# The appropriateness of international heat stress standards for use in tropical agricultural environments

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*Keywords:* ISO; Standards; Heat Stress; Developing Countries; Agriculture

Where a danger to health from heat stress is identified, standards allow decisions for implementing measures to reduce the heat stress to be made. These standards, specifically ISO 7243 (Wet Bulb Globe Temperature Index, WBGT) and ISO 7933 (Sweat Required, $SW_{req}$) were designed with European and American subjects, primarily for use in those countries. Whilst the scope of the standards is international, little consideration has been made as to how valid and usable they are in industrially developing countries. This investigation evaluated ISO 7933 and ISO 7243 in terms of validity and usability. A tropical agricultural task was simulated; 16 subjects plucking tea leaves for 2 hours, ($t_a = t_r$ = 37.18°C; $v_a$ = 0.16m/s; $rh$ = 70.17%). Whilst ISO 7243 was found to be valid (if slightly over protective) and usable, ISO 7933 was over protective and underestimated sweat and evaporation rates in its predictions. The discrepancies between predicted and observed results were attributed primarily to the calculations related to clothing in the standard. Furthermore, ISO 7933 was found to be unusable without a computer; in regions where access to such technology may be limited, a simpler method of presentation is required.

## 1. Introduction

International standards are, as their name implies, for international use. They are however predominantly designed and developed in the industrially developed world. International heat stress standards have mainly been developed in Europe and the USA. Problems of validity, ambiguity and usability are therefore probable when implementing standards in industrially developing countries (IDCs). They may be culturally incompatible, ignore physiological and anatomical differences and be unworkable in practices which differ from the industrialized norm.

This paper describes an investigation into the appropriateness of heat stress standards for use in hot, outdoor, agricultural environments. Such environments are predominantly found in developing countries where nearly 70% of the energy used for crop production activities is of human origin (FAO 1987).

In light of the dangers that a hot environment can present to a human, heat stress indices have been developed to predict the physiological strain on an individual from stressful environmental conditions. Such predictions will allow safe working practices and environments to be introduced to protect the individual from a dangerous rise in body core temperature. Heat stress indices aim to give "a single number which integrates the effects of the basic parameters in any human thermal environment such that its value will vary with the thermal strain experienced by the person exposed to a hot environment" (Parsons 1993.) Heat stress indices can be divided into three categories; direct indices, using measuring instruments which will respond to a thermal environment in a similar way to human responses; empirical indices, derived from measured human responses to a range of environmental conditions; and rational indices which use the heat balance equation. By calculating the heat transfer from thermal parameters, (given that in heat balance, storage is zero) it is possible to provide the required evaporation to retain heat balance. The indices which have been adopted by ISO are the WBGT (direct) and Required Sweat Rate-$SW_{req}$ (rational) indices.

In the first instance of assessing a hot environment, a rapid evaluation is made using ISO 7243. This is based upon the wet bulb globe temperature index (WBGT). The Wet Bulb Globe Temperature (WBGT) was evaluated by Yaglou and Minard in 1957 as an index of climatic stress. It was adopted by the American Conference of Governmental Industrial Hygienists (ACGIH 1989), who established permissible heat exposure limits in WBGT units for different metabolic rates and work-rest regimens. These threshold limit values refer to conditions where 95% of the worker population can be repeatedly exposed to heat stress with no adverse health effects (ACIGH 1989, Dukes-Dobos & Henschel 1973). These reference values have been adopted in ISO 7243 and are based upon the assumption that acclimatized, fully clothed workers with adequate salt and water intake would be able to work effectively without exceeding a body core temperature of 38$^{o}$C (WHO 1969, ACGIH

1989). If the WBGT values exceed the provided ‘reference’ values, a more detailed analysis is made using ISO7933.

ISO 7933 is based upon the work of Vogt *et al*. (1981) in the CNRS laboratories in Strasbourg, France, being extensively evaluated in industrial and laboratory settings. ISO 7933 adopts a rational approach using the heat balance equation. It provides a method for calculating the evaporation required to maintain heat balance. From this calculation the required sweat rate can be estimated, from which it is possible to predict warning and danger levels for allowable exposure times in a given environments. In extreme environments, thermal strain can be evaluated by physiological measurements using ISO 9886. A number of other supporting standards exist for use in conjunction with the above. These include standardizing equipment specifications (ISO 7726); determining metabolic heat production (ISO 8996); and estimating clothing insulation (ISO 9920).

There has been much work assessing the validity of these standards, however this has mostly been with western subjects in industrial contexts. Little work has been performed on assessing their use in other areas such as in IDCs. This experiment investigated the validity of heat stress standards in an agricultural working environment found in many IDCs; that of plucking tea leaves.

### *1.1 Validity, usability and ambiguities*

To be used, the standards must not only be valid, they must also be usable. They should be free of ambiguities, be clearly presented and easy to use in the field. The user population will differ in IDCs, specifically in their lack of resources. Thus this experiment aimed to assess the usability and validity of the standards for these users.

#### *1.1.1 Validity*

For the standards to be acceptable they must have validity. They must measure what is intended. Thus the standard must have a scope that is realistic. The methods provided must achieve the objectives set forth in the scope. They must be appropriate to their intended user population. A method which caters only for a specific population will have little validity if it is to be transferred to other populations. Hence the methods of an International Standard must be valid for use in any population.

Although the standards are presumed to be appropriate for any hot environment, they have been designed for, and generally used in, industrial settings in industrialized countries. Their validity has not been tested in agricultural settings where outdoor workers are exposed to tropical climates. In IDCs, unorganized sectors of agriculture such as subsistence farming, will, where possible, work to their own timetables avoiding the hottest part of the day and therefore reducing the risk of heat strain. Workers in the organized sector, however, work set shifts and do not have the liberty to stop work when a risk of heat strain may be evident. At present, agriculturists work according to empirical experience, trial and error and guess-work (Hall 1971). The ISO standards for evaluating heat stress can thus be of use to workers in agricultural occupations. For example, ISO 7933 could be expected to give a quantitative guide to work-rest schedules, adequate fluid balance and improving the working environment. However, the validity for its use in such situations remains untested. Part of this investigation therefore aims to ascertain whether ISO 7243 and ISO 7933 accurately predict the human responses to a hot environment whilst undertaking a tropical agricultural task.

