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ABSTRACT

Included in these proceedings are 11 formal papers presented by leading researchers in the field of thermal comfort and heat stress at a symposium held for the purpose of exploring new aspects of indoor thermal environments, caused primarily by the impact of energy conservation in new and existing buildings. The contributed papers were from Denmark, Sweden, and several research institutions in the United States, including the John B. Pierce Foundation at Yale University, Kansas State University, and Pennsylvania State University. Information was presented on a variety of approaches to determining human response to thermal environments. These included laboratory studies in environmental chambers utilizing instrumented human subjects, field studies involving surveys and questionnaires, mathematical modeling of humans, an analysis of some types of instruments used in assessing the quality of environments, and a discussion of the relationships between productivity and the thermal environment. (Author/MLF)

DEPARTMENT OF COMMERCE · NATIONAL BUREAU OF STANDARDS

NBS SPECIAL PUBLICATION 491

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Thermal Analysis— Human Comfort— Indoor Environments

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Thermal Analysis—Human Comfort—Indoor Environments

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February 11, 1977

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PREFACE

A symposium on "Thermal Analysis - Human Comfort - Indoor Environments" was held at the National Bureau of Standards, Gaithersburg, Md., February 11, 1977. The symposium was sponsored by the National Bureau of Standards and co-chaired by Dr. B. W. Mangum, Institute for Basic Standards and Dr. J. E. Hill, Institute for Applied Technology.

The symposium was prompted by the increasing emphasis on energy conservation practices in existing buildings as well as new building designs that emphasize energy conservation. Some of the practices have no effect on the thermal comfort of occupants. Others, such as limiting the use of both cooling and installed capacity of heating, ventilating, and air conditioning equipment, lower thermostat settings in winter, higher thermostat settings in summer, and eliminating climate control in halls, entryways, and storerooms may have an adverse effect on occupants, however.

The purpose of the symposium was to bring together leading scientists, engineers, architects, physiologists, and government officials who were interested in how new energy conservation strategies in buildings will affect human comfort. The symposium was successful in identifying and reviewing the vast amount of research work done in this field over the past fifty years. In addition, material on new and current research was presented as well as some specific suggestions for work that should be undertaken in the near future. It is hoped that the proceedings will stimulate a desire on the part of government organizations conducting major research programs to recognize the need for additional research in this field.

The proceedings of the conference reflect, in chronological sequence, the main presentations by the speakers. Every effort has been made to minimize the editing and to reflect each author's original material as submitted prior to the symposium.

Conversion Table to SI Units

This publication uses customary English units for the convenience of engineers and others who use them habitually. The table below is for the reader interested in conversion to SI units. For additional information see:

(1) NBS LC1078, Dec., 1976, "The Metric System of Measurement".
(2) Z210.1-1976, "ASTM/IEEE Standard Metric Practice".

Quantity	To convert from	To	Multiply by
Length	inch	m (meter)	2.540×10^{-2}
	foot	m	3.048×10^{-1}
	mile	m	1.609×10^{3}
Area	in^2	m^2	6.452×10^{-4}
	ft^2	m^2	9.290×10^{-2}
Volume	in^3	m^3	1.639×10^{-5}
	ft^3	m^3	2.832×10^{-2}
	gallon	m^3	3.785×10^{-3}
Temperature	°F	°C	$t_{°C} = (t_{°F}-32)/1.8$
T. Difference	$\Delta t_{°F}$	K	$\Delta T_K = \Delta t_{°F}/1.8$
Mass	pound	kg	4.536×10^{-1}
	ounce	kg	2.835×10^{-2}
Pressure	psi	Pa	6.895×10^{3}
	in H_2O	Pa	2.488×10^{2}
	in Hg	Pa	3.386×10^{3}
	mmHg	Pa	1.333×10^{2}
Energy	Btu	J	1.055×10^{3}
	MBtu	J	1.055×10^{9}
	kWh	J	3.600×10^{6}
	ft·lbf	J	1.356×10^{0}
	kilocalorie	J	4.184×10^{3}
Power	Btu/h	W	2.931×10^{-1}
	hp	W	7.457×10^{2}
Flow	gal/min	m^3/s	6.309×10^{-5}
	ft^3/min	m^3/s	4.719×10^{-4}
Density	lb/ft^3	kg/m^3	1.602×10^{1}
	lb/gal	kg/m^3	1.198×10^{2}
Heat Capacity	Btu/(lb·°F)	J/(kg·K)	4.187×10^{3}
	Btu/(ft^3·°F)	J/(m^3·K)	6.707×10^{4}
Met	met	W/m^2	5.800×10^{3}

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ABSTRACT

These are the proceedings of a symposium sponsored by the National Bureau of Standards and held in Gaithersburg, Maryland on February 11, 1977. The symposium was held for the purpose of exploring new aspects of indoor thermal environments, caused primarily by the impact of energy conservation in new and existing buildings. Included in these proceedings are eleven formal papers which were presented by leading researchers in the field of thermal comfort and heat stress. The contributed papers were from Denmark, Sweden, and several research institutions within the United States including the John B. Pierce Foundation at Yale University, Kansas State University, and Pennsylvania State University. Information was presented on a variety of approaches to determining human response to thermal environments. These included laboratory studies in environmental chambers utilizing instrumented human subjects, field studies involving surveys and questionnaires, mathematical modelling of humans, an analysis of some types of instruments used in assessing the quality of the environments, and a discussion of the relationships between productivity and the thermal environment.

Key words: Energy conservation in buildings; heat stress; human comfort; indoor environment; mean radiant temperature; thermal comfort.

Disclaimer

OPENING REMARKS

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It is a great pleasure and an honor for me to have been asked to welcome you to the National Bureau of Standards today to discuss a subject of mutual interest, namely, that of the effects of energy conservation in buildings on human comfort. With the increased emphasis on energy conservation practices in existing buildings as well as new building designs that emphasize energy conservation, you, our leading scientists, engineers, government officials, architects, physiologists, and manufacturers are faced with the challenge of protecting the comfort, health, and performance of building users. This symposium, therefore, is unusual because we will be trying to explore how much we really know about the effects of interior thermal environments on people.

We are very fortunate to have with us today some of the leading experts of the world in this field, scientists who have been conducting research in this area for some years. We have speakers from Denmark, Sweden, and a variety of research institutions in this country including the John B. Pierce Foundation at Yale University and from Kansas State University and Penn State University. We also have representatives from both U.S. Army and Navy research organizations who will give us some insight into the work they are doing on heat stress. This work has relevance to the general problem being discussed because as we move further away from comfort conditions, we begin to move into a region of heat or cold stress.

We will also hear about a variety of approaches for obtaining information about human reactions to thermal environments. These include laboratory studies in environmental chambers using instrumented human subjects, field studies involving surveys and questionnaires, mathematical modeling of humans and their environments, and a discussion of some types of instruments used in assessing the quality of the environments.

We will also take this opportunity to describe some of the work the National Bureau of Standards has been doing over the past several years in promoting energy conservation in the design, construction, and operation of our nation's buildings. Based, in part, on the work done here, it is now relatively easy to predict how much energy is conserved as a result of any one of a number of building design or operation strategies. Recommendations made in this area, however, must consider what effect the resulting indoor environment has on the building occupants. President Carter's recent request to conserve energy by keeping the interior temperature of buildings at 18° Celsius (65°F) during the day and 13° Celsius (55°F) at night prompts further consideration of this impact. The question that arises is what do we really know about the short-term and long-term effects of this type of building control? This is a big part of the challenge, and we in the National Bureau of Standards' Institute for Applied Technology and Institute for Basic Standards are pleased to be able to rise to the challenge by sponsoring today's symposium.

On behalf of all of our staff members, I bid you welcome and trust that you will find the sessions both enjoyable and worthwhile.

THERMAL COMFORT IN INDOOR ENVIRONMENTS

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ABSTRACT

A review is given of existing knowledge regarding the conditions for thermal comfort for man, emphasizing research data obtained during recent years.

Equations, indices, and diagrams predicting man's thermal sensation, comfort, and discomfort as a function of air temperature, mean radiant temperature, air velocity, humidity, clothing, and activity are discussed. The influence on comfort conditions of age, adaptation, sex, seasonal, and circadian rhythm, temperature swings, color, and noise are dealt with. The term "climate monotony" is considered.

Local discomfort due to radiant asymmetry, vertical air temperature gradients, and non-uniformity of clothing are discussed.

New preliminary research data are presented on limits for draft and on comfort limits for floor temperatures.

Future research needs are identified.

KEY WORDS

Thermal comfort - human comfort - thermal neutrality - thermal environment - indoor environment - indoor climate.

INTRODUCTION

In a modern industrial society, man spends the greater part of his life indoors. A large proportion of the population spends 23 out of 24 hours in an artificial climate - at home, at the workplace, or during transportation.

During recent decades this has resulted in a growing understanding of and interest in studying the influence of indoor climate on man, thus enabling suitable requirements to be established which should be aimed at in practice.

At the same time an increasing number of complaints about unsatisfactory indoor climate suggest that man has become more critical regarding the environment to which he is subjected. It seems that he is most inclined to complain about the indoor climate of his workplace (offices, industrial premises, shops, schools, etc.) where he is compelled to spend his time in environments which he himself can control only to a very limited degree. Field studies indicate that in practice many of these complaints can be traced to an unsatisfactory thermal environment.

About one third of the world's energy consumption is used to provide thermal comfort for man. It is no wonder, therefore, that efforts towards energy conservation in recent years have led to an increased interest in man's comfort conditions in order to assess the human response to different conservation strategies.(1,2,3,4)

In this paper the conditions for man's thermal comfort will be discussed, as well as the thermal environments which should be aimed at and the methods which should be employed in practice to evaluate a given thermal environment.

DEFINITION OF COMFORT

In agreement with ASHRAE's Standard 55-74 (5), thermal comfort for a person is here defined as "that condition of mind which expressed satisfaction with the thermal environment." This means that he feels thermally neutral for the body as a whole, i.e., he does not know whether he would prefer a higher or lower ambient temperature level. Furthermore, it is a requirement that there is no local warm or cold discomfort at any part of the human body, e.g. due to asymmetric radiation, draft, warm or cold floors, vertical temperature gradients, non-uniform clothing, etc.

People are not alike, thermally or otherwise. If a group of people is exposed to the same room climate, it will, therefore, normally not be possible, due to biological variance, to satisfy everyone at the same time. One must aim at creating optimal thermal comfort for the group, i.e., a condition in which the highest possible percentage of the group are thermally comfortable.

COMFORT PARAMETERS

What is required in practice is that the comfort conditions are expressed in controllable factors, namely, the following four main environmental parameters:

1. Mean air temperature around the human body.
2. Mean radiant temperature in relation to the body.
3. Mean air velocity around the body.
4. Water vapor pressure in ambient air.

Besides the environmental factors, man's comfort is also influenced by the following two factors:

5. Activity level (internal heat production in the body).
6. Thermal resistance of clothing.

As suggested by Gagge et al (6), activity is often expressed in met-units (1 met = 58 W/m^2 corresponding to sedentary activity) and the thermal resistance of the clothing is expressed in clo-units (1 clo = 0.155 m^2 °C/W).

Seppanen et al (7) have used a thermal manikin to measure the clo-value of many typical garments and Sprague and Munson (8) have suggested formulas from which the clo-value of a clothing ensemble can be calculated when the clo-value of the individual garments is known. Madsen (9) has measured clo-values of different bed clothing with a thermal manikin. Nishi et al (10,11) have suggested a simple method by which the clo-value of a clothing ensemble can be measured while being worn by man, and Azer (12) has suggested a theoretical model for estimating clo-values. The above-mentioned clothing studies during the last couple of years have established quite a comprehensive list of clo-values for typical clothing ensembles. A similar table of met-values for typical activities has existed for a long time. The activity and the thermal resistance of the clothing can thus be estimated with reasonable accuracy by considering the application of the room concerned.

In practice, quantitative knowledge is needed as to which combinations of the above-mentioned six main variables will lead to thermal neutrality for man. But according to the definition of comfort, it is furthermore requested that there be no local discomfort on the human body. It can, therefore, be necessary to consider also the following factors: the asymmetry of the radiant environment, the fluctuations of the air velocity, the vertical air temperature gradient, the floor temperature (and material).

PHYSIOLOGICAL COMFORT CONDITIONS

The purpose of the human thermoregulatory system is to maintain a reasonably constant deep body temperature around 37 °C; a requirement for this is the maintenance of a heat balance so that the heat lost to the environment is equal to the heat produced by the body. Man possesses the most effective physiological mechanisms for maintaining a heat balance: the sensible heat loss can be altered by a variation of the cutaenous blood flow and thus of the skin temperature, latent heat loss can be increased by sweat secretion, and internal heat production can be increased by shivering or muscle tension.

These mechanisms are extremely effective and ensure that the heat balance can be maintained within wide limits of the environmental variables. Maintenance of heat balance is, however, far from being a sufficient condition for thermal comfort. Within the wide limits of the environmental variables for which heat balance can be maintained, there is only a narrow interval which will create thermal comfort.

It has long been known that man's thermal sensation is related to the state of his thermoregulatory system, the degree of discomfort being greater the heavier the load on the effector mechanism. Experiments by Yaglou (13) in the 1920's indicated a correlation between the skin temperature and the sensation of thermal comfort; later and more complete studies by Gagge and several others (14,6,15) showed a correlation between thermal sensation and skin temperature, independent of whether the subjects were nude or clothed. Therefore, it was generally accepted for a long time that the physiological conditions for comfort were that a person had a mean skin temperature of 33-34 °C and that sweating (or shivering) did not occur. This was later confirmed in experiments by Fanger for sedentary subjects. At activities higher than sedentary ones, man prefers a lower mean skin temperature and prefers to sweat (16,17). By setting up a heat balance equation for the human body, Fanger then used the comfort values of skin temperature and sweat secretion (both as a function of the metabolic rate) to derive his comfort equation (16).

Gagge et al (18,19,20) found that cold discomfort is related to skin temperature while warm discomfort is more closely related to the wettedness of the skin, defined as the relation between the actual evaporation from the skin and the maximum possible evaporation from a completely wet skin. Gagge later used these observations in his derivation of the New Effective Temperature Scale (ET*).

Although the skin temperature is important for comfort during steady state (or quasi steady state) conditions, it is obvious that the thermal sensors in the skin do not in themselves determine the sensation of comfort. This is apparent just from the fact that the skin temperature during comfort decreased with increasing activity. Furthermore, transient experiments by Gagge et al (18,19) show that subjects, when transferred from a cold or a warm to a neutral environment, felt immediately comfortable although their skin temperature was far from the steady state level considered comfortable. This indicates that the rate of change of the skin temperature is also important for the thermal sensation.

Other transient experiments by Cabanac (21,22) and by Hardy (23) with subjects immersed in a water bath indicate that an interaction of internal and skin temperature might be important in evoking discomfort.

As yet, we have not reached a full understanding of the physiological factors determining man's thermal sensations and his sensation of comfort and discomfort. Future research aimed at establishing these factors and their quantitative influence on man's subjective sensations will not only be of scientific significance but will also provide a better foundation on which to evaluate thermal environments in practice.

ENVIRONMENTAL COMFORT CONDITIONS

When, in practice, artificial climates are to be created which will provide thermal comfort for man, it is, of course, insufficient merely to have some knowledge of the physiological comfort conditions. What is necessary is a detailed quantitative knowledge of those combinations of the environmental variables which will provide thermal comfort.

Such information exists today due to a comprehensive experimental research effort during the last decade, especially at Kansas State University (KSU) and Pierce Foundation Laboratory in the U.S., at the Electricity Council Research Center in England, and at the Technical University of Denmark. Besides these laboratories, which have advanced experimental facilities at their disposal, several other research groups have performed comfort studies in the field.

Fanger (16) derived in 1967, based on experimentally determined physiological comfort criteria and heat transfer theory, the comfort equation, which determines all combinations of the six main parameters which will provide thermal neutrality for man, and the equation was depicted in 28 comfort diagrams, applicable in practice. Subsequently, he derived the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied) indices which predict the degree of discomfort and the percent of people who will experience discomfort for any combination of the six comfort parameters measured in practice (24).

Nevins, Rohles, McNall and their co-workers at KSU used a more emperical method where they related the subjective response of their subjects directly to the environmental parameters to which they were exposed, without taking any physiological measurements. Their classical experiment comprised 1600 sedentary subjects clothed at 0.6 clo who were exposed to different combinations of ambient temperature and humidity and they derived regression equations from which the mean vote could be predicted as a function of temperature and humidity (25,26,27). They later used the same method to study the effect of activity (17), clothing (28), mean radiant temperature (29) and velocity (30). The results showed an excellent agreement with Fanger's comfort equation.

Gagge, Stolwijk, Nishi and Gonzalez (31,32,33,34) established the New Effective Temperature Scale (ET*) which is a rationally derived thermal index based on physiological criteria for discomfort (skin temperature and wettedness) and heat transfer theory. The New Effective Temperature (ET*) is defined as the temperature of an imaginary uniform enclosure with 50% relative humidity at which man would feel the same level of warmth, acceptability, or coolness as he would in the actual environment.

Lines of equal ET* were depicted in a psychrometric diagram for lightly clothes sedentary or slightly active persons at low air velocity, and regions for different degrees of discomfort and for heat tolerance were identified in the diagram. A graphical method for the construction of diagrams for other activities, clothings, and velocities was recommended (35). They introduced later the Standard Effective Temperature (SET*) defined as the temperature of an imaginary uniform enclosure with 50% relative humidity and still air, in which sedentary man in standard clothing (0.6 clo) would feel the same level of warmth, acceptability, or coolness as he would (while sedentary) in the actual environment and with the actual clothing worn.

The SET* thus combines clothing and the four environmental factors into one index from which man's thermal sensation and discomfort can be evaluated at a given activity level. Diagrams showing SET* as a function of ambient temperature for humidities, air velocities, clothings, and activities typical in normal offices during winter and summer have recently been published (36).

Griffiths and McIntyre studied the relative influence of air temperature and mean radiant temperature (37) on man's thermal sensation based on subjective votes and they used a similar method to study the influence of humidity (38) and clothing (39,40).

A comparison of the results of the above-mentioned studies show remarkably good agreement. It seems fair, therefore, to state that we today have the necessary information to identify all the combinations of the six main parameters which most likely will provide optimal thermal comfort (neutrality) for a large group of people. We are, furthermore, able to predict the thermal sensation or the degree of discomfort for any other combination of the parameters.

This applies to steady state conditions or when the environmental variables are changing slowly (41,42). For sudden or quick changes of the variables, more studies will be needed in the future.

INDIVIDUAL DIFFERENCES

Everyone is not alike. How then is it possible, from an equation, to specify one particular temperature which will provide comfort? The answer is that this temperature does not necessarily satisfy everyone. It gives, however, combinations of the variables which will provide comfort for the greatest number of people. This is exactly what should be aimed at when a large group of people are together in the same room climate (optimal comfort for the group).

It has been found from experiments involving 1300 subjects that the best result attainable is 5% dissatisfied (Fanger (24)). Any deviation from this condition will result in an increase in the percentage of dissatisfied.

The individual differences can also be described by the standard deviation of the preferred temperature defined as that ambient temperature at which a person does not know whether he would prefer a warmer or a cooler environment. The preferred temperature for a given person can be determined in a climatic chamber by changing the temperature according to the wishes of the subject (43,44). Fanger and Langkilde found the standard deviation for sedentary, lightly clothed subjects to be 1.2 °C (45).

VARIABILITY IN MAN'S COMFORT CONDITIONS FROM DAY TO DAY

How reproducible are the comfort conditions for the individual? Is not the subjective thermal sensation so uncertain that large variations in comfort requirements can be expected from day to day? This has recently been investigated by determining the preferred ambient temperature for each subject under identical conditions on four different days (Fanger (46)). A standard deviation of only 0.6 °C was found.

It is concluded that the comfort conditions for the individual can be reproduced and will vary only slightly from day to day.

AGE

It has often been claimed that due to the fact that metabolism decreases slightly with age, the comfort conditions based on experiments with young and healthly subjects cannot be used as a matter of course for other age groups. Studies by Fanger (24), Rohles and Johnson (47), and Griffiths and McIntyre (48) with the young and the elderly showed, however, no difference in the comfort conditions for the different age groups. The lower metabolism in elderly people seems to be compensated by a lower evaporative loss.

It should be kept in mind that the experiments were performed at the same standardized activity level for young and elderly subjects. In certain cases in practice, e.g. homes for the aged, the activity level will often be quite low, and there will thus be a natural tendency to prefer a higher temperature.

ADAPTATION

It is widely believed that, by exposure to hot or cold surroundings, people can acclimatize themselves so that they prefer other thermal environments, and that the comfort conditions vary in different parts of the world, depending on the outdoor climate at the relevant place.

Comparison between results of identical experiments in the U.S. and in Denmark showed no difference between the comfort conditions for Europeans and Americans (24). In other Danish comfort experiments, people who daily had been exposed to cold by working in the meat-packing industry or who were winter-swimmers were not found to prefer indoor temperatures lower than that preferred by other people (49,50).

People from tropical countries were also tested in Copenhagen shortly after their arrival by air, and they were found to prefer a temperature only about 1 °C higher than that preferred by Europeans (51). A small difference was found also between Melanese and Australian subjects in a comprehensive field study in Papua by Ballantyne et al (52). Humphreys (53) found in an interesting comparative analysis of more than thirty field studies throughout the world that people from the tropics voted comfortable at temperatures higher than would be predicted from the comfort equation. McIntyre and Griffiths (54) discuss this result and suggest that the subjective scale applied might influence the result; dwellers in hot climates may prefer a lower temperature than the one they describe as comfortable.

In conclusion, it seems fair to state that the effect of adaptation (if it exists) is quite small and that the comfort criteria established in climate chamber studies in Europe and the U.S. can be applied with good approximation throughout the world.

MEN AND WOMEN

The climate chamber studies of Kansas State University (25,26,27) and at the Technical University of Denmark (24,45) showed no significant differences between the comfort conditions for men and women. Women's skin temperature and evaporative heat loss are slightly lower than those for men, and this balances the slightly lower metabolism of women (43,45). But in practice women may tend to wear less clothing and be slightly more sensitive to cold (Gagge and Nevins (2)).

SEASONAL AND CIRCADIAN RHYTHM

As adaptation seems to have only a minor effect on man's thermal preference, there is no reason to expect major differences between comfort conditions in winter and in summer. This was confirmed by a KSU study where results of winter and summer experiments showed no difference (McNall et al (55), while McIntyre and Gonzalez (40) found a slightly higher preferred temperature late in the summer than early in the summer. Although the comfort conditions seem to be constant or vary little with season, it should be kept in mind that the clo-value is usually lower during the summer, resulting in a higher preferred temperature.

On the other hand, it is reasonable to expect the comfort conditions to alter during the day as the internal body temperature has a daily rhythm, a maximum occurring late in the afternoon and a minimum early in the morning. We have recently investigated this experimentally by comparing the preferred temperature for subjects in the morning and in the evening (56), during a normal 8-hour simulated working day (57), and during the night (shiftwork) (58). No significant difference was found in the ambient temperature preferred during a 24-hour period, provided that the activity, clothing and the other environmental parameters were the same.

CLIMATE MONOTONY

It has sometimes been claimed that a constant thermal environment is not ideal as it produces so-called climate monotony - increased fatigue, lower arousal, lower performance, etc. But such claims have not so far been supported by experimental evidence.

We have performed a preliminary study of this problem by exposing subjects to temperature swings of varying amplitudes and frequencies around the comfort level (Wyon et al (59)). At the same time, their thermal sensations, mental performance, and behavior were studied. Slight positive effects on performance were observed but only with large temperature swings which were felt to be definitely uncomfortable. McIntyre (60) studied the effect of quick swings of the mean radiant temperature, but the subjects disliked the swings. More comprehensive studies are needed. Until then, I would not recommend aiming at temperature swings.

COLOR AND NOISE

During the energy crisis, the idea was put forward that by using "warm" colors (red and yellow) on walls or by the use of reddish lighting, a psychological feeling of heat could be conveyed to people, so that thermal comfort could possibly be maintained at lower ambient temperatures. Similarly, in summer "cold" colors should be aimed at, or blue lighting used. Some people have even spoken of "color conditioning" rooms instead of air conditioning them.

Unfortunately, no energy saving seems to be involved in such measures. Fanger, et al (61) studied subjects in rooms with extreme blue or red lighting but found practically no difference in the temperature preferred. Neither did the noise level (white noise, 40-85 dB(A)) have any psychological effect on man's thermal comfort.

LOCAL THERMAL DISCOMFORT ON THE BODY

Although a person may feel thermally neutral for the body in general, i.e., he would prefer neither a warmer nor a cooler environment, he might not be in thermal comfort if one part of the body is warm and another is cold.

This might be caused by an asymmetric radiant field, a local convective cooling of the body (draft), by contact with a warm or cool floor, by a vertical air temperature gradient, or by non-uniformity of the clothing. Besides the comfort conditions for the body in general, it is, therefore, essential to establish limits for how non-uniform the heat loss from the body can be without evoking discomfort.

ASYMMETRIC RADIATION

Limits for asymmetric radiation were recently studied experimentally by Olesen et al (62). The following formula for estimating the limits of acceptable temperature differences of a local radiant source for sedentary persons in thermally neutral environments with still air was recommended:

$$-2.4 - 1.8I_{cl} \leq \Delta t_w F_{p-w} \leq 3.9 + 1.8I_{cl}$$

where I_{cl} = clo-value of clothing

F_{p-w} = angle factor between person and radiant source

Δt_w = temperature difference (°C) between radiant source and mean radiant temperature in relation to the person.

This formula is in reasonable agreement with other recent data by McNall and Biddison (63) and by McIntyre and Griffiths (54).

DRAFT

Draft is defined as an unwanted local convective cooling of the body. It is perhaps the most common reason for complaints in ventilated spaces. As mentioned earlier, the mean air velocity around the body influences the ambient temperature necessary for thermal neutrality for the body as a whole (64,44,65,30). However, in spite of thermal neutrality, local velocities can provide an unwanted cooling (= draft) of some parts of the body; the neck and the ankles seem to be the most sensitive parts of normally clothed persons. Unfortunately, very few experimental results on this subject have been published.

However, extensive studies (yet unpublished) on this problem have been performed at the Technical University of Denmark during the last couple of years. More than one hundred college-age students have been involved in experiments where subjects were exposed at the neck and the ankle to fluctuating and uniform air flows with different mean velocities, with different amplitudes and frequencies of the fluctuating velocity, and with different air temperatures. Based on the subjective reactions of the subjects, it has been possible to establish a mathematical model which predicts the percentage of uncomfortable persons (due to draft) as a function of the above-mentioned factors.

As examples of the preliminary results, the diagrams in Figs. 1 and 2 are shown. For two different frequencies and amplitudes (expressed as the relationship between maximum and mean velocity), the diagrams show the mean velocity which at different air temperatures would create draft discomfort among 5, 10, 20, and 30% of the occupants.

The diagrams show that much higher mean velocities are acceptable when the velocity is uniform than when it is fluctuating. They show, furthermore, that frequencies around 0.33 Hz are more uncomfortable than frequencies around 0.05. Preliminary analyses of velocity fluctuations in a number of real spaces indicate, however, that the characteristic frequencies are closer to the conditions given in Fig. 1 (0.05 Hz).

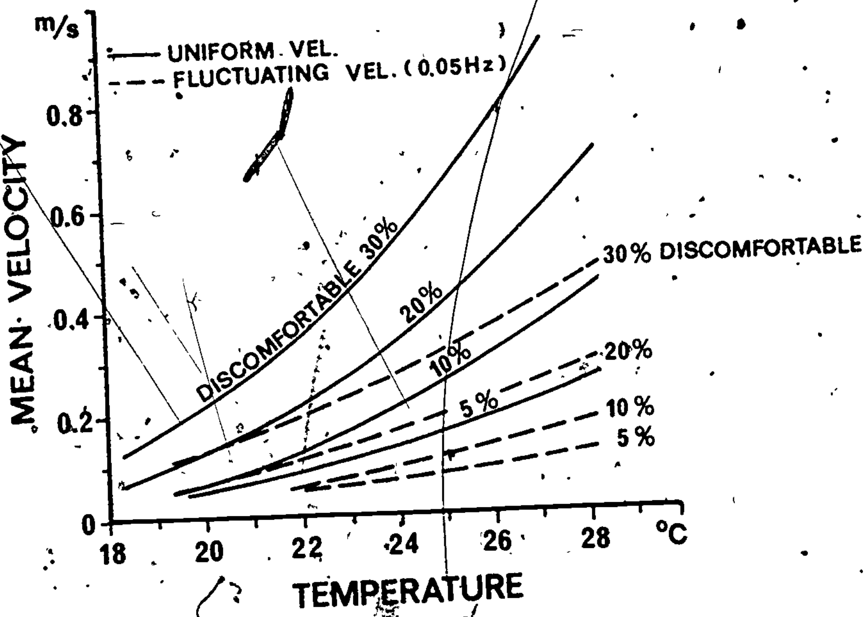

Figure 1. Mean air velocities (as a function of air temperature) which are predicted to create draft-discomfort among 5, 10, 20 or 30% of the occupants. The dotted lines correspond to a fluctuating velocity with a frequency of 0.05 Hz and a relation between max - and mean - velocity, $v_{max}/\bar{v} = 2$. The solid lines correspond to "uniform" velocity, where $v_{max}/\bar{v} = 1.2$. The diagram applies for sedentary persons with a neutral temperature around 23 °C.

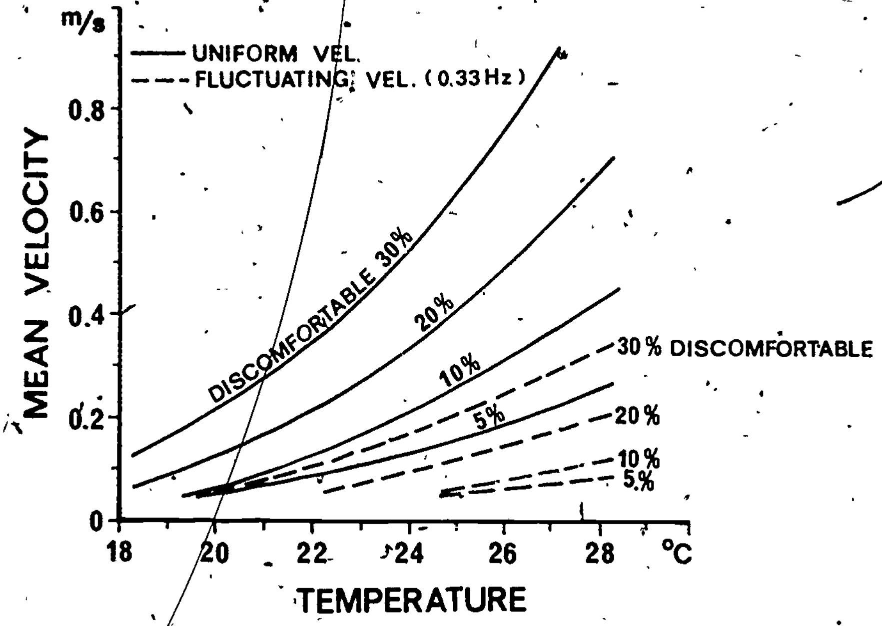

Figure 2. Mean air velocities (as a function of air temperature) which are predicted to create draft-discomfort among 5, 10, 20 or 30% of the occupants. The dotted lines correspond to a fluctuating velocity with a frequency of 0.33 Hz and a relation between max - and mean - velocity, $v_{max}/\bar{v} = 2$. The solid lines correspond to "uniform" velocity, where $v_{max}/\bar{v} = 1.2$. The diagram applies for sedentary persons with a neutral temperature around 23 °C.

FLOOR TEMPERATURE

Due to the direct contact between the feet and the floor, local discomfort of the feet can often be caused by a too high or too low floor temperature. Studies on comfort limits for floor temperatures have recently been performed at the Technical University of Denmark by Olesen (66), who found the following main results.

For floors occupied by people with bare feet (in swimming halls, gymnasiums, dressing rooms, bathrooms, bedrooms, etc.), the flooring material is important. Based on the results of experiments comprising 16 subjects and based on heat transfer theory, Olesen found the optimal temperatures and recommended temperature intervals, given in Table 1, for a number of typical flooring materials. For 10 minutes occupancy, about 10% of the people can be expected to experience discomfort at the optimal floor temperature while fewer than 15% can be expected to be uncomfortable within the recommended temperature interval.

For floors occupied by people with footwear (normal indoor footwear), the flooring material is without significance. Olesen found, based on his own experiments and a re-analysis of the results of Nevins et al (25,68,69), an optimal temperature of 25 °C for sedentary and 23 °C for standing or walking persons. At the optimal temperature, 6% of the occupants felt warm or cold discomfort at the feet. If one accepts up to 8% uncomfortable, the floor temperature should be within the interval 22-30 °C for sedentary and 20-28 °C for standing or walking persons.

VERTICAL AIR TEMPERATURE GRADIENTS

In most spaces in buildings, the air temperature is not constant from the floor to the ceiling; it normally increases with the height above the floor. If this gradient is sufficiently large, local warm discomfort can occur at the head, and/or cold discomfort can occur at the feet, although the body as a whole is thermally neutral. Little information on this subject has been published but preliminary results from studies at the Technical University of Denmark by Schøler (70), and results by McNair (71) and Eriksson (72) indicate that the risk of local discomfort is negligible provided that the air temperature difference between head and feet level is less than 2-3 °C.

NON-UNIFORMITY OF THE CLOTHING

The clo-value is an expression for the mean thermal resistance of a clothing ensemble over the entire body. But if the clothing is very non-uniformly distributed over the body, it is likely that local warm and cold discomfort can occur at different parts of the skin, although the body as a whole is thermally neutral. No systematical studies of this phenomenon have been performed, but McIntyre and Griffiths (73) found that although the general thermal sensation of sedentary subjects at 15 and 19 °C was altered when they put on an extra sweater, this did not decrease the local cold discomfort on the hands and feet.

FUTURE RESEARCH NEEDS

Conclusive new evidence has come to light on man's comfort conditions as a result of extensive research carried out during recent years. This knowledge is quantified so that it is directly applicable in practice. However, several problems still exist which demand our efforts in this field of research in the future.

It is partly a matter of establishing comfort conditions during transients (including temperature and humidity fluctuations and sudden changes, for instance, when a person moves from outdoors to indoors). In this connection, it would be appropriate to perform more fundamental studies to clarify the correlation between man's thermal sensation and comfort and the function of his thermoregulatory system.

Comfort studies on children are needed to investigate whether the comfort conditions for adults apply also to this age group.

Table 1.—Comfortable Temperatures of Floors Occupied by People with Bare Feet.

Flooring Material	Optimal Floor Temperature for 1 min Occupancy °C	Optimal Floor Temperature for 10 min Occupancy °C	Recommended Floor Temp. Interval °C
Pinewood Floor	25	25	22.5 - 28
Oakwood Floor	26	26	24.5 - 28
PVC-Sheet with Felt Underlay on Concrete	28	27	25.5 - 28
Hard Linoleum on Wood	28	26	24 - 28
5 mm Tesselated Floor on Gas Concrete	29	27	26 - 28.5
Concrete Floor	28.5	27	26 - 28.5
Marble	30	29	28 - 29.5

Information on the effect of the thermal environment on sleep quality is required. The establishment of optimal thermal conditions for sleep is of practical significance for the planning and operating of heating and air-conditioning systems, e.g., for hotels and hospitals.

More studies are needed on the thermal properties of clothing ensembles, on the effect of non-uniform clothing, and on the connection between clothing habits and behavioral temperature regulation.

Development of new light-weight clothing ensembles with easily adjustable clo-value, high permeability for transfer of water vapor; and acceptable to people seems required. Development of thermally rationally designed uniforms for different typical industrial jobs requires special attention.

Information on the acceptability of spot heating and cooling in industry are required. Possibilities of individual heating or cooling of the body should be considered.

A study should be made on how people evaluate thermal discomfort compared to other types of discomfort in a building (visual, acoustical, etc.). Such information could be useful for building designers when deciding how given resources should be spent optimally to minimize the "total" experience of discomfort in a building.

It would be useful to investigate whether people find any of the combinations of the environmental parameters which provide comfort preferable to other combinations ("positive" comfort?).

Furthermore, studies are needed on whether thermally comfortable environments also are optimal for human performance, productivity, learning, and health. The influence on these factors of slight warm and cold discomfort also requires further investigation.

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THE USE OF MODELING HUMAN RESPONSES IN THE ANALYSIS OF THERMAL COMFORT OF INDOOR ENVIRONMENTS

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ABSTRACT

Modeling the thermoregulatory system is used in evaluating the threshold WBGT Values of OSHA Heat Stress Standards. It is shown that physiological reactions above or within the tolerance limits can be experienced during exposure to environments having the same threshold WBGT Values, particularly at heavy work loads. Also, the use of modeling human subjective reactions in planning energy conservation strategies in buildings is also discussed.

Key Words: OSHA Standards; WBGT; core temperature; modeling; thermal sensation; energy conservation

INTRODUCTION

OSHA Heat Stress Standards [1] were developed in an attempt to establish work conditions which would insure that workers' deep body temperature would not exceed 38°C (100.4°F). The 38°C limit was based on the recommendations of a panel of experts of the World Health Organization (WHO) [2]. The Standards consider the Wet Bulb Globe Temperature (WBGT) Index as the most suitable index to specify the work environment. In these Standards, threshold WBGT values, for three different work loads and two different air velocity ranges, were recommended. Also recommended were certain work practices, which emphasized the need for acclimating the workers, and adopting work-rest regimens to reduce peaks of physiological strain in order to improve recovery during rest periods. The WBGT Index was chosen to identify the environment because it is simple as far as measurements needed for its determination. It also consolidates into a single value the four environmental factors, namely, the dry bulb temperature T_{db}, the relative humidity RH or vapor pressure, the mean radiant temperature T_{mr}, and the air velocity V. For indoor environments with no solar load

$$WBGT = 0.7\ T_{nw} + 0.3\ T_g$$

where

T_{nw} = natural wet bulb temperature obtained with a wetted sensor exposed to the natural air movement

T_g = temperature at the center of a 6 inch (15cm) diameter hollow copper sphere, painted on the outside with a matte black finish (globe temperature)

One aspect which makes the WBGT Index attractive is the fact that the air velocity need not be measured, since its value is reflected in the measurement of the natural wet bulb temperature T_{nw}.

One of the deficiencies in the WBGT Index is the fact that the natural wet bulb temperature is not a thermodynamic property. As a result, different combinations of environmental parameters could have the same WBGT. Undoubtedly, when man is exposed to different combinations of environmental factors, having the same WBGT, he experiences different physiological reactions. Therefore, the experimental evaluation of all possible combinations of environmental parameters, having the same threshold WBGT values, recommended by OSHA Standards, is time consuming and expensive. In addition, nowhere in the Standards was the planning of the work-rest regimens specified. It is a fact also, that the durations of the work and rest periods depend on the work load, clothing, and the work environment. The first objective of the present paper is to show how modeling of the thermoregulatory system can be used in evaluating the validity of using the WBGT as a heat stress index, and in the planning of the work-rest regimen for any work load and environment.

During the past fifty years, extensive studies were conducted to determine man's physiological and subjective reactions when exposed to different combination of environmental parameters, clothing, and activity levels. Most of the efforts in this area were primarily experimental. One of the major contributions of such studies was the identification of generally acceptable thermal conditions for comfort for slightly active, healthy, normally clothed subjects when the air movement is less than 0.2 m/s (40 fpm). These studies were conducted without any regard to energy conservation. Because of the current drive towards energy conservation, new aspects of indoor thermal environments need to be explored. For example, one needs to consider the possible "trade-off" between clothing insulation value and the different environmental factors which can allow lowering the thermostatic setting in winter, and raising it during the summer. The experimental evaluation of all possible combinations of factors involved, and the identification of the optimum combination of these factors, which can result in energy conservation while providing a reasonable degree of comfort, is also time consuming and expensive. The alternative approach is the use of modeling of the human responses, to specific environments, to provide this needed information. This is the second objective of the present paper.

ASSESSMENT OF THE WBGT INDEX

Table 1 lists the recommended threshold WBGT values of OSHA Standards [1]. To assess the validity of the WBGT index by the use of modeling the thermoregulatory system, one needs to identify different combinations of environmental parameters having the same threshold WBGT values.

TABLE 1: RECOMMENDED THRESHOLD WBGT VALUES OF OSHA STANDARDS

Work Load	Threshold WBGT Values	
	Air Velocity < 300 fpm (1.5 m/s)	Air Velocity ≥ 300 fpm (1.5 m/s)
Light (200 kcal/hr or below)	86°F (30.0°C)	90°F (32.2°C)
Moderate (201 to 300 kcal/hr)	82°F (27.8°C)	87°F (30.6°C)
Heavy (above 300 kcal/hr)	79°F (26.1°C)	84°F (28.9°C)

Determination of the WBGT in Terms of the Environmental Factors

The instruments required for determining the WBGT Index, for an indoor environment, are the natural wet bulb and globe thermometers. If both thermometers are placed in an environment having certain T_{db}, T_{mr}, RH or vapor pressure, and V, and if both thermometers reach equilibrium with the environment, one can write two equations which govern the heat and mass transfer of both thermometers. The governing equations can then be solved using an iterative procedure to yield the natural wet bulb and globe temperatures T_{nw} and T_g, respectively, from which the corresponding WBGT can be calculated. Following this procedure, a summary of which is given in Appendix A, lines of constant threshold WBGT values, of Table 1, were generated and plotted on the psychrometric charts in Figs. (1), (2), and (3). In Fig. (1), the threshold values are plotted for the case $T_{db} = T_{mr}$ at two velocities. In Fig. (2), the threshold values are plotted for the case $T_{mr} = T_{db} + 30°F$ (16.6°C), also at two different velocities, while in Fig. (3) the WBGT lines were plotted for $T_{mr} = T_{db}$, and $T_{mr} = T_{db} + 30°F$ (16.6°C) at a velocity 400 fpm (2 m/s). Values of T_{mr} and V were arbitrarily selected. Different constant WBGT lines can result for different values of T_{mr} and V. The question arises at this point as to how would one react physiologically when exposed to all possible different combinations of environmental factors, having the same threshold WBGT values? It is quite obvious that the determination of these physiological reactions experimentally in a climatic chamber is a tremendous if not an impossible task. A more direct approach is through modeling of the thermoregulatory system.

