

11 Ramsey J D and Beshir M Y Thermal standards and measurement techniques. In: Di Nardi S R, ed. The occupational environment. Amer. Ind. Hyg. Assoc. 1997.

12 Sawka M N, Wenger C B and Pandolf K B, 1996. Thermoregulatory responses to acute exercise-heat stress and heat acclimation. Chp 9 of Handbook of Physiology Section 4 Environmental Physiology Volume 1 ed Fregly M J and Blatteis C M, p 157. Oxford University Press.

13 Schutte P C, Van der Walt W H, Marx H E, Trethowen S J and Kielblock A J, 1991. Heat Stress Limits for a Screened Unacclimatised Mine Population. Chamber of Mines Research Organisation of South Africa. Report 13/91, Project GE1B, April.

14 Wyndham, C H, Allan A McD, Bredell G A G and Andrew R. 1967. Assessing the heat stress and establishing the limits for work in a hot mine. Brit J Ind Med 24:255-270.