### *1.1.2 Ambiguity*

The standard must provide information pertaining to all situations in which it may be used, as described in its introduction and scope. Whilst this may be context dependent and never exact, for the standard to be effective, the methods must not be ambiguous. They must be clear and easy to follow and not be open to interpretation. Sufficient information must be provided and the wording must not be ambiguous; a standard which can be interpreted differently by different users will not be effective in attaining its objective.

### *1.1.3 Usability*

ISO standards are essentially products with a market value and thus should be usable if they are to be adopted in the workplace. As the user population will vary, the product should be flexible. The principles and functions which are universal should be presented so as to be applied in all user/context dependent situations.

The standards are designed for use by individuals with knowledge and experience in the field of thermal environments who have resources to measure and calculate temperatures and air velocity. However resources and technical knowledge are often lacking in IDCs and the standards therefore may not always be usable there. Furthermore, ambiguities may be present which will prevent the standards being used as intended. If they are found to be difficult to use or confusing in their format, their use as valuable tools for protecting workers at risk from heat strain will be limited.

There are many methods that can be employed in evaluating the usability of a product; Rennie (1981) identifies three principal types of ergonomics tests; the user trial, the expert analysis and the performance test. In the user trial, potential users are asked to use the product over a period of time and an assessment is made of their interaction with that product. The expert analysis is an evaluation of the product by an expert with knowledge and experience of that product, independent of users. In a performance test, use of the product is simulated without the involvement of human subjects.

User trials are both expensive and time consuming. Performance tests are not appropriate to this investigation. Rennie (1981) considers that in the final analysis, whilst experts may be biased, the ergonomist's opinion should be accepted. In light of this, a method for finding usability problems has been introduced. Known as heuristic evaluation, it is a method where specialists inspect user interfaces and evaluate the usability aspects based upon their expertise using recognised usability principles (Nielsen 1992, McClelland 1995). These principles, such as *consistency, simple and natural dialogue, speak the user's language,* and *provide feedback* are the 'heuristics' (Dumas and Redish 1993). Nielsen (1992) found that major usability problems have a high probability of being found in heuristic evaluations. He estimates that with several evaluators ± 90% of usability problems may be detected.

Evaluation of a system based upon a written specification is one of the strengths of heuristic evaluations (Nielsen 1992). Due to the cost effectiveness of the heuristic method and the difficulty in conducting a user trial in IDCs, heuristic evaluation was deemed the most appropriate method for evaluating the standards in terms of their usability and identifying ambiguities.

### *1.2 Tea plantations*

In 1994 2 ½ million tons (metric) of tea were produced world wide (Anon 1996). The tea plant *Camellia Sinsensis* is generally cultivated in equatorial zones in countries such as India, Sri Lanka, China and Kenya. Depending upon the variety, it usually enjoys temperatures between 21-30$^{o}$C with high levels of humidity (Eden 1965). In tea plantations in north-east India, the tea bushes are plucked between April-November each year, June-August being the peak period (Sen *et al*. 1983). Typically the 'tips' are plucked off shoots that are between 70 - 90 days old. Tea plucking is done by hand; this enables mature shoots to be distinguished from immature and involves considerable skill. Most tea estates are not designed for mechanization as many are over 100 years old. Thus tea plucking remains a manual task.

Harvesting the crop is the most expensive of all the individual operations entailed in tea production. Being a skilled task it is important to ensure the good health of the workers as productivity will suffer with inexperienced tea pluckers. The use of ISO heat stress standards may be one method of protecting the workers from heat related illnesses, and costly absences due to sickness.

Ergonomics investigations into tea-leaf plucking have been carried out by Sen *et al*. (1981,1983), studying workloads, environmental studies, and criteria for selection and categorisation of tea-leaf pluckers. It is climatic data from these studies upon which the thermal and physiological conditions in the present study are based.

## 2. Methodology

Sixteen subjects of European origin and residence, eight male and eight female (Table 1), were exposed to the experimental conditions for two hours. During this time they simulated an agricultural task undertaken in tropical climates; that is plucking tea leaves. Measurements were be made according to both ISO 7243 and ISO 7933.

[Insert Table 1 about here]

### *2.1 Clothing*

The subjects wore a clothing ensemble typical of Indian agricultural workers. Cotton underwear was worn. The males wore a *punjabi* (a long sleeved, thigh length shirt, 65% cotton, 35% polyester) and a *lungi* (an ankle length wrap-around, 100% cotton). The females wore a *shalwar kamize* (a long sleeved, thigh length blouse, 65% cotton, 35% polyester with tight fitting pyjama style trousers, 65% cotton, 35% polyester.) No footwear was worn. The effective clothing insulation of the male and female ensembles was estimated using ISO 9920 to be 0.5 clo and 0.46 clo respectively.

### *2.2 Procedure*

A pilot study was run to evaluate the experimental procedure. The conditions found in Indian tea gardens (Table 2), were simulated in a thermal chamber. As tea bushes were unavailable, Rhododendron bushes were placed on tables in aisles. Subjects walked around these 'tea bushes' and randomly plucked leaves, one at a time. The subjects were allowed to drink a controlled amount of water on request. Physiological measures were taken as described below.

[Insert Table 2 about here]

### *2.3 Environmental measurements*

Air temperature ($t_a$), radiant temperature ($t_r$), humidity (*rh*) and air velocity (*v*) were measured according to ISO 7726. The characteristics of each measuring instrument were within the range, accuracy and response time of *class s* (thermal stress.) As the environment was judged to be homogenous, measurements were taken at abdomen height, 1.1 m (ISO 7726). Measurements were taken using the Brüel & Kjær type 1213 indoor climate analyser at six minute intervals. WBGT values were recorded on a Grant Squirrel logger (Type SQ16-16U) using a wet bulb globe thermometer constructed according to specifications presented in ISO 7243.