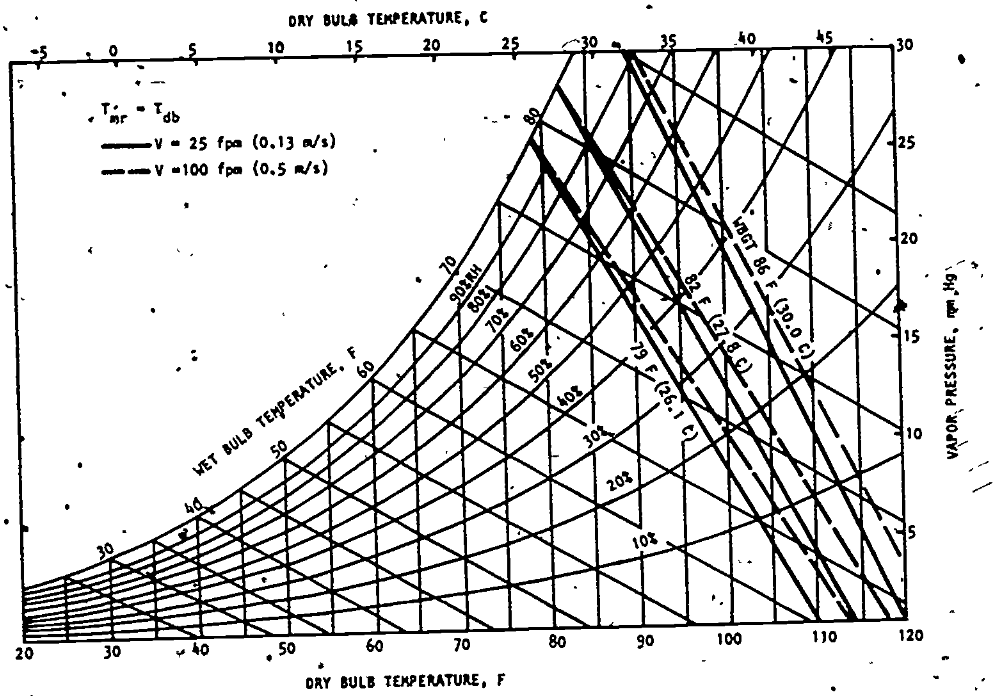

Fig. (1) Constant Threshold WBGT Lines of OSHA Standards

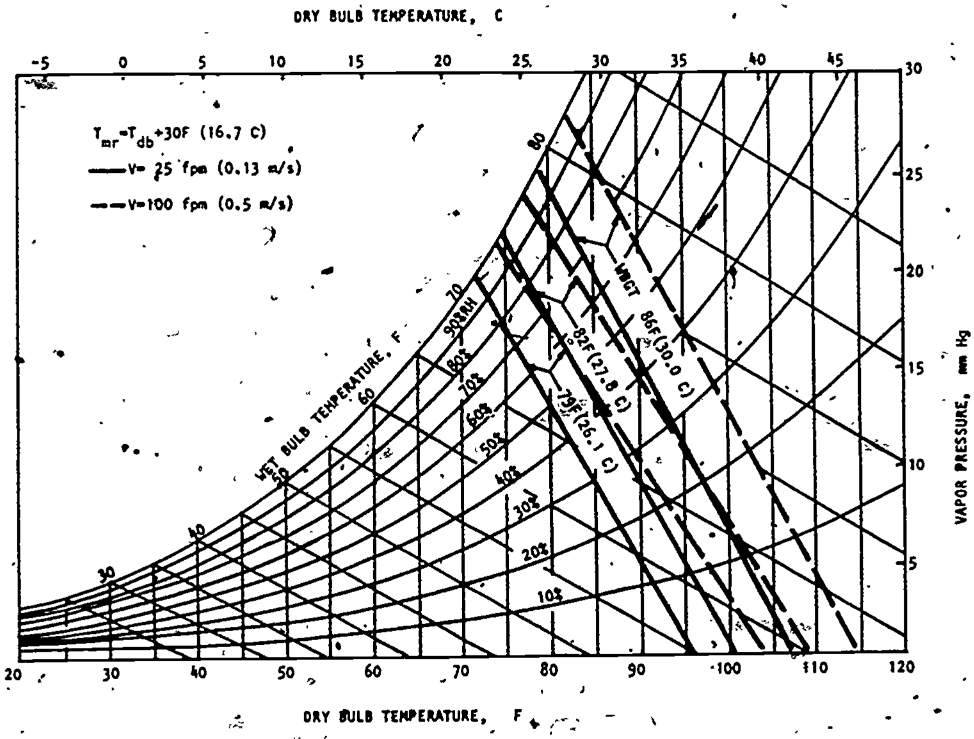

Fig. (2) Constant Threshold WBGT Lines of OSHA Standards

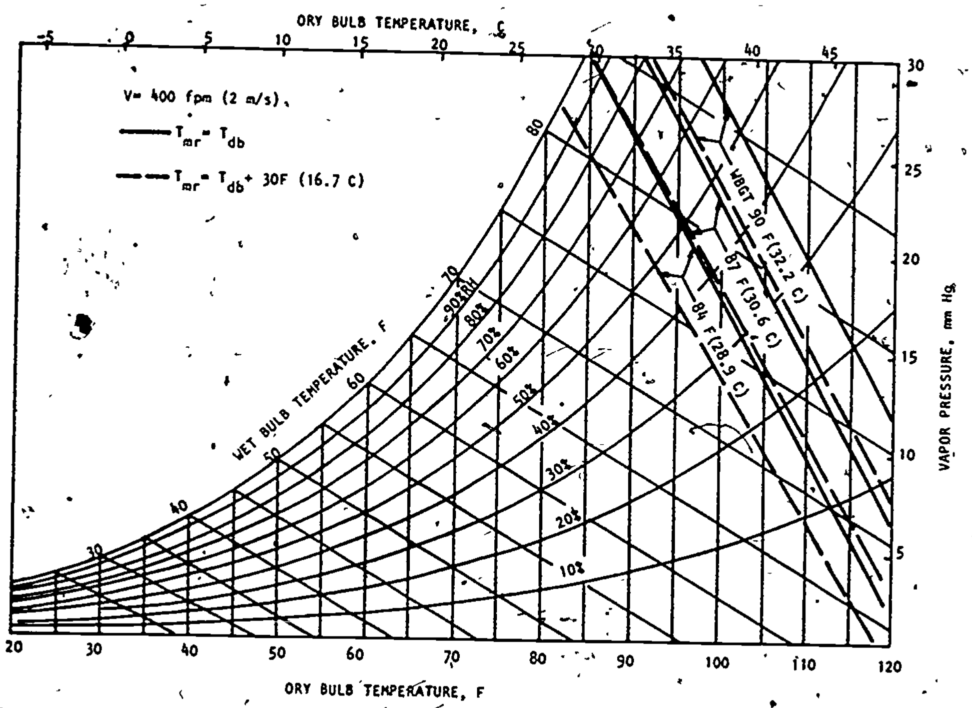

Fig. (3) Constant Threshold WBGT Lines of OSHA Standards

Modeling of the Thermoregulatory System

Interest has developed during the past fifteen years by engineers in applying the principles of control theory to the regulation of body temperature. As a result, several thermoregulatory models were developed [3,4,5,6,7,8,9]. In all these models, the human body is divided into a number of geometrical segments, and each segment into a number of layers or compartments. Passive state equations for thermal balance, due to blood flow between the various compartments, and energy exchange between the skin surface and the environment are developed on the basis of known thermal and circulatory characteristics of the human body. Control signals based on set-point temperatures in the skin, core, and muscle are introduced into the passive state equations to form a regulatory model for predicting changes in body temperature after exposure to any combination of environmental variables, clothing, and activity.

In 1971, Gagge et al. [5] developed a two-node thermoregulatory model. In the present paper, a modified form [10] of the two-node thermoregulatory model was adopted. A summary of the passive state equations and the control function of this model is given in Appendix B. A computer program was developed to integrate the passive state equations of the model. The input parameters to the program were the four environmental factors (T_{db}, T_{mr}, RH, and V), the clothing insulation value, and the metabolic heat production rate M which is a function of the work load. The output of the program gives the physiological reactions, namely, the core and skin temperatures, and the sweat rate or skin wettedness.

To assess the WBGT Index, different combinations of environmental factors having the same threshold WBGT values listed in Table 1 were selected, from Figs. (1), (2), and (3), together with their recommended work loads, and a clothing insulation value 0.60 clo. These were used as input parameters to the thermoregulatory model computer program to predict the physiological reactions after two hours exposure. The results are summarized in Tables 2, 3, and 4. The first column in each table lists the work load. The second column lists the recommended threshold WBGT Index corresponding to each load. The following three columns list the environmental parameters having the same WBGT at two different air velocities. The last three columns list the predicted physiological reactions. These are the core temperature T_{cr}, the mean skin temperature T_{sk}, and the skin wettedness WSW. Since the heat stress criteria of OSHA Standards were developed to insure that the workers' deep body temperature would not exceed 38°C (100.4°F), the emphasis in the discussion of the results in the tables will be on the core temperature results. Situations where such temperature reached or exceeded 38°C are identified by an asterisk (*) in the tables. In Table 2, at light work load,

TABLE 2: PHYSIOLOGICAL RESPONSES IN ENVIRONMENTS HAVING THE SAME THRESHOLD, WBGT VALUES WHEN $T_{mr} = T_{dp}$, I_{cl} = 0.60 clo, AFTER TWO HOURS OF EXPOSURE

OSHA STANDARDS		ENVIRONMENT					PHYSIOLOGICAL RESPONSES		
		T_{db}		RH	V		T_{cr}	T_{sk}	WSW**
Work Load	WBGT	°F	°C	%	fpm	m/s	°C	°C	
Light 150 kcal/hr (600 Btu/hr)	86°C (30.0°C)	87.8	31.0	90	25	0.13	37.3	35.1	1.00
		88.0	31.1	90	100	0.50	37.3	34.2	0.81
		96.6	35.9	50	25	0.13	37.3	35.1	0.79
		97.2	36.2	50	100	0.50	37.3	34.6	0.59
		107.0	41.7	20	25	0.13	37.3	35.5	0.65
		108.5	42.5	20	100	0.50	37.3	35.1	0.40
Moderate 250 kcal/hr (1000 Btu/hr)	82°F (27.8°C)	83.7	28.7	90	25	0.13	38.0*	36.1	1.00
		83.8	28.8	90	100	0.50	37.7	34.2	0.96
		92.0	33.3	50	25	0.13	37.7	35.3	1.00
		92.8	33.8	50	100	0.50	37.7	34.6	0.75
		101.8	38.8	20	25	0.13	37.7	35.3	0.87
		103.8	39.9	20	100	0.50	37.7	35.0	0.63
Heavy 350 kcal/hr (1400 Btu/hr)	79°F (26.1°C)	80.7	27.1	90	25	0.13	39.3*	36.9	1.00
		80.8	27.1	90	100	0.50	38.0*	35.0	1.00
		88.8	31.6	50	25	0.50	38.8*	36.4	1.00
		89.3	31.8	50	100	0.50	38.0*	34.8	0.89
		98.2	36.8	20	25	0.13	38.3*	35.6	1.00
		99.9	37.7	20	100	0.50	38.0*	35.1	0.76

* T_{cr} reached or exceeded 38°C, ** See Appendix B for its definition

T_{cr} reached 37.3°C (99.1°V) after two hours exposure in all environments. T_{sk} ranged between 34.2 and 35.5°C (93.6 and 95.9°F) while the skin wettedness WSW ranged between 0.49 and 1.0. The higher the skin wettedness the higher is the thermal discomfort, according to Gagge et al. [11]. At moderate work load, the 38°C (100.4°F) T_{cr} was reached in the environment with 90% RH and air velocity 25 fpm, while it reached 37.7°C (99.9°F) in the other environments. The skin temperature and wettedness were different for all environments. At heavy work load, when the air velocity was 0.5 m/s (100 fpm), the core temperature reached 38°C (100.4°F). At air velocity 0.13 m/s (25 fpm), the core temperature varied between 38.3 and 39.3°C (100.9 and 102.7°F). Also, the skin temperature and wettedness were different for different environments. Similar observations can be made on the results in Table 3, which were obtained for the case when $T_{mr} = T_{db}$ + 30°F (16.7°C). Table 4 gives the physiological reactions at an air velocity 400 fpm (2.0 m/s) when $T_{mr} = T_{db}$, and T_{dp} + 30°F (16.7°C). Although the observations made about the two previous tables could also be made about the results of this table, yet it is significant to point out that at similar work loads, particularly at the heavy work load, the final core temperatures, for all environments, were lower than their corresponding values at the lower velocities. This emphasizes the significance of air velocity in reducing the heat stress.

TABLE 3: PHYSIOLOGICAL RESPONSES IN ENVIRONMENTS HAVING THE SAME THRESHOLD WBGT VALUES, WHEN $T_{mr} = T_{dp} + 30°F$ (16.7°C), $I_{cl} = 0.60$ clo, AFTER TWO HOURS EXPOSURE

OSHA STANDARDS		ENVIRONMENT					PHYSIOLOGICAL RESPONSES		
Work Load	WBGT	T_{db} °F	T_{db} °C	RH %	V fpm	V m/s	T_{cr} °C	T_{sk} °C	WSW
Light 150 kcal/hr (600 Btu/hr)	86°F (30.0°C)	80.2	26.8	90	25	0.13	37.3	35.3	0.88
		83.1	28.4	90	100	0.50	37.3	34.9	0.68
		87.9	31.1	50	25	0.13	37.3	35.7	0.75
		91.6	33.1	50	100	0.50	37.3	35.3	0.57
		97.1	36.2	20	25	0.13	37.4	35.0	0.71
		102.3	39.1	20	100	0.50	37.3	35.8	0.53
Moderate 250 kcal/hr (1000 Btu/hr)	82°F (27.8°C)	76.1	24.5	90	25	0.13	38.0*	36.2	1.00
		79.0	26.1	90	100	0.50	37.5	35.5	0.76
		83.3	28.5	50	25	0.13	37.8	35.9	1.00
		87.0	30.6	50	100	0.50	37.5	35.6	0.68
		91.9	33.3	20	25	0.13	37.7	35.9	0.97
		97.0	36.1	20	100	0.50	37.6	35.8	0.64
Heavy 350 kcal/hr (1400 Btu/hr)	79°F (26.1°C)	73.0	22.8	90	25	0.13	39.2*	36.8	1.00
		77.9	25.5	90	100	0.50	38.1*	35.5	1.00
		80.0	26.7	50	25	0.13	38.8*	36.4	1.00
		83.7	28.7	50	100	0.50	38.0*	35.2	0.86
		87.7	30.9	20	25	0.13	38.5*	36.0	1.00
		93.0	33.9	20	100	0.50	38.0*	35.5	0.78

* T_{cr} reached or exceeded 38°C

At this point one can argue the accuracy of the thermoregulatory model in predicting the physiological reactions. Irrespective of the accuracy of the predictions, the fact that different combinations of environmental factors, having the same threshold WBGT values of OSHA Standards, can result in different physiological reactions, is still valid. These reactions could vary between tolerable and intolerable limits depending on the work load, the air velocity and its relative humidity as well as the mean radiant temperature. Such observations point clearly to a major deficiency in the WBGT if adopted as a heat stress index.

Gagge and Nishi [12] pointed out the fact that there is no single physical index of the thermal environment universally useful for judging both comfort and varying levels of heat strain. They also pointed out that the only true environmental index temperature is the one based on the heat balance equations between man and his thermal environment, and it is then limited to the specific activity concerned and to the specific heat and mass transfer coefficients in terms of clothing insulation and air movement of the test environment. Such observations of Gagge and Nishi [12] support the observation made by the present authors regarding the deficiency of the WBGT as a heat stress index. Since the OSHA Standards for work in hot environments were developed to establish work conditions which would insure workers' deep body temperature would not exceed 38°C (100.4°F), it is proposed here that safe hot work environments be identified by plotting, on a psychrometric chart, lines of constant 38°C (100.4°F) core temperature for different periods of exposure at specified work loads, air velocities, mean radiant temperatures, and clothing insulation values. This can be accomplished using modeling of the thermoregulatory system. For the purpose of illustration only, constant 38°C core temperature lines were generated for two work loads, namely, 1 and 3 mets (1 met = 58 W/m^2), at velocities 0.15 m/s (30 fpm) and 1 m/s (200 fpm) when $T_{mr} = T_{db}$, when dressed in a 0.6 clo uniform, and after one and two hours of exposure. The results are plotted in Fig. (4). These lines were generated using a modified form of the computer program of the two-node thermoregulatory model of the present paper. In Fig.

(4) the region above the constant core temperature line at a specified work load and exposure time identifies unsafe environments while the region below identifies safe environments. As one would expect, as the work load, and the exposure time increase, the safe region moves toward cooler environments.

TABLE 4: PHYSIOLOGICAL RESPONSES IN ENVIRONMENTS HAVING THE SAME THRESHOLD WBGT VALUES AT V = 400 fpm (2 m/s), and I_{cl} = 0.60 clo, AFTER TWO HOURS EXPOSURE

OSHA Standard		Environment			Physiological Responses		
		$T_{mr} = T_{db}$					
Work Load	WBGT	T_{db} °F	T_{db} °C	RH %	T_{cr} °C	T_{sk} °C	WSW
Light 150 kcal/hr (600 Btu/hr)	90°F (32.2°C)	91.9 101.7 115.0	33.3 38.7 46.1	90 50 20	37.3 37.3 37.3	34.6 35.0 35.6	0.88 0.55 0.46
Moderate 250 kcal/hr (1000 Btu/hr)	87°F (30.6°C	88.8 98.2 110.8	31.6 36.8 43.8	90 50 20	37.7 37.7 37.7	34.5 34.8 35.3	1.00 0.68 0.56
Heavy 350 kcal/hr (1400 Btu/hr)	84°F (38.9°C)	85.6 95.0 107.1	29.8 35.0 41.7	90 50 20	38.0* 38.0* 38.0*	34.7 34.9 35.3	1.00 0.77 0.65
		$T_{mr} = T_{dp}$ + 30°F (16.7°C)					
Slight 150 kcal/hr (600 Btu/hr)	90°F (32.2°C)	89.2 98.8 111.5	31.8 37.1 44.2	90 50 20	37.3 37.3 37.4	35.2 35.5 36.0	0.72 0.55 0.48
Moderate 250 kcal/hr (100 Btu/hr)	87°F (30.6°C)	86.2 95.4 107.4	30.1 35.2 41.9	90 50 20	37.7 37.7 37.7	35.0 35.3 35.7	0.88 0.67 0.58
Heavy 350 kcal/hr (1400 Btu/hr)	84°F (28.9°C)	83.2 92.1 103.4	28.4 33.4 39.7	90 50 20	38.0* 38.0* 38.0*	35.3 35.3 35.3	0.76 0.76 0.67

* T_{cr} reached or exceeded 38°C

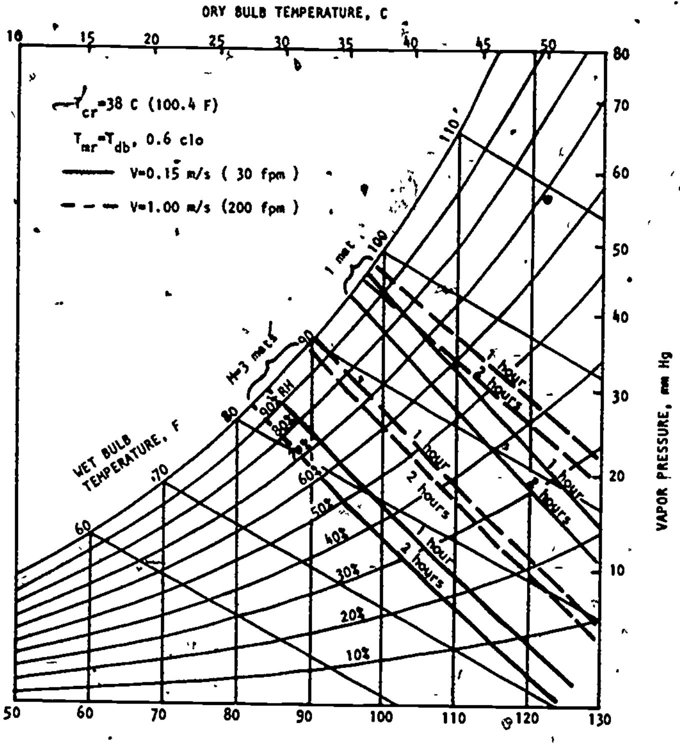

Fig. (4) Lines of Constant Core Temperature (38°C) at One and Three Mets, after One and Two House Exposure.

Planning of the Work-Rest Regimen

In OSHA Standards, in addition to the recommendation that during any two-hour period of the workday, workers are not to be exposed to hot environmental conditions and work-loads in excess of the levels shown in Table 1, certain work practices were recommended. One of these recommended practices specifies that work-rest regimens be established to reduce the peaks of physiological strain and improve recovery during the rest period. The duration of the work period in any extreme heat exposure is to be determined by experienced or professional judgment based on similar work under similar conditions. It is a fact that no work place or conditions are like another. It is also a fact that the durations of the work and rest periods depend on the work load, and the environment of the work and rest places. Establishing suitable work-rest schedules for every possible work situation in the laboratory is also impossible. A practical approach to planning the work-rest regimen is through the use of modeling of the thermoregulatory model. To illustrate such possible use, three work-rest schedules were developed in which the core temperature was not allowed to exceed 38°C when the worker works at a load 226 W/m^2 (heavy load) while dressed in a 0.6 clo uniform, in environments where the velocity is 25 fpm (0.13 m/s) and the WBGT value is equal to 79°F (26.1°C). The three environments having such WBGT were selected from Table 2 where $T_{mr} = T_{db}$. The rest environment was arbitrarily selected to be 75°F (23.9°C), 50% RH, and air velocity 25 fpm (0.13 m/s). The activity level during the rest period was sedentary (58 W/m^2). The work-rest schedules were developed through a computer program, which integrates the passive state equations of the two-node thermoregulatory model. The model predicts the changes in core temperature, as well as other physiological reactions, with time after exposure and work in the hot environment. The initial input parameters to the program were the environmental factors and the work load. The initial core and skin temperatures were arbitrarily selected 37°C (98.6°F) and 34°C (93.2°F) respectively. When the core temperature reached 38°C, the computer, through the program, was instructed to change the environmental factors and the work load to those of the rest period specified above. Figure 5 shows a plot of the core temperature variation with time during the work and rest periods. Arbitrarily, the rest period was terminated when the core temperature

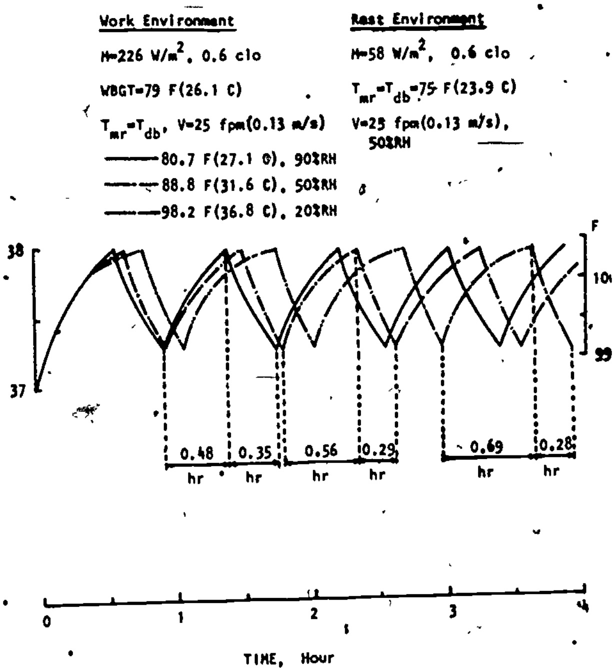

Fig. (5) Work-Rest Schedules for Three Different Environments at a Specified Work Load.

reached 37.3°C (99.1°F). Had the core temperature been allowed to return to the original value 37°C (98.6°F), the rest period would have lasted longer. If one disregards the first work-rest cycle, the results suggest that for the environment with 90% RH, the duration for the work and rest periods are 0.48 and 0.35 hours, respectively, compared to 0.56 and 0.29 hours at the 50% RH environment, and 0.69 and 0.28 hours at the 20% RH environment.

On the basis of the previous discussions, the point was made about the inadequacy of the WBGT Index. An alternative approach in developing a heat stress standard was suggested. It was based on using the modeling of the thermoregulatory system in identifying on a psychrometric chart lines of constant 38°C core temperature for different environmental parameters, work loads, and durations of exposure, and in planning the work-rest schedule. A two-node thermoregulatory model developed by the authors [10] was used for this purpose. The predictions of the model were checked against limited experimental data and the correlations can be ranked between good and fair [10]. This statement is also true for other existing models. Therefore, there appears to be a need for identifying the most reliable thermoregulatory model, among the existing ones, to be used in developing heat stress standards.

MODELING HUMAN SUBJECTIVE REACTIONS TO INDOOR ENVIRONMENTS

To determine the range of thermal conditions at which men and women report feeling comfortable when dressed in 0.60 clo uniforms, at a sedentary level of activity, at air movements less than 40 fpm (0.2 m/s), when $T_{mr} = T_{db}$, Rohles and Nevins [13] conducted a series of tests at 20 dry bulb temperatures ranging from 60°F to 98°F (15.6 to 36.7°C) at 2°F (1.1°C) increments, and at 8 relative humidity levels ranging from 15 to 85% in 10% increments. From these data, regression equations were developed for predicting thermal sensations for men, women, and combined sexes after 1.0, 1.5, 2.0, 2.5, and 3.0 hours of exposure. These data also constituted the basis of the Comfort Envelope of the ASHRAE Comfort Chart. Because of the current drive towards energy conservation, new aspects of indoor environments need to be explored. For example, one needs to refocus attention on the area of comfort/environmental factors/activity/clothing interactions by generating data similar to those of Rohles and Nevins [13], when subjects are dressed in uniforms having clo values different from 0.60 (lower than 0.60 for summer and higher than 0.60 for winter) at activity levels different from sedentary, at air velocities higher than 40 fpm (0.2 m/s), when $T_{mr} \neq T_{dp}$. Undoubtedly, this is a time-consuming proposition. For example, to test human reactions at the 160 combinations of Tdb and RH of Rohles and Nevins [13], at 3 levels of activities, 3 velocities, and 3 clothing insulation values, while still maintaining $T_{mr} = T_{dp}$, requires performing 4320 experiments. This is on the basis that both sexes will be tested simultaneously. If five experiments were to be conducted each week all year around, barring any delays due to breakdown of equipment, etc., approximately 17 years will be required to complete the testing, and even then not all possible combinations of parameters would be covered. A practical approach to this problem is through modeling the human subjective reactions.

Recently, a model [14] was developed by the authors to predict thermal sensation on a nine point scale in which zero represents thermal neutrality, and numerically positive and negative values represent warm and cold sensations, respectively. Warm thermal sensation was correlated with a new factor identified as wettedness factor. Cold thermal sensation was correlated with a new factor identified as vasoconstriction factor. For a given combination of environmental parameters, clothing, and activity, both factors could be determined by the two-node thermoregulatory model of Appendix B. Predicted thermal sensations of the model were compared with steady state and transient experimental thermal sensation data over a wide range of environmental conditions (cold, hot-dry, and hot-humid), clothing insulation (0.05 to 0.7 clo), and activity levels (1 to 6 mets). The accuracy of the predictions was comparable to the uncertainties in experimental measurements and the individual differences among subjects. A summary of the model is included in Appendix C. The objective now is to show the capability of this model in supplying some of the information referred to earlier.

A computer program was developed for the thermal sensation model to predict the thermal sensation for any combination of environmental factors, clothing, and activity. Through a search technique the program is also capable of identifying the proper combination of factors which can result in a specific thermal sensation. For illustration purposes, a few of the model predictions are shown in Figs. (6) through (9). Figure (6) shows a comparison between the thermal sensation predictions of the model and the experimental data of Rohles and Nevins [13] plotted on the psychrometric chart. The agreement is good over the entire range of the dry bulb temperature and relative humidity. Figures (7) and (8) show the constant thermal sensation lines predicted by the model at activity levels 2 and 3 mets, respectively, for air movement 0.15 m/s (30 fpm), 0.6 clo, and $T_{mr} = T_{dp}$ respectively. On the hot side, thermal sensation lines were terminated when the skin wettedness WSW reached unity. At this point, it is assumed that the tolerance limit has been reached. Figure (9) was reproduced from the previous 3 figures and it shows the lines of thermal neutrality at activity levels 1, 2, and 3 mets. All other factors being the same, the lines of thermal neutrality move to cooler zones with the increase of the metabolic rate. Similar charts can be generated for other air velocities, clothing insulation values, and mean radiant temperatures. Although no experimental data are available at the present time to check the predictions in Figs. (7) and (8), yet because of the fact that the predictions of the model were tested for a wide range of environmental factors, activity levels and clothing [14], it is safe to say that the model is reliable in its predictions. However, if experimental verification of the predictions in the above figures is needed, one needs to be mainly concerned with lines of thermal neutrality. In such a case, a limited number of experiments will be needed. This is one of the principal advantages of modeling the human subjective reactions.

One of the recommended measures to conserve energy in existing buildings is raising the thermostatic setting in the summer, and lowering it during the winter, without any consideration to the effect on the thermal comfort of people occupying these buildings. It is also conceivable that these new thermostatic settings might become the basis for designing cooling and heating systems in new buildings. Other measures need to be considered besides changing the thermostatic setting. For example, raising the setting during the summer can be compensated for by increasing the air movement, and changing the clothing habits. Therefore, what is needed most at the present time is the identification of those combinations of environmental factors (T_{db}, T_{mr}, RH and V), and clothing insulation values which can provide a reasonable degree of thermal comfort for a given level of work. The identification of these combinations can be achieved by the thermal sensation model discussed in the previous section. A few of these combinations were identified in Fig. (9). These lines were for air velocity 0.15 m/s (30 fpm). The determining factors in selecting any combination would be its energy demand, and the acceptability of certain factors such as the air velocity, and relative humidity of the environment.

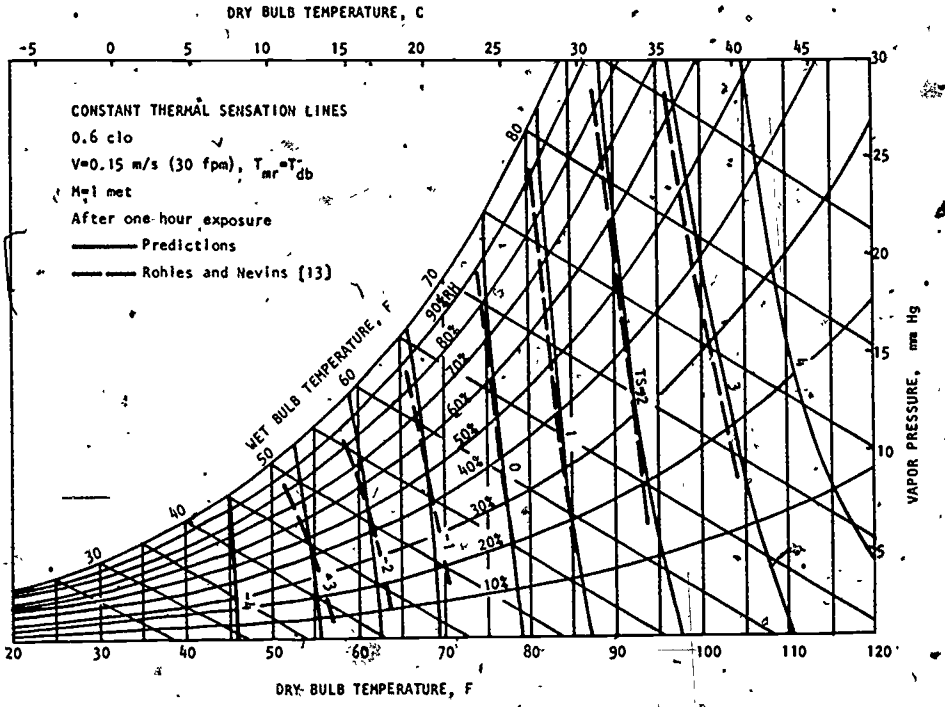

Fig. (6) Lines of Constant Thermal Sensation at one Met.

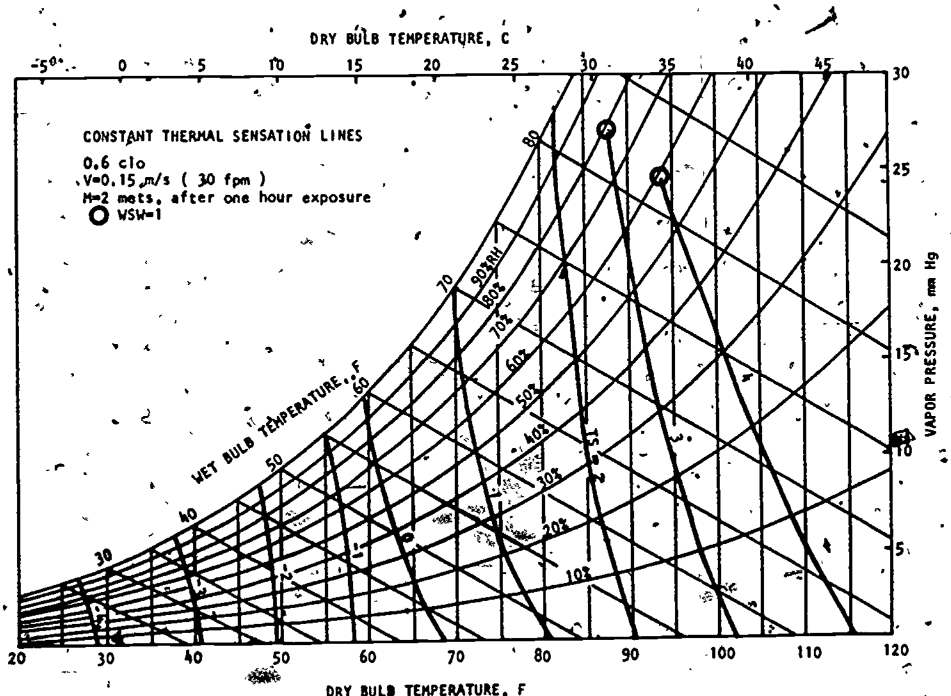

Fig. (7) Lines of Constant Thermal Sensation at Two Mets.

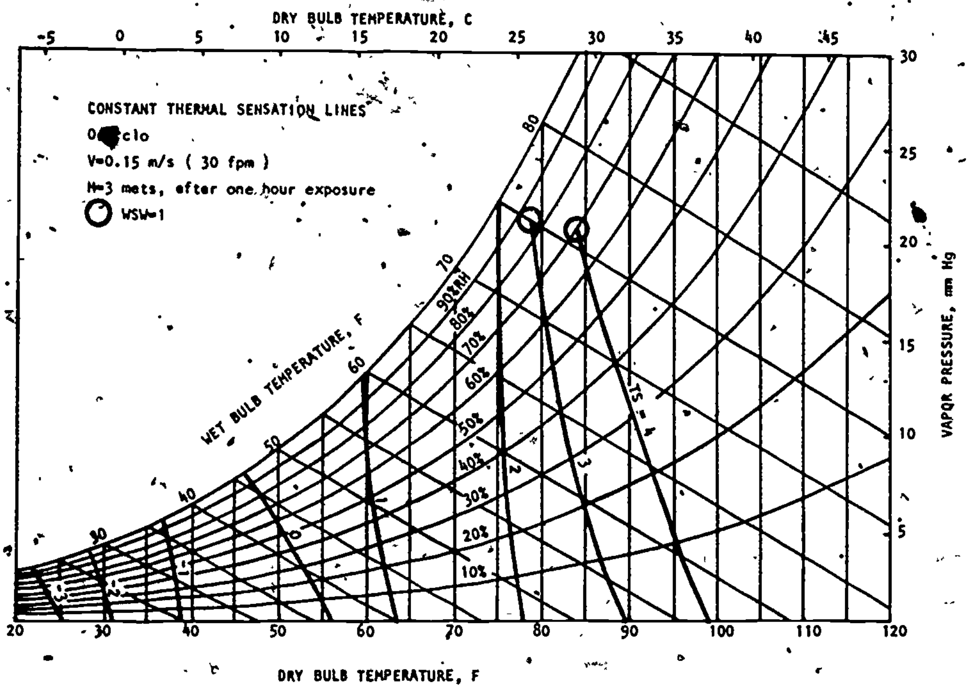

Fig. (8) Lines of Constant Thermal Sensation at Three Mets.

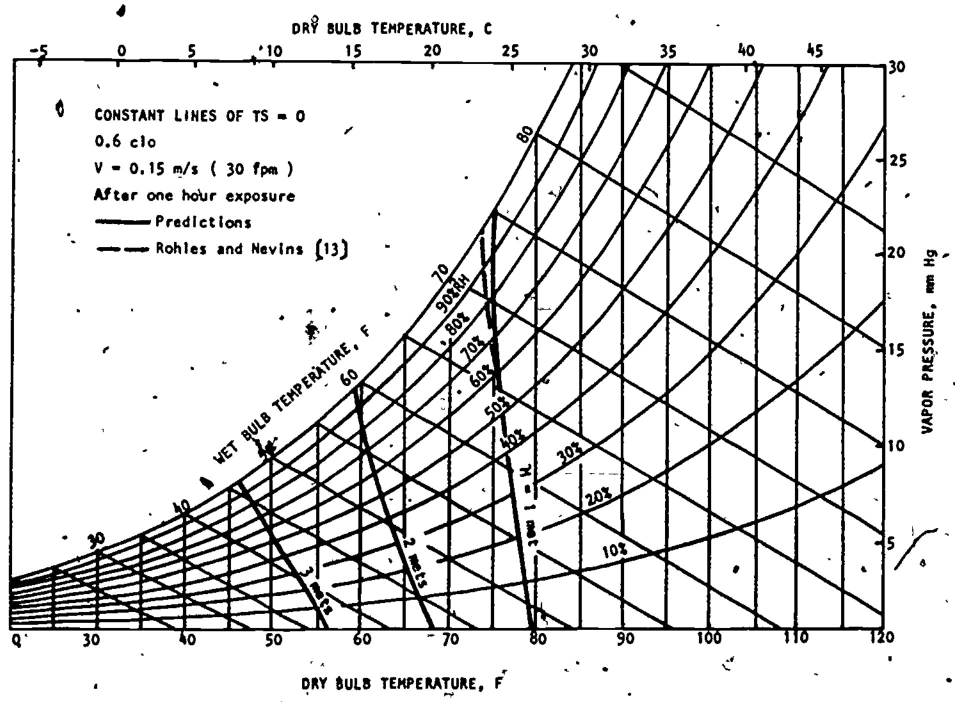

Fig. (9) Lines of Thermally Neutral Thermal Sensation at Different Metabolic Rates.

Modeling the human subjective reactions can also play a significant part in making decisions regarding energy use and conservation in building design. Hill, Kusuda, Liu and Powell [15] made a feasibility study in which combinations of selected weather data for a selected locale and selected building data were combined in a computerized thermal simulation program called National Bureau of Standards Load Determination (NBSLD), the output of which was a daily profile of indoor conditions of the building over an extended period of time. The frequency and duration of the various indoor parameters were then evaluated in terms of an index which was called the Predicted Indoor Habitability Index (PIHI). The object of the index was to determine whether the space should be air-conditioned or not. Conceptually, the PIHI was described as a numerical index covering a range of values that is consistent with human comfort under the environmental conditions that are likely to be produced indoors as a result of diurnal weather cycles outdoors, typical living functions, and a range of building parameters. Several subjective and physiological indices were considered for determining the extent of indoor thermal comfort for inclusion as part of the PIHI Index. Some of these indices were: old ET [16], Rohles and Nevins [13], PVM of Fanger [17], new ET* [5], HSI [18], and P4SR [19]. Each of these indices has its limits of applicability in terms of metabolic production (mostly sedentary), clothing, dry bulb and wet bulb temperatures, and air velocity. Figure (10) depicts how the feasibility study was carried out. It is proposed here that the thermal sensation model, discussed earlier, be used as the PIHI Index. On this basis, Fig. (10) can be modified to Fig. (11). By integrating the weather data, building data, and the thermal sensation prediction model into a computer program, one can predict the profile of indoor thermal comfort on a daily, weekly, or monthly basis during the heating or cooling seasons and then decide what actions regarding controlling the environment within the building need to be taken to insure the comfort of its occupants. Such integrated programs can also be used during the design stage of a building to select the best combination of building parameters (insulation materials, ratio of class to wall areas, etc.) as well as environmental parameters within the building which can result in the best energy usage.

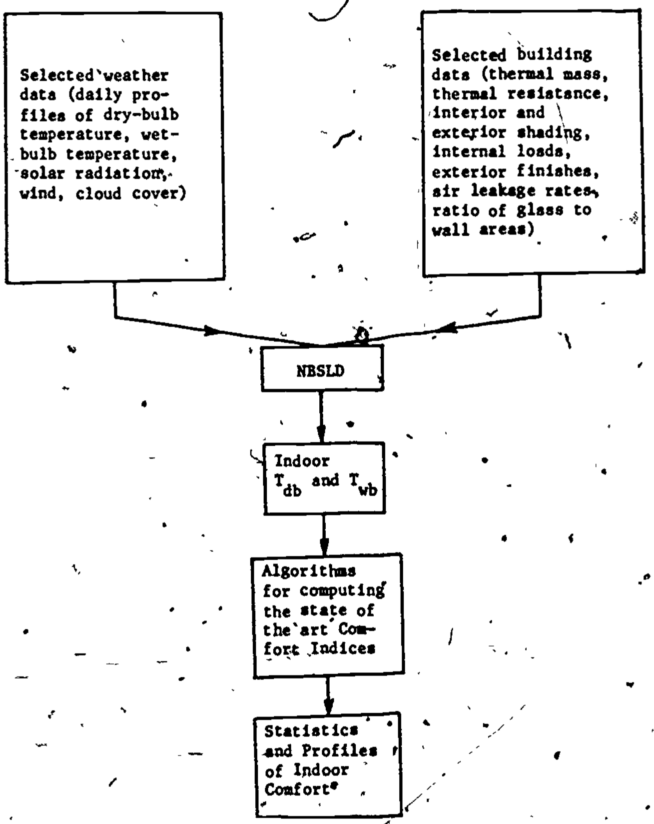

Fig. (10) Approach of the Feasibility Study, Ref. [15].

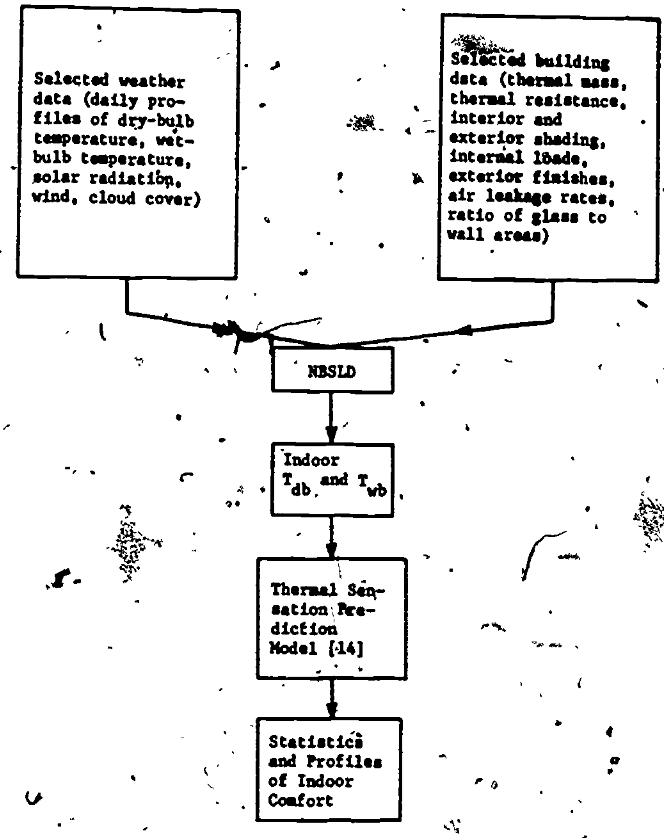

Fig. (11) Proposed Modification of the Feasibility Study of Ref. [15].

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APPENDIX A
DETERMINATION OF THE WBGT IN TERMS OF THE ENVIRONMENTAL FACTORS

Figure (A-1) shows a schematic view of the wetted wick of the natural wet bulb thermometer. At equilibrium, the energy exchange by convection and radiation with the surrounding environment is dissipated by evaporation. Therefore,

$$h_c\,(T_{db} - T_{nw}) + \varepsilon_{nw}\,\sigma\,(T_{mr}^4 - T_{nw}^4) = h_e\,(P_{snw} - RH \cdot P_{sa}) \qquad \text{(A-1)}$$

where

T_{db} = dry bulb temperature of the environment, °K

T_{nw} = natural wet bulb temperature, °K

T_{mr} = mean radiant temperature, °K

ε_{nw} = emissivity of the surface of the wetted wick

P_{snw} = saturated water vapor pressure at T_{nw}, mm Hg

h_c = convective heat transfer coefficient, $W/m^2 \cdot °C$

h_e = evaporative heat transfer coefficient, $W/m^2 \cdot$ mm Hg

RH = relative humidity ratio

σ = Stefan-Boltzman constant, 5.6696×10^{-8} $W/m^2 \cdot °K^4$

The convective heat transfer coefficient can be calculated by

$$h_c = 42.024\ V^{0.466} \quad W/m^2 \cdot °C \qquad \text{(A-2)}$$

where V is the air velocity in m/s. The evaporative heat transfer coefficient is related to the convective heat transfer coefficient by

$$h_e = 2.2\ h_c \qquad \text{(A-3)}$$

where 2.2 is the modified Lewis relation in °C/mm Hg

Figure (A-2) shows a schematic view of the globe thermometer. At equilibrium, with the surrounding environment the energy received by radiation is dissipated by convection. Therefore,

$$h_c\,(T_g - T_{db}) = \varepsilon_g\,\sigma\,(T_{mr}^4 - T_g^4) \qquad \text{(A-4)}$$

where

T_g = globe temperature, °K

ε_g = globe surface emissivity

The convective heat transfer coefficient from the surface of the globe can be calculated by

$$h_c = 15.889\ V^{0.6} \quad W/m^2 \cdot °C \qquad \text{(A-5)}$$

where V is in m/s.

The emissivities of ε_{nw} and ε_g are assumed equal to unity. To determine the saturation vapor pressure P_{snw} and P_{sa} at T_{nw} and T_{dp} respectively, the following equation, relating the saturation pressure of water vapor P_s (mm Hg) to the saturation temperature t_s (°C) can be used

$$P_s = 6.168 + 0.0358\ t_s^2 - 0.55 \times 10^{-3}\ t_s^3 + 0.105 \times 10^{-4}\ t_s^4 \qquad \text{(A-6)}$$

If the four environmental factors, namely, T_{db}, T_{mr}, RH, and V are specified, Eqs. (A-1) and (A-4) can be solved, by iteration, for T_{nw} and T_g from which the WBGT can be calculated. A computer program was written and is available for the solution of the governing equations.

In the program, the mean radiant temperature T_{mr} was set $T_{mr} = T_{dp} \pm C$, where C is a constant which can be arbitrarily specified. Specifying T_{mr} in this manner permits solving Eqs. (A-1) and (A-4) separately by iteration for T_{nw} and T_g respectively.

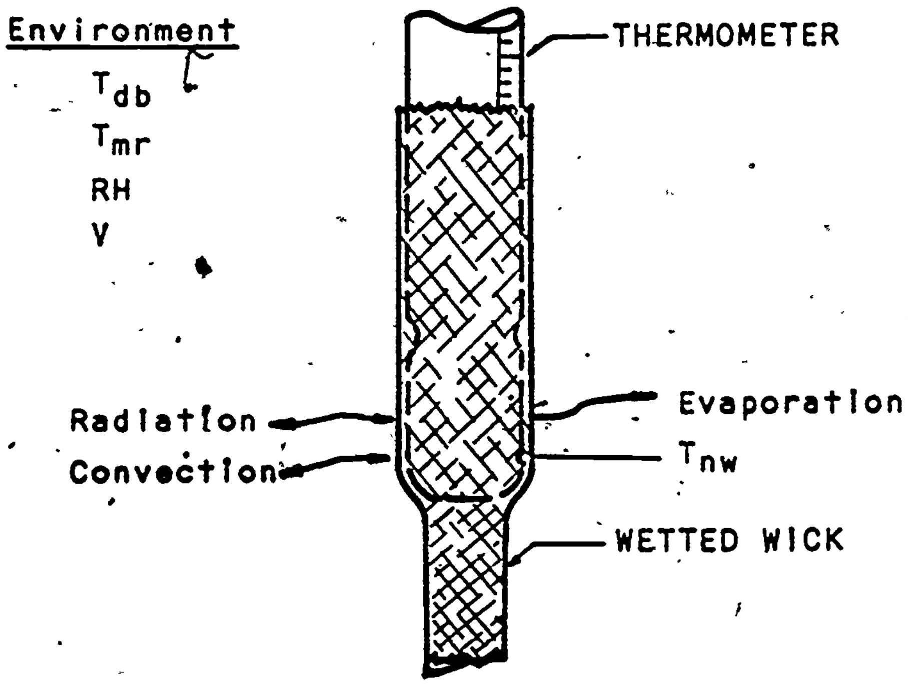

Fig. (A-1) A Naturally Convected Wet Bulb Thermometer

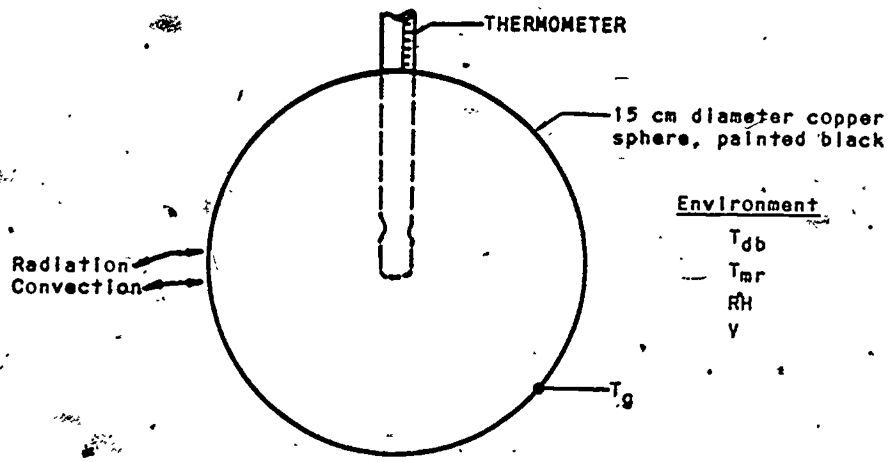

Fig. (A-2) The Globe Thermometer.

APPENDIX B

A SUMMARY OF THE TWO-NODE THERMOREGULATORY MODEL

In this model, the human body may be represented by two concentric cylinders as shown in Fig. (B-1). The inner cylinder represents the body core, which includes the skeleton, muscle, and all internal organs and has a uniform temperature. The outer layer represents the skin. A third layer may be added to represent the clothing. Energy is exchanged between the core and the skin through direct contact and peripheral blood flow. This is expressed in terms of conductance KS. Metabolic heat production M is generated in the core and it depends on the activity level. The core also exchanges energy E_{res} with the environment through respiration. The outer layer, the skin for nude and the clothing for clothed body, exchanges energy with the environment by convection and radiation. In addition, body heat is dissipated through evaporation of sweat and/or water vapor diffusion through the skin. These principles are used to write the following passive system equations.

$$M_{cr}\, C_{cr} \frac{d\,T_{cr}}{d\,t} = M \mp W - E_{res} - KS\,(T_{cr} - T_{sk}) \tag{B-1}$$

$$M_{sk}\, C_{sk} \frac{d\,T_{sk}}{d\,t} = KS\,(T_{cr} - T_{sk}) \mp (R + C) - E_{sk} \tag{B-2}$$

where

M_{cr} = core mass per unit body surface area
= 90% of the body mass per unit body surface area, kg/m^2

M_{sk} = skin mass per unit body surface area
= 10% of the body mass per unit body surface area, kg/m^2

C_{cr} = average specific heat of body core = 0.97 W.hr/kg.°C

C_{sk} = specific heat of skin = 0.97 W.hr/kg.°C

T_{cr} = core temperature, °C

T_{sk} = mean skin temperature, °C

t = time, hr

M = total metabolic heat production rate per unit body surface area
= sum of basal metabolic rate (M_b), activity (M_{act}), and shivering (M_{sh}) if any, W/m^2

W = external mechanical work, W/m^2

E_{res} = sensible and latent respiratory energy exchange with the environment, W/m^2

KS = overall skin conductance, $W/m^2.°C$

E_{sk} = total evaporative energy loss from the skin by diffusion and regulatory sweating, W/m^2

R + C = dry energy exchange by radiation R, and convection C, W/m^2

The total heat exchange (latent + sensible) through the respiratory system E_{res} can be calculated by the expression suggested by Fanger [17].

$$E_{res} = 0.0023\, M\, [44 - (RH)\, P_{as}] + 0.0014\, M\, (34 - T_{db})$$

The first term on the right hand side represents the latent part, while the second term represents the sensible part.

The dry heat exchange by radiation R and convection C can be calculated as follows:

$$(R + C) = h\, f_{cl}\, F_{cl}\, (T_{sk} - T_o)$$

where

h = the combined convective and linear radiative heat exchange coefficients, $W/m^2 \cdot °C$

f_{cl} = the ratio of the surface area of the clothed body to that of the nude body

F_{cl} = thermal efficiency factor of the clothing

$$= \frac{1}{1 + 0.155\, h\, I_{cl}}, \; h \text{ in } W/m^2 \cdot °C, \; I_{cl} \text{ in clo units}$$

T_o = operative temperature of the ambient, °C

$$= \frac{h_c T_{db} + h_r T_{mr}}{h_c + h_r}$$

h_c, h_r = convective and linear radiative heat exchange coefficients, respectively, $W/m^2 \cdot °C$

T_{mr} is the mean radiant temperature, and T_{db} is the ambient temperature in degrees Centigrade. The convective heat transfer coefficient can either be estimated from the values suggested by Nishi and Gagge [20] for certain laboratory exercises or calculated from the formula suggested by Kerslake [21]:

$$h_c = 8.3 \sqrt{V}, \; W/m^2 \cdot °C, \; V < 5 \text{ m/s}$$

where V is the air velocity in m/s. The linear radiative heat transfer coefficient can be estimated from the relationship suggested by Iberall et al. [22]:

$$h_r = 3.87 + 0.031\, T_{mr}, \quad W/m^2 \cdot °C$$

$$5°C \le T_{mr} \le 50°C$$

The total evaporative heat loss from the skin E_{sk}, in W/m^2, takes place by diffusion of water vapor through the unwetted area and by the evaporation of sweat:

$$E_{sk} = SW + (1 - WSW)\, E_{diff}, \text{ if } SW \le E_{max}$$

$$= E_{max}, \qquad \text{if } SW > E_{max}$$

where

$$WSW = \text{sweat wettedness} = SW/E_{max} \le 1$$

and SW is the equivalent evaporative heat loss of sweat, in W/m^2, and will be determined later. E_{diff} is the evaporative heat loss due to skin diffusion [17].

$$E_{diff} = 0.408\, [P_s - (RH)\, P_{as}], \; W/m^2$$

E_{max} is the maximum evaporative capacity from the skin surface to the ambient and is given by:

$$E_{max} = 2.2\, h_c\, F_{pcl}\, [P_s - (RH)\, P_{as}], \quad W/m^2$$

F_{pcl} = clothing moisture permeation efficiency factor [23]

$$= \frac{1}{1 + 0.143\, h_c\, I_{cl}}, \; h_c \text{ in } W/m^2 \cdot °C, \; I_{cl} \text{ in clo units}$$

P_{as} = saturated vapor pressure at T_{db}, mmHg

P_s = saturated vapor pressure at T_{sk}, mmHg

RH = relative humidity ratio

Three control signals, based on set-point temperatures in the skin and body core modulate the thermoregulatory mechanism. These are the skin conductance KS, thermoregulatory sweating SW, and the metabolic response by shivering M_{sh}. These are given by the following expressions.

$$KS = 5.3 + \frac{6.75 + 42.45\ (T_{cr} - 36.98) + 8.15\ (T_{cr} - 35.15)^{0.8}\ (T_{sk} - 33.8)}{1.0 + 0.4\ (32.1 - T_{sk})}, \quad W/m^2 \cdot °C \qquad (B-3)$$

and

$$SW = \Phi \frac{[260(T_{cr}-36.9) + 26(T_{sk}-33.8)]\ \exp\ [(T_{sk}-33.8)/8.5]}{1.0 + 0.05(33.37-T_{sk})^{2.4}}, \quad W/m^2 \qquad (B-4)$$

where

Φ = suppression factor due to skin wettedness [24]

= 1.0, when WET $\leq$ 0.4

= 0.5 + 0.5 exp [-5.6 (WET - 0.4)], when WET > 0.4 (B-5)

WET = skin wettedness = E_{sk}/E_{max}

and

$$M_{sh} = 20\ (36.9 - T_{cr})\ (32.5 - T_{sk}) + 5\ (32.5 - T_{sk}), W/m^2 \qquad (B-6)$$

When $T_{cr} \geq 37.1°C$, no shivering occurs irrespective of the skin temperature. Such a situation was identified as the central warm inhibition effect, according to Benzinger [25]. All bracketed terms in Eqs. (B-3), (B-4) and (B-6) must be positive. Negative values are assigned a zero value. After the control signals equations are introduced into the passive system equations, Eqs. (B-1) and (B-2), they can be integrated numerically for small time increments (Δt = 0.01 hr) or small increments in core and skin temperature (0.01°C) whichever is smaller, with certain initial values of T_{cr} and T_{sk}, for any combination of environmental parameters (T_{db}, T_{mr}, RH and V), clothing insulation I_{cl}, and metabolic heat production M. The integration results give the variations in T_{cr} and T_{sk}, with time and the associated values of WSW and KS.

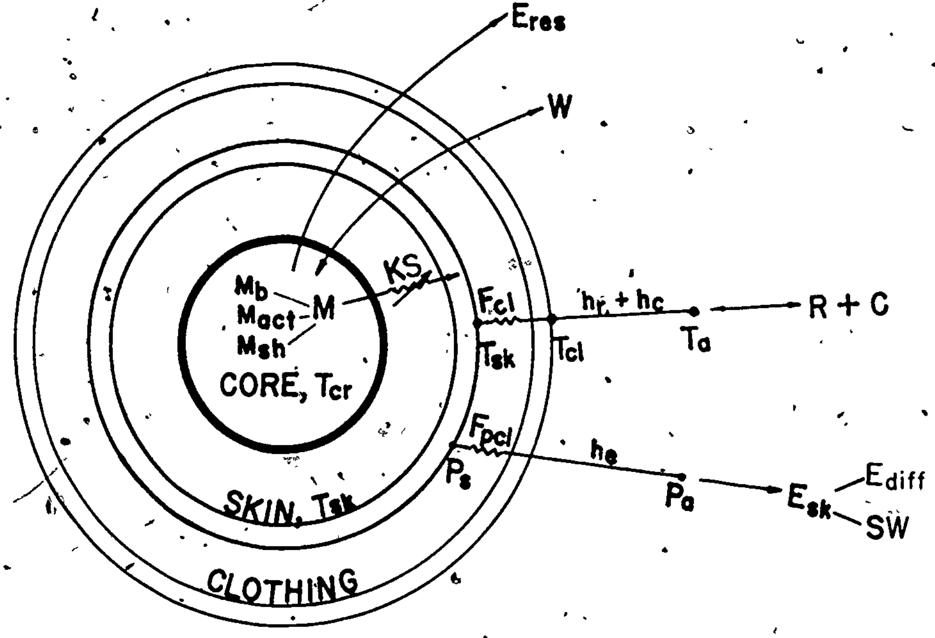

Fig. (B-1) Schematic Representation of the Two-Node Thermoregulatory Model.

APPENDIX C

A SUMMARY OF THE THERMAL SENSATION PREDICTION MODEL

In the model the following thermal sensation scale was adopted:

Thermal Sensation (TS^-)	-4	-3	-2	-1	0
Category	Very Cold	Cold	Cool	Slightly Cool	Neutral
Thermal Sensation (TS^+)	1	2	3	4	
Category	Slightly Warm	Warm	Hot	Very Hot	

Positive numerical values are for warm sensations, and negative values are for cold sensations. In the model, warm thermal sensations (TS^+) can be predicted by

$$TS^+ = [5.0 - 6.56\ (RH - 0.50)]\ E_{SWS} \qquad (C\text{-}1)$$

where RH is the relative humidity ratio, and E_{WSW} is a wettedness factor defined by

$$E_{WSW} = \frac{WSW - WSW_o}{1.0 - WSW_o} \qquad (C\text{-}2)$$

where

WSW = skin wettedness due to regulatory sweating

= SW/E_{max}, dimensionless

WSW_o = skin wettedness at thermal neutrality, dimensionless

WSW can be determined from the two-node thermoregulatory model discussed in Appendix B. WSW_o can be calculated by

$$WSW_o = 0.02 + 0.4\ \{1.0 - \exp\ [-0.6(NMET - 1.0)]\} \qquad (C\text{-}3)$$

where

$$NMET = \frac{M-W}{58} \qquad (C\text{-}4)$$

M = metabolic heat production, W/m^2

W = external body work, W/m^2

Cold thermal sensation (TS^-) can be predicted by

$$TS^- = 1.46\ E_{vc} + 3.75\ E_{vc}^2 - 6.19\ E_{vc}^3 \qquad (C\text{-}5)$$

where E_{vc} is a vasconstriction factor defined by

$$E_{vc} = \frac{KS_o - KS}{KS_o - KS_{(-4)}} \qquad (C\text{-}6)$$

KS is the overall skin conductance given by Eq. (B-3) of the two-node thermoregulatory model. KS_o is the overall skin conductance at thermal neutrality and is given by

$$KS_o = 12.05\ \exp\ [0.23\ (NMET - 1.0)],\ W/m^2 \cdot {}^\circ C \qquad (C\text{-}7)$$

where NMET is defined by Eq. (C-4). $KS_{(-4)}$ is the overall skin conductance at thermal sensation very cold (-4 on the thermal sensation scale). It can be calculated by

$$KS_{(-4)} = 5.3 + 0.261\ (KS_o - 5.3),\ W/m^2 \cdot {}^\circ C$$

At a given activity level and a set of environmental parameters, the overall skin conductance KS can be calculated from the two-node thermoregulatory model in Appendix B. If $KS \geq KS_o$, the thermal sensation will be on the warm side of the scale and can be determined by Eq. (C-1). If $KS < KS_o$, the thermal sensation will be on the cold side of the scale and can be determined by Eq. (C-5). Any detailed information about the development of this model can be found in reference [13].

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INDUSTRIAL HEAT STRESS MONITORING

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When assessing the heat load which is imposed on a worker by his job, the method of choice will depend on the purpose for which this information is needed. If the question is whether the heat load exceeds the threshold limit value (TLV) adopted by the American Conference of Governmental Industrial Hygienists (ACGIH) or whether the job is in compliance with the standards recommended by NIOSH or by the OSHA Standards Advisory Committee, the method to be used is the WBGT index. There are some important differences, however, between the monitoring requirements in the three documents which will be discussed in detail.

Since work metabolism is fairly constant for a given job, once it has been reliably established, no further monitoring is required. However, since environmental conditions of the job-site vary with changing outdoor temperatures, environmental monitoring has to be either continuous or at least measurements have to be repeated in certain intervals. To eliminate the need for either continuous or repetitive monitoring, NIOSH initiated studies for the development of mathematical models to predict job-site WBGT values from outdoor temperatures. Such a model is of particular value when jobs have to be rated according to the heat load they impose on the worker throughout a year. This information is necessary for studying the long range health effects of work in hot environments.

If the question is how to reduce the heat load most efficiently or if human responses to heat stress are analyzed, monitoring has to be performed by one of the physical heat stress indices. Several investigators recommended that industrial heat exposure limits shall also be expressed in terms of physical indices. However, this cannot be done until the permissible exposure limits expressed in units of these indices are validated for all combinations of environmental factors, clothing, metabolic rates and then displayed in a simple graph, such as the present TLV. The limits must also be validated to be safe for the worker population, as it was done with the WBGT index.

Key words: Industrial heat stress; heat stress monitoring; environmental monitoring; heat stress indices; metabolic heat load; heat stress control.

INTRODUCTION

Industrial heat stress is defined as the heat load which is imposed on the worker by hot climatic conditions of the work environment and by the metabolic heat generated inside the worker's body. The assessment of the magnitude of heat stress to which a worker is exposed on his job is a very difficult problem which is far from a satisfactory solution. The reason for this difficulty is that there are many factors which influence the heat exchange between man and his environment and these factors may vary a great deal with time and space as well as from one individual to the other. In order to make this point clearer, a short review is presented here of the problems which may arise when measuring the environmental and metabolic heat load.

Environmental Heat Load. There are four climatic factors contributing to heat stress: air temperature, humidity, wind speed and mean radiant temperature. A worker's exposure to these may change a great deal within a short period of time, particularly when the character of his task is such that he or she has to move frequently from one place to another or the climatic conditions of the job site change very rapidly. The instruments available for measuring the climatic factors, especially those for humidity and radiant heat, are not well suited to follow rapid changes. Furthermore, the readings of the instruments do not tell us directly the magnitude of the environmental heat load. They have to be inserted into mathematical equations in order to calculate the heat gain and/or loss by conduction, convection, radiation and evaporation. However, heat exchange between man and his environment depends greatly on skin temperature, surface area, wettedness, body position, speed of movement and clothing. All of these factors have a great intra- and inter-individual variability so that even if we could measure all of the climatic factors accurately, the calculated heat load would be valid only for the moment when the instruments were read, and for a single set of combinations of all the variables listed above.

Metabolic Heat Load. The amount of heat generated within the worker's body is the other component of heat stress, and it may vary greatly as the work rate changes; it also varies from one individual to the other even if performing the same job, depending on body weight, age, sex, physical fitness and skill. In addition, even the best methods for measuring work metabolism have an accuracy no better than ± 10% in skilled hands.

Heat Stress Indices. In an effort to simplify the assessment of the worker's heat load, several heat stress indices have been developed which combine either the four climatic factors or both the climatic and metabolic factors into a single number by using equations or nomograms. The authors of these heat stress indices claim that if a heat stress condition is characterized by a certain index value, no matter in what proportion the climatic or metabolic factors contribute to the condition, the resulting physiological strain will be identical. However, in a recent well-controlled experiment, Wenzel[1] could not confirm these claims for most of the heat stress indices, even while keeping wind speed constant and mean radiant temperature equal to air temperature. It is fair to assume that if wind speed and radiant heat would also be treated as variables, the claim for identical physiological strain for each combination of climatic factors would be even less tenable. Furthermore, the heat stress indices were derived from data obtained from experiments which did not reproduce the complex real life situation of an industrial workshop. First of all, the experimental subjects were highly trained young men whose physical fitness was above that of an average worker population of hot plants; they were dressed in gym shorts and shoes instead of work uniforms; the climatic conditions and work rate were kept constant, thus bypassing most of the problems encountered when measuring the climatic factors and work metabolism in the real life situation. As was pointed out by Belding,[2] all heat stress indices are poor predictors of physiological strain when used under conditions which differ substantially from those used in the experiments for developing the index. Gagge and Nishi[3] rated several empirical heat stress indices according to the accuracy by which they can predict heat discomfort and wettedness of skin in the average acclimatized individual, but this by itself is not the most important criterion for the applicability of an index for industrial heat stress monitoring. Other factors related to the worker's heat exposure in industry vary so rapidly and to such a great extent that even the most accurate prediction of heat strain will be valid only for a specific individual and for a short-lived situation. Simplicity of application is a much more important requirement in heat stress indices for industrial use.

Other investigators recommended assessing heat strain directly by measuring the workers' physiological responses characteristic of heat strain, such as heart rate, body temperature or sweat rate instead of monitoring the climatic factors and work metabolism. Whereas such measurements are indeed most helpful in preventing heat illnesses, they cannot be used in industry because the presently available methods for monitoring physiological responses are not acceptable for routine use on workers. Furthermore, physiological measurements per se will not tell us anything about the magnitude of different heat sources on the job site. Thus, they do not eliminate the need for the assessment of the climatic and metabolic factors for developing corrective procedures.

In spite of their shortcomings, certain heat stress indices can be applied for a number of practical and scientific purposes such as developing guidelines for industry to safeguard workers' health in hot jobs, for establishing workers' tolerance to different combinations of heat stress factors and for determining the most efficient ways of reducing heat stress in specific jobs. Each of these applications requires a different level of simplicity and accuracy, as well as different type of information. Let us now examine which of the available heat stress indices satisfy best the requirements of industrial heat stress monitoring.

HEAT STRESS MONITORING FOR PREVENTION OF HEAT ILLNESS

Environmental Heat Load. There are two different basic approaches possible for the prevention of heat illnesses among workers of hot industries: one is to prescribe limits for permissible heat exposure levels; the other is to specify certain preventive measures, i.e. work practices which have to be introduced in a workshop when the heat stress exceeds established levels. The first approach has been adopted by the American Conference of Governmental Industrial Hygienists (ACGIH) in their Threshold Limit Value (TLV) for heat stress.[4] The second has been followed in the recommended heat stress standards of NIOSH[5] as well as of the Standards Advisory Committee on Heat Stress (SACHS)[6] which was convened by the Occupational Safety and Health Administration (OSHA) in 1972. All the three above mentioned documents prescribe the use of the Wet Bulb Globe Temperature (WBGT) index[7] for the purpose of monitoring the environmental heat load. Other indices considered by the committees approving these documents were the Effective Temperature (ET),[8] the Heat Stress Index of Belding and Hatch (HSI),[9] and the Predicted 4 Hour Sweat Rate (P4SR).[10] They all agreed to select the WBGT index because of its simplicity of application. The equations for calculating the WBGT index are indeed very simple:

For indoor use: $$\text{WBGT} = 0.7\ \text{NWB} + 0.3\ \text{GT} \quad (1)$$

For out-of-doors use: $$\text{WBGT} = 0.7\ \text{NWB} + 0.2\ \text{GT} + 0.1\ \text{DB} \quad (2)$$

where NWB = Natural Wet Bulk Temperature

GT = Globe Temperature

DB = Dry Bulk Temperature

Another way by which the use of the WBGT index simplifies environmental heat stress monitoring is that it does not require the measurement of wind velocity. It has been assumed that since both the natural wet bulb thermometer and the globe thermometer are sensitive to air movement, the WBGT index includes the cooling effect of increased wind speed satisfactorily.[11] However, Romero's[12] experiments showed that the natural wet bulb thermometer loses its sensitivity to wind speed if that exceeds 250 fpm. Therefore the SACHS document stipulates that the threshold WBGT values (above which preventive work practices have to be introduced) shall be 4 to 5 °F higher if the air velocity exceeds 300 fpm as shown in Table 1.

TABLE 1 Threshold WBGT Values

Workload	Threshold WBGT Values Degrees Celsius and Fahrenheit: Low air velocity (Up to 300 fpm)		High air velocity (300 fpm or above)	
Light (Level 2) (200 kcal/Hr or below)	30	(86)	32	(90)
Moderate (Level 3) (201 to 300 kcal/hr	28	(82)	31	(87)
Heavy (Level 4) (Above 300 kcal/hr)	26	(79)	29	(84)

This provision of the SACHS makes industrial heat stress monitoring more complicated because it requires either wind speed measurement or at least some rough estimate of the air velocity at the job site. Interestingly, recent experiments performed at the Pennsylvania State University by Eliezer Kamon under NIOSH auspices, cast severe doubt on the need for correcting the threshold WBGT for the effect of air velocity. The results of these experiments indicate that there seems to be no benefit to the worker in terms of physiological responses if the air velocity is increased from 100 to 800 fpm in hot environments ranging from 27.2 °C (81.0 °F) to 34.4 °C (94 °F) WBGT, with no radiant heat sources present. One possible explanation of these results is that the subjects in these experiments wore regular work uniforms, the type of clothing worn by workers in hot jobs. Such clothing acts as a wind buffer and reduces the air velocity substantially by the time it reaches the subject's skin surface. Thus, it is entirely possible that even though the wind speed was increased up to 800 fpm in the test chamber, the air movement at the skin surface never exceeded 300 fpm. If these results are confirmed in further studies, it will not be necessary to use a correction for wind speed, and thus not have to estimate air velocity when applying the WBGT index for heat stress monitoring.

The use of the natural wet bulb thermometer and the globe thermometer is quite time consuming. Depending on the climatic conditions the equilibration time may be as long as 30 minutes. Olander[13] in Sweden recommends the use of an aspirated wet bulb thermometer instead of the natural wet bulb and an aluminum sphere or a balloon instead of the copper globe, thus reducing the time needed for a WBGT index assessment to 10 minutes. The only correction needed in calculating the WBGT index by use of aspirated wet bulb thermometer is that at air velocities below 100 fpm (0.5 m/sec) the WBGT index value has to be increased by 4 °F (2 °C). A lagtime of 10 minutes is still very long for measuring the climatic factors in a workshop where the level of heat stress may change substantially from one minute to the next. To overcome this problem, the SACHS document stipulates that in extremely high heat exposures the workers should be permitted to withdraw from the heat whenever they feel that they may become overheated. Furthermore, all three heat stress standards, (NIOSH, SACHS, and ACGIH TLV), express their limits in terms of time-weighted average WBGT index values. According to the NIOSH and SACHS standards, these time-weighted WBGT index values will determine whether or not preventive measures have to be introduced. According to the provisions of the ACGIH TLV, the time-weighted WBGT values can also serve for calculating how much time has to be spent in the cooler areas of the workshop so as not to exceed the TLV values for continuous work, as shown in Table 2.

TABLE 2

Permissible Heat Exposure Threshold Limit Values
Values are given in °C and in (°F) WBGT

Work — Rest Regimen	Work Load: Light	Moderate	Heavy
Continuous work	30.0 (86.0)	26.7 (80.1)	25.0 (77.0)

The NIOSH and ACGIH documents prescribe that in jobs with continuous heat exposure, the time-weighted average WBGT value has to be calculated hourly, whereas for jobs where heat exposure is intermittent this calculation has to be done for periods of 2 hours. This provision is based on the assumption that in continuous heat exposure, one hour may be long enough for a worker to develop a heat illness if the heat exposure is at a level which does not force the worker to move away from time to time to cooler areas but high enough to cause excessive heat accumulation in the body. In intermittent exposure, if heat accumulation does occur, it will be slower, thus it will be safe to do the averaging over a period of two hours. The SACHS version, however, eliminated the requirement for calculating hourly averages in continuous exposure and prescribes for all hot jobs, continuous and intermittent, that the averaging be performed for periods of 2 hours. The assumption here is that only in very rare instances would a 2-hour time-weighted average WBGT remain below the threshold values shown in Table 1 when the 1-hour average exceeds these same threshold values.

According to the SACHS document, heat stress monitoring is not mandatory as long as preventive measures are practiced. This policy is supported by the observation[14] that where workers are provided with adequate drinking water and supplementary salt, where they are given time to become acclimated before they are required to carry a full load of heat exposure, where they are given advice how to prevent heat illnesses and to take rest breaks whenever they start to feel overheated, where the management is thoughtful of reducing the workers' heat exposure by all possible means, including protective clothing and engineering control of climatic conditions, in hot industries like this the occurrence of heat illnesses will be extremely rare.

If heat stress monitoring is required only for the purpose of determining whether or not preventive measures are required, the main problem of heat stress monitoring in most hot plants will be not so much the accuracy of environmental measurements but the relationship between the climatic conditions out of doors and at the job site. According to the NIOSH heat stress standard, a WBGT profile has to be established for each work place by monitoring the climatic conditions of the jobs both during the winter and summer so as to determine during which part of the year preventive work practices are required. After this has been accomplished, heat stress monitoring is required only during the hottest months of each year, i.e. in July and August. According to the SACHS version, heat stress monitoring must be performed during the hottest two-hour period of the work shift, in order to determine whether or not preventive measures must be applied. However, as mentioned before, once preventive measures are observed, heat stress monitoring is not mandatory. The text of the ACGIH TLV does not address the question at all at what time of the day or of the year the environmental measurements shall be performed. Mutchler et al[15] under NIOSH contract developed a methodology for assessing the relationship between the climatic conditions out of doors and on-the-job site. This requires a minimum of 30 simultaneous assessments of the climatic factors out of doors and at the job site. In order to predict the climatic conditions at the job site at a given out-of-doors temperature, one of 7 equations have to be used, depending on the degree of difference between inside and outside ambient temperatures specific to that particular job. There are three regression constants in each equation which have to be calculated from the simultaneous measurement results by multiple regression analysis. Subsequently, from the U. S. Weather Bureau reports, a prediction can be made concerning the dates when the job site temperature may exceed the Threshold WBGT values, i.e. when preventive measures will have to be observed. Another important application of this method is in the area of assessing the long-term health effects of employment in hot jobs. In studies dealing with this problem, there is a need for estimating the workers' heat load retrospectively over a period of several years. This can be done by obtaining the U. S. Weather Bureau records and inserting the values in the appropriate equations selected in accordance with the difference between outdoor and job-site temperatures.

Last but not least, the prediction of heat load on the job site from the records of the U. S. Weather Bureau can be helpful in planning the energy needs for climate control in a particular industry as well as planning for the increased manpower need in view of the necessary rest allowances in hot plants. However, before this methodology can be recommended for general use, its accuracy has to be tested in further field studies. Several industries and investigators are already trying to use this approach, but the results have not yet been published.

An alternative approach for simplifying environmental measurements would be to develop a technique for personal heat stress monitoring. This would have the advantage that the instruments would be exposed to the same climatic conditions as the worker all the time. If fast responding sensors for measuring the climatic factors would be available, personal monitoring could give us a true picture of the workers heat exposure over the whole work shift. Studies for developing such a system have been carried on by Peters et al[16] under NIOSH contract. The approach they recommended was to develop miniaturized sensors for the different climatic factors to be attached to the workers and the readings should be either recorded on magnetic tape by a small recorder also carried by the worker or telemetered to a nearby receiver. They prepared a mock-up model showing the sensors attached to a safety helmet (Figure 1). Simultaneously, Gempel et al[17] experimented with Botsford's Wet Globe Thermometer[18] in rubber tire manufacturing plants. They also fastened this instrument on the workers' helmets and found the obtained readings are comparable with stationary WBGT measurements. However, in earlier studies at NIOSH, Sundin et al[19] found that the relationship between the Wet Globe Temperature (WGT) and WBGT is curvilinear with a correlation coefficient of 0.9755 (Figure 2). At different job sites where the WGT reading was 80 °F, the simultaneously observed WBGT values ranged from 80 to 94 °F WBGT. Compared to other single reading instruments described earlier in the literature, the Wet Globe Thermometer

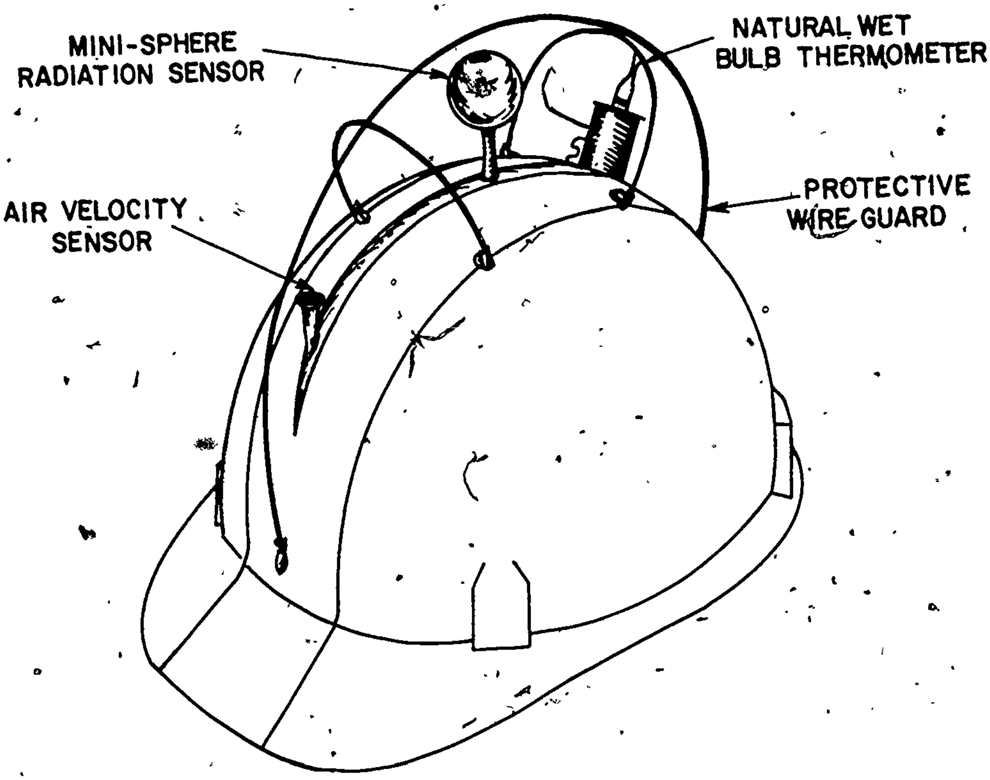

FIGURE 1: Mock-up model of miniaturized sensors for measuring the climatic factors of the work environment in hot jobs. The sensors are mounted on a safety helmet.

has the advantage of simplicity and is relatively inexpensive. Thus, it may be a useful tool for preliminary exploratory measurements in hot plants. The idea of developing such an instrument explored at NIOSH by Hughs[20] led to the conclusion that even if modern technology would permit the construction of such an instrument, it would be too complicated and expensive for routine use in industry. Similar experiments at the University of Pittsburgh performed by P. C. Magee (under NIOSH grant) utilized the ideas of T. Hatch[21] and resulted in some definite progress in making the instrument's heat exchange coefficients resembling that of man's; however, a number of problems still remained unresolved.

Metabolic Heat Load. The most accurate method for measuring the heat generated in the body during work and rest is indirect calorimetry, i.e. the assessment of oxygen consumption. This requires the measurement of expired air volume as well as its oxygen and carbon dioxide content. This method requires that the worker carry on his back an air-collecting bag or a gasometer connected through a flexible tube with the worker's mouth. A face mask or a mouth-piece with a nose clip has to be worn in order to assure an airtight connection. Wearing such equipment and breathing through the tube against the resistance of the system, is quiteburdensome and therefore cannot be tolerated for a long period of time. Furthermore, wearing the equipment in hot jobs interferes with heat loss from the body and with moving rapidly back and forth around furnaces and other extremely hot areas. Therefore, in order

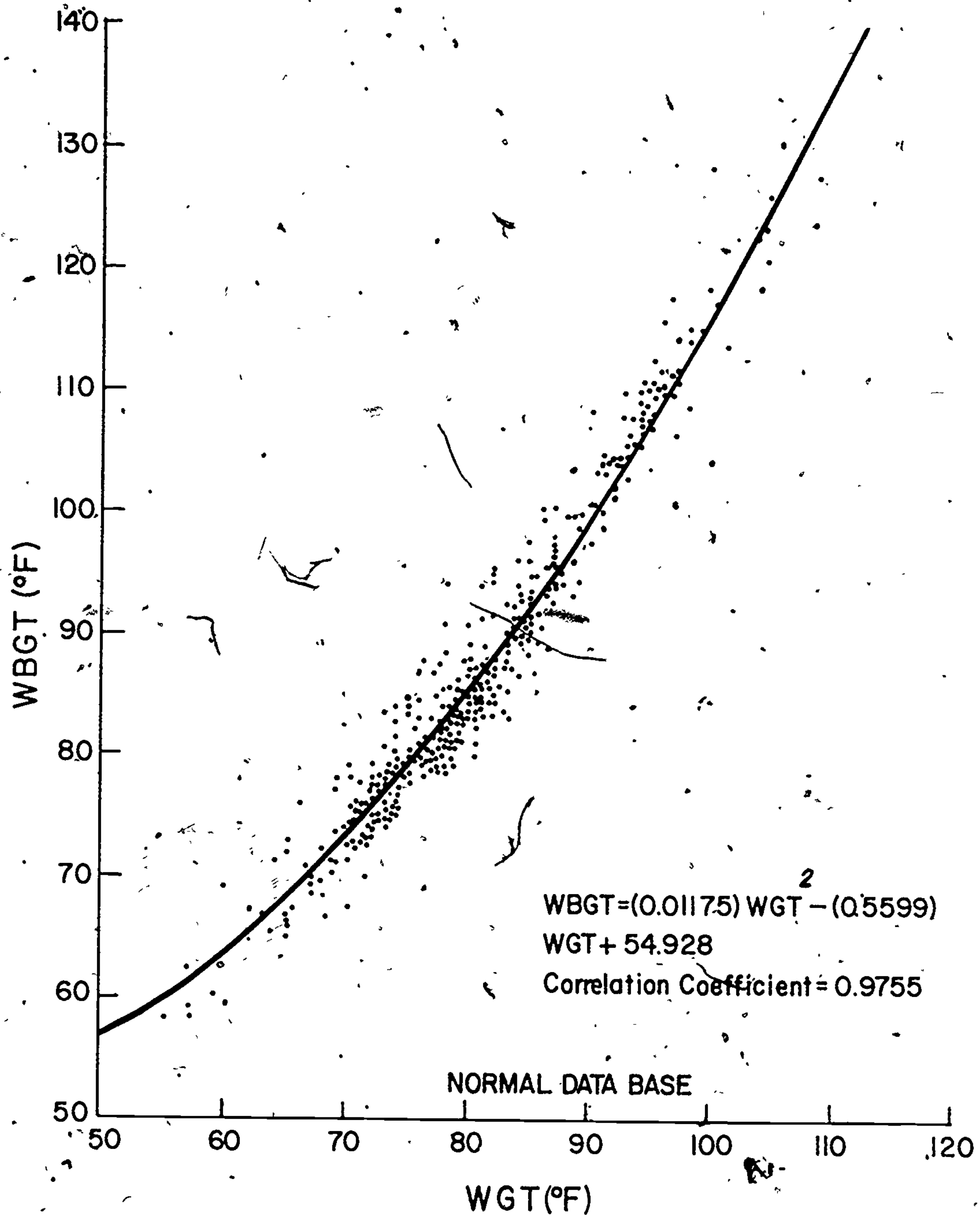

FIGURE 2: Relationship between WBGT and WGT. Each point represents one simultaneous pair of measurements in a hot industry or out of doors.

to determine the metabolic heat generated during a long period of time, the tasks performed have to be broken down into small components, such as standing, walking, lifting, carrying, machine operating, etc. and the metabolic cost of each component has to be assessed. Thereafter, a time study has to be performed to determine how much time is spent during the workday with each component activity so that the hourly or daily metabolic heat load can be estimated. This whole procedure is quite complicated, requires some expensive instruments and its accuracy is quite limited because of the variable intensity by which each task is carried out and the intra- and inter-individual variability of metabolic rate as mentioned above. Therefore, none of the three heat stress standards (NIOSH, SACHS, and ACGIH TLV) requires the application of indirect calorimetry. The SACHS version prescribes rough categorization of jobs into light, moderate, and heavy workload, as shown in Table 1. The ACGIH TLV mentions indirect calorimetry as one of several alternatives for measuring metabolic heat. The TLV lists several references to energy requirement tables published in the literature for estimating work metabolism. Such methods are much simpler but still require experience to achieve an acceptable level of accuracy (± 10%). In unskilled hands, the scattering of the estimates can be as high as ± 30 - 100%. A time study is required to calculate hourly time-weighted average metabolic rates for continuous heat exposures. For intermittent heat exposures, the averaging has to be done for periods of two hours, similarly as with the time-weighting of the WBGT values.

Realizing the cumbersomeness and limited accuracy of all the available methods for assessing metabolic heat, the NIOSH heat stress standard refrained from prescribing such measurements. Instead, it establishes fairly low limits: 79 °F WBGT for men and 76 °F WBGT for women to be estimated in terms of one or two hour time-weighted averages for continuous or intermittent work, respectively. This limit applies only to deciding whether or not preventive measures should be introduced for a job. According to the ACGIH TLV, 79 °F is the permissible heat exposure TLV for continuous work between heavy and moderate levels, as shown in Table 2. Since most of the hot jobs are in the moderate or light work category, the 79 °F WBGT seems to be too restrictive. However, it was the concensus of the review committee that the restrictiveness of this provision is well compensated by the fact that metabolic measurements are not required.

The recommended lower limit for women was based on data in the literature[22,23] showing that women have a higher heart rate and body temperature than men when exposed to identical levels of heat stress. However, recent studies performed by Kuhlmeier[24] under NIOSH auspices showed that the upper limit of the prescriptive zone (ULPZ) of heat acclimatized women, working in hot jobs, is not significantly different from the ULPZ of men. In view of these results, it may not be necessary to prescribe lower limits for women, if the limits are used only for deciding when and where to introduce preventive measures. Actually, the SACHS version and the ACGIH TLV do not have a different set of limits for women.

Several hot industries have available the experts and instruments for measuring work metabolism and have in the past applied these techniques for heat stress monitoring. For these industries, it may be advantageous to abide by the SACHS version or by the ACGIH TLV because they permit higher environmental heat loads for moderate and light work. Furthermore, once the work metabolism of a job has been measured, it does not have to be repeated as long as the tasks to be performed on the job remain the same. Recently, several direct reading, self-contained, portable instruments for measuring oxygen consumption became commercially available.[25] They are quite expensive, but if their accuracy can be verified, they may be well suited for the purpose of monitoring metabolic heat load.

Monitoring for Engineering Heat Stress Control. When faced with the problem of how to reduce the workers' heat load most efficiently, it is necessary to know the proportion that the different climatic and metabolic factors contribute to the existing condition. The empirical heat stress indices such as the WBGT, ET or P4SR are not well suited for this purpose. Physical or rational indices such as the HSI and the operative temperature (T_o)[26] make it possible to calculate the amount of heat gained or lost by an individual through different heat exchange mechanisms such as convection, radiation, and evaporation as well as by metabolic heat generation. If the results show that most of the heat is gained through convection, then the most effective way of reducing heat stress will be in lowering the air temperature. On the other hand, if most of the heat is gained through radiation, then the lowering of the mean radiant temperature will be more helpful. This can be done by placing a reflecting barrier between the radiation source and the worker. However, it is even more useful to better isolate hot ovens or furnaces in the workers' surroundings. This may require initially a large investment, but in the long run, the pay off is much greater because it not only reduces the need for air cooling devices but also reduces the energy need for both air conditioning and the manufacturing process.

If the main problem is high humidity, the most efficient method of climate control will be dehumidification of the air by cooling. However, by using a rational index, it is possible to predict whether facilitation of sweat evaporation by increasing the wind speed would be sufficient enough by itself to reduce the heat stress. If this turns out to be the case, then substantial amounts of energy can be saved by making cooling of the air unnecessary. Similarly, it is possible to calculate by a rational index, whether the worker can be kept in heat balance without excessive strain by making available near the hot job sites air conditioned resting cabins instead of air conditioning the whole plant. If this can be accomplished, the energy saving can be tremendous. However, on the negative side of the balance, there will be some loss in per capita productivity due to the need for increased rest allowances and also due to higher wages paid to workers who have to tolerate the discomfort and health risks connected with working in hot environments.

Heavy physical work in hot environment is undesirable not only because it causes great discomfort but also because the metabolically generated heat imposes twice as much stress on the circulatory system as the environmental heat load.[2,28] The method for reducing the physical work load is either mechanization or employing more workers. The decision between the two alternatives should be based on the availability of energy sources and manpower and economic payoff.

Recently Gagge et al[29] developed a new effective temperature scale based on a mathematical model of human physiological regulatory response. This new index not only corrects some of the distortions of the original ET scale but also makes it possible to use a computer for estimating the heat load of a worker and the most effective way of reducing the heat stress of a hot job.

Several investigators recommended that industrial heat exposure limits should also be expressed in terms of rational or physical indices; however, for industry-wide use, they are too complicated at the present, as was explained before. Furthermore, the rational indices are based on laboratory experiments on subjects not representative of industrial worker populations. In order to make rational indices applicable for a practical heat stress standard, permissible exposure limits would have to be established in terms of these standards, and they would have to be validated in field studies of industrial workers, in a fashion similar to that done with the WBGT index.[30] Furthermore, the estimation of these indices would have to be greatly simplified and limits displayed in a simple table or graph, encompassing all combinations of environmental and metabolic factors, as well as clothing worn, encountered in hot jobs.

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ESTABLISHMENT OF THE BOUNDARIES TO COMFORT BY ANALYZING DISCOMFORT

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ABSTRACT

The simple word "comfort" confounds a variety of social, psychological and physiological perceptions. Even if one delimits the comfort area to the physiological correlates of human thermal comfort, there are still a number of facets which must be addressed. Physiologically, thermal comfort is an integrated system state, with primary inputs from the mean weighted skin temperature ($\bar{T}_s$), the % skin wettedness and the temperature of the extremities (particularly T_{toe} and T_{finger}) and secondary inputs from alterations of deep body temperature (T_{re}) and heart rate (H.R.). These secondary inputs result from the body attempting to compensate for the strain imposed changes in the resting level of body heat content (ΔS) by the environment and work load. As one might expect, comfort exists across a range of these various parameters, rather than at any single, unique, state point. It is easier to delineate the boundary between comfort and discomfort, or between comfort and performance decrement, than it is to delineate comfort per se. The following table provides some representative values for comfort, discomfort and performance decrement levels, and adds the confounding factor that the comfort zone can be dramatically altered by clothing insulation (clo):

	COMFORT	DISCOMFORT	PERFORMANCE ↓
T_A	25.5 °C	f (clo + RH)	f (clo + RH)
RH/VP	50%	<5 mm Hg >18 mm Hg	–
Wind	<0.2 m/sec	>4 m/sec	>6 m/sec
Eff. Temp.	21.6 °C ET	26° – 29.5 °C ET	>30 °C ET
WIND CHILL	200 kcal/m^2 · hr	>600	f (clothing)
$\bar{T}_s$	33.3 °C	31 °C	30 °C
% Wet Skin	<20%	>20%	>40%
T_{finger}	>21 °C	<20 °C	<15 °C
T_{toe}	>18.5 °C	<17 °C	<13 °C
T_{re}	37 ± 0.5 °C	?	>38.2 °C <36.0 °C
ΔS	0 kcal	± 25 kcal	± 80 kcal
% H_2O LOSS	0%	2%	4%
WORK	100 kcal/hr	>300 kcal/hr	>425 kcal/hr
H.R.	60 – 80 min	>30/min↑	?

Key Words: Clothing effects; comfort; heat storage; work effects

There has been a great deal of work on assessment of comfort, usually by comfort vote. Other studies have shown that subjective interpretations of comfort are different from those of pleasant versus unpleasant, and different again from those of temperature sensation. All three are clearly related to the immediately preceding environment of the subject, with a pronounced hysteresis loop in pleasantness, comfort and temperature sensation depending upon the direction of change from an existing baseline.