### 2.4 *Physiological measurements*

Aural temperature ($t_{au}$), and mean skin temperatrue ($t_{sk}$) (using Ramanathan's four point weighting coefficient) were recorded every minute using a Grant Squirrel datalogger (Type SQ16-16U and SQ32-16U.) Heart rates were taken using Polar Sports testers, sweat loss was calculated from the body mass loss and metabolic rate (using the Douglas bag indirect calirometetry method) was taken after 30, 60 and 90 minutes.

### 2.5 *Identification of ambiguities and evaluation of usability*

A hierarchical task analysis of ISO 7243, ISO 7933 and ISO 7726 was carried out with the overall goal of evaluating the environmental heat stress on a human in a given thermal environment. This gave a sequential and complete analysis of all the tasks to be undertaken when using the standards, approaching them as a comprehensive tool rather than as individual stand-alone documents. From this it was possible to identify ambiguities and inconsistencies in the standards.

Usability of the standards was expertly evaluated according to nine basic usability principles, known as heuristics (Table 3). Each paragraph as presented in the standards was read and analysed according to these heuristics, and problems were subsequently identified.

[Insert Table 3 about here]

## 3. Results

### 3.1 *Environmental Conditions*

Climatic conditions were maintained at similar values to the maximums found in Sen *et al*. (1983). It was not possible to simulate a radiant heat load, indeed $t_r$ was generally less than $t_a$. Due to the cyclic nature of the chamber temperature regulation controls, the air temperature, humidity and WBGT within the chamber fluctuated. These fluctuations were within ±2 standard deviations of the mean. Mean values for the environmental parameters over all 8 sessions are presented in Table 4.

[Insert Table 4 about here]

### 3.1.1 *WBGT*

The mean WBGT (weighted over time and according to the three positions measured), for all sessions was 33.43$^{o}$C with a standard deviation of ± 0.56$^{o}$C. The WBGT values were consistently above the reference values for moderate and high metabolic rates in all the sessions and above the values for all low metabolic rates in all but the first hour of session 1.

## 3.2 *Physiological parameters*

Aural and four point mean skin temperature, body mass loss and heart rate were obtained for all subjects. Two female subjects withdrew after 80 minutes. Their results were not included in the statistical analyses. Male and female results for all physiological responses were compared using the Mann-Whitney (U) test.

The mean aural temperature for all subjects steadily rose, reaching the ISO 7933 alarm limit (+0.8$^{o}$C) after 83 minutes (Figure 1). The final mean aural temperature was 37.97$^{o}$C. There was no significant difference between the male and female temperatures.

[Insert Figure 1 about here]

### 3.2.1 *Skin temperature*

The mean four point skin temperature for all subjects rose rapidly for the first 20 minutes before levelling around 36$^{o}$C. No significant difference was found between the final male and female four point mean skin temperatures.

### 3.2.2 *Sweat loss*

There was a significant difference between the male and female sweat lost ($p$<0.05); whilst the mean male sweat lost was 1.155Kgs (sd=0.277), the female mean sweat loss was 0.657Kgs (sd=0.0.5). Greater vapour permeability was found in the female clothing ensemble with 6 times more sweat being trapped in the male clothing than with the female clothing.

### *3.2.3 Heart rate*

The heart rates for all subjects gradually rose throughout the experiment, however at the end male heart rates were significantly higher ($p$<0.05) indicating that the males were under greater strain than the females. Subject 10 had a heart rate of 168bpm when she withdrew. Sen *et al*. (1983) found a mean heart rate of 115bpm whilst plucking tea leaves. They do not indicate at what intervals heart rates were taken. It may however be assumed that the heart rates in this experiment are greater than those of Sen *et al*. towards the end of the two hour exposure because of the thermal strain experienced by the unacclimatized subjects.

### *3.2.4 Metabolic rate*

The mean metabolic rate for all samples taken was 126.27W/m$^2$ (sd=22.76). This was less than that of the Indian workers this study was simulating (129-160W/m$^2$) (Sen *et al*. 1983). Such a difference may be attributed to the Indians being skilled at tea plucking, whilst the Western subjects were unfamiliar with the correct techniques. There was no significant difference between the male and female metabolic rates taken after 30 minutes and 90 minutes. Significant differences however were found between males and females in the samples taken after 60 minutes ($p$<0.05) and for the mean metabolic rates ($p$<0.05).

The accuracy of the analysis of the expired air may be questioned. Due to the slow response time of the $CO_2$ gas analyser a constant reading during the evacuation of the sample was not always possible. This is consistent with Parsons and Hamley (1989), who suggest significant inaccuracies with the method of indirect calorimetery. This may also account for differences between this study and the results of Sen *et al*. (1983) and suggests a source of inaccuracy for the standards.

## *3.3 Comparison of ISO 7933 predictions with actual observed results*

No significant difference was found between the actual final 4 point mean skin temperature and the mean skin temperature ($T_{sk}$) predicted by ISO 7933 for the male subjects. A significant difference was however found between the actual and predicted mean skin temperatures for the female subjects ($p$< 0.05) and for all subjects ($p$< 0.02).

[Insert Table 5 about here]
[Insert Figure 2 about here]
[Insert Table 6 about here]
[Insert Figure 3 about here]

Of the 16 subjects, 12 recorded core body temperatures which reached the ISO 7933 alarm limit, whilst only 8 reached the danger limit. Of all those whose temperatures reached the alarm limit (n=12), the actual time taken was significantly different from the time predicted ($p<0.05$). There was however no significant difference between the predicted and actual values for the females. Of all those whose temperatures reached the danger limit (n=8, six being males), the actual time taken was significantly different from the time predicted ($p<0.02$).

## 4. Discussion

*4.1 Validity of ISO 7243*

The reference values are based upon the ability to work in a thermal environment without exceeding a deep body temperature of 38$^{o}$C "over a fairly long period of work" (ISO 7243). If the reference values are exceeded, a rise in body temperature can be expected. The reference values were exceeded for all subjects, with 6 male and 3 female subjects reaching or exceeding the 38$^{o}$C limit after two hours. ISO 7243 thus recommended either a direct reduction of the heat stress, or more detailed analysis to be carried out. The results therefore indicate that ISO 7243 was successful in evaluating the stressfulness of the environment. This is consistent with Hill and Parsons (1985) and Griefahn (1994).