One of the problems in the definition of comfort has been that in a comfortable environment little or nothing changes. There are clearly differences in comfort sensation associated with season of the year, with habituation as well as acclimatization, and perhaps with such other factors as age, sex and physical condition. Thus, studies of comfort which merely attempt to define the zone of comfort have to decide at what point the normal variability associated with the season, the individual, and his clothing, etc. diverges sufficiently to be considered a significant departure from the comfort zone. In addition, the "pass band" (i.e. the range over which comfort is not significantly altered) is fairly wide not only with regard to temperature, but also humidity, air motion and radiant heat exchange.

The approach taken to this problem in my laboratory has been rather different. Instead of trying to define comfort and its associated ranges, we have looked at tolerance to heat, to cold, and to work. We thus approach comfort along the other end of the axis; instead of working from comfort to discomfort, we work from discomfort or limits of physiological tolerance, where very dramatic changes in physiological status can be monitored, and approach less severe conditions. Thus, we interpret comfort as those conditions where significant physiological changes do not occur. The argument used is that somehow the cessation of physiological alterations is easier to detect and delineate than the onset of altered physiological status. This approach also involves an attempt to express the physical factors in the environments, and the relevant physiological factors of the individual, in fairly rigorous theoretical physical terms. These are assessed by either direct physical measurement or biophysical simulation, such as the heated copper manikin, by subsequent development of predictive models of what the physiological responses would be to any given combination of work, temperature, humidity, air motion and clothing and, finally, by controlled physiological studies to refine and ultimately validate the biophysical models developed.

This manuscript will review this approach to comfort and consider the comfort equation primarily from two aspects, heat production and heat loss. We will reference the comfort sensation associated with the percentage of the body surface area that is sweat wetted, but the primary emphasis will be on the terms in the classic heat balance equation which specify that change of heat storage (ΔS) should equal 0 for true physiological comfort. This equation is:

$$\Delta S = m + q_s \pm (R + C) - E \qquad (1)$$

where M equals metabolic heat production, q_s equals solar heat load if any, R + C represent radiant and convective heat exchanges respectively, and E represents evaporative heat loss.

In the usual resting situation, the metabolic heat production term (M) is readily described as a heat production of 1 Met, defined as 50 kcal/m^2/hr; roughly a heat production of 105 Watts for an average male with a surface area of 1.8 m^2. On the other hand during work, heat production can be varied over a significant range, perhaps by an order of magnitude of fifteen for short bursts of activity. Thus, definitions of heat production can pose a problem in assessment of comfort. There are several approaches that can be used other than actual measurement of metabolic heat production by the usual oxygen consumption measurements and calculations. Many tables exist which describe the heat production for almost all conceivable forms of recreation, work or other activity. In addition, we have explored this end of the heat balance equation quite thoroughly and can predict heat production as a function of the subject's weight, speed, the load he carries if any (and its placement), the type of terrain he is covering, and its grade. Alternatively, when the work involved is not simply walking and carrying a load, and if we know the physical work of an individual (i.e. foot pounds of lift work per minute), we can assume an efficiency factor of about 20% if the individual is using his large muscle masses and convert the physical work to a heat production merely by multiplying physical work (expressed in kcal/hr) by 5. If only arm work is involved, i.e. smaller muscle masses, then we can use an efficiency factor of about 10 or 12%.

Thus, for well defined work routines, we have a variety of approaches; either direct measurements, or tables of existing values, or estimation as a function of speed, grade, terrain and weight, or estimation of the physical work involved.

On the other hand, in the usual industrial situation, the individual tends to set his own pace rather than to work at a given rate. We have explored this problem and have determined that, given reasonably good motivation, a relatively fit 18 to 25 year old soldier will tend to pace himself as a function of his load, the type of terrain and its grade, so that the physical work will be regulated to give a heat production, at most, of about 425 kcal/hr ± 10%. This self-paced hard work level seems to be relatively independent of fatigue, ambient temperature, or time of day, but may be considerably different from 425 kcal/hr for less fit, older or female populations. The 425 kcal/hr level for these fit young male subjects represents between 40 and 50% of their maximum work capacity and is an intermediate value between the 600 kcal/hr rate which would exhaust them in about an hour if they worked at this rate continuously, and the 300 kcal/hr rate which, again for this population only, represents only moderately hard work. These then are our various alternative methods for assessment of the metabolic heat production in our heat balance equation.

The solar heat load is not usually a major consideration in indoor environments, but must of course be considered a prominent feature in outdoor environments. Without dwelling deeply on this rather specialized portion of the heat balance equation, I should merely like to indicate that solution of this term involves knowing 3 terms in the radiant surround--the direct, the diffuse, and the reflected terrain albedo radiation, and the surface area of the individual exposed to these three radiations in an XYZ plane, for a given individual, how his surface area is changed by his clothing, and the transmissivity and absorptivity of his clothing. We have developed such a model. It appears to be able to predict the net solar heat load arriving at the skin within 5 or 10 Watts of that actually measured. Our major effort in this area at the moment is directed towards resolving how one adds solar heat load arriving at the skin to metabolic heat production in terms of physiological effects. Surely the effects of solar heat are quite different from the effects of an equivalent wattage of metabolic heat produced internally, but the relative proportioning and effects on skin temperature, rectal temperature, heart rate, sweat production, and evaporation require elucidation.

Turning next to the heat loss side of the equation, let us consider the radiant and convective heat losses. Conductive heat loss is ignorable in most practical cases since it usually involves only a very small surface area (e.g. merely the soles of the shoes for a standing individual). While rigorous physical equations do exist for the heat transfer between a nude individual and his environmental surround (as a function of the temperature differences and vapor pressure differences using such sophisticated theoretical physical terms as Reynolds, Grassoff, and Prandtl numbers), no such analyses or equations exist for the clothed man. Indeed the problems of combined evaporative and sensible heat transfer through multiple clothing layers, with their associated multiple layers of trapped still air, is one that currently defies rigorous theoretical solution and will probably continue to do so for many years. Instead, to resolve this problem we have resorted to a biophysical analog, a heated life-sized copper manikin which, when fitted with a thin nylon-cotton skin which can be saturated with water, can define not only the radiant and convective heat exchanges of a human through a given clothing system, but also his evaporative maximum heat transfer.

One can measure the actual change in body heat content using the classic relationship that there is a mean temperature for the mass of the body, T_b, (usually defined as $T_b = 1/3\ \overline{T}_{skin} + 2/3\ T_{rectal}$) and that the specific heat of human tissues is 0.83 kcal/kg · °C. Thus the change in heat content (heat storage or ΔS) can be defined as:

$$\Delta S = 0.83 \cdot \text{mass} \cdot \Delta\overline{T}_b \qquad (2)$$

If we define the mass of a standard reference man as 70 kg, the simple multiplication 0.83 x 70 implies that a change of 58.1 kcal corresponds to a 1 °C change in mean body temperature ($\Delta\overline{T}_b$). Thus we have a physiologically measurable quantity to use as the basis for heat storage (ΔS) in the heat balance equation (Equation 1).

Having defined the metabolic heat production, and indicated an approach to resolving the solar load problem if necessary, it only remains for us to interpret the data from our anthropomorphic copper manikins, for us to be able to completely resolve the comfort equation, using as the criterion for comfort that there should be no change in heat storage.

We have based this interpretation upon the classic work of Gagge et al., who defined the clo unit of thermal insulation as that insulation which allowed the transfer of 5.55 kcal/m^2 of surface area per hour for each °C difference between skin and air temperature. We then introduced, following Woodcock, the concept of the permeability index (i_m). This describes the ratio of the possible evaporative heat loss to the maximum that could exist in any given ambient vapor pressure environment, as a function of the difference between the vapor pressure of the skin (P_s) and ambient vapor pressure (P_a). When this difference is converted to an equivalent temperature gradient using the physical relationship (Lewis relationship) that 1 mm Hg vapor pressure differential is equivalent to a temperature difference of 2.2 °C (as observed in the slope of the wet bulb lines on a psychrometric chart), we can write the following two equations for radiation and convection, H (R + C) and maximum evaporative (H_e) heat transfer from the body, for our standard man with 1.8 m^2 of surface area, as a function of the clothing (clo) and its permeability (i_m):

$$H\ (R + C) = 10 \cdot 1/\text{clo} \cdot (T_s - T_a) \tag{3}$$

$$\dot{H}_e = 10 \cdot i_m/\text{clo} \cdot (2.2) \cdot (P_s - P_a) \tag{4}$$

Assuming a standard reference skin temperature of 35 °C (95 °F) for a nude man, there is an associated saturated vapor pressure of 42 mm Hg for sweat at the skin surface; for a clothed man we generally have found skin temperatures of approximately 36 °C, and therefore an associated vapor pressure of 44 mm Hg. It can readily be seen that, having established the skin temperature (and its associated vapor pressure) of men in a hot environment, we can estimate the radiation and convective heat exchanges and the evaporative heat loss for any ambient temperature and humidity, since equations 3 and 4 above give these heat losses per °C and per mm Hg of vapor pressure difference between skin and ambient environment conditions. Thus, we can define, for a given uniform of measured clo and i_m/clo characteristics, the actual radiation and convective heat transfers, and the maximum evaporative heat transfer possible in any given environment.

We now can define the "Psychrometric Range" of a given clothing system. The lower limit of this range is the lowest dry bulb temperature at which an individual seated at rest (losing about 25% of his resting heat production from the respiratory tract and by diffusion of water vapor from the skin without active sweating) will lose only 75% of his resting heat production, i.e. no more than 75 kcal/hr (300 BTU/hr) of a total 100 kcal/hr (400 BTU/hr) of heat production at rest. Note that this limit parallels the dry bulb temperature lines on a psychrometric chart. The upper limit is a line paralleling the wet bulb temperature lines and defines those combinations of air temperature and vapor pressure below which an individual having a heat production of 300 kcal/hr (1200 BTU/hr) is able to eliminate 75% of it by a combination of radiation plus convection and evaporation, when he is 100% sweat wetted (assuming roughly that 25% of his metabolic heat production can be lost from the respiratory tract as a result of the increased respiratory response associated with the increased oxygen demand of the work). This concept is illustrated in Figure 1, which shows the predicted psychrometric range for an individual with and without body armor, at rest (100 kcal/hr = 400 BTU/hr of heat production), with a need to lose not more than 75 kcal/hr (300 BTU/hr) by radiation and convection, and at work (heat production of 300 kcal/hr = 1200 BTU/hr), with the requirement to lose 225 kcal/hr (900 BTU/hr) by combined evaporative and non-evaporative heat transfers through these two clothing systems.

This concept of psychrometric range is clearly an imprecise statement because of the alteration of the insulation and vapor permeability of clothing with varied air motion, the ability of the body to produce different amounts of sweat, to accustomize to different degrees of heat storage, and to alter skin temperature as a function of state of acclimatization and hydration etc. Nevertheless, it is a very useful concept in delineating those environmental conditions under which tests of several clothing systems are most apt to show physiological differences. This can be exemplified by considering that if two clothing systems are studied under conditions well below the upper psychrometric range of either, then the body can come to a common physiological state (as indicated by measurements of evaporative sweat loss, rectal temperature and heart rate) by relatively minor variation in the sweat wetted surface areas. Thus any difference between the two uniform ensembles is apt to be lost between this immeasurable and the normal variability inherent in small sample analyses. On the other hand, should the study of these two theoretical clothing systems be conducted well above the theoretical upper range of either, then the physiological responses of subjects wearing either

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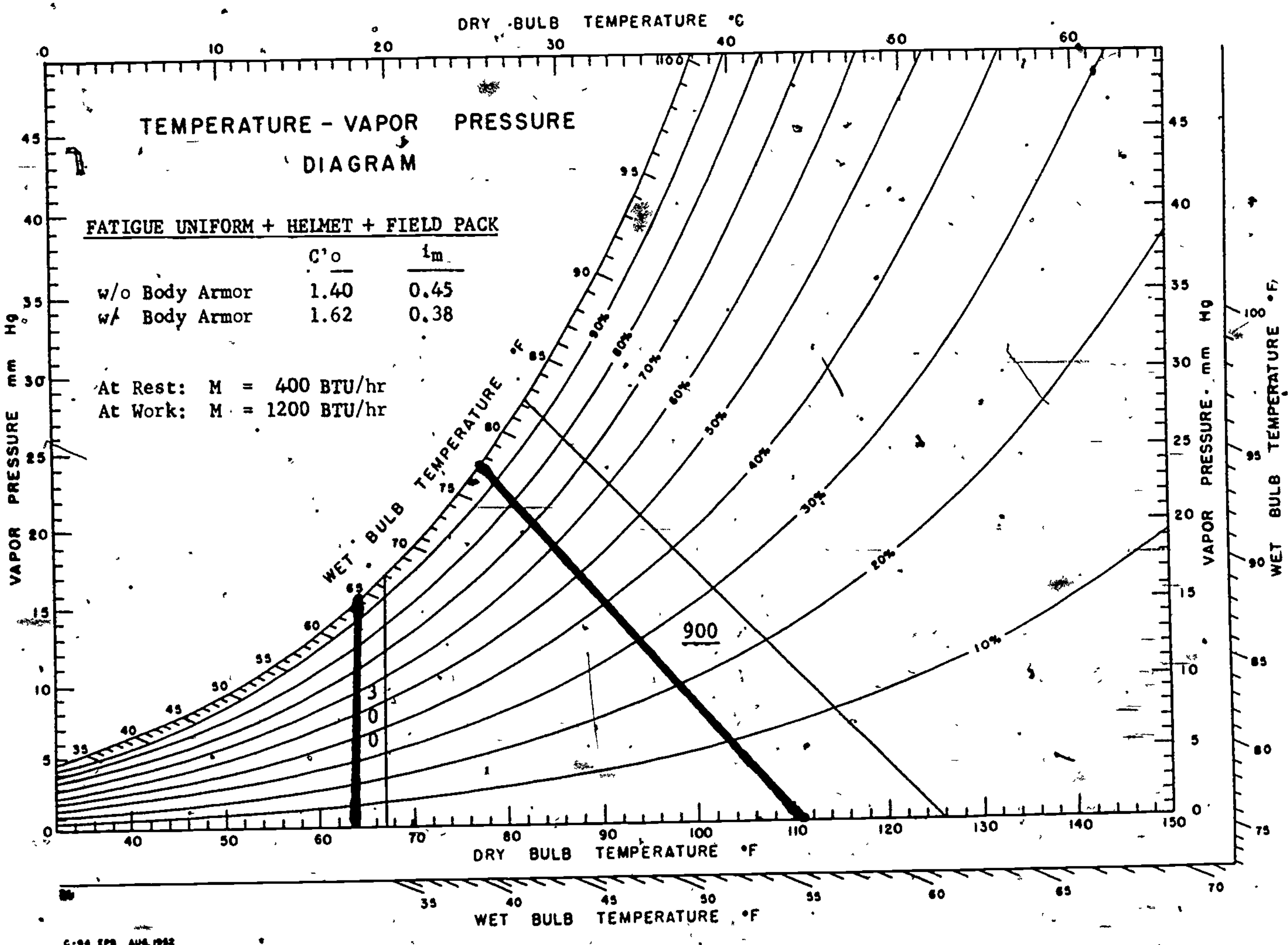
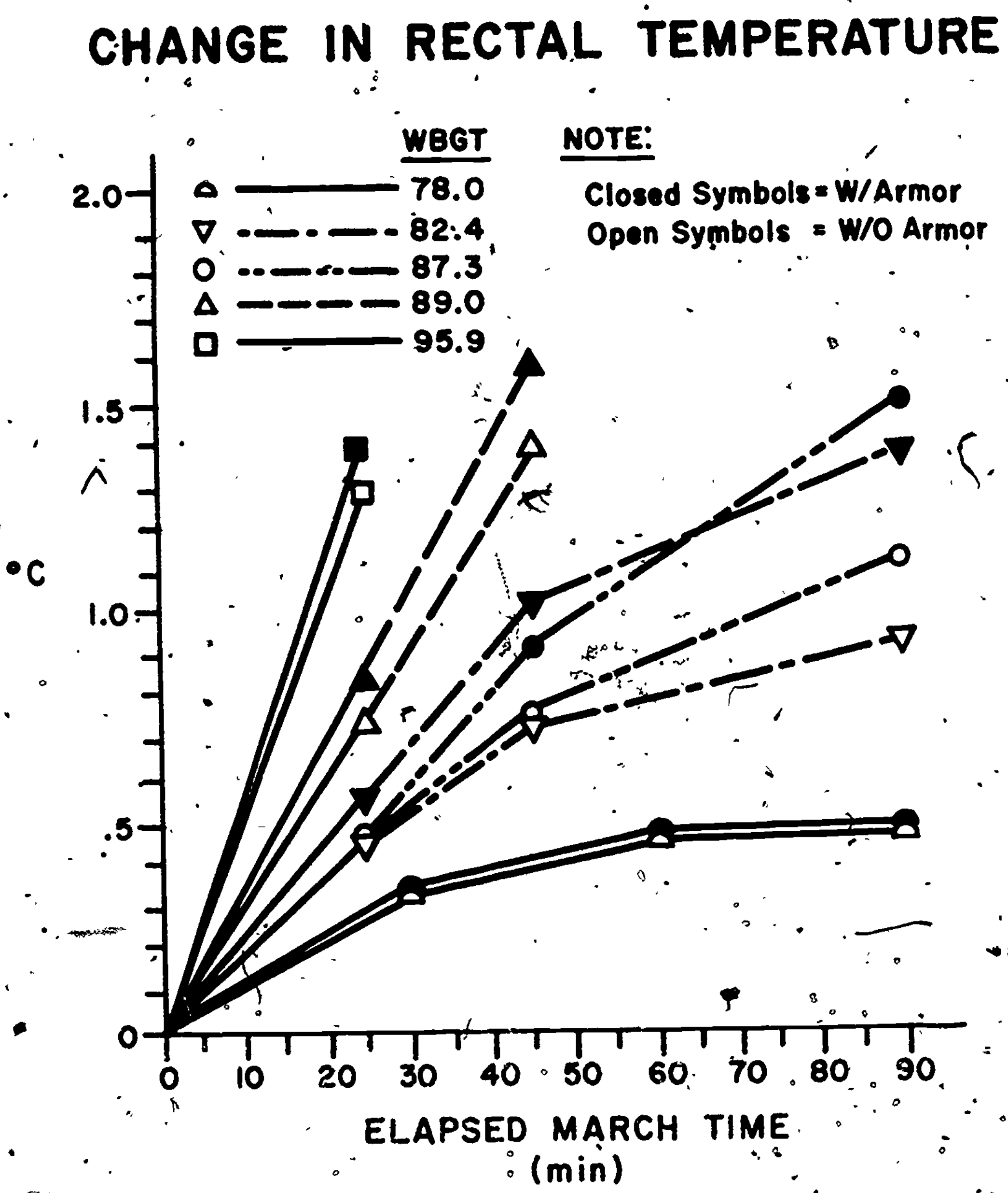

DRY BULB TEMPERATURE °C
TEMPERATURE - VAPOR PRESSURE DIAGRAM
FATIGUE UNIFORM + HELMET + FIELD PACK
C'o
i_m
w/o Body Armor 1.40 0.45
w/ Body Armor 1.62 0.38
At Rest: M = 400 BTU/hr
At Work: M = 1200 BTU/hr
VAPOR PRESSURE mm Hg
WET BULB TEMPERATURE °F
90%
80%
70%
60%
50%
40%
30%
20%
10%
300
900
DRY BULB TEMPERATURE °F
WET BULB TEMPERATURE, °F
C-94 EPB AUG. 1962

Figure 1

garment will be driven to their maximum heart rates, rates of rectal temperature change, and 100% sweat wetted areas. Rather than studying the differences in uniforms, one will be studying the differences in physiological tolerances of the wearers under extreme stress. The results will be relatively independent of whether, with one uniform, the stress is 130% of the maximum the individual can bear or 115% with the other. This lack of discrimination is shown in Figure 2, where the change in rectal temperature for men during a 100 minute march is graphed at 5 different environmental conditions, expressed as the WBGT index (WBGT = $0.7\ T_{wb} + 0.2\ T_q + 0.1\ T_{db}$). It can readily be seen that the 100 minute march cannot be completed at either of the two highest WBGT conditions and that the difference between the rectal temperature change with or without armor is barely distinguishable. In a similar manner, although all subjects can complete the march without difficulty under the lowest WBGT condition, there is again no difference in rectal temperature response. The comparability of rectal temperatures is achieved by small, relatively immeasurable differences in sweat wetted body surface area. Only in the mid range, i.e. conditions which lie between the psychrometric upper ranges of the two uniforms, can one clearly see the difference of wearing or not wearing body armor. The advantage of the Psychrometric Range concept is that it allows the scientist to select those conditions which are most likely to exhibit any differences in the physiological responses of men wearing various clothing systems. In other words, the investigator can dramatically alter the signal (data) to noise (variability) ratio in his study by appropriate selection of the environmental condition under which he studies a given clothing system, based upon consideration of its insulating clo and vapor permeability i_m values, as determined on the heated copper manikin.

An example of this approach is given in Figure 3, which shows the average change in heat storage for 8 subjects walking at 29.5 °C (85 °F), 50% R.H. wearing either a full length plastic raincoat, or the same coat cut down to 3/4, 1/2 and 1/4 length. The copper manikin values, given at the right hand side of the figure, were used to calculate that at the ambient temperature of 85 °F and 50% relative humidity, the maximum combined heat loss by radiation, convection and evaporation is 142 kcal/hr wearing the 1/4 length raincoat. This is reduced to 126 kcal/hr by the 1/2 length and to 108 kcal/hr by the 3/4 length raincoat while, when wearing the full length raincoat the wearer will have only a total 92 kcal/hr of non-evaporative plus maximum evaporative heat loss. A resting individual, producing perhaps 90 kcal/hr (105 Watts), should have no problem with heat storage; however, during work (walking at 3 mph), there should be a distinct difference in the relative heat storages of men when they wear these 4 raincoat systems. The agreement with this prediction is clearly demonstrated in the figure (cf. Fig. 3). With no heat storage at rest, there is good agreement in the rank ordering of the 4 raincoats as a function of their clo and i_m/clo ratio rank order. Similar agreement between the relative rank ordering of clothing systems suggested in the i_m/clo ratios and the actual heat storages, is shown in Figure 4, for 7 men walking in a 95 °F environment. This condition minimizes the differences between the clothing systems associated with differences in clo. In the absence of a significant skin to air temperature gradient, there will be almost no radiation and convective heat transfer. The heat storage when wearing the two garments with a 0.34 i_m/clo are obviously identical during the two walk periods, as are the heat storages of the men wearing the two garments with 0.22 and 0.23 i_m/clo ratios, at least for that portion of the time when enough of the subjects (small numbers in circles represent subjects remaining) are still able to continue. The heat storage of these men when they wear the 0.27 i_m/clo ratio garment can be clearly seen to be between the heat storage with the 0.34 and 0.22 garments.

Another point illustrated by Figure 4 is our usual finding that 80 kcal of heat storage represents the usual limit of voluntary heat tolerance; i.e. the "ouch" level at which our volunteer subjects usually choose not to continue to participate in the exposure. Obviously, if one can define the limit of voluntary tolerance, and add to it the knowledge that subjects of this age and size who store approximately 160 kcal of heat in their body run a 50% risk of being a heat exhaustion collapse casualty, this information, in combination with the ability to predict heat production as a function of the task and heat losses as a function of the clothing, forms a complete system for prediction of tolerance time. Tolerance time can simply be defined as the time to accumulate either 80, or 160 kcal of body heat storage. This time is a function of the difference between the working heat production and the ambient environmental heat loss capacities. Similarly, evidence suggests that the threshold of discomfort is an alteration of ± 25 kcal of body heat storage; thus the comfort zone can be considered as those work, clothing, environment combinations which do not alter body heat storage by more than 25 kcal.



CHANGE IN RECTAL TEMPERATURE
WBGT
NOTE:
78.0
82.4
87.3
89.0
95.9
Closed Symbols = W/Armor
Open Symbols = W/O Armor
°C
2.0
1.5
1.0
.5
0
0
10
20
30
40
50
60
70
80
90
ELAPSED MARCH TIME
(min)

Figure 2

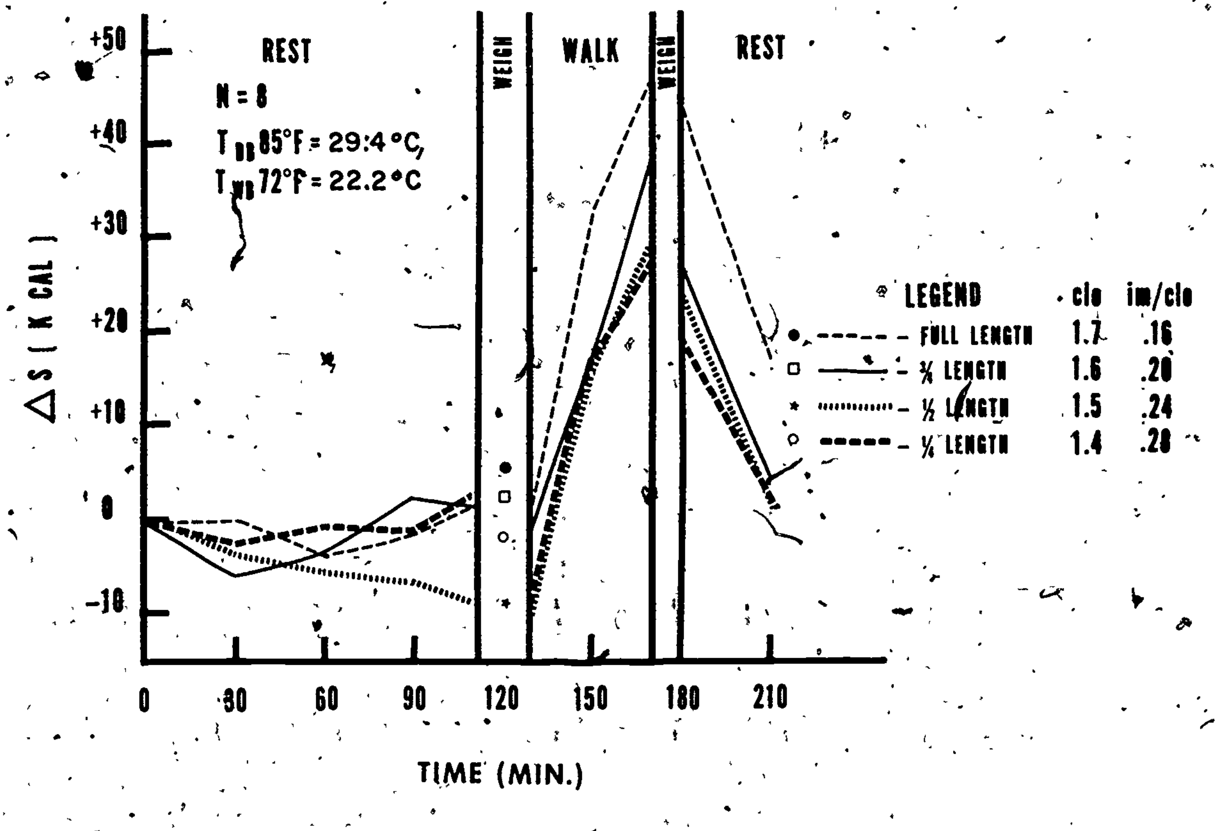

REST
WEIGH
WALK
WEIGH
REST
N = 8
T_{DB} 85°F = 29.4°C,
T_{WB} 72°F = 22.2°C
+50
+40
+30
+20
+10
0
-10
ΔS (K CAL)
0
30
60
90
120
150
180
210
TIME (MIN.)
LEGEND clo im/clo
FULL LENGTH 1.7 .16
¾ LENGTH 1.6 .20
½ LENGTH 1.5 .24
¼ LENGTH 1.4 .28

Figure 3

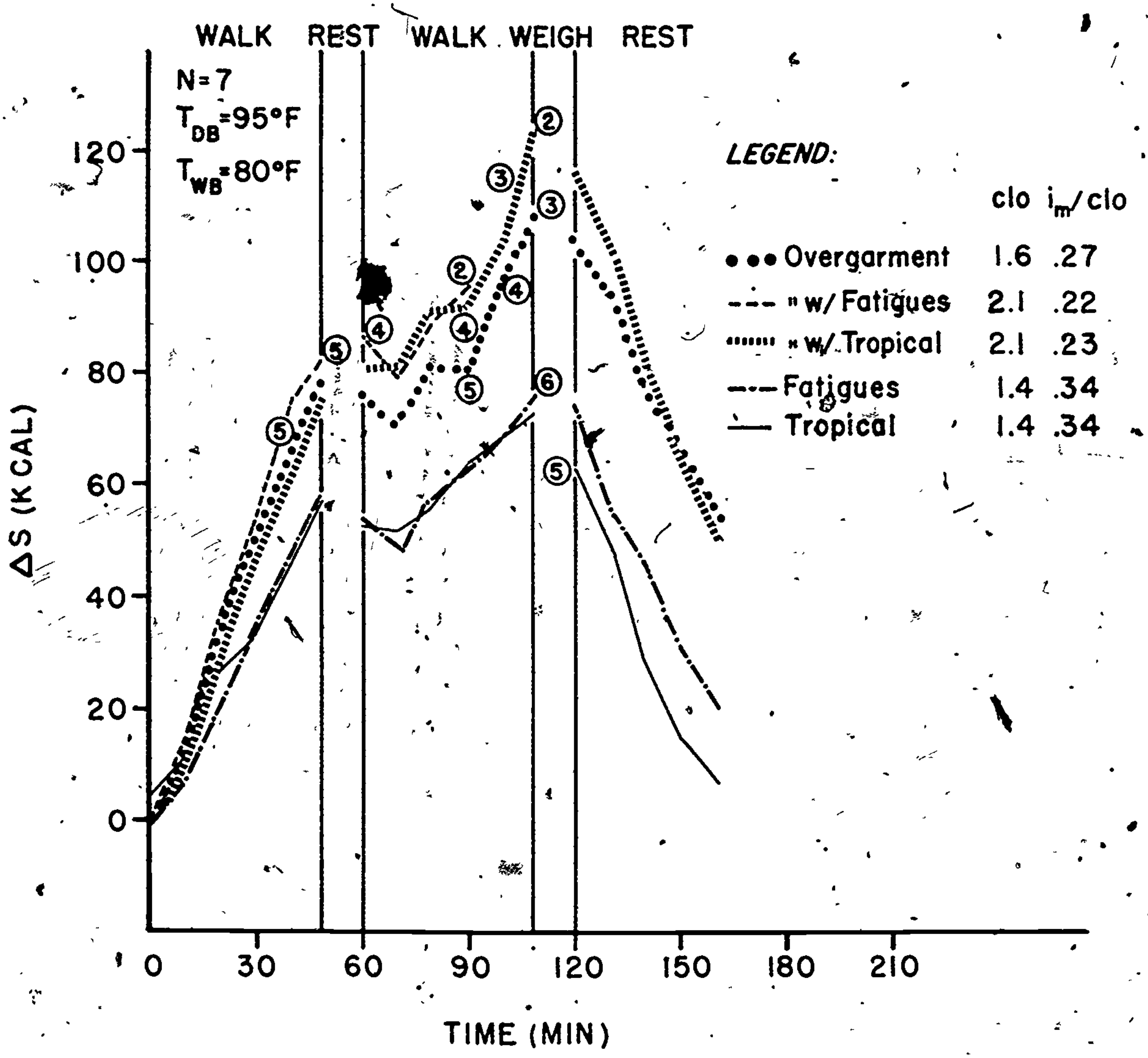

WALK REST WALK WEIGH REST
N=7
T_{DB}=95°F
T_{WB}=80°F
LEGEND:
clo i_m/clo
Overgarment 1.6 .27
" w/Fatigues 2.1 .22
" w/Tropical 2.1 .23
Fatigues 1.4 .34
Tropical 1.4 .34
ΔS (KCAL)
TIME (MIN)

Figure 4

One problem in this otherwise ideal system is that the observed heat storages, while almost always ranking in the order predicted by the static copper manikin values, very seldom actually equal the predicted heat storages. The observed heat storages are almost always significantly less than those predicted from the static copper man values. The difference reflects the fact that clo and i_m change as a function of the air motion. The air motion occurring in the studies are usually different from those used during the determination of the clo and i_m on the copper manikin, and the subjects generate air motion while walking and wearing the clothing. The change in clo and i_m as a function of wind velocity can be readily determined by exposing our copper manikin in the wind tunnel while measuring clo and i_m. These changes in clo and i_m with wind speed are illustrated for a standard tropical fatigue uniform in Figure 5.

The problem of dealing with the air motion generated by the wearer while walking is more complex. Studies have been conducted using naphthalene spheres set off the skin surface, but attached by bands to the skin surface. The rate of air motion across the naphthalene spheres is directly determined by the rate of sublimation (weight loss) of the naphthalene while subjects wearing the spheres walk either on a regular flat surface or on treadmill. Treadmill walking obviously results in different air motion from road walking because of lack of forward progression. This data is currently being correlated with the effective air motion we calculate by assessment of the "effective clo and i_m" values, "which must have existed", for subjects wearing given clothing systems in given environments while walking at given speeds and accumulating the heat storage. In essence, one uses the physiological heat storages and matches them against the ambient temperature and vapor pressure differences to determine what the effective clo and i_m values must have been. The effect of the combination of wind and subjective air motion is expressed in our models as a "pumping coefficient", an exponent which modifies both clo and i_m as a function of what we have chosen to call the effective wind velocity, V_{eff}. This is the sum of the ambient wind speed plus a mathematical constant times the metabolic heat production generated while walking.

Using either measured or predicted heat production, and the clo, and i_m for a given clothing system as modified by the pumping coefficient, V_{eff}, we have been able to predict both the rectal temperature and heart rate response patterns for a wide variety of work, rest and recovery over a wide range of warm to hot temperatures with low to high humidities. A sample of the agreement between predicted and measured rectal temperatures is shown in Figure 6. One can see that the agreement is usually with 0.1 °C for the average of a group of 8 subjects. The agreement between the predicted and measured heart rates is shown in Figure 7 and, again, the agreement is quite good, usually on the order of 3 to 6 bpm.

In summary, our approach to comfort is to use this well validated prediction model to predict those environmental conditions (i.e. those combinations of temperature, humidity, solar heat load and wind speed) which do not significantly alter either rectal temperature or heart rate. Heat production, skin temperature, skin wettedness and heat storage can also be predicted. This approach allows us to consider comfort for almost any clothing system and work—rest—recovery combination. It is, we believe, a fruitful approach to the prediction of discomfort and to the establishment of appropriate working conditions and appropriate recovery times. Indeed, we feel that this approach to defining the discomfort boundaries to comfort is a valuable supplement, and offers several distinct advantages over the usual subjective comfort vote evaluation.

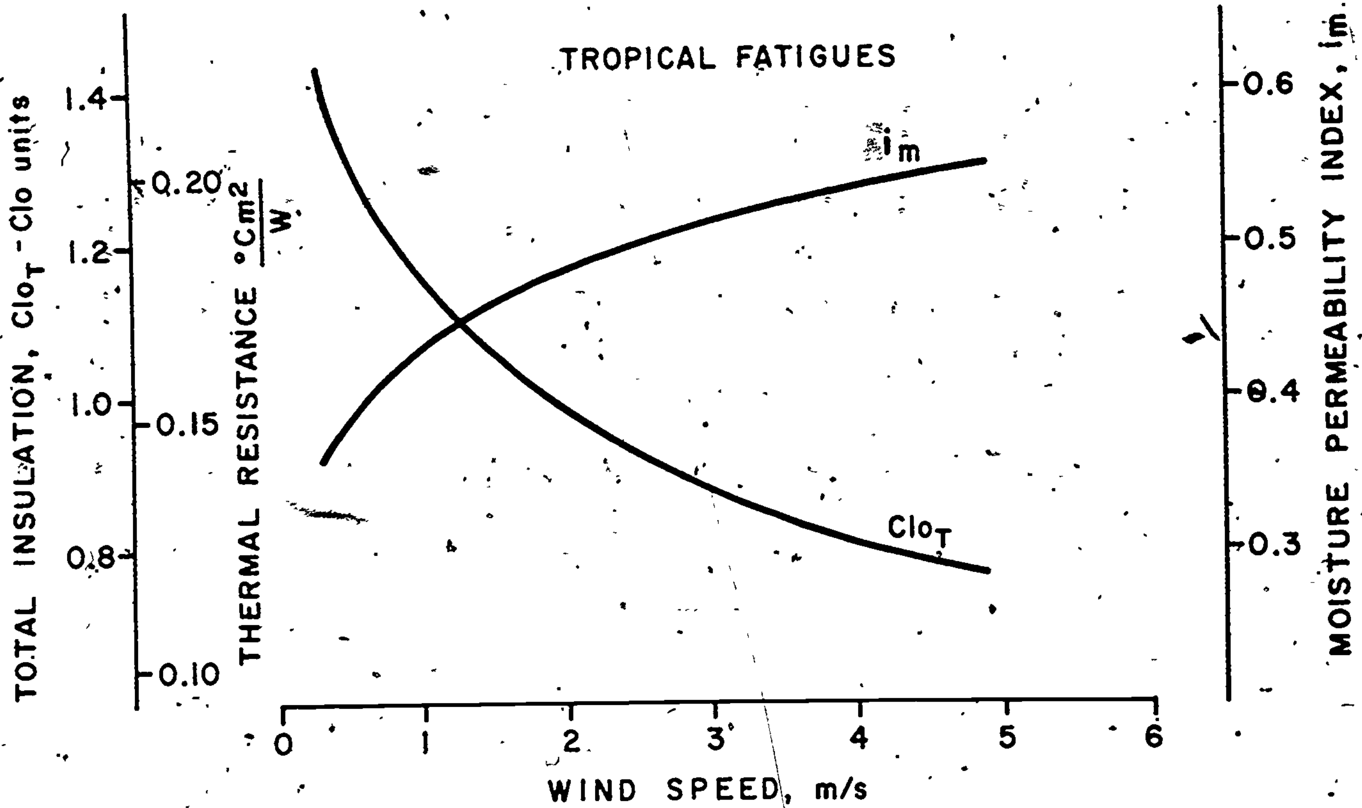
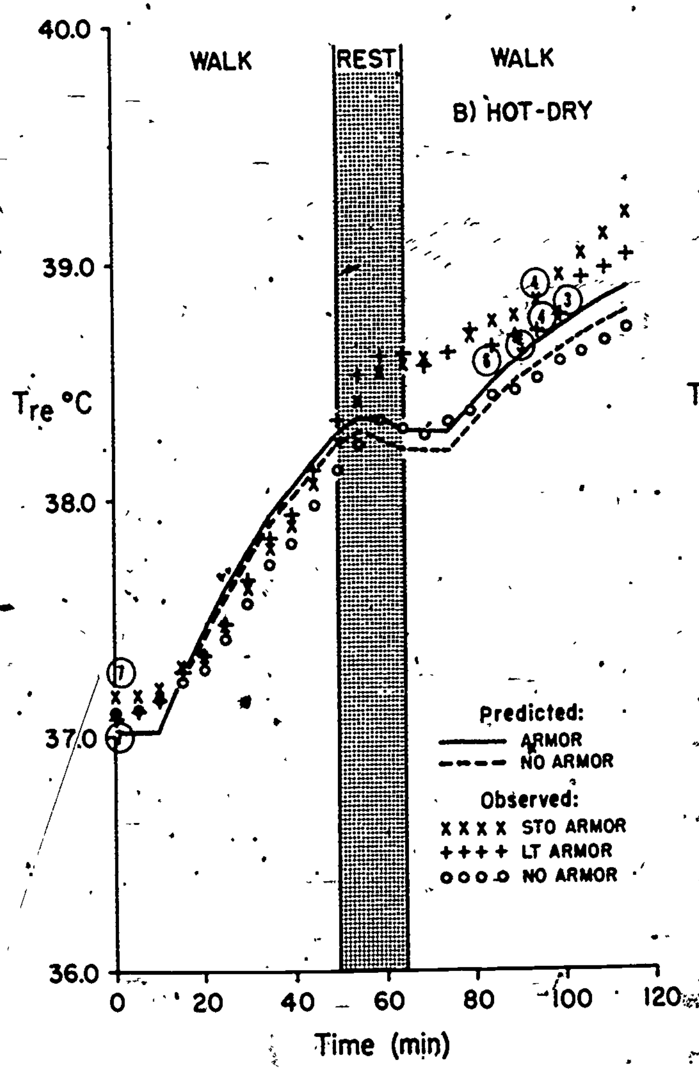
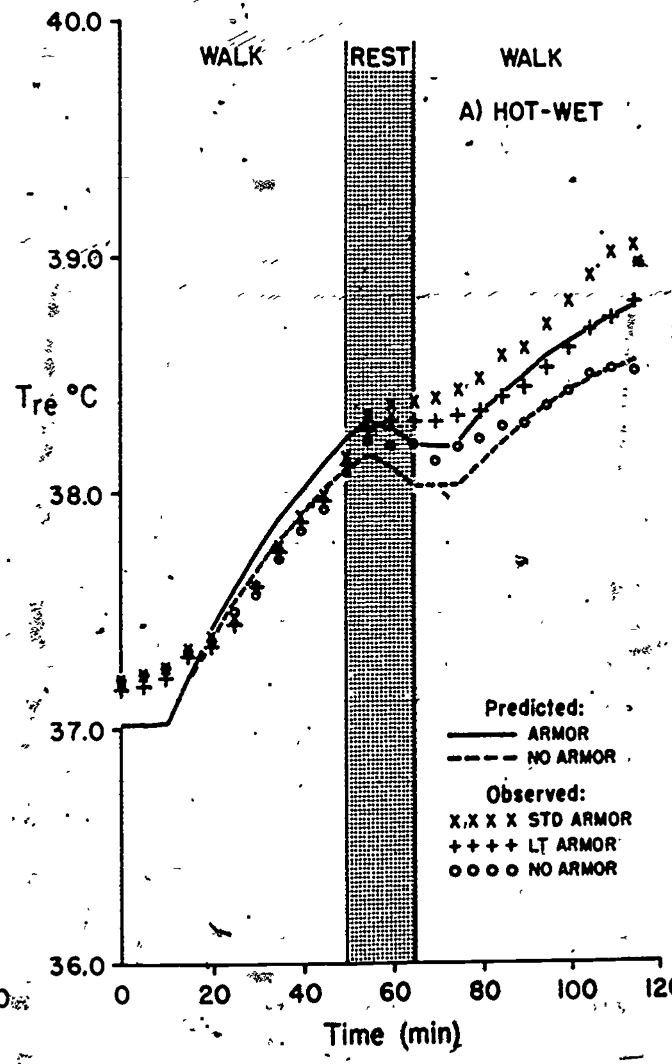

TROPICAL FATIGUES
TOTAL INSULATION, Clo_T - Clo units
1.4
1.2
1.0
0.8
THERMAL RESISTANCE $\frac{°C m^2}{W}$
0.20
0.15
0.10
i_m
Clo_T
MOISTURE PERMEABILITY INDEX, i_m
0.6
0.5
0.4
0.3
0
1
2
3
4
5
6
WIND SPEED, m/s

Figure 5



WALK
REST
WALK
B) HOT-DRY
40.0
39.0
38.0
37.0
36.0
Tre °C
0
20
40
60
80
100
120
Time (min)
Predicted:
ARMOR
NO ARMOR
Observed:
X X X X STD ARMOR
+ + + + LT ARMOR
o o o o NO ARMOR



WALK
REST
WALK
A) HOT-WET
40.0
39.0
38.0
37.0
36.0
Tre °C
0
20
40
60
80
100
120
Time (min)
Predicted:
ARMOR
NO ARMOR
Observed:
X X X X STD ARMOR
+ + + + LT ARMOR
o o o o NO ARMOR

Figure 6

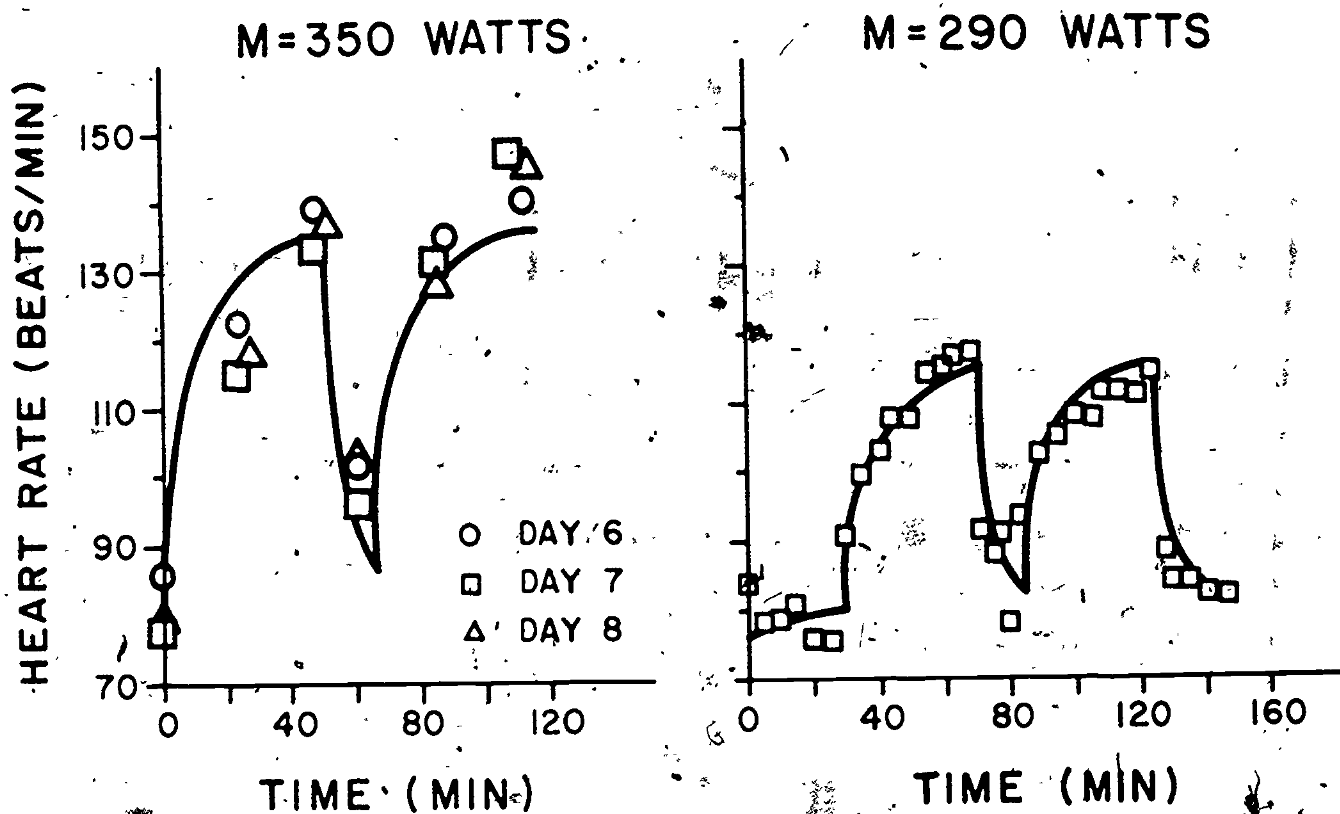

M=350 WATTS
HEART RATE (BEATS/MIN)
150
130
110
90
70
0
40
80
120
TIME (MIN)
DAY 6
DAY 7
DAY 8
M=290 WATTS
0
40
80
120
160
TIME (MIN)

Figure 7

HEAT STRESS, WORK FUNCTION AND PHYSIOLOGICAL HEAT EXPOSURE LIMITS IN MAN

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Abstract

Various operational trials using tolerance criteria available in the literature revealed that predictions of physiological exposure limits were rarely compatible with the observed status of men in a wide range of heat stress and work conditions. Computer integration of laboratory and industrial-type data led to establishing a comprehensive set of physiological criteria for tolerance limits appropriate to man at work within time-weighted-mean (t_{wm}) metabolic rates from 76 - 126 kcal/($m^2 \cdot hr$) [88.4 - 146.5 $W \cdot m^{-2}$]. These criteria and work rates were integrated with industrial-type heat stress conditions over the t_{wm} WBGT Index range of 82 - 130°F [27.8 - 54.4°C]; which resulted in developing the Physiological Heat Exposure Limits (PHEL) concept. Several electronic heat stress monitor-devices were evaluated and employed in determining environmental conditions. In all laboratory and field studies the dry- and wet-bulb and globe temperatures were recorded. Physiological data were obtained at the same time as the environmental data. Although the physiological data obtained in the laboratory were much more broad in scope than in the field settings, the field approach included physical characteristics of the subjects, body temperatures (skin and rectal), cardiovascular (heart rates and blood pressures) and metabolic-respiratory (O_2 consumption, respiratory minute volume and respiration rates) data during rest and performance of dynamic work; sweat rates were determined by body weight changes when feasible in the non-laboratory trials. Coefficients for physiological factors in the heat stress and strain equations were automatically adjusted for physiological changes determined in the actual situations. Comparison of over 200 sets of environmental and physiological data supported the PHEL concept and permitted more definitive identification of material areas requiring corrective engineering actions in the industrial-type settings. Corrective engineering actions based upon results of the data analyses have permitted nearly a sixfold increase of the maximum physiological exposure times; simultaneously, the estimated cardiovascular reserve increased from 15% to as much as 85% during routine work.

Key Words: Heat Stress, Exposure Limits, Thermal Analysis

Introduction

Heat stress and strain have a profound impact upon man and industry. Regardless of the specific causes, the immediate consequences of uncompensated heat stress upon man are observed as a major loss of man's performance efficiency and the loss of work productivity time. It is generally known that excessive heat stress exposures lead to a progressive loss of performance capability, lowered resistance to some stresses, and low retention of personnel.

Establishment of the Occupational Safety and Health Act of 1970 was a significant

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The opinions and statements contained herein are the private ones of the author and are not to be construed as official or reflecting upon the naval service at large.

stimulus for the civilian community to recognize the need for much greater awareness and initiation of corrective actions relative to heat stress problems. Lengthy deliberations were held by the Steering Committee for the Occupational Safety and Health Administration (OSHA). Numerous testimonies were given and a number of drafts of a proposed U.S. Federal Heat Exposure Standard were submitted to OSHA. The Steering Committee's final document was submitted on 11 January 1974. The main intent of the proposed Standard document was to provide guidelines as to when sound health practices should be introduced to protect workers. In the final document it was clear that questions regarding heat tolerance limits remained unanswered. In other words, the proposed Standard was to serve as a basis whereby industry should begin to institute sound health practices as the thermal environment and rate of work began to impose strain within workers; conversely, the document did not truly address tolerance limits where exposures and work rates would have to be terminated. A number of pitfalls in attempting to establish a more encompassing heat exposure standard were recently presented,[1] and it is very likely that many of the limitations in the proposed standard have had a major impact upon the absence of a currently OSHA approved set of heat exposure guidelines in this country.

Progress in identifying and combatting the adverse effects of heat stress and attempting to minimize the physiological strain in men have been extremely varied over the years. It is readily apparent that the total problem is far more complex when research is confronted with the real world of multiple combinations of physical factors in the environment and the physiological capabilities of man, whether it is a civilian or military situation. The majority of prior efforts were limited to studying only a few variables simultaneously. The technology-of-the-day did not permit development of concise solutions to involved questions; the scope of generally used physiological variables was extremely narrow; and, occasionally some past research was influenced by subjective information. Exploitation of modern technology has increased the ability to integrate numerous research findings and to improve bilateral cross-overs between laboratory and field efforts. It was through the use of the practical state-of-the-art technology today that the questions regarding heat stress, work function and physiological heat exposure limits were examined. The product, in terms of what can be assessed objectively at this time, has been the demonstration that it is feasible to dramatically reduce high heat stress levels and obtain a marked improvement in physiological performance.

Physiological Criteria of Heat Tolerance in Man

Studies of man's capacity to endure heat stress, or heat tolerance as used herein, have utilized a wide range of upper limits for the same physiological parameters. The conventional physiological criteria of heat tolerance have been associated with a range of heart rate (HR) values from 150 - >200 beats$\cdot$min^{-1}, rectal temperature (T_{re}) from 38.0 - 40.8°C, and sweat rates (SR) to 3.5 liters$\cdot$hr^{-1}.[2-13] Furthermore, there has been the "too late" approach of allowing exposures to continue until personnel demonstrate imminent collapse or an overt illness.[8,10]

It has been shown that HR, by itself, is a poor predictor of cardiovascular limits when dealing with various ages of workers, rates of work, and states of physical conditioning and acclimatization.[2,14-16] On a sound physiological basis it is not surprising that a HR limit cannot be well-defined as there are numerous offsetting cardiovascular factors which are not illustrated by HR alone.[17] In occupational situations the sole use of HR may be of little significance relative to heat tolerance under a variety of conditions;[10,18-20] HR may be altered by the influence of items such as sodium chloride,[21] or may be misleading in comparison with other changes within the cardiovascular system.[15,22] On the other hand, Tre is subject to various interpretations, dependent upon the rates of change,[11,12,23] and the dynamics of other internal body temperatures are such that in transient states T_{re} is the least reliable of the internal body temperatures to depict the more meaningful thermal status of man.[10,12,23] Also, the use of SR must be done with caution as there is evidence that SR's are subject to decrease in comparison with high SR's found early in the total heat acclimatization profile,[4,24] and SR's are markedly reduced with varying amounts of sodium chloride ingestion.[21]

Driven by a basic common sense question regarding what are tolerance limits to heat stress over a variety of general work tasks, and an urgent need for a simplified method which employs factors essential for practical engineering actions, a review of physiological data from over 160 experiments resulted in Table 1. Application of Table 1 required at least two objectives to be reached in order to define physiological heat exposure limits within man; the most appropriate for laboratory and field studies are indicated by "*" of "†" respectively.

Table 1

Improved Physiological Heat Exposure Limits Criteria

I.	**At Any Time During An Exposure:**	
	Heart Rate	>180 beats·min^{-1}
*†	Rectal Temp.	≧39.0°C or ≧1.6°C·hr^{-1}
*	Tympanic Temp.	≧39.5°C or ≧3.5°C·hr^{-1}
*	Esophageal Temp.	≧40.0°C or ≧4.4°C·hr^{-1}
*†	Total Vascular Resistance	≦20% of Control value
	or	
*†	Cardiovascular Reserve[15,22]	0%
	Mental	Disorientation
II.	**During Sustained Physical Work:**	
*†	Systolic Blood Pressure	≧40 mm Hg decrease within 3.5 min. interval
*	Electrocardiogram	R-wave height ≦1 mm of T-wave (using Lead I or Transthoracic) or T-wave inversion
	Korotkoff Sound Intensity	>3-fold increase from Control value
	Ventilation Equivalent	≧47% increase from Control value
	Ratio of Oxygen Removal	≧33% decrease from Control value
	Mental	Onset of euphoria <u>immediately</u> post-irritable
III.	**Recovery:**	
*†	Total Vascular Resistance	<80% of Control value within 20 min. post-exposure
*†	Cardiovascular Reserve	<75% within 20 minutes post-exposure
	Heart Sound Intensities	Sounds I and II remain >3-fold higher than Control even though Heart Rate back to Control level
	Creatinine Phosphokinase—	Blood level >1000 units 24-hours post-exposure

* These factors most common in controlled laboratory experiments.

† These factors most common in field experiments where monitoring is less extensive than in laboratory experiments.

Selection of a Simplified Index of Environmental Heat Stress

Earlier experiments in high temperature situations illustrated the difficulties in using available heat stress indices to scale short to long exposure times for men performing a range of routine tasks in industrial-type environments.[7,8,18-20,26] As the U.S. Navy Psychrometric Chart for High Temperature Habitability Limits (NAVSHIPS 4767) had a potential of application, a series of experiments were conducted to examine the validity of the NAVSHIPS Chart for exposures from 15 minutes to 6 hours. Results of the study clearly indicated that the NAVSHIPS Chart was able to provide reasonable agreement with heat tolerance in the so-called "4-hour" and "3-hour" zones, as long as no radiant heat was present and the metabolic rate (MR) was between 55 - 94 $W \cdot m^{-2}$. However, when radiant heat was present there was virtually no agreement with the "4-hour" and "3-hour" zones, and absolutely no agreement with any time zones of less than three hours. Careful examination of the original Bureau of Ships files indicated that the limits for less than three hours, in the proposed but unissued Chart, were based upon the original coefficients of the Belding and Hatch Heat Stress Index (HSI)[27] and that men were dressed only in shorts, socks and shoes; whereas, the "3-" and "4-hour" zones were very wide and were based upon data from men normally clothed. Obviously, the NAVSHIPS 4767 Psychrometric Chart for High Temperature Habitability Limits was unsatisfactory in dealing with combinations of radiant heat environments, was not sufficiently specific even in the absence of radiant heat for short exposure time, required a broader range of MR and should have been consistent with men wearing normal working clothes throughout delineated zones.

The HSI, with revised Fort Knox coefficients, was a likely candidate for selection as it developed the rational concepts of evaporation required to maintain heat balance (E_{req}) and maximum evaporative capacity (E_{max}) in order to obtain the HSI (See Appendix). Unfortunately, even the new nomograms of McKarns and Brief[28] to estimate E_{req}, E_{max} and HSI are much more complicated than a simplified chart for lay usage. Furthermore, using the improved coefficients and making corrections for actual skin temperatures, numerous calculations of the HSI revealed that the HSI values were either negative, implying mild cold stress when in reality there was high heat stress, or the values were far beyond the upper limit of 100. In separating out the factors within the HSI that may have been subject to further modifications, it was determined that when the partial vapor pressure (P_W partial) of the air exceeded the corrected vapor pressure at the skin the value for E_{req} became negative; in other words, a negative E_{max} in high heat stress denoted that at the higher P_W partial of the air, water would condense on the skin of man. These results also meant that the HSI concept was limited, in its current scaling terms, to environmental conditions where evaporative cooling (compensated heat stress) was present. Rescaling of the HSI was considered unwarranted to fit environmental conditions of uncompensated heat stress and tolerance times of less than 8-hour exposures. (Data relative to these negative and greater than 100 values are given later in this text.)

Selection of the Prescriptive Zone (PZ)[2,29] relative to physiological heat tolerance and the physiological heat exposure limits criteria, as given in Table 1, was not appropriate. By definition, the PZ is based upon 95% of an average population not exceeding a body temperature of 38.0°C. The PZ concept emphasizes the need for a nearly steady level of equilibrium in a wide range of climates. Above the upper limits of the PZ an increase in heat stress would result in a disportionate increase in cardiovascular strain unless T_{max} increased beyond 38.0°C. As indicated previously,[7,8,10-12,18-20,26] heat tolerance limits rarely can be defined by internal body temperatures as low as 38.0°C; tolerance limits must be judged by objective criteria which truly reflect the upper points (which are limits) rather than the points of departure from equilibrium. Data comparing "1-hour" and "30-minute" "heat tolerance" using the PZ versus HSI and other indices of heat stress are discussed later in this text.

Review of information on the Wet-Bulb Globe Temperature (WBGT) Index indicated that there were no less than six WBGT equations used in both theoretical and practical situations. Furthermore, reports of Yaglou et. al.,[30] and Yaglou and Minard,[31] did not specify which WBGT equation must be applied indoors. Although usage of $WBGT_a$* for outdoors and $WBGT_b$** for indoors has been widely referenced back to these reports, there was information[32-33] that $WBGT_c$*** was applicable indoors with varying radiant heat levels and was the significant form of WBGT in establishing standard criteria for heat tolerance limits. This latter approach utilizes the integration of time-weighted-mean (t_{wm}) metabolic rates (MR) and t_{wm} $WBGT_c$ with scaling for physiological heat tolerance limits, as given in Table 1, to permit practical utilization of essential environmental factors for physiological tolerance limits, corrective engineering actions and routine surveillance of work areas in industrial-type situations.

Physiological Heat Exposure Limits (PHEL) Chart

Curve fitting of radiant heat research data obtained by the Heat Stress Division, Naval Medical Research Institute (NMRI), revealed that the best fit curves were power regression relationships (r's = -0.985 and -0.998) between t_{wm} MR's of men in normal work clothes, t_{wm} $WBGT_c$ and exposure time limits when the physiological heat exposure limits criteria (Table 1) were met but not exceeded. On an initial basis there were two t_{wm} MR's (88.8 and 111.7 $W \cdot m^{-2}$) and the majority of the 70 sets of data from 15 subjects for each t_{wm} MR were within the t_{wm} WBGT's from 31.1 - 36.7°C. At approximately the same time Royal Navy researchers[8] combined $WBGT_d$**** with a continuous MR of about 170 $W \cdot m^{-2}$, but without the presence of radiant heat. Results of combining three phases of the Royal Navy effort included a total of 87 subjects, 440 sets of observations, and $WBGT_d$ from 32.1 - 53.9°C. Replotting the Royal Navy data revealed that again the best fit curve was described by a power regression (r = -0.983). One major difference between the NMRI research and that of the Royal Navy was that in the NMRI studies exposures were terminated in accordance with the criteria associated with Table 1, whereas, the Royal Navy researchers terminated exposures at the point of imminent collapse or overt illnesses. Another major difference was that the Royal Navy studies were based upon continuous work at a much higher MR than in the t_{wm} MR method used by the Heat Stress Division of NMRI. The Royal Navy goal was predominately directed to problem situations where emergency work would have to be performed continuously at a very high rate of energy expenditure. The goal within the U.S. Navy was directed to a broader spectrum of exposure times (up to six hours) with t_{wm} MR and t_{wm} WBGT values representing a more normal range of environmental and physical work conditions encountered in hot, industrial-type civilian and military situations alike. Noise levels in both the NMRI and Royal Navy studies were maintained at 90 dbA. In NMRI trials away from the laboratory the subjects were required to wear standard stock hearing protection devices when the noise levels exceeded 90 dbA.

Research was continued by the Heat Stress Division, NMRI, and in September 1971 the Navy established the Physiological Exposure Limits (PEL) Chart for use in high temperature environments. It could be said at that time that the PEL Chart permitted determination of the maximum physiological exposure limits, which if not exceeded would permit reversibility of the physiological strain without detectable harm provided rest was allowed in a cool environment. The acronym PEL came into general usage within the Navy[35] until identical acronyms also appeared. In 1973 the Environmental Protective Agency initiated a series of Public Exposure Limits (PEL) covering a broad scope of circumstances which did not include heat stress; furthermore, the National Institute of Occupational Safety and Health (NIOSH) published Permissible Exposure Limits (PEL) in September 1973.[9] In order to avoid confusion in referring to the three identical acronyms, the Navy, in November 1973, adopted the more appropriate title Physiological Heat Exposure Limits (PHEL).[36] The PHEL Chart,

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* $WBGT_a = [(0.1\ T_{db}) + (0.7\ T_{wb\ natural}) + (0.2\ T_g)]$

** $WBGT_b = [(0.7\ T_{wb\ natural}) + (0.3\ T_g)]$

*** $WBGT_c = [(0.1\ T_{db\ shielded}) + (0.7\ T_{wb\ psychrometric}) + (0.2\ T_g)]$

**** $WBGT_d = [(0.7\ T_{wb}) + (0.3\ T_{db})]$

as of 1973, consisted of the previous U.S. Navy PEL curves of 1971 with an additional curve for t_{wm} MR (146.5 $W \cdot m^{-2}$) and extension of the t_{wm} WBGT range to 51.7°C for all three curves. Clearly there is a difference between the U.S. Navy PEL or PHEL Charts and the NIOSH PEL concept; it must be recognized that heat strain will be readily apparent with the U.S. Navy PEL or PHEL when physiological heat exposure limits are reached, but the strain will be reversible if the limits are not exceeded. On the other hand the NIOSH PEL was designed to restrict deep body temperature rises to a maximum of 38°C.

Following the original research design of six equal increments of t_{wm} MR from "76 - 126 kcal/($m^2 \cdot hr$)" [now in equivalent metric units of 88.4 - 146.5 $W \cdot m^{-2}$] the PHEL Chart development continued by obtaining exposure limit curves for 100.0, 123.3 and 134.9 $W \cdot m^{-2}$. The number of subjects, number of observations and other pertinent information regarding each curve are summarized in Table 2 below, with equations for the respective PHEL curves given in the Stress/Strain Evaluation Program (STEP-M2) Abbreviated in the Appendix. As indicated previously, the t_{wm} WBGT range was 31.1 - 51.7°C.

Table 2

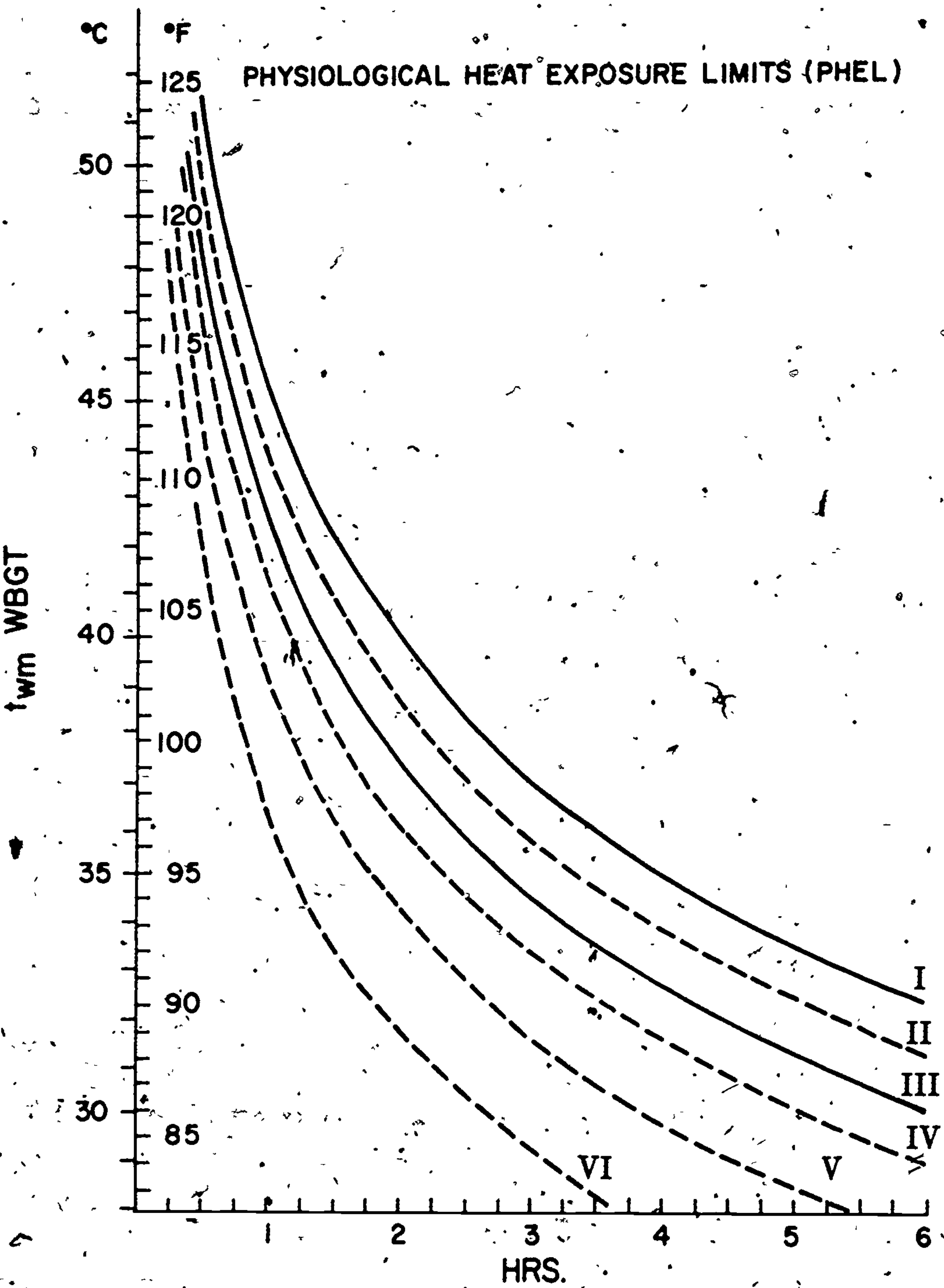
t_{wm} MR ($W \cdot m^{-2}$)	Laboratory Data: No. Subj.	Laboratory Data: No. Obser.	Laboratory Data: Power Reg. r	Field Data: No. Subj.	Field Data: No. Obser.	Field Data: Power Reg. r
88.4	32	147	-0.997 *(t = 155.1063)	18	66	-0.995 *(t = 79.6997)
100.0	26	132	-0.998 *(t = 180.0070)	16	52	-0.994 *(t = 64.2589)
111.7	28	137	-0.997 *(t = 149.6623)	18	57	-0.992 *(t = 58.2778)
123.3	25	128	-0.997 *(t = 144.5875)	15	48	-0.993 *(t = 57.0198)
134.9	17	67	-0.987 *(t = 49.3516)	7	20	-0.978 *(t = 19.8907)
146.5	11	46	-0.989 *(t = 44.3516)	5	12	-0.975 *(t = 13.8756)

* t statistics from correlation coefficients, using Hewlett-Packard HP-65 STAT 2-16A transposed for Hewlett-Packard HP-67/97; df = $n_{obser.} - 2$; all t values significant at $p < 0.0001$. Ages of subjects from 19 - 43 years; all subjects health classified as "fit for duty" and each subject experienced in work tasks performed at the t_{wm} MR's.

Utilization of all of the data resulted in the equation $PHEL_{specific}$ given in the Appendix (STEP-M2 Section) for t_{wm} MR's 88.4 - 146.5 $W \cdot m^{-2}$ and t_{wm} WBGT's 31.1 - 51.7°C. Comparing $PHEL_{specific}$ exposure times with the "Safe Exposure Times" given by Bell et. al.[8] indicated that the upper and lower 99% confidence limits of $PHEL_{specific}$ are safe for >95% of the population of subjects; for >99% of the population the lower 99% confidence limits from $PHEL_{specific}$ were safe, but the upper 99% confidence limits exceeded the classification of "safe".

Figure 1 is the PHEL Chart as developed for operational usage and released in the revision of Chapter 3 (Ventilation and Thermal Stress Ashore and Afloat) of the Manual of Naval Preventive Medicine.[37] However, for practical situations which do not need all six of the PHEL curves, an abbreviated PHEL Chart was issued[38] which contains only PHEL curves I ("A"), III ("B") and VI ("C"); the abbreviated PHEL Chart is also given in the Manual of Naval Preventive Medicine.[37]

Figure 1



Curve I ("A") for t_{wm} MR 88.5 $W \cdot m^{-2}$; Curve II for t_{wm} MR 100.0 $W \cdot m^{-2}$; Curve III ("B") for t_{wm} MR 111.7 $W \cdot m^{-2}$; Curve IV for t_{wm} MR 123.3 $W \cdot m^{-2}$; Curve V for t_{wm} MR 134.9 $W \cdot m^{-2}$; and, Curve VI ("C") for t_{wm} MR 146.5 $W \cdot m^{-2}$.

Statistical comparison of adjacent PHEL curves I - IV, within the t_{wm} WBGT range of 35 - 45°C, are presented in Table 3. Paired data from field trials show that the adjacent PHEL curves, based upon the physiological heat tolerance criteria from Table 1, are significantly different.

Table 3

Statistics	Comparison Of Adjacent PHEL Curves		
	I vs. II	II vs. III	III vs. IV
Paired t	10.8489	7.9242	6.4916
df	33	18	19
p	< 0.0001	< 0.0001	< 0.0001

The series of intermittent work-rest cycles in Table 4 demonstrate the utility of the PHEL Chart within the steady state oxygen consumption versus physical activity descriptions given in the ASHRAE Handbook of Fundamentals.[39] In contrast with the intermittent work-rest limits suggested by Esso Research & Engineering Co.,[40] a limited number of calculations using $PHEL_{specific}$ for light and moderate work showed that the large percent differences between the Esso approach and PHEL are related to the more conservative physiological limits criteria used by Esso compared to the criteria limits in Table 1 of this text.

Table 4

PHEL Curves For Intermittent Work-Rest *

Physical Activity **	Work O_2 Consump. ($L \cdot min^{-1}$)	No. Minutes Work/No. Minutes Rest				
		10/50	20/40	30/30	40/20	50/10
Standing	0.50	---	---	---	---	I
Average Light Work	0.75	---	I	II	III	IV
Upper Light to Lower Moderate Work	1.00	---	II	IV	VI	---
Average Moderate Work	1.25	I	III	VI	---	---
Upper Moderate to Lower Heavy Work	1.50	II	V	---	---	---
Average Heavy Work	1.75	II	VI	---	---	---
Upper Heavy to Lower Very Heavy Work	2.00	III	---	---	---	---
Average Very Heavy Work	2.25	IV	---	---	---	---
Upper Very Heavy Work	2.50	IV	---	---	---	---

* Use of this approach involves the selection of the closest PHEL curve representing the t_{wm} MR appropriate to the work-rest cycle at the specified level of physical activity. An alternate approach is to use $PHEL_{specific}$ as given in STEP-M2 of the Appendix.

** As indicated in Table 5 of ASHRAE Handbook of Fundamentals.[39]

Another important set of comparisons with the PHEL concept is given in Table 5. As WBGT increased 8 - 11 percent and MR remained the same it was expected that heat tolerance times would decrease and cardiovascular strain would increase, or cardiovascular reserve would decrease. In Table 5, due to changing the environmental temperatures, WBGT increased within each set of physical activities, the PHEL decreased and estimated cardiovascular reserve[15,22] (CVR) decreased; therefore, the stress increased and the strain also increased. However, the work of Nishi and Gagge[41] to predict both comfort and heat tolerance through use of the PZ does not agree with the above expectations. Although a deep body temperature rise limit of 38.0°C for the PZ may be practical for instituting sound health practices of a preventive nature (such as providing drinking water, etc.), as environmental temperatures increase (like that in the proposed OSHA Heat Standard), the limit of 38.0°C again does not define heat tolerance limits of man. Furthermore, as previously noted relative to the HSI, a negative HSI does not necessarily mean the presence of "mild cold stress".

Table 5

"1-Hr. Heat Tolerance" Using Prescriptive Zone *					Other Comparisons **			
Activity	T_{db} & T_g (°C)	T_{wb} (°C)	P_w partial (Torr)	RH*** (%)	HSI	WBGT (°C)	PHEL (hr:min)	CVR (%)
Sedentary	35.4	35.4	43.1	100	-52.1	35.4	5:10	56
(58.2 W·m^{-2})	42.2	34.8	37.9	61	137.9	37.0	4:00	52
	47.8	34.3	33.7	41	75.9	38.4	3:20	48
Light Work	34.3	34.3	40.5	100	-57.3	34.3	2:50	45
(116.3 W·m^{-2})	41.7	33.8	35.4	59	82.8	36.2	2:05	40
	46.9	33.3	31.4	40	62.3	37.4	1:40	37
Medium Work	34.1	34.1	40.1	100	-85.7	34.1	0:10	32
(174.5 W·m^{-2})	41.7	33.8	35.4	59	88.7	36.2	0:05	26
	47.2	33.4	31.5	39	66.5	37.6	0:05	22
"30-Min. Heat Tolerance" Using Prescriptive Zone *								
Medium Work	34.9	34.9	41.9	100	-55.8	34.9	0:10	30
(174.5 W·m^{-2})	42.2	34.8	37.9	61	157.9	37.0	0:05	24
	48.3	34.6	34.2	40	89.0	38.7	0:05	19

* Adapted from Nishi and Gagge.[41]

** Using STEP-M2 Abbreviated (See Appendix), with PHEL's rounded to the nearest 5 mins.

*** Relative humidity, as obtained from STEP-M2 Abbreviated.

Note: There are considerable differences within the literature as to definitions of physical activity relative to MR, therefore, the MR's given in this table are those appropriate to uses by Nishi and Gagge.[41] PHEL's of very short lengths of time are comparable with Bell et. al.[8] in the sense that the PHEL's would be "safe" for 99% of the population of unacclimatized, fit exposees.

Initial Field Surveys and Development of Analyses and Corrective Programs

A series of 15 special field surveys were conducted in industrial-type environments. The operational objectives of the surveys were to determine the range of thermal conditions to which workers were exposed, the magnitude of physiological strain during routine work in these environments, and to attempt to identify primary problem areas where corrective engineering actions could most significantly minimize high levels of heat stress. In order to permit comprehensive and more expeditious monitoring of the environment and physiological parameters a number of techniques, developed originally for laboratory research, were introduced into the field surveys. Critical data from the 15 initial surveys are summarized in Table 6.

Table 6

	Average Range	Maximum Range
Environmental Factors:		
Dry-bulb Temp. (°C)	46.7 - 55.0	65.6 - 73.9
Wet-bulb Temp. (°C)	29.4 - 33.9	40.6 - 73.9
Globe Temp. (°C)	63.3 - 67.2	68.3 - 82.2
Effective Air Movement Over Men (m/sec)	0.10 - 1.78	1.78 - 7.62
Mean Radiant Temp. (°C)	75.6 - 85.0	87.2 - 106.7
Partial Vapor Pressure In Air (Torr)	17.6 - 53.9	11.9 - 82.0
Relative Humidity (%)	14.9 - 68.9	6.2 - 100.0
Physiological Factors:		
Mean Skin Temp. of Men (°C)	38.8 - 41.6	41.9 - 45.4
Rectal Temp. (°C)	38.6 - 39.3	39.4 - 40.2
Heart Rates (beats·min^{-1})	147 - 176	180 - 190

As has been presented in this text, there are many combinations of environmental and physiological factors which can be used to obtain practical estimates of environmental stress and to predict the impact of heat stress upon and within man. Fortunately, the computer programs SPEEDARD-I and -II* have been in large scale usage[42] to integrate heat stress and strain data. These programs, designed for bulk data processing in a Univac 1108 at the National Bureau of Standards, were reviewed and markedly condensed to provide the most significant 20 outputs for these special field surveys. The resultant SHIP-6/4 program, requiring only 7 inputs, was modified for operation in a Hewlett-Packard HP-65 Programmable Pocket Calculator.[42] SHIP-6/4 was gradually improved as there were needs for more descriptive information as the surveys proceeded. The most important change, prior to designing the third generation program STEP**, was to develop the equations for estimating mean skin temperature (T_{sk}) and rectal temperature (T_{re}) from 213 sets of data (See Table A-1 of the Appendix); in turn, the estimated T_{sk} was used as a means of better correcting radiant (R) and convective (C) heat transfer, E_{req}, E_{max} and HSI. Furthermore, cardiovascular factors monitored in both laboratory and field studies, within the heat stress ranges noted in Table 6, were selected for their value in STEP programs. The techniques for monitoring the cardiovascular factors, steps to carry out the necessary calculations, and meaning of the products have been presented elsewhere.[15,22] The pertinent aspects relative to t_{wm} MR's from 50.0 - 146.5 W·m^{-2} and t_{wm} WBGT's from 19.8 - 49.7°C are presented in the Appendix (Tables A-2 - A-5 and STEP-M2). Therefore, in the

* Unique computer programs within the Heat Stress Division, NMRI.

** STEP is the master program used to develop STEP-M2 Abbreviated as given in the Appendix.

final development of the STEP series of programs, for the most advanced, programmable, self-contained, portable calculator*, the cardiovascular factors were incorporated with heat stress analysis equations such that one could easily obtain practical estimates of environmental heat stress and resultant physiological strain. To assist the many requests for the now obsolete SHIP-6/4 program written for the HP-65, and the increasing number of requests for STEP-M2 Abbreviated, the HP-97 program is given in the Appendix for STEP-M2 Abbreviated. STEP-E2 is the same as STEP-M2, but STEP-E2 is written for mixed English and metric inputs and outputs. Another advantage of the STEP programs is the section which permits calculation of maximum allowable exposures (MAE) for noise levels without hearing protection; as noise levels were monitored in all heat stress surveys, this portion of the STEP programs became very important.

Key to analysis of heat stress data from surveys is the quality of the heat stress data obtained from the industrial-type environments. Therefore, two series of evaluations were conducted to find a simple, light weight, fast response, small electronic device which measures and displays values for T_{db}, T_{wb}, T_g and air velocity within desired accuracies while exposed to dynamic heat stress conditions.[43,44] Over the range of temperatures to be encountered and the types of hard usage and shipping constraints, there were five such devices** evaluated in changing environmental situations, as viewed by the devices. In reality, there were fixed environments of different T_{db}, T_{wb}, T_g and air movements which the electronic monitoring devices were moved into and out of for 30 minutes or more. From the standpoint of T_{db} and T_{wb} sensors absorbing radiant heat, the Bendix units were the most influenced and the Reuter-Stokes units were the least influenced by the radiant heat. From the standpoint of fastest T_g response, the Reuter-Stokes devices were the most comparable (within less than three minutes) with the values obtained from a Vernon globe that had been in position for 30 minutes or more. The electronic device which best met the defined performance needs[45] was the Reuter-Stokes digital display unit that had been built as part of a six-sensing head monitor system.

A composite of the environmental and physiological findings from the special heat stress surveys was assembled and subjected to critical review at various levels of policy, research and development, and operational supervision. This led to the formulation of a high temperature/heat stress correction program which was divided into seven major categories; maintenance, medical, design, development, education/training, emergency ventilation problems, and related topics. Each of the categories had a number of sub-elements to accomplish the objectives of the categories. The most decisive phase of the total program was to determine if a routine engineering overhaul was sufficient to minimize the heat stress and strain or if additional corrective engineering actions were required.

Three separate industrial-type settings were used to compare the impact of routine overhauls and the additional corrective engineering actions. Settings No. 1 and No. 2 were alike in terms of layout of machinery, types of machinery and operational status. Setting No. 3 was documented to be the highest heat stress industrial-type setting found during the special heat stress surveys. A general comparison of what was to be done is given in Table 7. The emphasis of the additional corrective engineering actions was to ensure that steam leaks were reduced as much as possible, that the majority of heat radiating surfaces were sufficiently insulated, and that there was a more effective delivery of ventilating air to work sites and improved exhaust of air from the areas. These actions were undertaken to produce a combined effect of increasing the economy and performance of both the workers and the equipment. Followup evaluations, after returning the Settings to full

* Hewlett-Packard HP-97; for HP-67 operations delete SPC steps and it is recommended that R/S steps be substituted for PRTX steps.

** Light Laboratories Min-Lab 3 (England), with anemometer; Bendix WBGT Meter (manufactured 1972), finely adjusted prototype with anemometer; Bendix WBGT Meter (manufactured 1975), pre-production unit without anemometer; Reuter-Stokes RSS-211 Analog Readout, commercial grade without anemometer; and Reuter-Stokes RSS-211 Special Digital Readout unit [also known as the NMR&D MK-I/S(LED)], a linearized unit with anemometer.

operation, were scheduled at approximately six month intervals for no less than one year.

Table 7

Industrial Setting No.	Basic Approach
1	To receive a routine overhaul and completion of previously scheduled alterations.
2	To receive a routine overhaul, completion of the same previously scheduled alterations as Setting No. 1, and accomplishment of additional corrective engineering actions. (Setting No. 2 was used for the most direct comparison with Setting No. 1)
3	To receive a routine overhaul, completion of previously scheduled alterations, and accomplishment of additional corrective engineering actions. (Setting No. 3 was to serve as a means of evaluating the benefits of the additional engineering actions in what had been the highest heat stress setting found during the special heat stress surveys.)

Present Results of Engineering Actions to Minimize High Heat Stress

Comparative environmental and physiological data from followup evaluations for the corrective action program in industrial-type Settings No. 1 - No. 3 have revealed significant reductions of high heat stress and physiological strain through a comprehensive approach to the total problem, rather than pursuing routine overhauls in anticipation that the overhauls alone will significantly minimize heat stress. Table 8 clearly shows that it was possible to decrease the level of heat stress, even in the worst thermal stress situation reported here, to the point where routine maintenance could be conducted much more efficiently and a small reduction of heat stress continued over a one year time after restoring the Setting back into operation.

Table 8

Averaged Data from 14 Sites in Setting No. 3

Environmental Factors and PHEL's	Pre-Corrective Actions	Post-Corrective Actions 6 Months	12 Months
T_{db} (°C)	53.9	37.1	39.6
T_{wb} (°C)	33.5	26.8	27.0
T_g (°C)	71.5	43.9	41.2
Effective Air Velocity Over Workers (m/sec)	1.15	1.27	1.27
* T_r (°C)	102.5	53.9	43.3
P_w partial (Torr)	29.7	21.6	20.7
t_{wm} WBGT (°C)	43.2	31.3	31.2
PHEL's for t_{wm} MR's: (hrs:mins)			
88.4 $W \cdot m^{-2}$	1:20	7:10	7:10
146.5 $W \cdot m^{-2}$	0:20	2:10	2:10

* T_r = mean radiant temperature.

Summarized results of PHEL values, body temperatures and cardiovascular factors are presented in Table 9 for all three industrial-type settings. This information clearly indicates the value of a comprehensive approach to heat stress rather than expecting routine engineering overhauls alone to combat high heat stress.

Table 9

Averaged Data from Settings No. 1, No. 2 & No. 3

Setting No.	Corrective Action Phase	PHEL (hrs:mins) Normal t_{wm} MR	PHEL (hrs:mins) Maximum t_{wm} MR	T_{sk} (°C)	T_{re} (°C)	Cardiovascular Factors * HR	SP/DP	MAP	CVR
2	30 Days Post-Action	8:00+	6:00	34.6	37.8	98	138/77	95	83
	6 Mos. Post-Action	8:00+	6:00	34.8	37.5	98	137/76	95	84
	12 Mos. Post-Action	8:00+	3:40	35.0	37.6	98	134/74	93	87
1	8 Mos. Post-Action	3:20	1:00	37.5	39.0	128	207/51	75	15
3	Pre-Action	1:20	0:20	44.9	39.8	180	184/42	71	1
	6 Mos. Post-Action	7:10	2:10	36.4	38.1	107	165/75	93	63
	12 Mos. Post-Action	7:10	2:10	34.8	37.5	109	171/72	92	59

* The cardiovascular factors are defined and in the following units: HR = heart rate (beats·min^{-1}); SP = systolic blood pressure (mm Hg); DP = diastolic blood pressure (mm Hg); MAP = estimated mean arterial blood pressure (mm Hg); and, CVR = estimated cardiovascular reserve (%).

The cardiovascular responses in Setting No. 1 were such during the first one-third of the trials that compensation was approaching its maximum; thereafter, there was rapid decompensation due to the excessively high level of heat stress at the same time that workers were attempting to perform their normal tasks. As discussed earlier, the low HR's were not descriptive of heat tolerance limits being reached as the strain was shifted to other aspects of the cardiovascular system.

Summary

Major accomplishments have been achieved during the past few years in the control of industrial heat stress. It is highly encouraging to note that, through the strong support of management[46] and the capability of biomedical R&D to assist both management and industrial-type workers that significant reductions of excessive heat stress are a reality today. The utilization of research technology has permitted the establishment of an objective basis to dramatically improve highly-limiting heat stress situations which have had a profound, adverse impact upon man and industry.

Documentation of the ranges of industrial heat stress and the physiological responses to that stress was the first step in initiating a direct attack upon high levels of heat stress. Once evidence could be produced to show the problems involved, a series of phases were formulated whereby the goals of reduced levels of heat stress, increased work function and availability of objective exposure limits were instituted to guide the design of better working environments. The establishment of comprehensive physiological heat exposure criteria was imperative in order to develop true exposure limits. As exposure limits are a function of the intensity of the exposure, length of time in the specific environment and the rate of performing work under those conditions, it was possible to develop the PHEL concept and exposure limit curves which recognized that physiological strain would be present but also would be reversible. Meanwhile, a series of computer programs were prepared to integrate the variables of heat stress and strain. This was done in such a manner as to permit practical partitioning of the components of the stress, serve as a guide in making recommendations that would produce significant changes of the environment, and better predict alterations of limiting physiological systems.

The benefits of the program to date have been illustrated in terms of a marked reduction of physiological strain and nearly a sixfold increase of maximum exposure times for greater productivity. In areas where corrective engineering actions from the program are not yet existent or are not completed, the PHEL concept and associated guidelines[37] have not resulted in a detectable increase of morbidity. However, it is very likely that none of the operational exposure limiting methods today can be safe for all workers, even though there is reasonable assurance that the PHEL concept is safe in a practical sense up to the limits for greater than 95 percent of the fit population of workers within the range of 19 - 43 years of age. Therefore, in support of Dinman et. al.,[47] a standard for heat stress must neither be overly conservative on the side of the workers nor too liberal on the side of management. The most practical approach to an industrial-type standard for heat tolerance limits is where workers perform within their limits as shown herein, while at the same time a concerted effort is made to minimize the intensity of the environmental stresses.

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Appendix

Table A-1 Summary of T_r Encountered versus T_{sk} Determined and T_{re} Measured *

T_r Range (°C)	N	T_r Encountered (°C)	T_{sk} Determined (°C)	T_{re} Measured (°C)
32.2 - 37.7	24	33.9 ± 0.37	33.4 ± 0.13	36.6 ± 0.31
37.8 - 43.3	44	40.9 ± 0.18	34.5 ± 0.14	37.5 ± 0.04
43.3 - 48.8	16	45.7 ± 0.42	35.1 ± 0.24	37.7 ± 0.04
48.9 - 54.4	22	51.3 ± 0.28	35.8 ± 0.13	38.0 ± 0.07
54.5 - 59.9	20	57.3 ± 0.30	36.6 ± 0.18	38.1 ± 0.09
60.0 - 65.5	15	63.3 + 0.41	38.3 ± 0.36	38.4 ± 0.03
65.6 - 71.1	22	68.0 ± 0.33	39.3 ± 0.31	38.6 ± 0.03
71.2 - 76.6	12	74.1 ± 0.47	39.7 ± 0.08	38.8 ± 0.02
76.7 - 82.2	12	79.5 ± 0.52	40.6 ± 0.09	39.1 ± 0.03
82.3 - 87.7	15	84.4 ± 0.43	41.4 ± 0.07	39.2 ± 0.02
87.8 - 93.3	11	90.4 ± 0.51	42.5 ± 0.08	39.5 ± 0.02

* Subjects age range 19 - 43 years. Subjects normally clothed. T_r range 32.2 - 93.3 °C. t_{wm} MR range 50.0 - 146.5 $W \cdot m^{-2}$. All values given in above Table are expressed as Mean ± Standard Error when appropriate. Total N = 213.

Best fit estimates of T_{sk} and T_{re}:

Estimated T_{sk} (°C)

$$T_{sk} = 28.857 \cdot e^{4.321 \cdot 10^{-3}\, T_r}$$

N = 213
r = 0.953
t = 45.4796
p < 0.0001

Estimated T_{re} (°C)

$$T_{re} = 27.366 + (2.678 \ln T_r)$$

N = 213
r = 0.944
t = 41.5976
p < 0.0001

T_r = mean radiant temperature. T_{sk} = mean skin temperature. T_{re} = rectal temperature. t_{wm} MR = time-weighted-mean metabolic rate.