*4.2 Validity of ISO 7933*

The reference values of ISO 7933 protected all but one of the subjects. It was generally over protective, predicting alarm limits ($t_{au}$ =37.8$^{o}$C) and danger limits ($t_{au}$=38$^{o}$C) to be reached before the measured values. In only one case was the alarm level reached before the predicted time (subject 5). Whilst 50% of subjects experienced an excessive rise in body temperature to the danger level, this occurred after a consistently longer period than that predicted. It can therefore be seen that

ISO 7933 was over protective and subjects could have worked for longer than the standard permitted.

The standard, for all but one subject (subject 5) significantly underestimated the sweat rate ($SW_p$) for all the subjects together and for the male subjects. The predicted sweat rate was accurate for the female subjects.

### *4.2.1 Clothing*

Reasons for the poor predictions of ISO 7933 can be identified to be primarily concerned with clothing. ISO 7933 gives a list of the estimated thermal insulation of various clothing ensembles. They are taken from ISO 9920 (Ergonomics of the thermal environment- Estimation of the thermal insulation and evaporative resistance of a clothing ensemble) and there are no estimates given for clothing other than western garments and various forms of protective clothing. The values for the clothing in this study were estimated using ISO 9920 on comparable western clothing of similar composition as a guide. The accuracy of this method may be questioned, the consequences of which may be reflected in the $Sw_{req}$ calculations.

### *4.2.2 Estimation of rate of evaporation*

Measured evaporation ($E_{mes}$) was found to be consistently greater than $E_{max}$. In the given environment, the rate of evaporation was greater than predicted by ISO 7933. Thus the sweat rate, and consequently the limits for exposure (DLEs) were underestimated. $E_{max}$ is calculated from environmental parameters and from the permeation efficiency factor of clothing ($F_{pcl}$), hence;

$$E_{max} = h_e F_{pcl} (P_{sk,s} - P_a)$$

Where:

$H_e$= evaporative heat transfer coefficient (W/m$^2$.kPa)

$F_{pcl}$= permeation efficiency factor (Dimensionless)

$P_a$= partial pressure of water vapour in air (kPa)

$P_{sk,s}$= saturated water vapour pressure at skin temperature (kPa)

$F_{pcl}$ is derived from the intrinsic clothing insulation, $I_{cl}$. $I_{cl}$ does not account for any pumping effect of clothing which can reduce the thermal insulation of clothing by

20% (Holmér *et al*. 1992). In this study the clothing worn by subjects was loose and was seen to allow considerable movement and subsequent "pumping". If $F_{pcl}$ is adjusted to account for this pumping, $E_{max}$ will subsequently be dramatically increased. Furthermore, $F_{pcl}$ neglects the effects of moisture absorption by the clothing material (Kerslake 1972). It is unreliable for saturated clothing involving wicking and evaporation of water from the clothing surface (Parsons 1995). The clothing in this study trapped much moisture and this may be expected to have an added effect on the calculation for $E_{max}$.

If $E_{max}$ is increased to account for the limitations of the estimation of the vapour permeability of clothing, derivations from it, giving values for wettedness ($w_p$ and $w_{req}$), and evaporation ($E_p$) will also be altered. With a greater maximum rate of evaporation possible in the environment, DLEs will consequently be increased.

### *4.2.3 Mean skin temperatures*

Predicted skin temperatures ($t_{sk,p}$) were significantly less than those measured for female subjects and all subjects together. Only for the male subjects was $t_{sk,p}$ accurate. Although the differences were small (within ±0.9°C), underestimating $t_{sk}$ can lead to important errors in the heat balance equation (Mairiaux and Malchaire 1988) including an underestimation of $E_{max}$. $t_{sk}$ is derived from multiple linear regression techniques which have been considered to be over simplistic (Parsons 1995). An improved estimation of $t_{sk,p}$ is required.

### *4.2.4 Comparison with core temperature*

The environmental conditions did not allow significant dry heat loss; respiratory convection, and evaporation, convection and radiation from the skin were relatively small when compared with evaporative loss. Any heat loss balanced with the metabolic heat production $M$. This can be seen in the calculations from ISO 7933 with $M$ roughly equalling $E_{req}$. In such conditions, $E_{req}$ could be used to estimate the metabolic rate. Indeed there was no significant difference between $E_{req}$ and $E_{mes}$ for all subjects, with no significant difference between $E_{mes}$ and $M$. Only for the male subjects was $E_{mes}$ significantly greater than $E_{req}$, so these results suggest that $E_{req}$ was achievable. The actual results however, from the subjects, show that storage was occurring, the mean $T_{au}$ having risen to 37.97°C (s.d.=0.24) at the end of the 2 hour exposure. It is thus apparent that $E_{req}$ was incorrectly calculated by ISO 7933. It also raises the issue of whether the body allows heat storage as a function of $E_{req}$ as a form of thermoregulatory control.

For $E_{req}$ to be incorrect, inaccuracies must be identified in the heat balance equation. These can occur at a number of levels, and assumptions of practical significance must be tested. Of particular importance will be estimates of metabolic heat production and of quantifying the thermal properties of clothing.

When sweat loss is lower than the maximum sweat loss possible in an environment, the human thermoregulatory system can maintain the body in thermal equilibrium. Similar to results for the rate of evaporation, the measured sweat rate was significantly lower than the $SW_{req}$ and $SW_{max}$, indicating that there was no storage, yet storage was seen to occur. Inaccuracies in calculations of $E_{req}$ and $E_{max}$ are possible reasons for this anomaly.

$SW_{req}$ is calculated from the following formula using $E_{req}$ and $E_{max}$:

$$SW_{req} = \frac{E_{req}}{r_{req}}$$

Where:

$$r_{req} = 1 - \frac{w_{req}{}^{2}}{2}$$

And:

$$w_{req} = \frac{E_{req}}{E_{\max}}$$

With inaccurate values for $E_{req}$ and $E_{max}$ as discussed above, $SW_{req}$ is subsequently inaccurate.