Appendix

Table A-2 Summary of Cardiovascular Factors versus t_{wm} WBGT at t_{wm} MR 50.0 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 19.8 - 22.2°C)				
	20.8 ± 0.1 (n = 27)	21.4 ± 0.2 (n = 16)	20.7 ± 0.2 (n = 22)	18.9 ± 0.1 (n = 19)	20.6 ± 0.1 (n = 15)
HR	81.7 ± 1.5	94.0 ± 2.4	90.6 ± 1.6	83.7 ± 2.6	76.0 ± 3.5
SP	130.8 ± 1.2	130.9 ± 1.9	130.3 ± 1.1	128.3 ± 0.8	124.9 ± 2.5
DP	78.5 ± 1.4	80.7 ± 1.4	83.1 ± 1.1	84.5 ± 0.7	72.5 ± 2.0
MAP	95.9 ± 1.2	97.4 ± 1.4	98.6 ± 0.9	99.1 ± 0.5	89.8 ± 2.1
CO *	4.9 ± 0.1	5.2 ± 0.2	4.9 ± 0.1	4.4 ± 0.1	5.1 ± 0.1
TVR	1572.7 ± 48.9	1526.7 ± 57.0	1641.9 ± 42.2	1801.9 ± 50.9	1430.2 ± 57.2
CVR	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0	100.0 ± 0.0

Table A-3 Summary of Cardiovascular Factors versus t_{wm} WBGT at t_{wm} MR 88.4 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 2[illegible].8 - 39.5°C)				
	26.4 ± 0.5 (n = 22)	30.5 ± 1.1 (n = 5)	32.7 ± 1.4 (n = 5)	35.4 ± 1.0 (n = 8)	37.8 ± 0.0 (n = 4)
HR	86.0 ± 3.1	106.0 ± 1.9	119.0 ± 4.1	105.6 ± 1.6	152.5 ± 3.2
SP	122.8 ± 1.4	138.0 ± 4.0	119.0 ± 4.0	121.9 ± 3.2	103.8 ± 1.3
DP	73.3 ± 1.8	82.8 ± 2.3	82.4 ± 2.4	63.4 ± 5.0	34.8 ± 3.5
MAP	89.7 ± 1.5	101.2 ± 2.6	94.6 ± 2.9	82.7 ± 4.0	57.8 ± 2.6
CO *	5.6 ± 0.2	6.4 ± 0.5	6.3 ± 0.3	8.3 ± 0.5	15.7 ± 0.8
TVR	1288.4 ± 35.6	1277.9 ± 56.9	1216.3 ± 89.9	829.5 ± 83.1	298.6 ± 0.8
CVR	88.1 ± 3.5	91.1 ± 4.9	69.2 ± 3.2	32.8 ± 5.8	9.6 ± 3.6

Values given as Mean ± Standard Error. t_{wm} = time-weighted-mean. HR = heart rate ($beats \cdot min^{-1}$). SP = systolic blood pressure (mm Hg). DP = diastolic blood pressure (mm Hg). MAP = mean arterial pressure (mm Hg). CO * = estimated cardiac output ($liters \cdot min^{-1}$); these values are conservative estimates. TVR = estimated total vascular resistance ($dynes \cdot sec \cdot cm^{-5}$). CVR = estimated cardiovascular reserve (%).

Appendix

Table A-4 Summary of Cardiovascular Factors versus t_{wm} WBGT at 111.7 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 20.7 - 49.7°C)				
	24.1 ± 0.5 (n = 22)	29.3 ± 1.5 (n = 5)	31.3 ± 0.0 (n = 4)	30.7 ± 0.6 (n = 11)	44.9 ± 1.4 (n = 12)
HR	8[illegible].5 ± 1.8	112.4 ± 2.7	91.5 ± 0.3	99.8 ± 2.5	145.3 ± 9.7
SP	126.[illegible] ± 1.3	146.2 ± 1.9	117.5 ± 0.9	119.2 ± 3.8	143.4 ± 8.5
DP	72.7 ± 1.4	78.4 ± 2.7	69.0 ± 0.6	59.6 ± 4.0	51.3 ± 3.2
MAP	90.4 ± 1.1	101.0 ± 1.8	85.0 ± 0.8	79.3 ± 3.9	82.0 ± 4.0
CO *	6.1 ± 0.2	7.2 ± 0.5	6.5 ± 0.1	7.6 ± 0.3	14.4 ± 1.4
TVR	1208.7 ± 44.9	1142.4 ± 107.6	1047.5 ± [illegible].4	867.7 ± 76.6	505.[illegible] ± 55.3
CVR	83.2 ± 3.3	64.1 ± 13.8	63.7 ± 1.4	35.5 ± 5.4	15.3 ± 5.0

Table A-5 Summary of Cardiovascular Factors versus t_{wm} WBGT at 146.5 $W \cdot m^{-2}$

Factors	t_{wm} WBGT (range 21.7 - 37.3°C)				
	25.2 ± 0.4 (n = 31)	29.5 ± 0.6 (n = 19)	31.6 ± 1.0 (n = 12)	34.1 ± 0.8 (n = 12)	36.4 ± 0.0 (n = 6)
HR	90.9 ± 0.9	115.1 ± 3.3	122.6 ± 6.4	110.1 ± 1.9	131.8 ± 3.2
SP	131.7 ± 1.5	147.7 ± 3.0	136.3 ± 3.5	129.6 ± 3.5	116.8 ± 3.0
DP	79.1 ± 0.7	67.0 ± 1.7	70.3 ± 3.9	64.1 ± 3.8	27.5 ± 1.1
MAP	96.3 ± 0.7	93.9 ± 1.7	92.2 ± 1.9	85.9 ± 3.4	57.3 ± 0.4
CO *	5.1 ± 0.1	9.6 ± 0.4	8.1 ± 0.7	7.8 ± 0.4	14.7 ± 0.3
TVR	1534.4 ± 28.7	807.9 ± 38.5	971.4 ± 71.8	923.0 ± 89.5	313.5 ± 8.5
CVR	78.1 ± 2.1	43.9 ± 3.4	43.4 ± 5.5	38.6 ± 6.0	1.1 ± 0.8

Values given as Mean ± Standard Error. t_{wm} = time-weighted-mean. HR = heart rate ($beats \cdot min^{-1}$). SP = systolic blood pressure (mm Hg). DP = diastolic blood pressure (mm Hg). MAP = mean arterial pressure (mm Hg). CO * = estimated cardiac output ($liters \cdot min^{-1}$); these values are conservative estimates. TVE = estimated total vascular resistance ($dynes \cdot sec \cdot cm^{-5}$). CVR = estimated cardiovascular reserve (%).

Appendix

Thermal Analysis Metric Equations For Stress/Strain Evaluation Program (STEP-M2) Abbreviated

Saturated Vapor Pressures:

$$P_{s,T} = [\text{Antilog}\ (2.339 - X \cdot Y)] \cdot P$$

where: $P_{s,T}$ = saturated vapor pressure at T_{db} or T_{wb} = (Torr)

$$X = \frac{[A^3(1.17 \cdot 10^{-8})] + [A\ (5.868 \cdot 10^{-3}) + 3.244]}{1 + [A\ (2.188 \cdot 10^{-3})]}$$

$$A = 647.27 - [(T_{db} \text{ or } T_{wb}) + 273.15]$$

$$Y = \frac{A}{(T_{db} \text{ or } T_{wb}) + 273.15}$$

T_{db} = dry-bulb temperature (°C)

T_{wb} = wet-bulb temperature (aspirated) (°C)

P = barometric pressure (Torr)

Solve using T_{db} for $P_{s,T_{db}}$; and, T_{wb} for $P_{s,T_{wb}}$

Partial Vapor Pressure:

$$P_w \text{ partial} = P_{s,T_{wb}} - [[(6.6 \cdot 10^{-4}\ P)(T_{db} - T_{wb})] \cdot [1 + (T_{db} - T_{wb})\ 1.5\ 10^{-3}]]$$

where: P_w partial = (Torr)

Relative Humidity:

$$RH = (P_w \text{ partial} / P_{s,T_{db}}) \cdot 100 = (\%)$$

Mean Radiant Temperature:

$$T_r = [(T_g + 273.15)^4 + [(0.247 \cdot 10^9\ V^{0.5})(T_g - T_{db})]]^{0.25} - 273.15$$

where: T_r = mean radiant temperature (°C)

T_g = globe temperature (°C)

V = air velocity (m/sec)

Terms, where appropriate, are consistent with the International Union of Physiological Sciences. (Glossary of Terms for Thermal Physiology, JAP 6(35):941-961, 1973)

Once a symbol is defined herein the repeat of the symbol is not redefined.

Appendix

Estimated Skin Temperature:

$$T_{sk} = 28.857\, e^{4.321 \cdot 10^{-3}\, T_r} = (°C)$$

where: Estimated T_{sk} is applicable to normally clothed man within the ranges of T_r 32.2 - 93.3 °C and time-weighted-mean metabolic rate 50.0 - 146.54 $W \cdot m^{-2}$. ($N = 213$, $r = 0.953$, $t = 45.4796$, $p<0.0001$)

Estimated Rectal Temperature:

$$T_{re} = 27.37 + (2.68\ \mathrm{Ln}\ T_r) = (°C)$$

where: Estimated T_{re} is applicable to normally clothed man within the ranges of T_r 32.2 - 93.3 °C and time-weighted-mean metabolic rate 50.0 - 146.54 $W \cdot m^{-2}$. ($N = 213$, $r = 0.944$, $t = 41.5976$, $p<0.0001$)

Radiant Heat Exchange:

$$R = \frac{[13.130\ (T_r - T_{sk})]}{m^2}\ 0.7 = W \cdot m^{-2}$$ (reduced 30% due to clothing)

where: m^2 = DuBois surface area from $[71.84 \cdot 10^{-4}\ Ht^{0.725} \cdot W^{0.425}]$, where Height in cm. and Weight in kg.

Convective Heat Exchange:

$$C = \frac{[13.456\ V^{0.58}\ (T_{db} - T_{sk})]}{m^2}\ 0.7 = W \cdot m^{-2}$$ (reduced 30% due to clothing)

Evaporation Required For Heat Balance:

$$E_{req} = t_{wm}\ MR + R + C = W \cdot m^{-2}$$ (using R and C as reduced above)

where: t_{wm} = time-weighted-mean

As in the case of t_{wm} Metabolic Rate the following applies

$$t_{wm}\ MR = \frac{[(t_1 \cdot MR_1) + (t_2 \cdot MR_2) + \ldots + (t_n \cdot MR_n)]}{t_1 + t_2 + \ldots + t_n}$$

where: t_1 is the first time interval and MR_1 is the metabolic rate for the respective time interval, etc.

Appendix

Maximum Evaporative Capacity:

$$E_{max} = \frac{[25.15\ V^{0.58}\ [[(T_{sk} - 34.94)\ 2.34] + 42.00] - P_w \text{ partial}]}{m^2} 0.7$$

where: $E_{max} = W \cdot m^{-2}$ (reduced 30% due to clothing)

Heat Stress Index (Belding and Hatch):

$HSI = [(E_{req}/E_{max}) \cdot 100]$ (unitless)

Wet-Bulb Globe Temperature Index: (See Text)

$WBGT = [(0.1\ T_{tb}) + (0.7\ T_{wb}) + (0.2\ T_g)] = (°C)$

Physiological Heat Exposure Limits (Dasler): (See Text)

PHEL I ("A") for t_{wm} MR 88.39 $W \cdot m^{-2}$

$PHEL\ I = 741.594 \cdot 10^6\ WBGT^{-5.369}$

where: PHEL in hrs. with mins. in decimal; PHEL converted to hrs:min in STEP-M2 Abbreviated.

Laboratory data: $N = 147$, $r = -0.997$, $t = 155.1063$, $p < 0.0001$
Field data: $N = 66$, $r = -0.995$, $t = 79.6997$, $p < 0.0001$

PHEL II for t_{wm} MR 106.02 $W \cdot m^{-2}$

$PHEL\ II = 592.561 \cdot 10^6\ WBGT^{-5.356}$

where: PHEL in hrs. with mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 132$, $r = -0.998$, $t = 180.0070$, $p < 0.0001$
Field data: $N = 52$, $r = -0.994$, $t = 64.2589$, $p < 0.0001$

PHEL III ("B") for t_{wm} MR 111.65 $W \cdot m^{-2}$

$PHEL\ III = 487.461 \cdot 10^6\ WBGT^{-5.351}$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 137$, $r = -0.997$, $t = 149.6623$, $p < 0.0001$
Field data: $N = 57$, $r = -0.992$, $t = 50.2778$, $p < 0.0001$

PHEL IV for t_{wm} MR 123.28 $W \cdot m^{-2}$

$PHEL\ IV = 432.399 \cdot 10^6\ WBGT^{-5.371}$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 128$, $r = -0.997$, $t = 144.5875$, $p < 0.0001$
Field data: $N = 48$, $r = -0.993$, $t = 57.0198$, $p < 0.0001$

Appendix

PHEL V for t_{wm} MR 134.91 $W \cdot m^{-2}$

$$PHEL\ V = 334.370 \cdot 10^6\ WBGT^{-5.373}$$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 67$, $r = -0.987$, $t = 49.3516$, $p < 0.0001$
Field data: $N = 20$, $r = -0.978$, $t = 19.8907$, $p < 0.0001$

PHEL VI ("C") for t_{wm} 146.54 $W \cdot m^{-2}$

$$PHEL\ VI = 207.825 \cdot 10^6\ WBGT^{-5.344}$$

where: PHEL in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated.

Laboratory data: $N = 46$, $r = -0.989$, $t = 44.3516$, $p < 0.0001$
Field data: $N = 12$, $r = -0.975$, $t = 13.8756$, $p < 0.0001$

$PHEL_{specific}$ for t_{wm} MR range 88.39 - 146.54 $W \cdot m^{-2}$

$$PHEL_{spec.} = [17.251 \cdot 10^8 - (12.967 \cdot 10^6\ t_{wm}\ MR) + (18.611 \cdot 10^3\ t_{wm}\ MR^2)] . WBGT^{-5.360}$$

where: $PHEL_{specific}$ in hrs. and mins. in decimal; PHEL converted to hrs:mins in STEP-M2 Abbreviated. $PHEL_{specific}$ applies to WBGT's through 55 °C. The first three coefficients of $PHEL_{specific}$ were derived from PHEL's I - VI above; $N = 6$, $r = 0.994$, $t = 18.4887$, $p < 0.0001$. Exponent for WBGT based upon $N = 6$ with SE ±0.005.

Estimated Recovery Times:

Minimum Recovery Time = $PHEL_{spec.} \cdot 1.195$

where: $PHEL_{specific}$ prior to conversion to hrs:mins.
Minimum recovery time based upon a minimum Relaxation Allowance of 119.5% (See Footnote). STEP-M2 converts to hrs:mins.

General Recovery Time = $PHEL_{spec.} \cdot 1.994$

where: $PHEL_{specific}$ prior to conversion to hrs:mins.
General recovery time based upon a general Relaxation Allowance of 199.4% (See Footnote). STEP-M2 converts to hrs:mins.

Maximum Recovery Time = $PHEL_{spec.} \cdot 2.260$

where: $PHEL_{specific}$ prior to conversion to hrs:mins.
Maximum recovery time based upon a maximum Relaxation Allowance of 226.0% (See Footnote). STEP-M2 converts to hrs:mins.

Relaxation Allowance concept from: Curie, R. M. Work Study. Coppelark Pub., Co.; Toronto, Canada. (Chapter 12, pp. 156 - 164). Reprinted 1969.

Appendix

<u>Cardiovascular Factors Without Subjectively Detectable Levels Of Fuel Combustion Gases or Pre-Combustion Fuel Vapors:</u>

<u>Heart Rate</u> (beats$\cdot$min^{-1})

$$HR = [48.15 + (0.08\ t_{wm}\ MR) + (1.64\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.4052$	$t = 7.3497$	$p < 0.0001$
	$r_{y \cdot xz} = 0.6518$	$t = 14.2531$	$p < 0.0001$
	$r_{z \cdot xy} = 0.6519$	$t = 14.2544$	$p < 0.0001$

<u>Systolic Blood Pressure</u> (mm Hg)

$$SP = [125.67 + (0.06\ t_{wm}\ MR) \quad (0.08\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.5741$	$t = 11.6279$	$p < 0.0001$
	$r_{y \cdot xz} = 0.5627$	$t = 11.2876$	$p < 0.0001$
	$r_{z \cdot xy} = 0.1526$	$t = 2.5610$	$p < 0.012$

<u>Diastolic Blood Pressure</u> (mm Hg)

$$DP = [107.88 - (0.01\ t_{wm}\ MR) - (1.29\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.5215$	$t = 10.1349$	$p < 0.0001$
	$r_{y \cdot xz} = 0.7196$	$t = 17.1839$	$p < 0.0001$
	$r_{z \cdot xy} = 0.6906$	$t = 14.2607$	$p < 0.0001$

<u>Mean Arterial Pressure</u> (mm Hg)

$$MAP = [109.669 + (0.022\ t_{wm}\ MR) - (0.765\ WBGT)]$$

$N = 277$	$r_{x \cdot yz} = 0.4862$	$t = 9.2265$	$p < 0.0001$
	$r_{y \cdot xz} = 0.6079$	$t = 12.6957$	$p < 0.0001$
	$r_{z \cdot xy} = 0.4445$	$t = 8.2293$	$p < 0.0001$

Subscripts of multiple correlation coefficients (r's) apply as follows: $x = t_{wm}$ MR, y = WBGT, and z = cardiovascular factor.

Breakdown of sets of observations as follows: t_{wm} MR 50.01 W$\cdot$m^{-2} (N = 99), t_{wm} MR 88.39 W$\cdot$m^{-2} (N = 45), t_{wm} MR 111.65 W$\cdot$m^{-2} (N = 52), and t_{wm} MR 146.54 W$\cdot$m^{-2} (N = 81); WBGT's obtained as t_{wm} during the determine t_{wm} MR's. Total N = 277 per cardiovascular factor, t_{wm} MR and WBGT.

Appendix

Estimated Cardiac Output (liters·min^{-1}) (See Text regarding evidence of conservative estimates by the technique utilized)

$$CO = [-2.608 - (0.001\ t_{wm}\ MR) - (0.765\ WBGT)]$$

N = 277	$r_{x \cdot yz} = 0.5345$	$t = 10.4876$	$p < 0.0001$
	$r_{y \cdot xz} = 0.8186$	$t = 23.6327$	$p < 0.0001$
	$r_{z \cdot xy} = 0.7842$	$t = 20.9612$	$p < 0.0001$

Estimated Cardiovascular Reserve (%) (See Text)

$$CVR = [170.978 - (0.242\ t_{wm}\ MR) - (2.843\ WBGT)]$$

N = 277	$r_{x \cdot yz} = 0.6229$	$t = 13.2033$	$p < 0.0001$
	$r_{y \cdot xz} = 0.7879$	$t = 21.2174$	$p < 0.0001$
	$r_{z \cdot xy} = 0.8305$	$t = 24.7231$	$p < 0.0001$

Supplementary Section Of STEP-M2 Abbreviated:

Maximum Allowable Exposure Time Without Hearing Protection * Based Upon Noise Level

$$MAE_{noise} = [\text{AntiLn}\,[(db\ A - 105.00)/-7.21]]$$

where: db A = noise level on "slow" A scale

Note: The above equation is a transposition of a logarithmic curve fit with r = 1.0000; the equation may also be written as an exponential curve fit (with r = 1.0000) in the following form:

$$MAE_{noise} = 2097151.954\, e^{-0.138629\ db\ A}$$

* From data provided in: Control of Noise (12), American Foundrymen's Society, 3rd Ed., 1972.

Bureau of Medicine and Surgery, Navy Department, BUMED Instruction 6260.6B, 5 March 1970.

Data from these sources were subjected to the least squares family of regression curves to provide the above equations.

Appendix

STEP-M2 Abbreviated Program For Hewlett-Packard Calculator (HP-97)*

(Total running time, including inputs and all prints, averages 1 min. 56 sec.)

Inputs:

T_{db} (LBL A); T_{wb} (LBL B or R/S); T_g (LBL C or R/S); V (LBL D or R/S); t_{wm} MR (LBL E or R/S). [T_{db} must be entered using key "A"; T_{wb}, T_g, V and t_{wm} MR may be entered by using the designated key or by use of R/S key. Using the user defined key permits altering the sequence of entries; however, STEP-M2 starts running immediately after entering t_{wm} MR.]

Grouped Order of Printing: (each group separated by a space)

[T_{db}; T_{wb}; T_g; V; t_{wm} MR] [$P_{s,T_{db}}$; $P_{s,T_{wb}}$; $P_{w\ partial}$] [RH] [T_r] [R; C; E_{req}; E_{max}] [WBGT] [$PHEL_{specific}$] [Minimum Recovery Time; General Recovery Time; Maximum Recovery Time] [PHEL I; PHEL II; PHEL III; PHEL IV; PHEL V; PHEL VI] [HSI] [T_{sk}; T_{re}] [HR; SP; DP; MAP; CO; CVR] [T_{db}; T_{wb}; T_g; V; t_{wm} MR are repeated at the end as a means of rechecking and/or permitting comparisons]

Supplementary Portion of STEP-M2 for MAE_{noise}:

Two options exist for calculating MAE_{noise}: (1) After STEP-M2 has run as given above, input db A using key "A" and MAE_{noise} will be printed in hrs:mins provided the program from Card #4 is still in the HP-97; or, (2) Insert Card #4 (both sides) and input db A using key "A" to get MAE_{noise} printed.

Card #1

001	*LBLA	017	SPC	033	3	049	STO3	065	7	081	STO8
002	DSP2	018	.	034	.	050	RCLB	066	EEX	082	X
003	STOA	019	5	035	1	051	RCLI	067	CHS	083	÷
004	PRTX	020	8	036	5	052	÷	068	8	084	3
005	R/S	021	y^x	037	STOI	053	STO4	069	STO7	085	.
006	*LBLB	022	STO0	038	+	054	RCL6	070	X	086	2
007	STOB	023	RCLD	039	STO2	055	X≠Y	071	RCL3	087	4
008	PRTX	024	R/S	040	6	056	-	072	5	088	3
009	R/S	025	*LBLE	041	4	057	STO5	073	.	089	8
010	*LBLC	026	STOE	042	7	058	RCL3	074	8	090	STO9
011	STOC	027	PRTX	043	.	059	ENT↑	075	6	091	÷
012	PRTX	028	SPC	044	2	060	X^2	076	8	092	RCL3
013	R/S	029	SPC	045	7	061	X	077	3	093	2
014	*LBLD	030	RCLA	046	STO6	062	1	078	EEX	094	.
015	STOD	031	2	047	X⇄Y	063	.	079	CHS	095	1
016	PRTX	032	7	048	-	064	1	080	3	096	8

* (from title) STEP-M2 Abbreviated provides 68% of the full STEP-2 Program. The program as given herein permits autoloading of Sides #1 of Cards #2 - #4; when Sides #2 of Cards #2 - #4 are entered the program restarts automatically, should and ERROR display occur reenter Sides #1 and #2 of that Card and press key R/S to continue program. All factors printed in units of time are printed as hrs.mins, the decimal point serves as a colon (:); e.g., 3.55 in units of time is 3:55 as hrs:mins.

Appendix

Card #1, continued

097	7	156	2	215	RCLI
098	8	157	.	216	+
099	EEX	158	3	217	ENT↑
100	CHS	159	3	218	ENT↑
101	3	160	8	219	ENT↑
102	X	161	8	220	X
103	1	162	X⇄Y	221	X
104	+	163	-	222	X
105	÷	164	10^x	223	PSE
106	RCL3	165	7	224	RTN.
107	RCL2	166	6		
108	÷	167	0		
109	X	168	X		
110	2	169	STO4		
111	.	170	PRTX		
112	3	171	6		
113	3	172	.		
114	8	173	6		
115	8	174	EEX		
116	X⇄Y	175	CHS		
117	-	176	4		
118	10^x	177	STO7		
119	7	178	RCLA		
120	6	179	RCLB		
121	0	180	-		
122	X	181	STO1		
123	STO2	182	RCL7		
124	DSP1	183	7		
125	PRTX	184	6		
126	RCL5	185	0		
127	ENT↑	186	X		
128	X^2	187	X		
129	X	188	RCL1		
130	RCL7	189	1		
131	X	190	.		
132	RCL5	191	1		
133	RCL8	192	5		
134	X	193	EEX		
135	+	194	CHS		
136	RCL9	195	3		
137	+	196	X		
138	RCL5	197	1		
139	2	198	+		
140	.	199	X		
141	1	200	RCL4		
142	8	201	X⇄Y		
143	7	202	-		
144	8	203	PRTX		
145	EEX	204	STO6		
146	CHS	205	SPC		
147	3	206	RCL2		
148	X	207	÷		
149	1	208	EEX		
150	+	209	2		
151	÷	210	X		
152	RCL5	211	DSPØ		
153	RCL4	212	PRTX		
154	÷	213	SPC		
155	X	214	RCLC		

Card #2

001	RCLC	048	2	107	4	166	5
002	RCLA	049	7	108	-	167	1
003	-	050	.	109	2	168	EEX
004	RCLD	051	3	110	.	169	8
005	$\sqrt{x}$	052	7	111	3	170	RCLE
006	.	053	+	112	4	171	1
007	2	054	STO3	113	X	172	2
008	4	055	RCL1	114	4	173	.
009	7	056	RCL2	115	2	174	9
010	EEX	057	÷	116	.	175	6
011	9	058	1	117	0	176	7
012	X	059	3	118	0	177	EEX
013	X	060	.	119	+	178	6
014	+	061	1	120	RCL6	179	X
015	$\sqrt{x}$	062	3	121	-	180	-
016	$\sqrt{x}$	063	0	122	RCLØ	181	RCLE
017	RCLI	064	X	123	X	182	X^2
018	-	065	-	124	2	183	1
019	STO1	066	7	125	5	184	8
020	DSP1	067	X	126	.	185	.
021	PRTX	068	1	127	1	186	6
022	SPC	069	.	128	5	187	1
023	4	070	8	129	X	188	1
024	.	071	5	130	.	189	EEX
025	3	072	STOI	131	7	190	3
026	2	073	÷	132	X	191	X
027	1	074	STO4	133	RCLI	192	+
028	EEX	075	PRTX	134	÷	193	RCL9
029	CHS	076	RCLA	135	STO8	194	5
030	3	077	RCL2	136	PRTX	195	.
031	X	078	-	137	SPC	196	3
032	e^x	079	RCLØ	138	RCL7	197	6
033	2	080	X	139	X⇄Y	198	0
034	8	081	1	140	÷	199	CHS
035	.	082	3	141	EEX	200	y^x
036	8	083	.	142	2	201	X
037	5	084	4	143	X	202	STO5
038	7	085	5	144	STO4	203	→HMS
039	X	086	6	145	RCLA	204	DSP2
040	STO2	087	X	146	.	205	PRTX
041	RCL1	088	.	147	1	206	SPC
042	LN	089	7	148	X	207	RCL5
043	2	090	X	149	RCLB	208	1
044	.	091	RCLI	150	.	209	1
045	6	092	÷	151	7	210	9
046	8	093	STO5	152	X	211	.
047	X	094	PRTX	153	+	212	5
		095	RCLE	154	RCLC	213	%
		096	RCL4	155	.	214	→HMS
		097	RCL5	156	2	215	PRTX
		098	+	157	X	216	RCL5
		099	+	158	+	217	1
		100	STO7	159	STO9	218	9
		101	PRTX	160	PRTX	219	9
		102	RCL2	161	SPC	220	.
		103	3	162	1	221	4
		104	4	163	7	222	PSE
		105	.	164	.	223	RTN
		106	9	165	2	224	R/S

Card #3

001	%	060	CHS	119	4	178	0
002	→HMS	061	y^x	120	CHS	179	8
003	PRTX	062	4	121	y^x	180	X
004	RCL5	063	8	122	2	181	-
005	2	064	7	123	0	182	PRTX
006	2	065	.	124	7	183	1
007	6	066	4	125	.	184	0
008	.	067	6	126	8	185	7
009	0	068	1	127	2	186	.
010	%	069	EEX	128	5	187	8
011	→HMS	070	6	129	EEX	188	8
012	PRTX	071	X	130	6	189	RCLE
013	SPC	072	→HMS	131	X	190	.
014	RCL9	073	PRTX	132	→HMS	191	0
015	5	074	RCL9	133	PRTX	192	1
016	.	075	5	134	SPC	193	X
017	3	076	.	135	DSP1	194	-
018	6	077	3	136	RCL4	195	RCL9
019	9	078	7	137	PRTX	196	1
020	CHS	079	1	138	SPC	197	.
021	y^x	080	CHS	139	RCL2	198	2
022	7	081	y^x	140	PRTX	199	9
023	4	082	4	141	RCL3	200	X
024	1	083	3	142	PRTX	201	-
025	.	084	2	143	SPC	202	PRTX
026	5	085	.	144	4	203	1
027	9	086	3	145	8	204	0
028	4	087	3	146	.	205	9
029	EEX	088	9	147	1	206	.
030	6	089	EEX	148	5	207	6
031	X	090	6	149	RCLE	208	6
032	→HMS	091	X	150	.	209	9
033	PRTX	092	→HMS	151	0	210	RCLE
034	RCL9	093	PRTX	152	8	211	.
035	5	094	RCL9	153	X	212	0
036	.	095	5	154	+	213	2
037	3	096	.	155	RCL9	214	2
038	5	097	3	156	1	215	X
039	6	098	7	157	.	216	+
040	CHS	099	3	158	6	217	RCL9
041	y^x	100	CHS	159	4	218	PSE
042	5	101	y^x	160	X	219	RTN
043	9	102	3	161	+	220	R/S
044	2	103	3	162	DSPØ		
045	.	104	4	163	PRTX		
046	5	105	.	164	1		
047	6	106	3	165	2		
048	1	107	7	166	5		
049	EEX	108	0	167	.		
050	6	109	EEX	168	6		
051	X	110	6	169	7		
052	→HMS	111	X	170	RCLE		
053	PRTX	112	→HMS	171	.		
054	RCL9	113	PRTX	172	0		
055	5	114	RCL9	173	6		
056	.	115	5	174	X		
057	3	116	.	175	+		
058	5	117	3	176	RCL9		
059	1	118	4	177	.		

Card #4

001	.	014	CHS	073	SPC
002	7	015	RCLE	074	RTN
003	6	016	.	075	*LBLA
004	5	017	0	076	DSP1
005	X	018	0	077	PRTX
006	-	019	1	078	SPC
007	DSP1	020	X	079	1
008	PRTX	021	-	080	0
009	2	022	RCL9	081	5
010	.	023	.	082	.
011	6	024	3	083	0
012	0	025	5	084	0
013	8	026	6	085	-
		027	X	086	7
		028	+	087	.
		029	PRTX	088	2
		030	1	089	1
		031	7	090	CHS
		032	0	091	÷
		033	.	092	e^x
		034	9	093	DSP2
		035	7	094	→HMS
		036	8	095	PRTX
		037	RCLE	096	SPC
		038	.	097	SPC
		039	2	098	SPC
		040	4	099	SPC
		041	2	100	SPC
		042	X	101	RTN
		043	-	102	R/S
		044	RCL9		
		045	2		
		046	.		
		047	8		
		048	4		
		049	3		
		050	X		
		051	-		
		052	DSPØ		
		053	PRTX		
		054	SPC		
		055	SPC		
		056	SPC		
		057	SPC		
		058	RCLA		
		059	DSP2		
		060	PRTX		
		061	RCLB		
		062	PRTX		
		063	RCLC		
		064	PRTX		
		065	RCLD		
		066	PRTX		
		067	RCLE		
		068	PRTX		
		069	SPC		
		070	SPC		
		071	SPC		
		072	SPC		

EFFECT OF ENERGY CONSERVATION GUIDELINES ON COMFORT, ACCEPTABILITY AND HEALTH

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Abstract

Both the Winter and Summer Surveys in a New York government building validate the recommendations of ASHRAE STANDARD 55-74 that the optimum acceptable thermal environment, in which at least 80% of normally clothed men and women living in the United States and Canada would express thermal comfort, lies in the range 72°-78° (°F) ET* (22.2°-25.6° C). The ASHRAE ET* is the dry bulb temperature of a uniform thermal environment at 50% rh with air movement in range 20-25 fpm (0.1-0.125 m/s) for sedentary man (1.-1.2 mets) while wearing an intrinsic thermal insulation of 0.6 Clo.

The FEA Summer Conservation Temperature limits of 78°-80° F (25.6°-26.7° C) can be made 80% acceptable (1) by use of light clothing with insulation less than 0.4 Clo, (2) by increasing the air movement above 50 fpm, (3) by reducing the relative humidity, or (4) by all. These FEA Guidelines, which require the elimination of thermostats and reheat processes, make (1) and (2) the more desirable approaches to 80% acceptability. In summer time heat, men tend to wear 50% more clothing (insulation) than women, while at work. In summer the practical minimum level of clothing insulation for men appears to be 0.4-0.5 Clo while for women, 0.2-0.3 Clo.

For the 68°-70° F (20°-21.1° C) FEA Conservation Guideline temperatures for winter, the 80% acceptability is possible for persons wearing 0.9-1.2 Clo insulation, provided proper care is made to cover legs with socks and trousers or wear dresses with stockings and with shoes without open toes.

Except for the seriously ill and those in hospitals, there appears to be no serious health hazard for properly clothed individuals due to exposure to the FEA Winter and Summer Guideline Temperatures.

For simple sedentary tasks, no decrements in performance can be expected for the FEA Guideline temperatures - winter or summer - as long as the applicable ASHRAE ET* falls within the 80% acceptability range defined by our Comfort Charts in terms of T_a, Clo, air movement and relative humidity. A loss of dexterity may occur when air temperature falls below 65° F (18.3° C). Decrements in the performance of simple manual and mental tasks may occur when the ASHRAE ET* rises above 90° F (32.2° C).

Comfort Charts are presented to show how various clothing insulations can be used to convert any combination of dry bulb temperature, relative humidity, air movement to an equivalent ASHRAE Effective Temperature ET*. From these charts the reader can recognize for himself additional strategies possible to meet the 72°-78° F (22.2°-25.6° C) ET* necessary for 80% acceptability.

Key Words: Effective Temperature (ET*), Clothing Insulation, Thermal Acceptability, Energy Conservation, Thermal Preference Survey, Winter Temperature Guidelines, Summer Temperature Guidelines

*late Fellow of the Pierce Foundation

CONSERVATION OF ENERGY BY REDUCING FUEL CONSUMPTION for heating during winter and for air conditioning during summer is an easy technical possibility when the living space is cooler than normal in the winter and warmer without humidity control in the summer. The question arises, how can these changes be accomplished without losing the general acceptability of such a working environment. Based on the combined advice of many professional organizations, assembled for a three day conference in November 1973 at Airlie House, Arlington, the Federal Energy Administration (FEA) introduced in summer 1974 their <u>Guidelines for Comfort Conditions in Government Buildings and Homes in General</u>. For winter, indoor temperatures were to be set at 68°-70° F (20-21.1° C) and for summer at 78-80° F (25.6-26.7° C). The summer setting would be accomplished <u>without</u> humidity control and reheat. These design values were chosen as being 6° F (3.3° C) above and below the optimum level of 75° F (23.9° C) currently set by ASHRAE Standard 55-74, Thermal Environmental Comfort Conditions for Human Occupancy.

In July 1974, the late Dr. Ralph Nevins, and the Pierce Foundation, were contracted by the FEA to initiate a series of laboratory tests and field surveys to determine occupant reaction to their proposed Guidelines. The complete report has been published (March, 1976)(1). In the present paper we will briefly summarize results and general implications of the two field surveys in a New York GSA multistory office building. My associate Dr. Richard Gonzalez is covering the laboratory tests associated with the present study and will present their behavioral implications. In the present paper we will summarize from a short literature survey the expected effect of the FEA Guidelines on man's health and performance. Finally we will present a series of working charts by which the reader can see how changes in humidity, ambient temperature, air movement, clothing habits and activity can attain environmental acceptability within the Guidelines as well as compliance with the ASHRAE Standard 55-74, which requires an Effective Temperature, (ET*) that lies in range 72-78° F (22.2 -25.6° C).

THE SUMMER SURVEY OF THERMAL PREFERENCE

The summer survey of thermal preferences was made of typical groups of workers in the General Services Building, 26 Federal Plaza, New York City. Of the 46 floors in the GSA Building, the 23rd, 26th, 33rd and 39th floors were selected for the survey. Approximately 230 people were questioned twice; in all approximately 460 responses were obtained. During the distribution and completion of the questionnaires, the dry and wet temperatures, the air movement, and the Black Globe temperature were evaluated in each local area. From these four basic measurements and from the clothing insulation worn (as determined from the questionnaire) it was possible to describe quantitatively the thermal environment and to correlate these values with the thermal preferences presented. The outside weather data was taken from the daily weather records for the test period (1300-1500 EST) at Central Park. These records agreed well with casual readings in the shade at street level outside of the GSA Building itself.

During the survey period the outside weather temperature averaged 75.3° F (24° C); the average dew point was 61.4° F (16° C) which corresponded to an average humidity of 60% rh. The average dry bulb temperature indoors, was 74° F (23.3° C) with a dew point of 58° F (14.5° C) and relative humidity of 59%. The range of indoor temperatures surveyed extended from 72.5° F (22.5° C) to 78° F (25.5° C). Over half the responses were made at temperatures between 72° F and 75° F. Due to the generally pleasant outdoor weather conditions and an obvious lack of need for air conditioning indoors, none of the test conditions fell in the FEA Summer Guideline area.

For the survey group the average intrinsic <u>clo</u> was 0.45 for males and 0.35 for females. For both sexes the metabolic rate was estimated as 1 met. There were no significant relationships to age.

By using cross-correlation methods of analysis, the following significant observations were made:

A. Cross-Tabulations: <u>Temperature Sense</u> vs <u>Comfort Sense</u> (entire group)

	Comfortable			Uncomf.			V. Uncomf.		Totals	
	(Row %)	N	(Col %)	(Row %)	N	(Col %)	(Row %)	N	(Row %)	N
Cold		2	(1)		27	(21)		6		35
Cool		67	(22)		19	(15)		0	(28)	86
Slt. Cool		77	(25)		10	(8)				87
Neutral		117	(38)		7	(5)			(61)	124
Slt. Warm		36	(12)		32	(25)				68
Warm		7	(2)		31	(24)		3	(11)	41
Hot					3	(2)		4		7
Totals	(68)	310	(100)	(29)	129	(100)	(3)	13	(100)	452

The above table shows that:

(1) The % of those voting "Sl. Cool-Neutral-Sl. Warm" and of those voting "Comfortable" were essentially equal at 68%. Thus either grouping may be considered as a good index of acceptable.

(2) Of those voting "Comfortable", there was a tendency to prefer parallel cool sensation over a warm one. This proved specially true both for females and for the 51-70 year age group. This asymmetry was not typical of a general population as most of the test conditions fell in temperature ranges expected for cool and comfortable.

B. Cross-Tabulation: Perspiration Sense vs Comfort Sense

	NONE	(Col. %)	Slight	Moderate	Heavy	% with + PSENS Row %	Col. %	Total
Comf.	222	(78)	70	16	0	28	52	308
Uncomf.	58	(20)	42	27	2	55	43	129
Very Uncomf.	6	(2)	2	4	1	54	3	13
N (Row %)	285	(63)	114 (25)	47 (10)	3 (2)			450

The above table shows that:

(3) Although only about a third of the group stated they had a strong perspiration sense, this sense was associated with "warm" and "uncomfortable" votes.

C. Cross-Tabulation: Dry-Humid Sense vs Temperature Sense

	Very dry		Dry	Normal (Neutral)	Humid		Very Humid	Total
Cold	3		15	14	3		2	37
Cool	2	$\boxed{64}$	19	51	13	$\boxed{27}$	2	87
Slightly Cool	2		23	56	7			88
Neutral	3		23	83	13		1	123
Slightly Warm	3		14	11	37		1	66
Warm		$\boxed{23}$	5	7	23	$\boxed{72}$	6	41
Hot	1			1			5	7
Totals	14		99	223	96		15	449

$\boxed{\Sigma}$ Sum of observations

(4) In judging air quality, described by "Dryness" and "Humid", the former significantly correlated with a sense of "Cool" and the latter with a sense of "Warm".

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D. Cross-Tabulation: Air Flow Sense vs Temperature Sense

Temp. Sense \ Air Flow Sense	Pleasant (with high air movement)	Neutral	Unpleasant (with low air movement)	Total
	N (row %)			
Cold-Cool Sl. Cool	86 (41)	62 (29)	64 (30)	212 (100)
Neutral	32 (26)	63 (51)	28 (23)	123 (100)
Sl. Warm-Warm-Hot	9 (8)	27 (23)	79 (69)	115 (100)
	127 (28)	152 (34)	171 (38)	450 (100)

(5) When air quality was judged by the "Pleasantness" of air flow sense, 66% of the group had a positive feeling divided between "Pleasant" and "Unpleasant". "Pleasant" was usually associated with "Cool" and "Comfortable" sensation and "Unpleasant" with "Warm" and "Uncomfortable" sensations.

E. Cross-Tabulation: Temperature Sense vs Air Temperature

	Cold	Cool	Sl. Cool	Σ Cool (Row %)	Neutral ΣN (Row %)	Σ Warm (Row %)	Sl. Warm	Warm	Hot	Total
≤ 22.5 (72.5° F)	13	13	10	36 (59)	18 (29)	9 (15)	5	2	2	63
22.7 22.5-22.9	6	21	12	39 (42)	30 (33)	33 (36)	15	7	1	92
23.2 23.0-23.4	7	19	26	52 (57)	24 (26)	16 (17)	9	7	0	92
23.7 23.5-23.9	4	11	8	23 (49)	11 (23)	13 (28)	8	4	1	47
24.2 24.0-24.4	0	4	7	11 (33)	7 (21)	15 (45)	6	8	1	33
24.7 24.5-24.9	0	2	6	8 (18)	14 (31)	23 (51)	13	10	0	45
25.2 25.0-25.4	0	0	2	2 (15)	4 (31)	7 (54)	3	2	2	13
≥ 25.0 (77° F)										
Col. Total (Row %) (% Total)	30 (8)	70 (18)	71 (18)	171 (45)	108 (28)	105 (27)	58 (15)	40 (10)	7 (2)	384

(6) Although the maximum probability of those voting both "Cool" and "Warm" occurring at 74.8° F (23.9° C), this temperature did not prove to be the temperature range where the greatest number voted "Acceptable" as judged by "Neutral" and "Comfort" sensations.

F. Cross-Tabulation: Comfort Sense vs Air Temperature

T_a	Comfortable	Uncomfortable	Very Uncomfortable	Total
	(Row %)			
≤ 22.5	37 (60)	22 (35)	3 (5)	62 (100)
22.5-22.9	71 (76)	19 (21)	3 (3)	93 (100)
23.0-23.4	67 (72)	25 (27)	1 (1)	93 (100)
23.5-23.9	31 (62)	18 (36)	1 (2)	50 (100)
24.0-24.4	22 (67)	9 (27)	2 (6)	33 (100)
24.5-24.9	27 (59)	18 (39)	1 (2)	46 (100)
25.0-25.4	9 (69)	2 (15)	2 (16)	13 (100)
≥ 25.5	0	0	0	0
Col. Total (% Total)	264 (68)	113 (29)	13 (3)	390

(7) The entire temperature range of the survey (72.5-77.9° F) or (22.5-25.5° C) was considered comfortable by 68% of those voting and lay, for the most part, on the cool side of the optimum, which would have been expected theoretically at 78° F (25.6° C), for the average clothing worn (≈ 0.4 Clo).

WINTER SURVEY OF THERMAL PREFERENCE

The winter survey was made at the same building location (GSA Building, Federal Plaza, NYC) as the Summer (Task II). The last two weeks in January and the first week in February were chosen for the study. The questionnaire for Winter was essentially the same as that for Summer except for the additional interest in the effect of cold extremities. The sections of the building surveyed were the same as before. All instrumentation was identical to the previous study. The mode of the survey was slightly different in that half of the observations were made in the afternoon and the other half in the morning before lunch.

The number of questionnaires completed was 514 from a maximum of 262 individuals. The number retested was 125.

The outside weather conditions were ideal for the survey and typical for the New York area. The average outdoor temperature was 34° F; the lowest was 17° F and the warmest, 43° F. The outside vapor pressure ranged from 1.6 Torr to 7.1 Torr with an average of 3.6, which value corresponds to a dew point of 30° F.

Indoor temperature during the survey varied widely, due to the poor control of internal temperature by the building engineer. The average indoor temperature was about 77° F; 80% of the observations were evenly distributed over the 73° F-81° F range. The highest zone temperature observed was 84° F while the lowest was 71° F. Although the indoor temperatures were well above the FEA Guideline level of 68°-70° F (in spite of frequent complaints to the building engineer that the test areas were too warm), this relatively even temperature distribution from 73° to 81° made possible a significant statistical analysis of thermal responses over this range so that reasonable projections could be made towards both the FEA Guidelines for both Winter and Summer.

The average dew point temperature was 44° F, corresponding to an average indoor relative humidity of 30%. The average indoor air movement was about 30 ± 10 fpm.

The average intrinsic clothing insulation worn to work was 0.7 clo for men and 0.65 for women. These values are 50% higher for men and 100% higher for women than those observed during the Summer Survey. Thus people dress for work according to outside weather conditions rather than for the expected ideal office temperature or for their often overheated offices in the present building.

From a cross-correlation analysis, the observations with high significance were as follows:

G. Cross-Tabulations: Temperature Sense vs Comfort Sense

Both Sexes	Comfortable	Uncomfortable	Totals
	N (Col %)	N (Col %)	
Cool and Cold	63 (16)	33 (32)	86
Sl. Cool-Neutral-Sl. Warm	299 (76)	9 (9)	308
Warm-Hot	43 (8)	61 (59)	104
Totals	395	103	498

Males	Comfortable	Uncomfortable	Total
	N (Col %)	N (Col %)	
Cool and Cold	18 (10)	6 (16)	
Sl. Cool-Neutral-Sl. Warm	143 (81)	3 (8)	
Warm-Hot	16 (9)	29 (79)	
Totals	177	38	215

Females	Comfortable	Uncomfortable	Total
	N (Col %)	N (Col %)	
Cool and Cold	40 (19)	25 (40)	
Sl. Cool-Neutral-Sl. Warm	143 (68)	6 (9)	
Warm-Hot	27 (13)	32 (51)	
Totals	210	63	273

Age	Col. % Comfortable Age yrs.			Col. % Uncomfortable Age yrs.		
Group	<30	31-50	>50	<30	31-50	>50
Cool-Cold	18	15	15	52	10	41
Sl. Cool-Neutral-Sl. Warm	68	73	76	10	7	10
Warm-Hot	14	12	9	38	83	48

The above tables show:

(1) As high as 79% of all observations were in the "Comfort" category. This sense of comfort was primarily associated with a general neutral thermal sense. Of the remaining, who voted "Uncomfortable", a majority (91%) always associate their feelings with either a sense of coolness (32%) or warmth (59%).