*4.3 Validity of the present study*

The physiological responses of the female subjects who withdrew from the investigation did not suggest they were suffering from heat stress. Subject 10 withdrew after 78 minutes with an aural temperature of 37.5°C, mean skin temperature of 34.22$^{o}$C and a heart rate of 160 bpm(mean over the last 5 minutes). Subject 14 withdrew after 76 minutes with an aural temperature of 37.5$^{o}$C, mean skin temperature of 34.22$^{o}$C and heart rate of 160 bpm. (mean over the last 5 minutes). These withdrawals may be attributed to reactions to the odoriferous rhododendron leaves in the chamber. With 50% of the air within the chamber being recycled, the olfactory environment became more unpleasant as each trial progressed. The experimenter experienced headaches towards the end of each trial; with little activity and progressive acclimation over the trials, this may not be solely attributed to the heat.

The Western subjects were unskilled in the task of tea leaf plucking. They worked considerably slower than those in the Sen *et al.* (1983) experiment and sustained a lower metabolic rate. Whilst this may be due to the lack of incentives for the chamber subjects to work hard, it is more likely that the metabolic rates obtained were inaccurate due to the slow response times of the equipment in measuring the quantities of expired air from the Douglas bags.

With the exception of the lack of solar radiation, the thermal conditions in the chamber simulated those found in previous studies conducted in tea plantations in India. Solar radiation will present a significant thermal load on workers; many tea pluckers wear wide brimmed hats called '*Jhapi*' (Sen *et al*. 1983) to protect them from the high radiant loads. It was not possible to include such radiant heat in this simulation.

It may be argued that the present study is flawed in the use of Western as opposed to indigenous Indian subjects. Whilst differences have been observed between different ethnic populations in their responses to heat, these can usually be attributed to differences in dietary habits, physical activity and acclimatization. Ethnic origin has not been found to have a modifying effect on human reactions to heat (Khogali 1992). It is reasonable to assume that the subjects were healthier than their Indian working counterparts, as populations in IDCs may be affected by diseases prevailing in the community, (Phoon and Tan 1992). The standards consider subjects to be fit and healthy, such a premise may not always be possible in IDCs. Permissible exposure times could be expected to be reduced for less healthy subjects. The present study did not consider this.

Similarly, ISO 7933 considers body sizes that may not be found in IDCs. Values given for $SW_{max}$ and $d_{max}$ are for a "standard subject with a body surface area of 1.8m$^2$". This standard value is for a 70Kg man of height 1.73m (Parsons 1993), i.e. a mean Western stature and weight. In IDCs where populations are often anthropometrically smaller, this value may not be valid. Anthropometric data from 44 Indian references found the mean body surface area from diverse male Indian groups to be 1.54m$^2$ (Wisner 1989). The mean body surface area of the female tea pluckers in Sen (1983) was 1.29m$^2$, considerably less than the standard value given in ISO 7933.

The choice of subjects may be criticized for their lack of acclimatization. Acclimatization is a relative and reversible process. Whilst workers in hot countries may be expected to be acclimatized, a period away from the heat may be expected to negate such heat tolerance. Acclimatization cannot therefore be presumed. Furthermore, calculations in the standards allow for the effects of acclimatisation. With these factors considered, it was not considered necessary for subjects to be of Eastern origin.

Most of the work on standards is derived from research carried out in industrialized countries. This study has investigated whether standards relating to heat stress are transferable to IDCs and whether they are appropriate for use in countries where social, organizational and environmental conditions may be very different in terms of validity, ambiguity and usability. The standards assume workers to be "in good health and fit for the work they perform" (ISO 7933.) Such assumptions cannot always be made in IDCs where diseases in the community may prevail, the work force may include young people and children, and hours of work are often longer (Phoon and Tan 1992). Furthermore, unlike in many industrialised countries, there may be no pre-employment examination of workers whose health status may not be satisfactory. Thus Phoon and Tan (1992) argue that workers in IDCs may need higher standards for the protection of their health. The results of this investigation suggest that ISO 7243 adequately protects the healthy unacclimatized workers in the

Indian agricultural tasks; the results would suggest that ISO 7933 should be used for a more detailed analysis. ISO 7933 however, was found to be over protective, predicting limits for exposure to be reached sooner than is observed. It is apparent that revisions in its calculations are required; specifically with estimation of mean skin temperature and permeation efficiency factor of clothing.

## 5. Usability results and discussion

### *5.1 Usability of ISO 7243*

The usability of ISO 7243 was expertly evaluated using a number of heuristics as presented in Table 3. The key usability problems and the heuristics that identified them (in italics) were as follows:

*Problem 1* ISO 7243 instructs for a rapid evaluation, a single measurement is to be taken "at the level where the heat stress is maximum." No instructions are given to establish where this position might be. *(Provide sufficient information)*

*Problem 2* ISO 7243 differentiates between a homogenous environment and a heterogeneous environment yet gives no method for establishing the heterogeneity of the environment save carrying out a full analysis on a previous occasion. (*Provide sufficient information)*

*Problem 3* Where the environment is heterogeneous The standard describes measurements to be taken "at three positions corresponding to the height of the head, abdomen and ankles in relation to the ground… when seated, 0.1m, 0.6m and 1.07m above the floor." This assumes the Western sitting posture, measurements are not given for the squatting posture which is common amongst many IDCs. (*Provide sufficient information)*

*Problem 4* A guide for establishing work-rest cycles is provided in the standard's annex. This is not referred to in the body of the standard. There is no explanation as to how it should be used and it is only appropriate to persons acclimatised to heat. *(Be consistent, provide sufficient information)*

Although several ambiguous assumptions were noted, no major usability problems identified in the evaluation. ISO 7243 was found to be inherently usable. The language used whilst being technical was understandable and easy to follow. Much of the standard is dedicated to specifications and design of the Wet Bulb globe thermometer. This information is superfluous to the user who already has the thermometer. For such a user, the method for use is of primary importance. An improved presentation of this methodology, such as a step by step procedural guide would add clarity and make ISO 7243 easier to use. If ISO 7243 is going to be used for establishing work/resting cycles, curves for unacclimatized workers, and a more detailed description of how they should be used should be provided.

### *5.2 Usability of ISO 7933*

ISO 7933 describes a method for calculating heat balance and $SW_{req}$ from which the thermal stress of an environment on a person can be assessed and if necessary be modified. Following the method as presented is a difficult and time consuming procedure with many calculations being required. A computer program is therefore presented to simplify the procedure. The evaluation of usability was thus divided into usability of the standard as a stand alone document, and usability of the standard using the program. The numbers in parentheses refer to prargraphs within the standard documentation.

#### *5.2.1 Paper based calculation*

*Problem 1.* Each parameter for the heat balance equation is to be calculated according to equations given in the standard. These equations depend on data found in Annex A of the standard, resulting in much movement around the document to complete the calculations. The formulae should be presented in their entirety. *(Minimize user memory load, consistency)*

*Problem 2.* The formulae for $C_{res}$ and $E_{res}$ differ between the main steps of the calculation (4.1.3-4) and in the annex (A.1, A.2), the former requiring the body surface area ($A_{du}$). *(Consistency)*

*Problem 3.* $r_{req}$ is required to calculate $SW_{req}$ (4.2) however there is no indication of how this is to be derived. *(Speak the user's language)*

*Problem 4.* The saturated vapour pressure at the skin temperature ($p_{sk,s}$) is required (4.1.8), however there is no formula provided to calculate this. *(Provide sufficient information)*

*Problem 5.* A value for skin wettedness $w$ is required (4.1.8) Whilst a definition is given, it is not clear how this value is to be arrived at. *(Speak the user's language/ provide sufficient information)*

*Problem 6.* In Annex A.4 the user is directed to equation 4 for a definition of $t_{sk}$. This definition is in fact to be found in Annex C.1. *(Prevent errors)*

*Problem 7.* The method of interpretation is not easily followed. Criteria of stress are given (5.1) however no data is given, for this the user must move to Annex C. *(Consistency)*

*Problem 8.* In the analysis of the work situation, new parameters are introduced ($w_p$, $E_p$, $SW_p$). Choice of formulae to use depend upon a decision whether $w_{req}$ exceeds $w_{max}$. This analysis is not clearly explained. Whilst a flow chart is provided in Annex D (D.3) this is not referred to in the body of the standard. *(Minimize user's memory load, prevent errors, use simple and natural language, consistency)*

*Problem 9.* Values for $Q_{max}$ and $D_{max}$ (5.3) are required. These are to be found in a table in Annex C, whilst referred to in (5.1), there is no reference to where they can be found when required. *(Consistency)*

*Problem 10.* The garments and their combinations given in the estimation of thermal insulation of clothing ensembles (ISO 7933 Annex B, ISO 9920) are typically Western items. Estimates for ethnic clothing ensembles are not provided. For the user in an IDC these must be estimated either using calculations provided in ISO 9920 or using values from comparable clothing. *(Provide sufficient information)*

The heuristic evaluation identified 10 major problems with the usability of the standard as a paper based tool. These were predominantly consistency problems; throughout the standard, the user must move around it to obtain all the information required for it to be used. Formula are not presented in a sequential order as required. Inadequate data were given to use the formula for each parameter in the main steps, the user must thus move to the Annex, returning periodically to substitute values into the main formulae. Whilst the presentation may be useful for understanding the principles behind the standard, it is a hindrance to its usability. Presentation in a sequential, tabular format, with data and formulae being provided when required, with clear instructions, would considerably improve the usability of ISO 7933 as a paper based tool. In its present format, use is a tedious, time consuming and difficult procedure and is ultimately unusable for anyone but the most dedicated of users. The method presented involves many calculations and invites errors throughout the procedure. It was found to be difficult and complex in use; the procedure being time consuming and often giving inadequate information or support to the user. ISO 7933 can thus only be feasibly used as a computer program given in Appendix D.2. The usability of this is discussed below.

*5.2.2 ISO 7933 Required Sweat Rate Calculation Program*

*Problem 1.* The parameters $t_r$ and $t_g$, and $t_{wb}$ and $P_a$ are interchangeable. The program does not make this clear. *(Consistency)*

*Problem 2.* The parameters are sequentially requested after an instruction so that when $t_r$ and $P_a$ are not introduced the program computes them from $t_g$ and $t_{wb}$. In entering the parameters $t_r$ and $P_a$ are requested separately from the values required. These parameters should be grouped together with instructions at the point of need. *(Memory load)*

*Problem 3.* In order to make the environmental measurements, ISO 7726 should be referred to. Instructions to do this are not presented in the program. *(Provide sufficient information)*

*Problem 4.* The program requires an input for Wet Bulb temperature. There is however no reference to, or characteristics of any such instrument being made in ISO

7726. The measurement this in fact refers to is the psychchrometric wet temperature $t_w$. *(Consistency, prevent errors, provide sufficient information)*

*Problem 5.* The program provides no estimates for the body area fraction exposed ($A_r/A_{du}$) Without prior knowledge the user must return to the paper based standard to find (with difficulty) the fractions presented in a sentence in the Annex A.4. Prompts for $A_r/A_{du}$ should be given. *(Speak the user's language, provide sufficient information)*

*Problem 6.* If mistakes are made during data entry, it is not possible to correct them, nor is there a prescribed quick method of terminating the calculation. This can be a problem if a number of sequences are being run. *(Prevent errors, provide good error messages, provide clearly marked exits)*

*Problem 7.* The presentation of the interpretation is cluttered, the DLE being presented after predicted data. *(Use simple and natural language)*

*Problem 8.* The interpretation is given in terms of "alarm" and "danger" criteria. The terminology differs from that found in the standard itself; in Annex C (C.2) "alarm" is referred to as a "warning level". *(Consistency)*

*Problem 9.* There is no risk for subjects suited to the environment analysed at the alarm criteria, yet a DLE is given. This is not made clear in the program's interpretation. *(Use simple and natural language)*