(2) For both men and women, the trend above for "Comfort" was the same. However, for "Uncomfortable", men associate this feeling primarily with warmth, while women were equally divided between cool and warm.

	Comfortable		Uncomfortable	
While Air Flow SENSE was:	Pleasant	Unpleasant	Pleasant	Unpleasant
Col ΣN	274	20	107	80
	(Col %)	(Col %)	(Col %)	(Col %)
Cool-Cold	41 (15)	21 (30)	6 (20)	25 (31)
≈ Neutral	211 (77)	65 (15)	3 (60)	6 (8)
Warm-Hot	22 (8)	21 (55)	11 (20)	49 (61)
			Total (N)	481

(3) A cool air flow sense improved Comfort.

While Comfort was (below), Air Sense was:	Dry			Normal			Humid			Total		
	Row (%)	N	Col (%)									
Comfortable	(48)	193	(75)	(46)	186	(94)	(16)	24	(52)	(100)	403	(80)
Uncomfortable	(66)	66	(25)	(12)	13	(6)	(23)	22	(48)	(100)	100	(20)
Total	(51)	259	(100)	(39)	198	(100)	(10)	46	(100)	(100)	503	(100)

(4) A sense of air dryness in air quality could account for 66% of those voting uncomfortable and coolness.

Cross-Tabulation: Temperature Sense vs Air Temperature

All observations: Winter Study

Temp. Range °C	22.-22.9	23.-23.9	24.-24.9	25.-25.9	26.-26.9	27.-27.9	Total
No. Obs.	38	108	79	102	125	45	497
% Cool-Cold	37	28	24	17	14	0	
% ≈ Neutral (Acceptable)	63	70	67	66	55	24	
% Warm-Hot	0	2	9	17	31	76	

(5) The temperature range for maximum acceptability (i.e. those who do not vote "cool-cold" or "warm-hot"), is (72.5°-76° F) for men at 80% level and (72.5°-78° F) for women at 60% level. For maximum acceptance at 70%, the temperature range is 74°-77.7° which falls within temperature range for Comfort prescribed by ASHRAE Standard 55-74. This is illustrated in Figure 1 for all subjects.

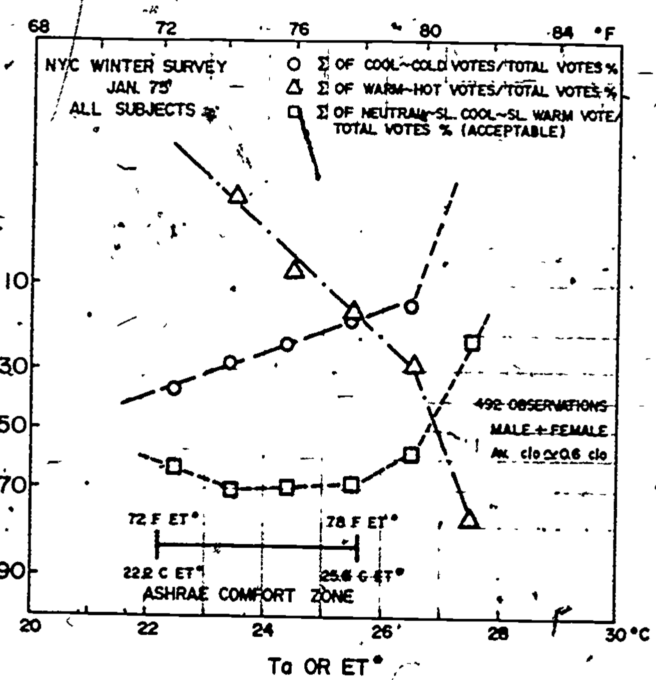


Figure 1. Percent thermal sensation vs T_a on probability coordinates - all subjects. Since average I_{clo} was 0.6 and humidity 40-50% RH, $T_a \cong ET^*$, by definition.

(6) The temperature range for 80% "Comfortable" is 71.5°-78°; for 90% comfortable, the range narrows to 74°-76°. The optimum temperature for Comfort is 75° F for our survey. In terms of ASHRAE ET* (i.e. equivalent temperature for 0.6 Clo and 50% rh), this optimum corresponds to 74° F. This is illustrated in Figure 2 for all subjects.

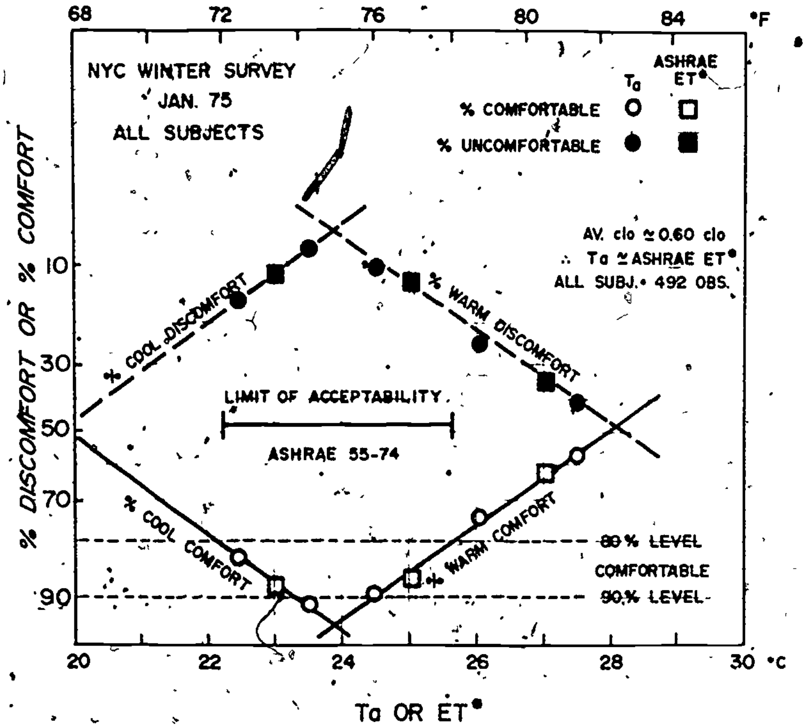


Figure 2. Percent comfort-uncomfortable sensation vs T_a on probability coordinates.

(7) The temperature range for Comfort found in the present survey matches the range for Comfort, prescribed by ASHRAE Standard 55-74.

HEALTH EFFECTS OF MODERATE THERMAL STRESS

The present phase of our FEA study on the effect of the Guidelines was a survey of the literature on the effects of moderate heat and cold stress.

The effects of moderate heat stress have received by far the greatest attention in the literature by clinicians, meteorologists, physiologists and statisticians. The most recent and perhaps now classical study was done by Lee and Henschel (1963)(2) on the effects of heat stress that might be encountered in fallout shelters - a great concern at that period of history. The conclusions of their study were clinical judgments for an abnormal minority of our population under heat stress well above moderate levels. A second now classical series of studies was the work of Burch and DePasquale (1962)(3) summarized in the book on the effects of air conditioning warm and humid chambers on the heart of normal and chronic patients. They did show that heart patients, who showed no deleterious health effects at 75°-76° F (23.9-24.° C) were selected for large exposures to 84°-86° F (28.9°-30° C), a level slightly above the FEA Guidelines.

There is very little in the literature on the effects of moderate cold, which can best be defined as occurring when skin temperature falls below 85° F (29° C). Extreme cold has long been an interest of the Armed Services, whose members must perform at temperatures well below freezing. The laboratory studies, to be reported by Dr. Gonzalez, are the best available for the lower Guideline temperatures (68°-70° F or 20°-21° C).

PERFORMANCE UNDER GUIDELINE TEMPERATURES

The earliest observations on the practical problem of performance of mental and physical tasks for working man appear to be those of Vernon (4) during the First World War. He equated accident frequency with atmospheric conditions (dry bulb temperature) in a munitions factory. For each work spell, the frequency of minor accidents was recorded. A rough calculation of the accident frequency showed that accident frequency was least among workers at shop temperatures of between 65 (18° C) and 69° F (20° C). For cooler ambient temperatures of less than 65° C (18° F) or higher ambient temperatures ≥ 69° F (21° C), the frequency of accidents increased.

The classic studies of Mackworth (1946)(5) and later Pepler (1965)(6) at Oxford were done specifically to quantify any deterioration in task performance as a function of warm ambient conditions. In the studies by Mackworth male wireless telegraph operators, in laboratory conditions, were studied. Their activity would be comparable to our everyday office work. Before the main study the men were acclimatized to heat at 95° F (35° C) for 3 hours a day, 5 or 6 days a week. The actual work procedure was for 3 hrs, at dry bulb temperatures of 85° (29.5° C) to 105° F (40.5° C) and wet bulb temperature 10° F (5.6° C) below DB, during which time 9 messages from a pool of 250 groups were transmitted at a speed of 22 words per minute. The subjects were dressed in gym shorts (approx. 0.1 Clo) and air velocity was at 100 fpm (0.5 m/s). The table below shows their averaged observed data.

Table 1. Average mistakes per hour.

Conditions	T_a °F (°C)	85 (29.4)	90 (32.2)	95 (35.0)	100 (37.8)	105 (40.5)
	Wet bulb °F (°C)	75 (23.9)	80 (26.7)	85 (29.4)	90 (32.2)	95 (35.0)
	RH%	63	65	66	68	69
Av. mistakes/subject per hour		12	11.5	15.3	17.3	94.7
Decrement in performance		0	0	30%	47%	700%

Mackworth's findings showed that increases in both dry bulb and wet bulb temperatures impaired the accuracy of the operators to record messages over the telephone and that decrements in task performance were primarily a function of the skill of the operator. Very skilled operators showed no significant mistakes until DB reached 100° F (38° C) and wet bulb was at 90° F (32° C).

By using the above tabulated basic data, plus the fact that the activity was about 1.1 met, which is typical of the metabolic rates for an office worker, his data have been standardized to the ASHRAE Effective Temperature ET* as shown in the following table.

ASHRAE ET* °F	°C	TSENS[1]	DISC[2]	(w) %	Av. mistakes/subj. per hour	Decrement in performance
74.0	(23.4)	-.1	0.1	6	12	0%
80.6	(27.0)	1.4	.4	13	11.5	0%
88.7	(31.5)	3.0	1.0	26	15.3	30%
98.6	(37.0)	4.6	2.3	51	17.3	47%
109.8	(43.2)	5.2	6.3	100	94.7	700%

[1] -1 - Sl. cool; 0 - Neutral; 1 - Sl. warm; 2 - Warm; 3 - Hot; 4 - Very hot; 5 - Intolerable

[2] 0 - Comfortable; 1 - Sl. uncomfortable; 2 - Uncomfortable; 3 - Very uncomfortable

From the above studies of Mackworth it was clear that up to ET* levels of 80° F (26.7° C) no significant decrement of performance would be expected. The initial decrement could be expected for an average person as ET* rises above 82-84° F (28°-29° C) levels.

Decrements in performance toward the cold for a similar type activity as Mackworth's would depend primarily on the temperature of the fingertips and hands. The vertical finger skin temperature lies about 75° F (24° C) which would occur for normally clothed persons (0.6 ≈ 1 Clo) for ambient temperatures well below the guideline temperature of 68° F (20° C)

Our final conclusion was that the FEA Guideline temperatures for heat and cold should cause no significant drop in performance <u>per se</u>.

ROLE OF CLOTHING IN MEETING BOTH FEA ENERGY CONSERVATION GUIDELINES AND ASHRAE STANDARD 55-74.

In reviewing, the ASHRAE Standard 55-74 (Thermal Environmental Conditions for Human Occupancy) describes the optimum "Comfort Envelope" as being the adjusted dry bulb temperatures falling within an envelope defined on a psychrometric chart by 71.6° F (21.9° C) and 77.6° F (25.3° C) at 14 Torr (1.9 kPa) and by 72.6° F (22.6° C) and 79.7° F (26.5° C) at 5 Torr (0.7 kPa). In terms of the new Effective Temperature (ET*), defined as the adjusted dry bulb temperature at 50% relative humidity, the optimum ET* range lies between 72° F (22.2° C)-78° F (25.6° C). Further this optimum range applies for normally clothed people while engaged in sedentary or near sedentary activities, such as light office work. The Federal Energy Conservation Guidelines for control of indoor environments in government office buildings require that dry bulb settings in the winter be within 68° F (20° C) - 70° F (21° C) and in the summer be 78° F (25.6° C) - 80° F (26.7° C). The feasibility of the higher guideline 80° F (26.7° C) - 82° F (27.8° C) has also been considered. Summer setting should be accomplished without humidity control and reheat. The question is now how do the Standard and Guidelines relate to each other.

The Pierce Laboratory's FEA survey of thermal preference in a typical government office building located in New York City during both the summer, 1974, and winter, 1975, produced two general observations. The first was that, during the winter, an acceptable environment (defined by Standard 55-74 as an expression of thermal comfort by 80% of those surveyed) occurred over the 72-78 ET* range and thus fell within the ASHRAE "Comfort Envelope." Further the average clothing insulation worn in winter was approximately 0.6 clo (intrinsic) for both males and females. The average activity was rated as sedentary office work and fell in range 1.0-1.2 mets (60-70 W/m^2). Air movement observed was within 20-30 fpm (0.10-0.15 m/s). A second general observation was that this same working population habitually clothed themselves for office work according to the season and outdoor weather conditions prevailing rather than for any expectation of the indoor climate, which was on an average 75° F (23.9° C) the year around. During the summer the average clothing insulation worn in New York was 0.4 clo; men wore a slightly higher value of 0.45 clo, compared to the women's 0.35 clo value. Adjusted dry bulb temperatures within 72-78° F range proved to be on cool side while wearing such light clothing during the summer.

Our laboratory study on FEA Winter Guideline Temperatures, which is being covered by my associate Dr. Richard Gonzalez today, shows that the 80% acceptability criterion was possible for groups of subjects exposed to 68° F (20° C), specially if they were given access to additional clothing insulation for comfort. In his study, the wearing of a clothing insulation of about 1.0 clo (intrinsic) proved sufficient to make 68° F (20° C) fall in the 80% acceptability range.

Our Summer Laboratory Study (also covered by Dr. Gonzalez) showed that, when light clothing insulation was worn, it fell in the range 0.3-0.5 clo, and thermal comfort was achieved by the majority of those tested up to 82° F (27.8° C).

Our studies on clothing requirements under FEA Temperature Guidelines Conditions indicate in general that there is a need to relate the equivalence of various levels of clothing insulation worn under various environmental conditions to the Comfort Envelope of ASHRAE Standard 55-74. For this purpose we have used the latest dynamic model of thermal regulation (7) to calculate ASHRAE ET*. The particular feature of this FORTRAN program is that the ET* can be calculated from the basic environmental conditions described by (1) activity (metabolism), (2) operative temperature or ambient air and mean radiant temperature, (3) room air movement, (4) ambient vapor pressure (or relative humidity) and (5) the intrinsic clothing insulation worn. The basic clothing and heat transfer conditions associated with the ASHRAE ET* are used as a standard for comparison. Any thermal environment can be described in terms of the temperature of a standard equivalent environment controlled at 50% relative humidity with air movement of 20-30 fpm (0.1-0.15 m/s) in which a sedentary subject (1-1.2 mets) wearing a standard 0.6 intrinsic clo would exchange the same amount of heat by radiation, convection and evaporation at the same thermal strain, as he would in the actual working environment, described by adjusted dry bulb or operative temperature, air movement and humidity and clothing insulation worn. See Appendix 1 for calculation of ET*.

The primary objective of this section is to show how clothing insulation worn can be used as a key parameter in choosing the proper combination of environmental factors that fit the ASHRAE ET* Comfort Envelope (72-78° F) as defined by ASHRAE Standard 55-74 and secondly to show what practical clothing strategies in conjunction with existing humidity and air movement are possible to make the FEA Winter-Summer Guideline Temperatures fit within the basic ASHRAE Comfort Envelope.

In Figs. 3-6, which are all applicable for sedentary activity, the upper and lower temperature limits for 80% acceptability have been drawn as horizontal lines at 72° F (22° C) and 78° F (25.6° C) ET* on the ordinate in accordance with Standard 55-74. The abscissa is ambient air temperature (T_a = MRT) or the adjusted dry bulb temperature. Our New York survey showed that 90% acceptability would fall within the ET* limits 74° F (23.1° C)-76.5° F (24.5° C). Each figure shows what clothing insulation will result in values of ASHRAE ET* that fall within the 80% acceptability ranges for the air movement and relative humidity indicated.

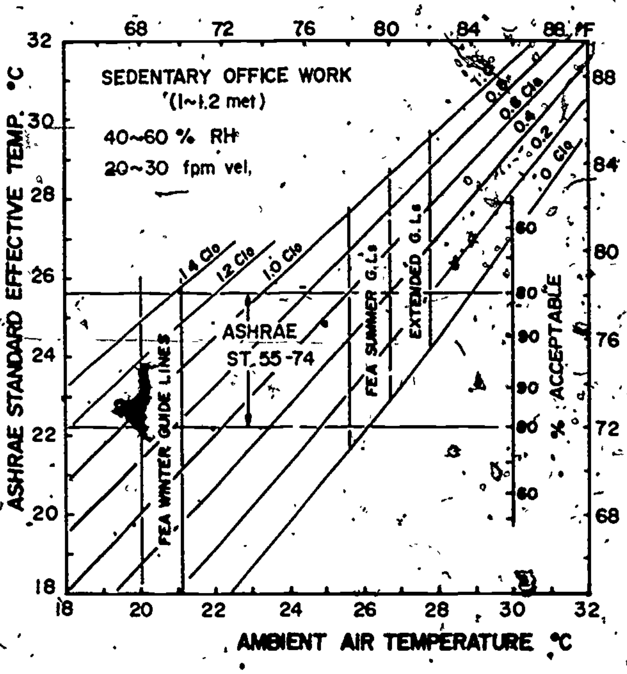


Figure 3. Relation of ASHRAE ET* temperature with varying clothing insulation for 40-60% relative humidity and 20-30 fpm. Note: Since by definition ASHRAE ET* describes the effective temperature as the dry bulb at 50% rh associated with 0.6 Clo and 20-25 fpm, the locus of ET* vs T_a for 0.6 Clo is always a straight line with unit slope.

Figure 3 relates ASHRAE ET* at normal humidity (50% RH) and air movement (0.1-0.15 m/s, 20-30 fpm), to the ambient air temperature or operative temperature (or adjusted dry bulb) for various Clo-levels. The 80% acceptability range of 72°-78° F is covered best by 0.6 clo (by definition). At the FEA Winter Guideline temperature of 68° F (20° C) an acceptable Clo range would be 0.9-1.5. At 72° F (22.2° C) the range of acceptable Clo is 0.6-1.2 clo; at 78° F (25.6° C) the acceptable clo range is 0.1 to 0.6 clo; at 82° F (27.8° C) the range of acceptable Clo narrows to 0-0.2 clo. For 0.4 clo the range of 80% acceptable extends from 74° F (23.3° C) to 80° F (26.7° C).

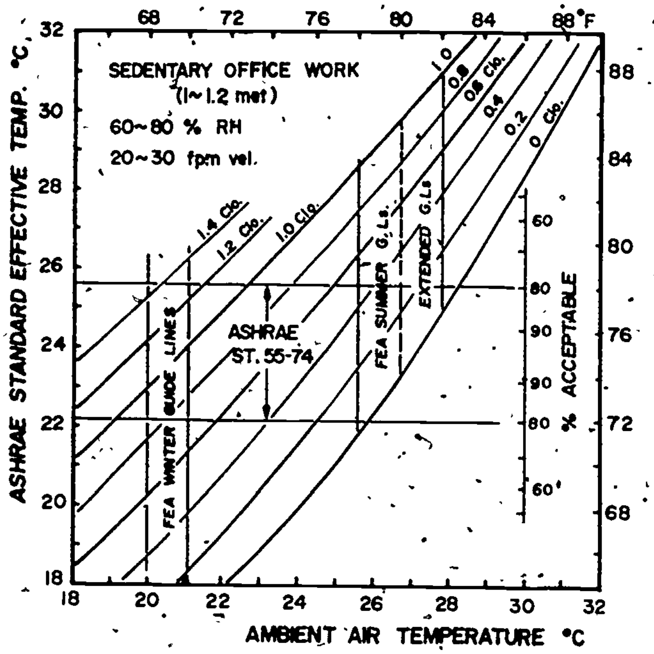


Figure 4. Relation of ASHRAE ET* to T_a with varying Clo insulation for 60-80% rh and other factors the same as in Figure 3. Note: Humidity is typical of summer indoors in NYC.

The conditions for high humidity and normal air movement, such as would occur in summer time, are illustrated in Figure 4. The acceptable clothing limits at 68° F (20° C) remain essentially unchanged over those in Fig. 3. At 80° F, the upper FEA Summer Limit, the acceptable Clo-range would be only 0-0.15 clo, which values are obviously impractical for daily wear. The temperature range for 80% acceptable with 0.6 clo narrows to 72-77° F (22°-25° C) and rises to 75-80° F (23.9-26.7° C).

Low humidities such as would occur indoors during winter time or in desert climates and with normal air movement are illustrated in Fig. 5. The acceptable Clo range for 68° F T_a is slightly higher (1.0-1.6 clo) than values for normal humidity in Fig. 2. A 0.3 clo ensemble would prove effective for the 78-80° F FEA Summer range but only marginally effective at 82° F.

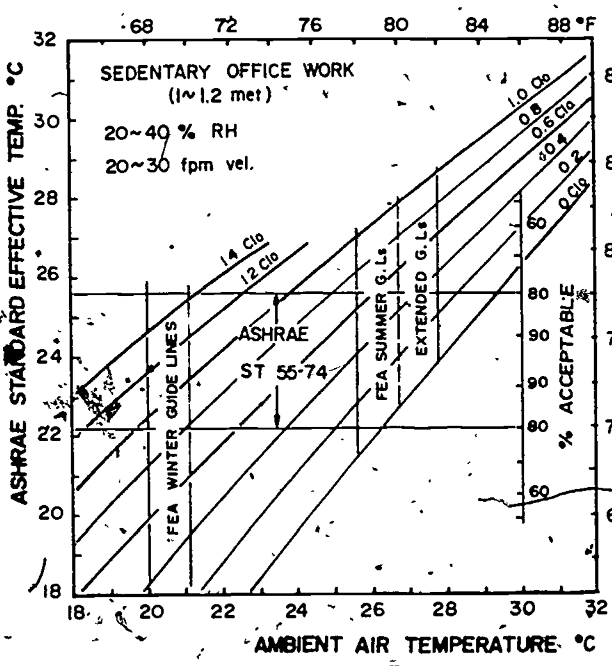


Figure 5. Relation of ASHRAE ET* to T_a with varying clothing insulation for 20-40% RH and other factors the same as in Figure 3. Note: Humidity is typical of winter indoors in NYC.

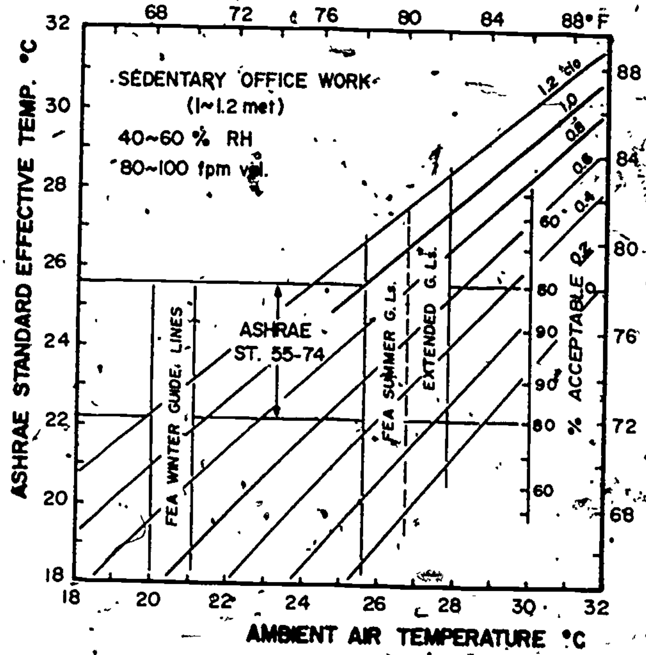
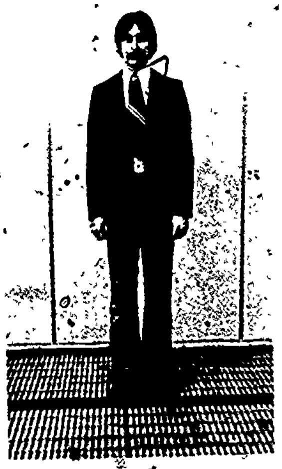


Figure 6. Relation of ASHRAE ET* to T_a with varying clothing for normal humidity and air movement in 80-100 fpm range. Note: Air movement typical under tropical ceiling fans.

Figure 6 demonstrates how air movement (80 ≈ 100 fpm), for example, caused by ceiling fans such as used in the tropics, greatly improves Comfort and acceptability while wearing clothing in range 0.5 ≈ 0.8 clo within the FEA Summer Guideline temperatures.

0.3 0.4 clo
Summer - FEA

0.4 0.6 clo
Summer - Normal



0.7 0.9 clo
Winter - Normal

1 1.1 clo
Winter - FEA

Figure 7: Clothing Ensembles for FEA Summer and Winter Guideline Temperature Ranges

A.

0.15 0.25 clo
Summer - FEA

0.4 0.5 clo
Summer - Normal

0.7 0.8 clo
Winter - Normal

0.9 1.1 clo
Winter - FEA

Figure 7. Clothing Ensembles for FEA Summer and Winter Guideline Temperature Ranges

B.

Figure 7 illustrates typical clothing combinations for both males and females that can be used to meet both the Guideline and ASHRAE Standard 55-74

From the accompanying figures it is clear that a proper choice of clothing insulation can make a wide range of ambient temperatures and air movements fit within the ASHRAE Comfort Envelope specified by Standard 55-74. The figures also show how habitual use of light clothing in summer and warmer clothing in winter allow readjustment of 80% acceptable ambient air temperature and still meet the 72-78° F ET* standard. Finally, these figures show why, as was the case for the old ASHVE Effective Temperature of Houghten and Yaglou (1923), clothing habits of the past caused the preferred ambient temperatures to be slightly higher in the summer than in the winter for the same optimum ET*.

ACKNOWLEDGMENTS:

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APPENDIX 1

Annoted FORTRAN Program for Calculation of ASHRAE ET*

The present program is designed to calculate the ASHRAE ET* when the following basic factors are known and evaluated:

TA	-	ambient air or dry bulb temperature	C
TR	-	the mean radiant temperature	C
VEL	-	room air movement	$m \cdot s^{-1}$
RH	-	relative humidity	as fraction
CLO	-	intrinsic insulation of clothing worn	clo
ACT	-	level of activity in met units	met
(ACT = ACT*58.2 in $W \cdot m^{-2}$ in program)			
WK	-	work accomplished	$W \cdot m^{-2}$

The above factors are defined by READ and DO statements.

The basic physiological terms used to describe the regulatory model are as follows. Secondary definitions will occur in the program itself.

TSK	=	mean skin temperature	C
TCR	=	internal body temperature	C
SKBF	=	skin blood flow	liters $\cdot m^{-2} \cdot h^{-1}$
REGSW	=	regulatory sweating	$g \cdot m^{-2} \cdot h^{-1}$

The following function relating saturation vapor pressure SVP in Torr to temperature T in C is used. The function is known as the Antoine Equation.

SVP(T) = EXP(18.6686-4030.183/(T+235.))

```
C  STEADY STATE CHARACTERISTICS OF MODEL AT THERMAL NEUTRALITY
      TTSK=34.0
      TTCR=36.6
      ALPHA=0.1
      TTBM=ALPHA*TTSK+(1.-ALPHA)*TTCR
      CSW=200.
      CSTR=0.5
      CDIL=150.

C  INITIAL CONDITIONS-PHYSIOLOGICAL THERMAL NEUTRALITY
      TSK=TTSK
      TCR=TTCR
      TBM=ALPHA*TSK+(1.-ALPHA)*TCR
      SKBFN=6.3
      SKBF=SKBFN
      EV=0.1*ACT

C  CLOTHING AND ENVIRONMENTAL HEAT TRANSFER FACTORS AT SEA LEVEL
C  CHCA IS EFF. CHC DUE TO ACT IN STILL AIR (TREADMILL WALKING)
      CHCA=5.66*(ACT/58.2-0.85)**0.39
C  CHCV IS FUNCTION OF ROOM AIR MOVEMENT (VEL)
      CHCV=8.6*VEL**0.53
      IF(CHCV-CHCA) 4,4,5
 4    CHC=CHCA
      GO TO 6
 5    CHC=CHCV
 6    CONTINUE
```

```
C  CHC VALUE FOR STILL AIR IS 3.0 AT SEA LEVEL
 7     IF(CHC-3.) 8,9,9
 8     CHC=3.0
 9     CONTINUE
       FACL=1.+0.15*CLO
       CHR=4.7
       CTC=CHC+CHR
       TO=(CHR*TR+CHC*TA)/CTC
       CLOE=CLO-(FACL-1.)/(0.155*FACL*CTC)
       FCLE=1./(1.+0.155*CLOE)
       FPCL=1./(1.+0.143*CHC*CLOE)
C  TIME OF EXPOSURE SET AT ONE HOUR
       TIM=0.
       TIME=1.
C  SIMULATION OF BODY TEMPERATURE REGULATION - START OF REG. LOOP
 100   CONTINUE
       CLOE=CLO-(FACL-1.)/(0.155*FACL*CTC)
       FCLE=1./(1.+0.155*CTC*CLOE)
       TCL=TO+FCLE*(TSK-TO)
       CHR=4.*5.67E-8*(((TCL+TR)/2.+273.2)**3)*0.725
       CTC=CHR+CHC
       TO=(CHR*TR+CHC*TA)/CTC
       ERES=0.0023*ACT*(44.-RH*SVP(TA))
       CRES=0.0014*ACT*(34.-TA)
C  HEAT FLOW EQUATION AT SKIN SURFACE
       DRY=FCLE*CTC*(TSK-TO)
       ESK=EV-ERES
       HFSK=(TCR-TSK)*(5.28+1.163*SKBF)-DRY-ESK
       HFCR=ACT-(TCR-TSK)*(5.28+1.163*SKBF)-CRES-ERES-WK
C  AVERAGE MAN 70KG, 1.8 SQ.METER
       TCSK=0.97*ALPHA*70.
       TCCR=0.97*(1.-ALPHA)*70.
       DTSK=(HFSK*1.8)/TCSK
       DTCR=(HFCR*1.8)/TCCR
       DTIM=1./60.
       DTBM=ALPHA*DTSK+(1.-ALPHA)*DTCR
       TIM=TIM+DTIM
       TSK=TSK+DTSK*DTIM
       TCR=TCR+DTCR*DTIM
C  DEFINITION OF REGULATORY CONTROL SIGNALS
       SKSIG=TSK-TTSK
       IF(SKSIG) 10,10,15
 10    COLDS=-SKSIG
       WARMS=0.
       GO TO 20
 15    COLDS=0.
       WARMS=SKSIG
 20    CRSIG=TCR-TTCR
       IF(CRSIG) 30,30,35
 30    COLDC=-CRSIG
       WARMC=0.
       GO TO  40
 35    WARMC=CRSIG
       COLDC=0.
 40    CONTINUE
```

```
C  CONTROL SKIN BLOOD FLOW
      STRIC=CSTR*COLDS
      DILAT=CDIL*WARMC
      SKBF=(SKBFN+DILAT)/(1.+STRIC)
C  RELATIVE WT. OF SKIN SHELL TO BODY CORE VARIES WITH SKBF
      ALPHA=0.04415+0.351/(SKBF-0.014)
C  DEFINITION OF CONTROL SIGNALS FOR SWEATING
      TBM=ALPHA*TSK+(1.-ALPHA)*TCR
      BYSIG=TBM-TTBM
      IF(BYSIG) 50,50,55
 50   COLDB=-BYSIG
      WARMB=0.
      GO TO 60
 55   WARMB=BYSIG
      COLDB=0.
 60   CONTINUE
C  CONTROL OF REGULATORY SWEATING
      REGSW=CSW*WARMB*EXP(WARMS/10.7)
      ERSW=0.68*REGSW
      EMAX=2.2*CHC*(SVP(TSK)-RH*SVP(TA))*FPCL
      PRSW=ERSW/EMAX
      PWET=0.06+0.94*PRSW
      EDIF=PWET*EMAX-ERSW
      EV=ERES+ERSW+EDIF
      IF(EMAX-ERSW)  70,70,75
 70   EV=ERES+EMAX
      ERSW=EMAX
      EDIF=0.
      PRSW=1.
      PWET=1.
 75   CONTINUE
      IF(TIM-TIME) 100,110,110
110   CONTINUE
C  END OF REGULATORY LOOP
```

At the end of exposure TIME, all the basic physiological terms listed above are now evaluated for activity and environment defined above. The state of thermal equilibrium (STORE) and the skin heat loss to the environment (HSK) now follow:

```
C  CALCULATION OF HEAT STORAGE
      STORE=ACT-WK-CRES-EV-DRY
C  CALCULATION OF SKIN HEAT LOSS( HSK )
      HSK=ACT-ERES-CRES-WK-STORE
C  CALCULATION OF ASHRAE STANDARD EFFECTIVE TEMPERATURE - SET
C  DEFINITION OF ASHRAE STANDARD ENVIRONMENT
      CHRS=CHR
C  CHCS IS CHCA VALUE FOR ACT SELECTED IN STILL AIR
      CHCS=CHCA
      CLOS=0.6
      FACLS=1.09
      CTCS=CHRS+CHCS
      CLOES=CLOS-(FACLS-1.)/(0.155*FACLS*CTCS)
      FCLES=1./(1.+0.155*CTCS*CLOES)
      FPCLS=1./(1.+0.143*CHCS*CLOES)
C  STANDARD ACTIVITY POINT
      TACTS=TSK-HSK/(CTCS*FCLES)
C  AT START OF ITERATION
      SET=TACTS
```

```
C  DEF. OF SET IS SOLUTION OF HEAT BAL. EQ. WHEN ERROR=0.
 200  ERROR=HSK-CTCS*FCLES*(TSK-SET)-PWET*2.2*CHCS*FPCLS*(SVP(TSK)
     X-0.5*SVP(SET))
      IF(ERROR)210,220,220
 210  SET=SET+0.1
      GO TO 200
 220  CONTINUE
```

For the present analysis, the following printout is useful.

```
      WRITE(1,4000)TA,CLO,ACT,PWET,EMAX,TSK,TCR,TBM,HSK,DRY,EV,STORE,SET
 4000 FORMAT(13F7.2)
```

END of program

The above program applies for sea level conditions and may be used to develop psychrometric tables for clothed subjects in heated, ventilated and air-conditioned environments encountered in normal engineering practice and for prediction of comfortable-acceptable environments, when basic indoor temperatures are determined by a Building Simulation Program such as the National Bureau of Standards NBSLD.

For Fig. 3-6 the following common inputs were used:

ACT	=	1.1 mets for sedentary office work
WK	=	0. $W \cdot m^{-2}$
TIME	=	1. hour
TA	=	TR = TO ^oC

Other environmental factors used are indicated on the figures themselves.

RADIATION MEASUREMENT FOR THERMAL COMFORT ASSESSMENT IN THE BUILT ENVIRONMENT

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Abstract

The major properties of the environment that affect thermal comfort include: air temperature, humidity, air velocity, and thermal radiation. The first two can be readily and accurately measured. Field instrumentation for measuring air velocity has greatly improved in recent years. The fourth quantity, thermal radiation, is still elusive to the HVAC engineers and has often been overlooked or neglected because of the difficulty in measuring it accurately. Thermal radiation as a factor in attaining comfort has traditionally been expressed in terms of the "Mean Radiant Temperature" of the environment. Various instruments have evolved to measure mean radiant temperature. Some are passive and elementary like the Vernon Black Globe while others are active and complex like the Panradiometer, for example. The present paper summarizes the operating principles and the technique of application of the various types of instruments developed in the past, and compares their advantages and disadvantages as to inherent accuracy, ease of operation, simplicity of design, and speed of response. Reviewed are those instruments applicable to the needs of environmental scientists and HVAC engineers for thermal radiation measurement in the built environment. Some development needs and design suggestions are also presented.

Key Words: Thermal radiation, mean radiant temperature, thermal comfort, directional radiant temperature, radiation measurement, radiometer

Introduction

Thermal comfort is perceived when body temperatures can be maintained within certain limits with a minimum amount of physiological regulatory effort. The major environmental properties that affect the outward flow of metabolic energy, physiological strain, and thermal comfort are: air temperature, humidity, velocity, and thermal radiation.

Extensive laboratory studies over the years have quantitized the effects of these parameters on comfort and energy flow. The experimental studies have led to mathematical models, some of the more popular of which are Fanger's Comfort Equation (1) and Gagge's et al Two-Node Physiological Model (2). The models have permitted the extrapolation of the experimental results to almost limitless combinations and have greatly expanded the engineers' comfort assessment and design potential. In the laboratory the determination or control of the environmental parameters has always been possible by some means or other. Such is not always the case when taking a field survey or assessing or improving the comfort environment of a building. Air temperature and humidity can be readily and accurately measured in both the laboratory and field. Field instrumentation for measuring air velocity has greatly improved in recent years. However, the measurement of thermal radiation in the built environment is still elusive to the HVAC engineer and has often been neglected because accurate measurement is difficult and time consuming. In the hope that radiation instrumentation for field use may be improved and made more available in the future the operating principles of various types of instruments developed in the past will be reviewed.

Radiation Theory

Radiation heat transfer ($\dot{Q}_r$) from a person in an enclosed space is classically modeled as:

$$\dot{Q}_r = A_D \; f_{cl} \; f_{eff} \; \epsilon \; \sigma \; (T_{cl}^4 - T_{mrt}^4), \tag{1}$$

where

A_D	=	the area of the skin surface as predicted by the DuBois equation
f_{cl}	=	the ratio of the area of the clothed body surface to that of the nude body itself
f_{eff}	=	the fraction of the body surface effective for radiation exchange
ϵ	=	emissivity of clothing or exposed skin surface
σ	=	Stephan-Boltzmann constant,
T_{cl}	=	absolute clothing or skin temperature
T_{mrt}	=	mean radiant temperature on absolute temperature scale

Mean radiant temperature is defined (3) as the uniform black body temperature of an imaginary enclosure in which a person will exchange the same heat by radiation as he would in the actual complex environment. It is, thus, a convenient property to express the radiant quality of an environment.

For long wavelength radiation ($\lambda \geq 3\mu m$), skin behaves very much like a black body with an absorptivity close to unity (4). Black body radiators of 200°C or less emit more than 99% of their radiation with wavelengths of 3μm or longer. In addition the emittance of most clothing surfaces is about 0.95 (5). Thus, in this region body surfaces may be modeled as gray bodies ($\epsilon = \alpha$ independent of λ). If surfaces in the built environment are hotter than 200°C, as with high temperature infrared heaters and sunlight, then skin and clothing surfaces are not gray ($\epsilon_{sk} = \alpha_{sk}$) and special precautions must be followed with radiation measuring equipment to enable T_{mrt} to fulfill the definition given above. This will be discussed further in a later section.

For some applications, the radiation equation is linearized to:

$$\dot{Q}_r = A_D \; h_r (T_{cl} - T_{mrt}), \tag{2}$$

where h_r is the radiation coefficient. By algebraic equivalence

$$h_r = f_{cl} \; f_{eff} \; \epsilon \; \sigma \; (T_{cl}^4 - T_{mrt}^4)/(T_{cl} - T_{mrt}) \tag{3}$$

Then if $T_{mrt} = T_{cl}$

$$h_r = f_{cl} \; f_{eff} \; 4 \; \epsilon \; \sigma ((T_{cl} + T_{mrt})/2)^3 \tag{4}$$

Another way to characterize and quantify the radiant environment is through the term Effective Radiant Field (ERF) (6). This is an energy flow term that relates T_{mrt} or surface temperatures of the enclosure to air temperature. If T_{mrt} is greater than air temperature (T_a), ERF will be positive and negative when T_{mrt} is less than T_a. The radiation per unit area can then be expressed in terms of ERF as

$$\dot{Q}_r/A_D = h_r(T_{cl} - T_a) - \text{ERF} \qquad (5)$$

where $\text{ERF} = h_r(T_{mrt} - T_a)$.

If the temperatures and geometries of the enclosure surfaces can be measured and further if the emissivities of these surfaces can be assumed to be near unity the mean radiant temperature can be calculated from

$$T_{mrt} = (F_{p-1}T_1^4 + F_{p-2}T_2^4 + + + F_{p-i}T_i^4)^{1/4} \qquad (6)$$

where F_{p-i} is the shape factor, which represents the fraction of the total energy that leaves the person and strikes surface i. If the surface emissivities are not all near unity or if short wavelength (high temperature) radiation is present the calculated estimate of T_{mrt} becomes more involved (5). Thus, for field assessment a reliable instrument that rapidly integrates the radiant effects of the enclosure in terms of MRT is desirable.

Surface integrating radiometers may be classed as either passive or active in their operation. Active radiometers either supply or remove energy from the sensor. Rate of energy flow can be interpreted in terms of mean radiant temperature. The active class can be further grouped into ones that are heated to a temperature greater than air temperature and those that are clamped at the air temperature.

Passive Radiometers

The first and simplest passive radiometer developed for comfort assessment in the built environment was the Vernon Globe thermometer (7). It is a black thin-walled hollow sphere with a thermometer bulb at its center. Probably because of its simplicity, ruggedness, and minimal cost, it is still the most commonly used field radiometer. Recently, NIOSH (8) has advocated the same 15 cm diameter globe as a component of its WBGT Heat Stress Index. Thermally, the temperature of the globe floats between the air and mean radiant temperatures of the enclosure (Figure 1).

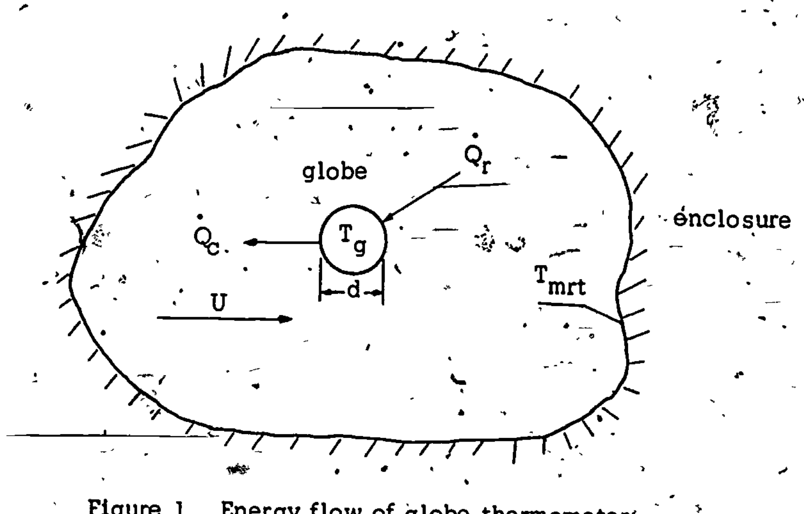

Figure 1. Energy flow of globe thermometer.

An energy balance on the globe yields

$$\dot{Q}_r - \dot{Q}_c = m\ c\ dT_g/dt \tag{7}$$

where m and c are mass and specific heat of globe.

At steady state, the rate of change of internal energy ($m\ c\ dT_g/dt$) is zero and

$$\dot{Q}_r = \dot{Q}_c \tag{8}$$

or

$$\epsilon\ \sigma\ A\ (T_{mrt}^4 - T_g^4) = A\ h_c(T_g - T_a)\ . \tag{9}$$

Solving for the mean radiant temperature

$$T_{mrt} = (T_g^4 + (h_c/\epsilon\sigma)(T_g - T_a))^{1/4} \tag{10}$$

where h_c is the convective heat transfer coefficient averaged over the surface of the sphere. When there is forced flow, h_c can be estimated from the following Nusselt equation:

$$h_c\ d/k = 0.37\,(U\ d/v)^{0.6} \tag{11}$$

where U is velocity, k is the thermal conductivity, and v is the kinematic viscosity of the fluid. For the case of natural convection ($U = 0$).

$$h_c d/k = 2 + 0.393\ (g\ (T_g - T_a)\ d^3/T_a\ v^2)^{1/4}\ . \tag{12}$$

The forced convection heat transfer mode dominates in the case of the 15 cm globe in air at comfort temperatures if

$$U \geq 0.03\ (T_g - T_a)^{0.42} \quad \text{m/s} \tag{13}$$

Therefore, the forced convection equation can be used with confidence at velocities down to about 0.1 m/s even with a globe air temperature difference of 5 °C. Equations 10, 11, and 12 show that to reliably calculate T_{mrt} with the globe, an accurate measurement of T_a, T_g, and U is required.

The transient response of the globe can be examined from equation 7 rearranged to

$$A\ h_r\ (T_{mrt} - T_g) - A\ h_c\ (T_g - T_a) = A\ \rho\ x\ c\ dT/dt \tag{14}$$

where x is the thickness of the sphere and ρ is its density. Rearranging and integrating, equation 14 yields

$$\frac{h_r\ T_{mrt} + h_c T_a - (h_r + h_c)\ T_{g2}}{h_r\ T_{mrt} + h_c T_a - (h_r + h_c)\ T_{g1}} = e^{-(t_2 - t_1)/\tau} \tag{15}$$

where $\tau = \rho c\ x/(h_r + h_c)$ is the globe's time constant.