*Problem 10.* There is no explanation of what is meant by "excessive increase in body temperature", "excessive water loss" and "medical surveillance required" Action to be taken after the evaluation should be more explicitly provided. *(Speak the user's language, provide sufficient information)*

*Problem 11.* The standard includes an objective to determine modifications to an environment to reduce thermal stress. There is no method provided for doing this. Paragraph D.4 (Annex D) suggests carrying out the program several times, modifying the working conditions parameters to determine a safe working environment. Such a procedure is tedious and time consuming, a more structured method should be introduced. *(Provide sufficient information)*

The computer program makes ISO 7933 inherently more usable than the paper based calculation, however in evaluation a number of usability problems were identified, predominantly involving insufficient information presented to the user, thus increasing the users memory load. For use without reference to the standard itself, considerable expert knowledge is required, for example in estimating the thermal clothing insulation value and the body area fraction exposed. Being presented in the computer language BASIC the scope is limited, particularly in determining what parameters are required to remove risks to the exposed workers. A program that allows an iterative procedure would be preferable, giving the user the option of changing each variable without having to run the program several times. More information should be provided to aid the novice user in order to prevent usability errors.

## 6. Conclusions

- The limitations of ISO 7933 have already been well documented, (Mairiaux and Malchaire 1988, Wadsworth and Parsons 1986, Peters 1995, Kampmann & Piekarski 1995, and Parsons 1995). The results of the present study highlighted several of these limitations, questioning the validity of ISO 7933. The DLEs were found to be 'on the safe side', the standard warning of increases in core body temperatures before the actual temperatures were reached. The standard significantly underestimated the sweat rate, and rate of evaporation. It was concluded that the poor predictions of ISO 7933 were largely due to the difficulties in calculating the permeation efficiency factor ($F_{pcl}$.)

- ISO 7243 adequately protected the workers, reference values being considerably exceeded. As there was only one experimental condition it was not possible to evaluate whether the reference values could be increased. Studies by Intaranont and Vanwonterghem (1993) suggest that in tropical environments the reference values of ISO 7243 can be increased.

- ISO 7243 was found to be a usable document with no major usability problems.

- ISO 7933 is not usable as a document, it must be used as a computer program, included in the standard's Annex. The program has a number of minor usability issues. These may be overcome by training. There is considerable scope for improving its presentation, to make iterations possible and provide a more 'user friendly' interface. ISO 7933 is unsuitable for use in IDCs where the presence of computers cannot be relied upon. For use in practical situations a standard is required that maintains the principles without the complicated procedures. Such a standard may include a checklist or similar simple method.

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Table 1 Details of subjects who participated in investigation.

| Sex | Subject | Age (years) | Heigh t (m) | Weight (Kg) |
|---|---|---|---|---|
| | 1 | 19 | 1.65 | 82.75 |
| M | 2 | 20 | 1.85 | 83.14 |
| A | 3 | 22 | 1.76 | 77.14 |
| L | 4 | 25 | 1.81 | 72.77 |
| E | 5 | 23 | 1.74 | 80.69 |
| S | 6 | 22 | 1.82 | 72.42 |
| | 7 | 20 | 1.79 | 69.73 |
| | 8 | 21 | 1.75 | 68.62 |
| | 9 | 20 | 1.75 | 77.3 |
| F | 10 | 23 | 1.53 | 55.5 |
| E | 11 | 19 | 1.66 | 70.94 |
| M | 12 | 20 | 1.7 | 60.9 |
| A | 13 | 18 | 1.74 | 60.38 |
| L | 14 | 18 | 1.72 | 71.5 |
| E | 15 | 19 | 1.7 | 58.57 |
| S | 16 | 23 | 1.78 | 60.07 |
| | Mean | 20.75 | 1.73 | 70.15 |
| | SD | 2.05 | 0.08 | 8.89 |

Table 2 Thermal conditions and energy expenditure levels prevailing in Indian tea gardens (From Sen *et al*. 1983)

| Parameter | Mean | Range |
|---|---|---|
| Dry bulb temperature ($^{O}$C) | 31.8 | 26.5-36.5 |
| Wet-bulb temperature ($^{O}$C) | 27.6 | 25.5-29.0 |
| Relative humidity (%) | 72.2 | 68.8-89.0 |
| Globe temperature ($^{O}$C) | 34.0 | 27.7-37.2. |
| Air speed (ms$^{-1}$) | 1.05 | .21-2.29 |
| Metabolic rate (plucking) | 144 | 129-160 |
| Metabolic rate (walking, full basket) | 175 | --- |

Table 3: Heuristics used in evaluation (after Neilsen 1992)

| |
|---|
| Use simple and natural language |
| Speak the user’s language |
| Minimise user memory load |
| Be consistent |
| Provide feedback |
| Provide clearly marked exits |
| Provide shortcuts |
| Provide good error messages |
| Provide sufficient information |
| Prevent errors |

Table 4 Mean environmental parameters for each session in the thermal chamber. WBGT reference values are according to the mean metabolic rate for subjects in each trial

| Session Number | $t_a$ ($^{o}$C) | $t_r$ ($^{o}$C) | v (m/s) | RH (%) | WBGT ($^{o}$C) | WBGT Reference Value (non-acclimatized) ($^{o}$C) | Reference Value (acclimatized) ($^{o}$C) |
|---|---|---|---|---|---|---|---|
| 1 | 37.10 | 36.48 | 0.24 | 65.10 | 32.07 | 26.00 | 29.00 |
| 2 | 36.96 | 36.69 | 0.13 | 68.10 | 33.20 | 29.00 | 29.00 |
| 3 | 36.86 | 36.48 | 0.13 | 70.71 | 33.43 | 26.00 | 26.00 |
| 4 | 37.53 | 37.30 | 0.16 | 70.86 | 34.06 | 26.00 | 29.00 |
| 5 | 37.32 | 37.00 | 0.17 | 72.10 | 33.69 | 26.00 | 32.00 |
| 6 | 36.88 | 36.89 | 0.11 | 71.81 | 33.69 | 26.00 | 29.00 |
| 7 | 37.56 | 37.17 | 0.21 | 70.71 | 33.64 | 26.00 | 29.00 |
| 8 | 37.21 | 36.90 | 0.17 | 71.95 | 33.63 | 26.00 | 29.00 |
| Mean | 37.18 | 36.86 | 0.16 | 70.17 | 33.43 | - | - |
| s.d. | 0.12 | 0.30 | 0.04 | 10.54 | 0.560 | - | - |

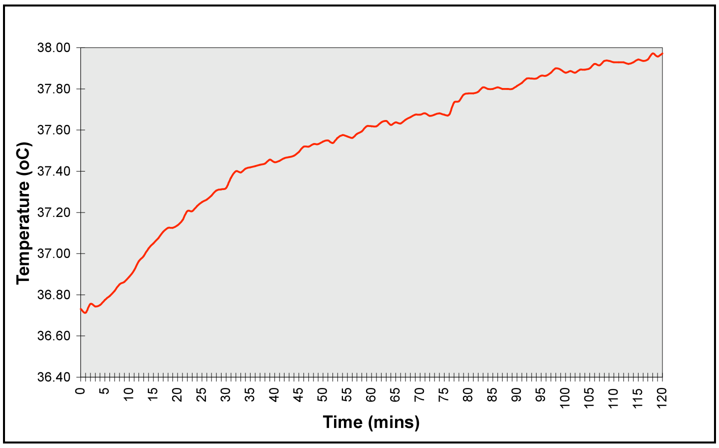


Figure 1: Mean aural temperature for all 16 subjects

Table 5 Differences between actual and predicted evaporation (Wilcoxon Match Pairs Signed Ranks test.)

| | $E_{req}$ | $E_{max}$ | $E_p$ |
|---|---|---|---|
| **All Subjects $E_{mes}$** | N/S | 0.002 | N/S |
| **Male Subjects $E_{mes}$** | 0.05 | 0.002 | N/S |
| **Female Subjects $E_{mes}$** | N/S | 0.002 | N/S |

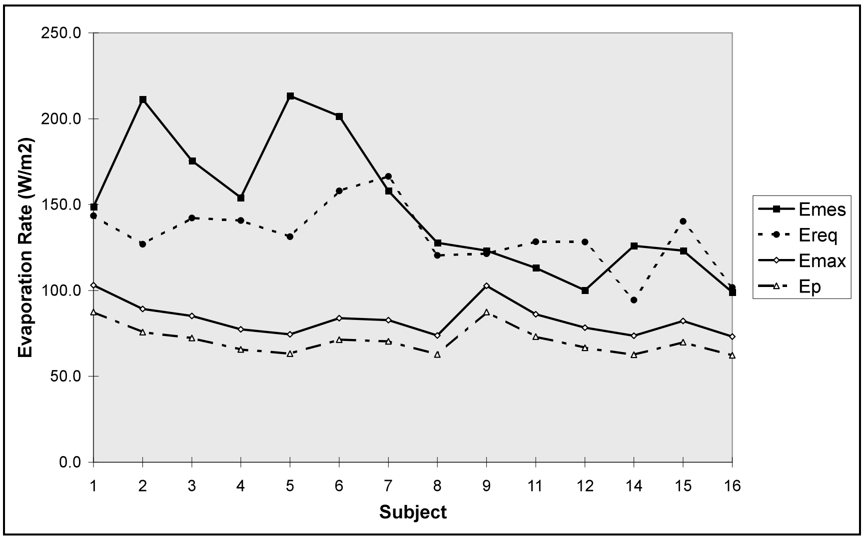


Figure 2 Actual hourly rate of evaporation ($E_{mes}$), and predictions made by ISO 7933 ($E_p$, $E_{max}$ and $E_{req}$) for all subjects. Subjects 1-8 are male, 9-16 female. Note that results for subjects who withdrew are not presented.

Table 6 Differences between actual and predicted sweat loss (Wilcoxon Match Pairs Signed Ranks test.)

| | $SW_{req}$ | $SWp$ | $SW_{max}$ (Alarm) | $SW_{max}$ (Danger) |
|---|---|---|---|---|
| **All Subjects $SW_{mes}$** | 0.02 | 0.02 | N/S | 0.02 |
| **Male Subjects $SW_{mes}$** | N/S | 0.02 | N/S | N/S |
| **Female Subjects $SW_{mes}$** | 0.05 | N/S | N/S | 0.05 |

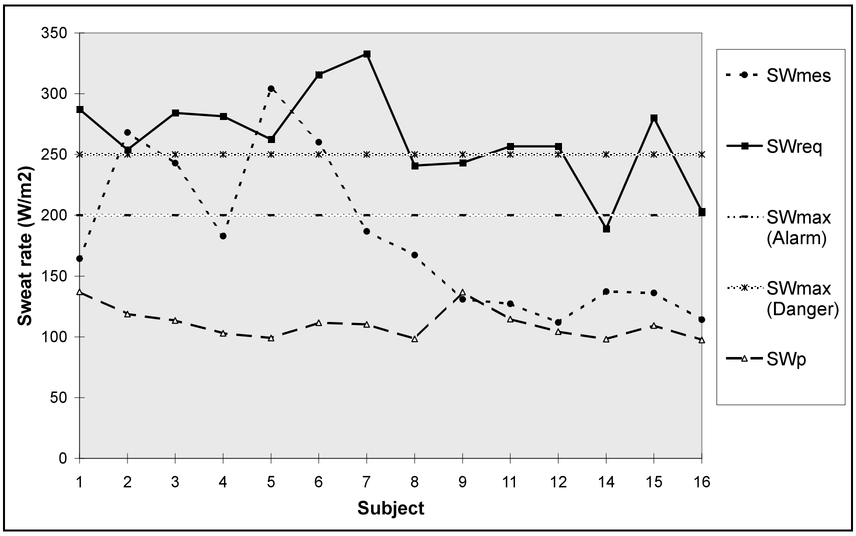


Figure 3 Actual hourly sweat rate $SW_{mes}$, and predictions made by ISO 7933 ($SW_p$, $SW_{max}$ and $SW_{req}$) for all subjects. Subjects 1-8 are male, 9-16 female. Note that results for subjects who withdrew are not presented.