Substituting the h_c equation for forced convection,

$$\tau = \rho c\ x/(h_r + 0.37\ k\ U^{0.6}/(d^{0.4}\ v^{0.6})) \tag{16}$$

which shows that the time constant decreases as the velocity increases and diameter decreases. Therefore, for a fast response the globe should be small. However, if the sphere is made too small, $T_g - T_a$ may be too small to measure accurately, resulting in an error in calculated T_{mrt}.

How the sensitivity of the globe to radiation $(T_g - T_a)/(T_{mrt} - T_a)$ is affected by its design can be seen from equation 8 written as

$$h_r(T_{mrt} - T_g) = h_c(T_g - T_a)$$

or

$$(T_g - T_a)/(T_{mrt} - T_a) = h_r/(h_r + h_c)$$

$$= 1/(1 + 0.37 \;\; k \;\; U^{0.6}/(4 \;\sigma\; T_g^{3} d^{0.4} v^{0.6})) \qquad (17)$$

It is seen that $T_g - T_a$ becomes small in comparison to the potential difference when the globe diameter is decreased. If the globe temperature is to be midway between air and mean radiant temperatures, equation 17 predicts for typical room temperatures and velocities (0.2 m/s or 40 fpm) that the diameter should be 15 cm.

For steady state applications, the original 15 cm Vernon globe is a simple and useful instrument. However, it is very slow to use and requires 10 to 20 minutes to reach equilibrium with a new steady state environment. For that reason it is awkward to use when taking comfort surveys in the field (e.g. when comparing comfort votes in an office building to the local environmental parameters as the radiometer is moved from place to place). Exact velocity measurement at low air speeds is difficult. A 0.1 m/s error in velocity measurement with a 15 cm globe at a 5°C difference between air and globe can result in a 1.6°C error in the calculated mean radiant temperature. If the globe is reduced to 2.5 cm for quicker response the calculated MRT error would also be 1.6°C in the same environment with the same velocity error. However, $T_g - T_a$ would be only 2.4°C instead of 5°C making accurate temperature measurement even more critical.

For a rapid radiometer to be used in an environmental survey of British operating rooms, Lidwell and Wyon (9) designed a tiny 2 mm diameter unheated globe inside a thin (0.1mm) polyethylene spherical (25 mm diameter) shell. Polyethylene is generally transparent to long wavelength radiation.

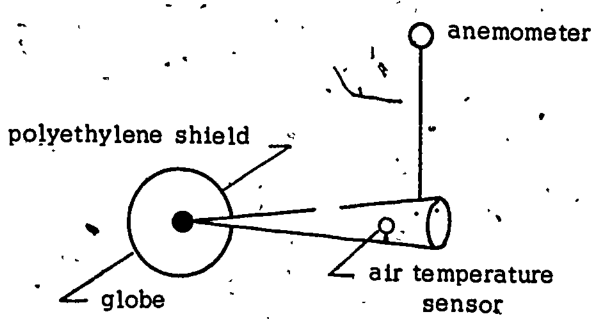

Figure 2. Polyethylene shield globe thermometer of Lidwell and Wyon.

The air space between the globe and the polyethylene shell acts as a thermal resistor (R_a) and h_c' at 25 mm is also much lower than at the 2 mm diameter. The steady state energy balance is:

$$A_g\, h_r(T_{mrt} - T_g) = (T_g - T_a)/(R_a + 1/A_g h_c) \quad (18)$$

Figure 3 shows that the polyethylene shielding greatly decreases the velocity dependence of the instrument as well as increasing its sensitivity. The time constant of this device is about 1.3 min.

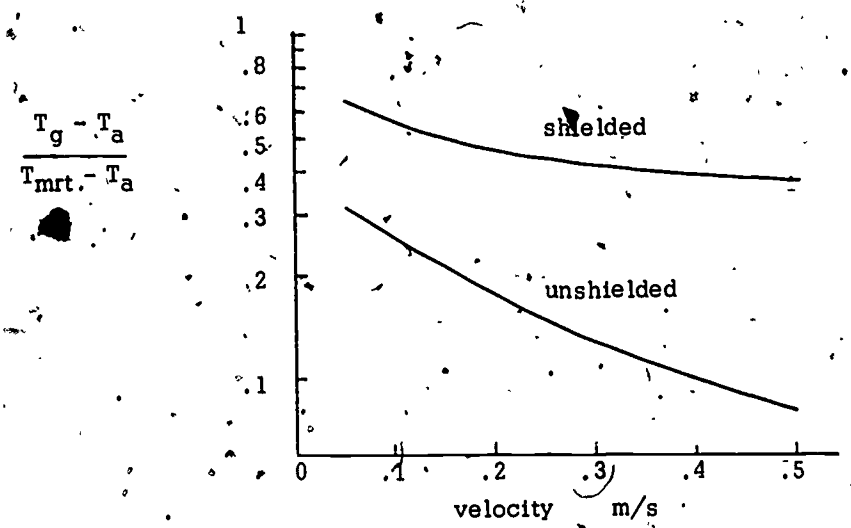

Figure 3. Velocity dependence of globe with and without polyethylene shield.

To make their radiometer convenient for field surveys, Lidwell and Wyon integrated an anemometer and air temperature sensor into the base of their small radiometer. More recently, McIntyre (10) has reported shielding a 50 mm black globe with a 100 mm diameter polyethylene sphere. The radiation sensitivity of this larger sensor is higher than that of Lidwell and Wyon's and has even less velocity dependence. McIntyre estimates that $(T_g - T_a)/(T_{mrt} - T_a)$ is 0.75 and 0.7 at velocities of 0.1 and 0.5 m/s respectively. Polyethylene shielded radiometers require calibration to measure T_{mrt} because of uncertainty in calculating the thermal resistance between the globe and the outside surface of the shield.

Another passive approach to determine MRT is through multiple unheated spheres with unequal emissivities (10). For two such spheres of equal diameters the steady state energy balance equations are:

$$h_{r1}(T_{mrt} - T_{g1}) = h_c\,(T_{g1} - T_a)$$

and

$$h_{r2}(T_{mrt} - T_{g2}) = h_c\,(T_{g2} - T_a)\ .$$

In the absence of natural convection, the convection coefficients can be assumed equal. Combining the two equations, with $h_r = 4\,\epsilon\,\sigma T^3$, yields:

$$T_{mrt} = \frac{T_{g2}\epsilon_2/\epsilon_1 - T_{g1}(T_{g2} - T_a)/(T_{g1} - T_a)}{\epsilon_2/\epsilon_1 - (T_{g2} - T_a)/(T_{g1} - T_a)} \quad (19)$$

With this method T_{mrt} can be determined without a knowledge of air velocity. Thus the instrument's performance potential would be limited only by the accuracy and sensitivity of the temperature measuring system and the knowledge of ϵ_1 and ϵ_2. From equation 16 the two spheres would have different time constants.

Active Radiometers

Active radiometers supply or remove energy from the MRT sensor and MRT is related to this flow of auxiliary power (P). There are two types of active radiometers; one uses the auxiliary power to keep the sensor above the ambient and the other type uses the power to hold the sensor at air temperature.

Radiometers heated above ambient.

The Panradiometer was developed by Richards, Stoll and Hardy (11) to measure the mean long wave radiation temperature and solar or high temperature radiation intensity while being independent of the air velocity. The radiometer consists of three 6.5 mm hollow spheres. One is black, one is white, and the remaining is polished metal. When the instrument is placed in an environment with a high temperature radiation source, the black sphere will become warm due to absorption of short wave radiation. The polished sphere, unable to absorb or emit well, will remain near air temperature. The white sphere will reflect the short wave radiation but emit long wave radiation and be cooled to a temperature below ambient if the surrounding surfaces and/or sky is below T_a. If the cooler spheres are electrically heated to the temperature of the black sphere the short wave radiation intensity and mean radiant temperature can be calculated from energy balances and surface properties of the spheres. The energy balances on the spheres are:

black

$$I\alpha_{bs} = \dot{Q}c + \sigma\epsilon_{bl}(T_b^{\,4} - T_{mrt}^{\,4}) \tag{20}$$

white

$$P_w + I\alpha_{ws} = \dot{Q}c + \sigma\epsilon_{wl}(T_w^{\,4} - T_{mrt}^{\,4}) \tag{21}$$

polished

$$P_p + I\alpha_{ps} = \dot{Q}c + \sigma\epsilon_{wl}(T_p^{\,4} - T_{mrt}^{\,4}) \tag{22}$$

where I = direct, diffuse and reflected solar or high temperature radiation

α_{bs} = absorptivity of black sphere for short wave ($\lambda \leq 3u$) thermal radiation

α_{ws} = absorptivity of white sphere for short wave radiation

α_{ps} = absorptivity of polished sphere for short wave radiation

P_w = power supplied to white sphere

P_p = power supplied to polished sphere

ϵ_{wl} = emissivity of white sphere for long wave radiation

ϵ_{pl} = emissivity of polished sphere for long wave radiation

Since the spheres are at the same temperature ($T_p = T_w = T_b$), the convection heat losses to the air are the same for each. Simultaneous solution of equations 20, 21 and 22 result in

$$I = \frac{P_w - P_p(\epsilon_{bl} - \epsilon_{wl})/(\epsilon_{bl} - \epsilon_{pl})}{(\alpha_{bs} - \alpha_{ws}) - (\alpha_{bs} - \alpha_{ps})(\epsilon_{bl} - \epsilon_{wl})/(\epsilon_{bl} - \epsilon_{pl})} \tag{23}$$

and

$$T_{mrt}^4 = T_b^4 + \frac{P_w - I(\alpha_{bs} - \alpha_{ws})}{\sigma(\epsilon_{bl} - \epsilon_{wl})} \tag{24}$$

The T_{mrt} from this calculation does not include short wave radiation. If no short wave radiation is present ($I = 0$), then only two spheres are needed and for better accuracy the black and polished should be used. Then

$$T_{mrt}^4 = T_b^4 + P_p/(\sigma(\epsilon_{bl} - \epsilon_{pl})) \tag{25}$$

Calibration studies showed that indoors the mean radiant temperature could be measured with an accuracy of ± 0.3°C and outdoors to within ± 1.8°C. The response is rapid with a time constant of approximately 1 minute.

Sutton and McNall (12) further modified the principles of the Panradiometer for better accuracy and less sensitivity to drafts. Their Two-Sphere Radiometer consists of two 51 mm diameter heated spheres (Figure 4). One is black and the other polished gold. Both of the spheres are heated to the same temperature, usually 10 to 20°C above air temperature. In the Panradiometer one of the three spheres is unheated. Substantially heating both spheres together with larger diameters, improved accuracy and decreased the sensor fluctuation due to drafts.

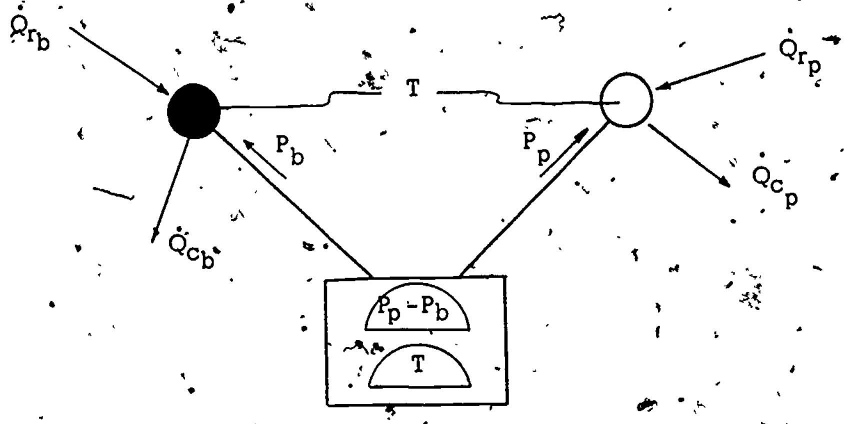

Figure 4. Two sphere radiometer.

The energy balance equations are:

$$P_b = \dot{Q}c + \sigma \epsilon_b (T_b^4 - T_{mrt}^4)$$

$$P_p = \dot{Q}c + \sigma \epsilon_p (T_p^4 - T_{mrt}^4)$$

and

$$T_b = T_p$$

Therefore

$$T_{mrt}^4 = T_b^4 + (P_p - P_b)/(\sigma(\epsilon_b - \epsilon_p)) \tag{26}$$

To use the instrument, one sets the globe temperature to the desired level and then records the differential power consumption when the instrument reaches equilibrium. Globe temperature uniformity was achieved by boiling a liquid which condenses inside on the shell walls. The temperature control of the sphere was automatic, regulated by vapor pressure. With this instrument, it is believed MRT measurements can be made with an accuracy of ± 1°C. A commercial version has recently been introduced in Germany (13).

In the mid 60's, Gagge et al (14) developed the R-Meter for measuring operative temperature. Operative temperature (T_o) is defined as the temperature of an imaginary enclosure with which man will exchange the same total dry heat by radiation and convection as in the actual environment.

$$(h_c + h_r)(T_{skin} - T_o) = h_c(T_{skin} - T_a) + h_r(T_{skin} - T_{mrt})$$

or

$$T_o = \frac{T_a + h_r/h_c(T_{mrt})}{1 + h_r/h_c} \qquad (27)$$

The R-Meter can also be used to measure MRT and ERF. It consists of a single heated pink skin colored 51 mm diameter globe. An energy balance at steady state shows:

$$P = \dot{Q}r + \dot{Q}c$$

$$P = A\,h_r(T_g - T_{mrt}) + A\,h_c(T_g - T_a)$$

or

$$T_{mrt} = T_g + h_c/h_r\,(T_g - T_a) - P/(A\,h_r) \qquad (28)$$

Therefore, T_{mrt} requires measurement of T_g, T_a, and power (P) together with estimates of h_c and h_r. In addition, h_c is a function of velocity. Therefore, overall accuracy is dependent on the individual accuracies of many parameters. For normal service, the temperature of the globe is set at 40°C. In the absence of a radiant field, the globe can be used as an anemometer. The interesting feature of the instrument is that the globe is constructed from 41 m of No. 36 enameled copper wire wound on two hemispheres. The wire once coated with thin epoxy serves as shell wall, uniform heat source, and temperature sensor.

Radiometers clamped at air temperature.

Two radiometers have evolved that eliminate convection problems altogether by controlling the globe temperature equal to air temperature. When this is done only one globe is required.

Aagard (15) designed a globe to measure the mean radiant temperature of the cold night sky. Because the radiant temperature is always colder than the air temperature, the 25 mm diameter black globe made from a single layer of #36 enameled constantan wire needs only heat to maintain its temperature at the air temperature. The control signal to regulate the power to the heater wire of the sphere's shell comes from a 12 couple thermopile between the shell wall and the surrounding air. Accuracy is not clearly reported but is said to deteriorate as air temperature fluctuation rates increase.

For application to the built environment where MRT may be either warmer or cooler than air temperature, Braun and McNall (16) modified the radiometer principle of Aagard so that it could be both heated and cooled. Their Thermoelectric Radiometer consists of a 51 mm hollow silver sphere supported by an insulated silver rod (Figure 5). The silver rod with thermocouples at each end serves as a heat flow path and meter between the sphere and a thermoelectric heating and cooling device. The output of a 4 couple thermopile with junctions on the sphere and radiation shielded in the air provides the error signal to control the thermoelectric unit.

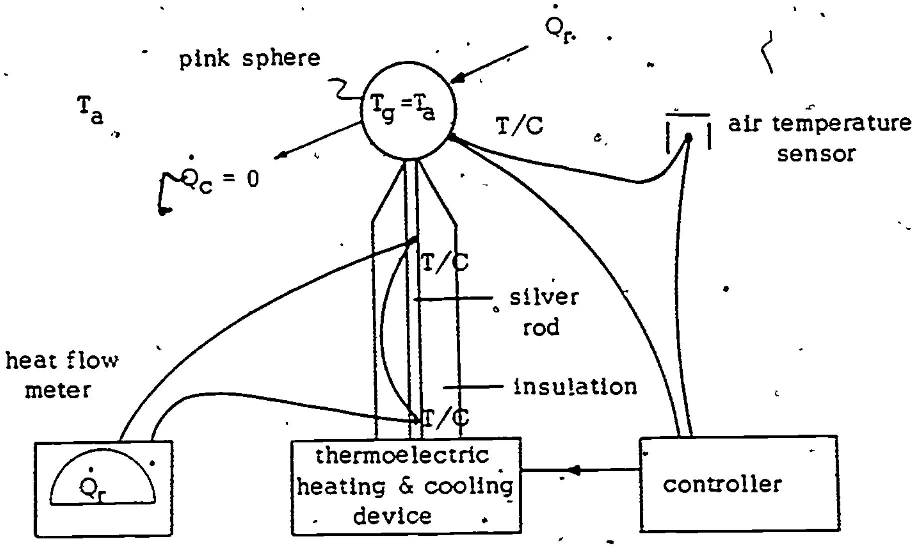

Figure 5. Thermoelectric radiometer.

The sphere is skin colored so that it reflects and absorbs high ($\lambda \leq 3\,u$) and low temperature radiation like skin and clothing (Figure 6).

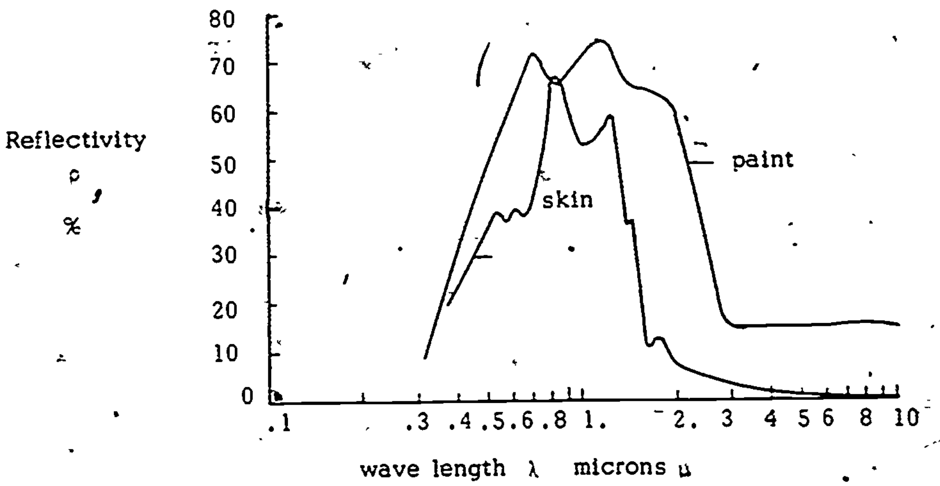

Figure 6. Reflective properties of skin and flesh-colored pink paint.

With paint, the emissivity of the sphere at skin and air temperatures is 0.87. The emissivity of skin and clothing at this temperature is about 0.95. With this paint, the measured MRT should more closely fit the demands of the definition and not be restricted to environmental surfaces which are less than 200° C. By comparison to other instruments and from MRT calculations based on wall temperatures the designers determined that MRT can be determined to within ±0.7° C. It takes 10 minutes to reach steady state after being turned on and it can automatically follow slow temperature changes in both air and MRT.

An interesting feature of this instrument is that it is a direct indicator of the Effective Radiant Field of the environment. If the controller must supply heat to the sphere, there is a negative ERF or the MRT is lower than ambient air. If heat is removed, there is a positive ERF or MRT is higher than ambient.

Directional Radiometers

While the mean radiant temperature obtained from a spacial integrating radiometer is an important comfort parameter for the successful design, control, or alteration of an environment, there is often a need for directional radiometers. They can be a valuable investigative tool for comfort and energy conservation applications. If an enclosure has an undesirable MRT, the directional or scanning radiometer permits the mapping of radiant surfaces. This can lead to identification and improvement through increased insulation, radiation shielding, etc.

The first directional radiometer measurements in the built environment were undertaken by Korsgaard (17). He proposed a directional radiant temperature (DRT) which is analogous to mean radiant temperature but refers to the temperature of a black hemispherical surface enclosing a plane element that would exchange radiant energy with the element at the same rate as the actual enclosure does. To measure this property he developed a sensitive net radiometer (18). It consisted of 4 small black and polished surfaces facing the unknown enclosure. The emf developed by a thermopile attached between these absorbing and reflecting segments is proportional to the average temperature of radiometer surfaces and the directional radiant temperature. However, the device is not a basic instrument and requires calibration. The NBS has recently developed an elegant scanning direction radiometer (19) based on this principle. The portable NBS machine is designed to produce 1 mv/ °C temperature difference between scanner and the DRT. It has a time constant of 5 s. Some commercial net radiometers are also applicable (20).

Hager (21) developed an Absolute Differential Radiometer that can be used without calibration (Figure 7). It consists of 2 black surfaces separated by a thin air space. One surface looks forward, the other backward. To minimize velocity effects the air in front of each black surface is insulated from the moving ambient by a thin polyethylene sheet. The unit can detect radiation intensity differences between front and back of the detector as small as 0.06 watt/m^2 and reaches equilibrium within 1 min.

Comfort researchers have shown that people are rather tolerant of asymmetric radiant fields. McIntyre (22) concluded that for resting clothed (0.6-0.7 clo) people, asymmetry does not contribute to discomfort until the difference in DRT in opposite directions is about 20° C or greater.

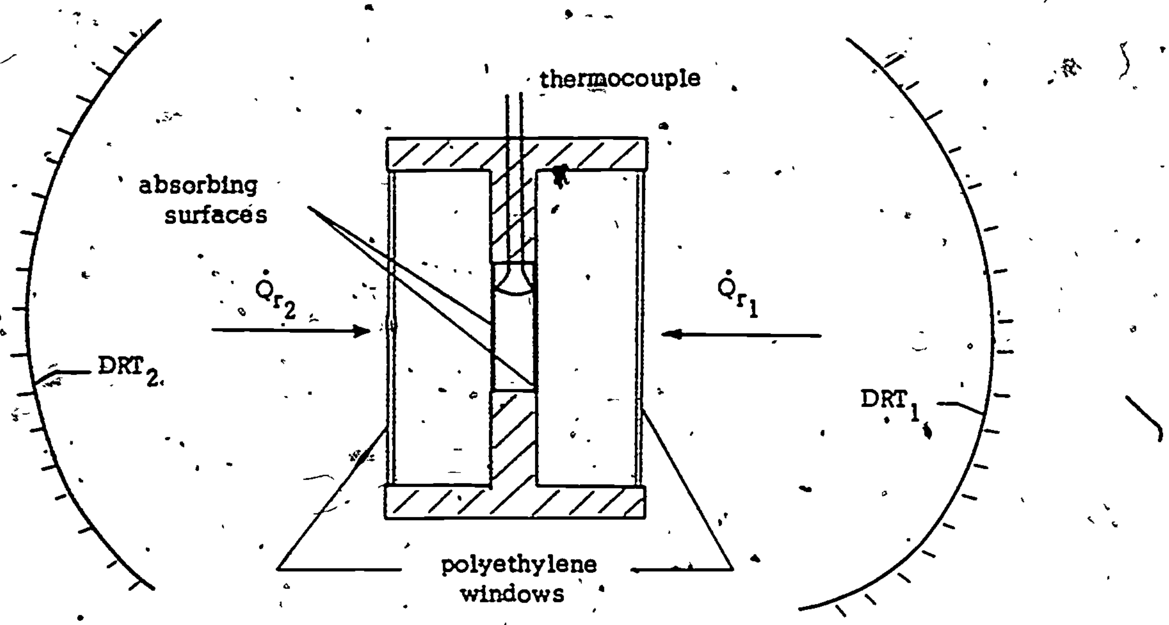

Figure 7. Absolute differential radiometer.

Development Needs

As seen above, the practicing engineer has a large number of radiometric instruments from which to choose. Unfortunately, most are laboratory prototypes unavailable except through self fabrication. What an engineer needs is a fast-acting, rugged, reasonably priced MRT indicator for field survey work. In past studies (23) we have compared comfort votes to environmental parameters in office and laboratory settings. This required polling the occupants in their work areas at various times during the day, while simultaneously measuring environmental parameters. Instruments were moved from place to place, with the measurements being made while the subject answered the questionnaire. For MRT determination, the 15 cm globe and R-Meter were used. Both proved to be somewhat unsatisfactory for reasons outlined above.

Of the instruments reviewed, the polyethylene shielded radiometer with integral anemometer and air temperature sensor by Lidwell and Wyon proved to be a desirable field package. Its dependence on air velocity for MRT determination and its need for calibration in a radiant wind tunnel is a disadvantage, however. An instrument with a MRT reading independent of the air velocity measurement is desired. With this in mind the two sphere radiometer concept appears well suited for field use in the built environment. It is a fundamental instrument allowing MRT to be calculated without directly measuring air temperature or velocity. Flesh-colored pink paint instead of black might be considered for the surface treatment of black spheres to approximate the thermal properties of exposed skin and clothing of the average person. Other design approaches should also be further explored. The thermoelectric radiometer concept of Braun and McNall is appealing. For better modeling the shape and surface orientation of the human, an ellipsoidal radiation sensor, as in the Comfy-test meter (24), has merit over a sphere, particularly if the radiant field is asymmetric.

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EXPERIMENTAL ANALYSIS OF THERMAL ACCEPTABILITY

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ABSTRACT

This paper reviews recent laboratory studies and research needs in human physiology that will be important in specifying thermal acceptability; it compares these results with guidelines proposed by the Federal Energy Administration for summer and winter months. Male and female subjects, in both younger and older age groups, were exposed while sedentary or slightly active, to fluctuating dry bulb temperature (at 50% RH) and to constant dry bulb temperatures (at 40, 60, 80% RH) in summer experiments. In winter experiments, subjects were exposed to 20°C and colder environments and were allowed the use of extra outer clothing to avoid cold discomfort. Clothing insulation was directly evaluated. In both studies judgments of whole body thermal discomfort and thermal sensation were made; in addition, in winter studies direct votes of acceptability, as well as regional thermal sensation (face, trunk and extremities) were taken. A method of estimating preferred comfort and neutral thermal sensation temperatures is described for fluctuating air temperature conditions.

The results of summer studies indicate that 60% RH (16 Torr) at 26.7°C is the maximum limit for thermal acceptability which corresponds to a 28 ET* or 2 °C ET* above the optimal ASHRAE neutral/comfort zone. The results of the winter experiments showed that the FEA winter temperature guideline lower limit (20°C) proved 80% acceptable. Specific groups of individuals have been identified for whom winter and summer guidelines will not be wholly acceptable.

Key words: Thermal acceptability, energy conservation, cold discomfort, humidity, temperature, clothing

INTRODUCTION

Energy conservation practices in many buildings have resulted in lower ambient temperature levels in the winter and either higher air temperatures or little humidity control in the summer. Such a direction offers a paradoxical reversal from the trend occurring since the 1920's in which human thermal preferences and engineering practices have been towards higher indoor dry-bulb temperatures (T_a). Generally in the U.S., optimal comfort zones (for sedentary persons, dressed at 0.6 clo and ambient air velocity around 0.10-0.20 m/s) in winter time have increased from 20°C to 25.6°C; summer T_a levels have remained roughly around 25.0 to 25.6°C (1). Most of the research done under the auspices of ASHRAE (2) in comfort has been towards securing environmental specifications for atmospheric conditions which achieve or describe maximal thermal acceptability for persons assumed to be in thermal balance at least one hour or more. This research has led to a description of an environmental zone in which the body is in the state of physiological thermal neutrality. In this region the resting person is able to maintain thermal steady-st.te (viz, heat balance) such that internal body and skin temperatures are constant without excessive physiological regulatory activity such as sweating, vasoconstriction or vasodilation of skin blood vessels. The body is also effectively "neutral" to any feelings of warmth or cold and generally the occupant is satisfied with the environmental conditions. Studies by Fanger (3, 4), Rohles and Nevins (5) and McNall (6) equate a thermal neutral point with preferred comfort state or temperature and show that for individuals at 0.6 clo, air velocity near still conditions (v at 0.10–0.15 m/s), 50% rh, and sedentary activity, the thermal neutral (comfort) temperature is invariable regardless of age span, sex or season. Fanger (3) also demonstrated that other preferred comfort temperatures during thermal balance may be ascertained for any metabolic heat production (≤ 3 met), from the variables most important in influencing heat balance: clothing insulation (I_{cl}), dry bulb and mean radiant temperature (MRT) and ambient vapor pressure as well as heat and mass transfer coefficients. The requirement is that during thermal neutrality there occurs: a) a linear relationship between skin temperature ($\bar{T}_{sk}$) and metabolic rate (M) i.e. activity state, and (b) a linear function between evaporation of sweat and metabolic heat production. Fanger (3) can therefore predict thermal sensation (PMV) for an individual from thermal load on the body; a thermal load is presumed to occur whenever there is a difference between heat production and the heat loss to the actual environment for a person kept in heat balance (i.e. comfort) at the mean skin temperature and sweat secretion of the specified activity level. Thus a change in heat loss is the prominent effect which occurs if a person (having a given metabolic rate, clothing insulation value) is displaced from a comfortable environment to the actual environment.

The alternative approach to assessment of a person's heat exchange with the environment relates thermal subjective responses (discomfort) to actual physiological changes. This approach utilizes a two node model of human thermoregulatory processes (7). The added feature is that proportional control coefficients for effector responses such as sweat secretion or skin blood flow, as well as sensible and insensible heat exchange coefficients, are accurate for wider thermal stress and exercise levels. Loci of constant physiological strain in the heat are dependent on skin wettedness which reflect the probable sweat secretion on the skin surface; in the cold, skin temperature level (T_{sk}) reflects the vasoconstrictor activity. Both of these factors are important in judgment of warm and cold discomfort. In the physiological neutral zone, comfort responses and "neutral" votes are equivalent. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) New Effective Temperature (ET*) was derived by using the Gagge et al two node model (2, 7).

Physiologists and sensory psychologists have recognized for a long while that thermal neutrality is not a totally sufficient criterion for thermal comfort; the affective responses are influenced by other physical factors besides those that change heat balance, and many other factors such as fatigue, endocrine (humoral) influences play a significant role. The relative state of hyper- or hypothermia of the body, as shown by Cabanac (8), has a marked influence on feelings of displeasure; also, while in thermal balance, whether thermal radiative heating of segmental areas such as the face is considered pleasant or unpleasant depends strongly on prestimulus skin temperature (9). There again the size of a particular skin area stimulated has as great importance as how much heat is applied. Hardy (10) has characterized, for ASHRAE, the major physiological factors which are important in judgment of thermal acceptability to any thermal stress. His account garnered from extensive studies makes a clear distinction between affective responses (i.e. those mediated by comfort or displeasure) and thermal sensations (thermal warmth and cold sense). Warm discomfort occurs whenever physiological mechanisms such as sweating and increase in skin blood flow are activated to bring heat loss into balance with metabolic heat production. Its antithesis, cold discomfort, arises predominantly from vasoconstriction and a subsequent decrease in skin temperature necessary for heat conservation.

In contrast to affective responses involving some degree of central nervous system (CNS) integration before effector action are those thermal sensations arising from skin heating or cooling (11). Although an adequate description of sensory responses to cold environments can be made by either cold discomfort or cold sensation, a quantification of warm discomfort or warmth sensation is possible only by assessing multiple physiological responses (12,13). Warm sensation essentially follows from warm skin heating; but, warm discomfort is composed of an interaction between physiological and physical factors all tied in with at least these variables: sweating, fraction of skin areas wet with sweat, peripheral blood flow, and central and peripheral temperatures. Subjective responses and thermal acceptability will be influenced by physical factors (T_a, P_a, etc.) and individual factors (sex and clothing effects). However, the final reactions are based on efferent control of physiological functions.

Although we know a great deal about the thermal sensations equated with comfort response in thermal neutrality from the work of others (4, 12, 5), very little is still known of the way internal and peripheral thermal signals affect thermal acceptability in persons. How the different sexes or age groups respond to warm stress and humidity and to moderate cold stress or whether local sensations of feet, hands and face aversely affect the acceptability in cold environments is also not fully understood. Such information is sorely needed since it is apparent (14) that the cross section of average office workers in large cities are not uniformly clothed and don't dress according to indoor weather conditions.

The following summer and winter laboratory studies were done as a part of a large multi-pronged field survey designed to investigate recent energy conservation guidelines on comfort, acceptability, and health by Gagge and Nevins (15).

METHODS AND PROCEDURES

Environmental Chamber and Dry Bulb Temperature-Cyclic Changes

All our summer ~~and winter experiments~~ were done in a 5.3 x 5.3 x 2.4 m^3 test chamber with a rapid system response in air temperature (± 2% rh at 25°C T_a). The design and control characteristics of the chamber have been described in detail by Kjerulf-Jensen et al (16). In the first part of the experiments relative humidity was kept constant at 50% (by controlling dew-point temperature) and dry-bulb temperature ($T_a = T_r$) altered + or − 5 °C from a starting temperature of 25°C with the room controls set at an average rate of + or − 0.3 °C/min over a 2-hr period.

Summer Studies

A total of 18 subjects were used in the experiments. The individuals were divided into 3 groups; each group was run on separate days. The groups consisted of 5 young females (age 22 ± 3 yrs), 6 older females (44 ± 11 yrs), and 7 males (25 ± 4 yrs). Elderly males were not available at the time of the experiments.

Each subject served in two sessions which took place on successive days between 9 and 12 A.M. in the month of July. In a preliminary session, which lasted 2 hr from time zero, each group was exposed simultaneously to the air temperature swing shown in Fig. 1.

Each of the subjects rested on a plastic/aluminum office chair for 15 min and walked about the chamber at a rate of 50 steps/min for 5 min. Average metabolic rate during the walking period was estimated to be about 88 W/m^2 (1.5 met) by spot measurements on the subjects. For the total 15 min rest plus 5 min walking period, the activity level for

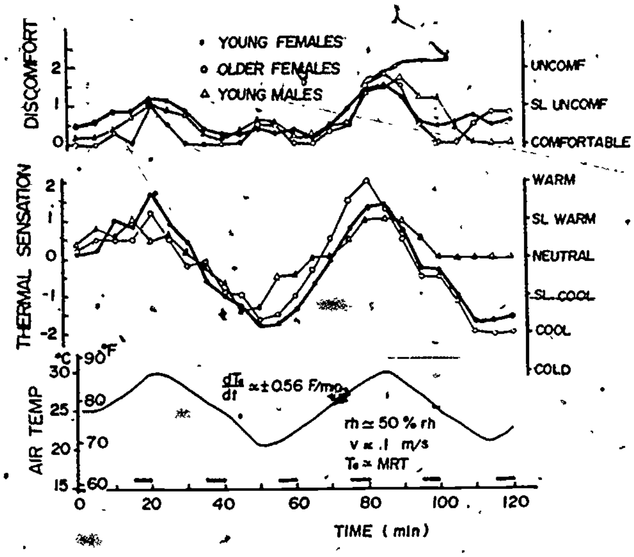

Figure 1. Typical changes in ambient temperature (T_a) at 50% rh and averaged discomfort and thermal sensation votes for the three groups of subjects used in summer study. Horizontal bars on time scale indicate cadence walking interval.

both male and female subjects was about 1.2 met, typical of light office work activity (3). The average relative air velocity for resting and walking was about 0.25 m/s or a mean heat transfer coefficient (h_c) = 3.3 W/(sq m °C).

In a second session each subject was exposed to 27°C dry-bulb temperature and the humidity level was changed each hour from 40% to 60% to 80% rh over a 3-hr experiment. The activity was similar to the first experiments; however, the time sequence was 5 min walk, 25 min rest. At the end of the 30th min a vote was taken. Only the terminal 1-hr votes for each group were averaged.

In two of the subjects, one female and one male, average skin temperatures were measured continuously by thermocouples at 8 locations (head, shoulders, chest, back, thigh, calf, arm, and hand). Core temperature was measured from a thermocouple in the rectum. Clo values were estimated from a check list which each subject answered before entering the test chamber (14). The subjects were requested to wear typical apparel for office work in summer months (i.e., no shorts permitted).

Winter Studies

The subjects were first exposed to a preliminary session in which T_a was changed cyclically as in the summer studies. In a separate run afterwards, a change (- 1° C/min) towards the desired exposure temperature occurred after the subjects had initially stabilized at 25°C for 1 hr. Each subject was exposed 3 times to 20° C and 3 times to 15° C for 1 hr on different days. Zero time of exposure at 20°C or 15°C began after T_a

reached a steady-level. Relative humidity was controlled at 30-40%. All experiments occurred in mid-February, typically the coldest part of the year in New Haven.

Twenty subjects were used in the winter experiment. Each subject attended as a member of his respective age group and sex: males age, 21 ± 1 and 52 ± 6 yrs and females 21 ± 2 and 49 ± 2 yrs. Each group consisted of 5 members who were exposed to the swing experiments and constant T_a level experiments on alternate days - morning and afternoon sessions interchanged. Each day afterwards, a different group was subjected to the constant T_a sessions of 20°C and 15°C.

The instructions given to the subjects, when they were initially hired, were to wear their typical winter indoor clothing but to bring additional outer wear such as sweaters, or light jackets but not overcoats. Most females attended with pant-suits and males with slacks and pullover sweaters.

The initial time (at 28°C) after arriving from the cold outdoors was spent in answering a preliminary clothing check list (14) as before in the summer study, in receiving specific instructions regarding voting scales and, in general, time was given in explaining the activity while in the chamber. Lavatory privileges were also given at this time. The activity (1.2 met)(as in the summer study) was a 5 min walk for the first 30 min of an experiment at 50 steps/min, kept constant with a metronome, and a 25 min sitting period on a plastic/aluminum chair (2). The sitting period was occupied in reading, writing or talking at leisure. No communication about the environmental conditions, nor any smoking or eating was permitted. Subjects voted, and each ballot was collected, every 1/2 hr. At the end of one hour at 20°C conditions, an effective clothing insulation measurement was taken (17). During constant air temperature level experiments, adding or removal of extra clothing was permitted at any time after the start of an experiment. Unlike the occurrence in the summer study, this behavioral activity was of major concern to us but subjects were given no encouragement to alter their ensemble. The only requirement was that a subject noted the article added or removed and the exact time he/she did it.

Comfort and Thermal Sensation Scales

Some mention should be given to the scales we used in the specific summer and winter studies. In the past we have used magnitude estimation techniques (9, 11). However, in order to directly compare our results with other studies done for ASHRAE (2, 5, 18), we used the ordinal scales previously discussed by Gagge et al (12). Additionally, in the winter study we used a direct vote of acceptability (+ or -) and a symmetrical scale for local thermal sensation votes. Subjects had no difficulty in understanding either type of scale. A category interval from neutral thermal sensation can be either positive or negative, for warm sensation and cold sensation respectively. For discomfort scale each category interval describes an increase from "comfort point."

ANALYSIS OF SPECIFIC SUMMER AND WINTER LABORATORY STUDIES

Thermal transients can have a decided effect on person's thermal acceptability by influences on physiological and sensory responses. The common way thermal transients occur is by a change in location; that is, movement from one room to another one, cooler or warmer (2). Another occurrence is while a person stays in the same place but air temperature or humidity vary either as ramp increases or decreases over time, or via cyclical changes (19, 20).

Early research was done using thermal transients by changes in room site. Houghten and Yaglou (21) were able to use this technique in arriving at an empirical index (effective temperature, ET) for human thermal response. They showed that thermal sensation e.g. judgment of warmth or coolness of an environment was closely associated with dry bulb temperature and humidity (P_a). Lines of equal thermal sensation formed the basis of their old ET scale which was described using the 100% rh environment. However, this scale was deficient in that it placed too much emphasis on humidity effects in cold environments and did not show clearly effects of humidity in warm environments. By transferring subjects to different room sites, Hardy and Stolwijk (22) and Gagge et al (12) were able to derive useful data from which they separated sensory and thermoregulatory processes and derived proportional control coefficients necessary for their model. In moving their subjects from a room at 29° C to a room set at 17.5° C, they found that cold sensation and discomfort were almost immediate; our estimate (from their thermal sensation and discomfort votes) is that towards the cold, owing to vasoconstriction, a change in one category of thermal sensation and cold discomfort occurred as a result of a drop of 7° C. When subjects were moved from 17.5°C to 29°C, thermal sensation and thermal comfort votes were not concurrent - thermal sensation votes lagged behind (Δ 11.5° C/category in sensation vote) the comfortable feeling (Δ 7.7° C/category discomfort vote). Thus the lag was related to rate of change of skin temperature, but the hedonic estimate was immediate.

Figure 1 shows the typical cyclical changes in T_a we used to derive comfort and thermal sensation thresholds in summer and winter studies. Figure 2 depicts for one subject how such thresholds were estimated by intersection of regression lines from these cyclical T_a changes. Table 1 compares comfort and thermal sensation votes for both summer and winter studies determined by this method.

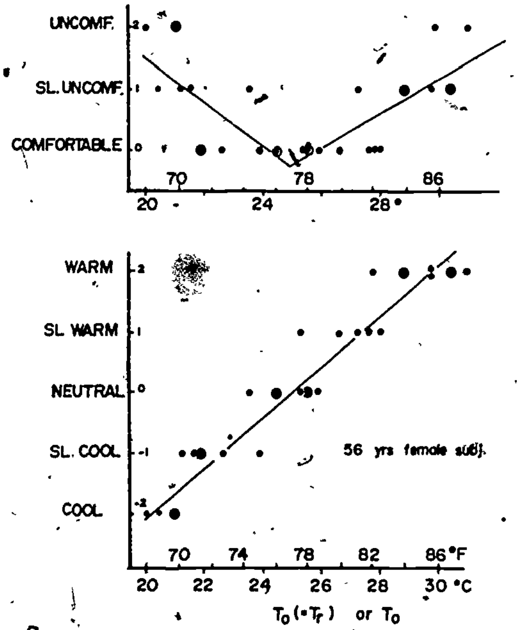

Figure 2. Discomfort estimates and thermal sensation judgments plotted as functions of ambient temperature for one female subject. Only votes between 5-120 min are plotted. Intersection of cold and warm discomfort lines indicate optimal T_a comfort point (24.6°C). Intersection of thermal sensation line occurring with 0 on ordinate is T_a neutral point (25°C). Votes at end of walk are indicated by outer circled points.

Table 1. Optimum T_a (= $\bar{T}_r$) conditions for comfort, neutral thermal sensation and calculated clo values (Nevins et al.) derived by temperature swing method in summer and winter laboratory studies.

Group	T_a for comfort	Warm disc sensitivity	Cold disc sensitivity	T_a for neutral thermal sensation	$\Delta T_{sens}/\Delta T_a$	I_{clo-n}
			SUMMER			
Males	24.7 ± 0.33	0.294 ±0.840	−0.182 ±0.138	24.8 ± 0.5	0.232 ±0.030	0.3
Young females	24.8 ± 0.20	0.327 ± .091	−0.157 ±0.119	26.1 ± 0.3	0.360 ± .022	0.3
Older females	25.0 ±0.30	0.338 ±0.018	−0.195 ±0.313	25.8 ± 0.5	0.318 ±0.044	0.5
			WINTER			
Young males	22.8 ± 0.56	0.26 ±0.11	−0.29 ±0.07	22.72 ± 0.70	0.34 ±0.06	0.78 ± 0.10
Older males	21.9 ± 1.05	0.32 ±0.12	−0.27 ±0.04	22.22 ± 0.59	0.37 ±0.03	0.75 ± 0.04
Young females	23.55 ±0.78	0.26 ±0.18	−0.37 ±0.07	24.08 ± 1.48	0.50 ±0.08	0.83 ± 0.14
Older females	22.54 ± 0.54	0.28 ±0.15	−0.38 ±0.15	22.36 ± 0.98	0.43 ±0.05	0.76 ± 0.16

Values are means (± S.D.); I_{clo} evaluated from Nevins et al (14).

In the summer study, (shown in Fig. 1), discrete subjective responses occurred between groups as a response to the cyclical changes in T_a. In the older females warmth sensation increased between the 50th to 80th min time period. For the most part these individuals were in the comfortable range despite the thermal sensation described as warm. At the peak of the second T_a cycle (85th min), feelings of warmth had decreased but a lag occurred in the discomfort vote. Two factors may have been associated with this effect: one associated with a subjective dissatisfaction (sticky feeling) as a result of permeability of clothing to water vapor which becomes reduced the higher the clothing insulation. This permeation efficiency factor (F_{pcl}) modifies evaporative heat exchange from under the clothing (17). Another factor related to F_{pcl} may have been the direct effect of this delayed evaporation cooling the skin but not reducing thermal discomfort perceived by the skin wettedness (7, 23, 13).

Our dry bulb temperature cyclical method proved a reliable means for assessing short term preferred comfort (thermal sensation) temperatures for both winter and summer studies as shown in Table 1. It was found that the mean preferred ambient temperature for comfort (24.7 to 25°C) does indeed agree well with the long period studies of Rohles and Nevins (5) and Fanger (24) in sedentary subjects. In the summer study, the activity level of 1.2 met, as in office work, did not alter appreciably the preferred temperature for comfort which was within the optimal ambient temperature described by the Fanger comfort equation (3). On the other hand, there were specific differences between men and women and between age groups within the females in thermal sensation regression lines and in optimal ambient temperature judged as neutral. Rohles and Nevins (25) have reported that males felt warmer than females during their first hour of exposure to various air temperatures. Rohles et al (18) suggest, from their observations of thermal sensation differences among males and females, that the "same clothing is responsible for different thermal sensations in men and women." Unfortunately, only combined equations go into formulation of their "Comfort Zone Envelope." In a study by Wyon 17-year-old males generally "felt hotter and reacted more rapidly to changes in air temperature" (10). Stolwijk (personal communication) has found that males exposed to thermal transients from 30 to 50°C had higher warm discomfort compared to females per change in central drive for evaporative heat loss. All these studies served to show that the thermoregulatory responses closely tied in with (and which modify) thermal acceptability are not uniform between sexes - a finding originally noticed by Hardy and DuBois (26). These differences become apparent only under fluctuating temperature conditions.

In contrast to other studies (24) with sedentary subjects, in which there was a constant preferred temperature regardless of age, we found that older females preferred warmer ambient temperatures during slight activity in the summer experiments. Since clothing habits in summer months differ widely among females and males, we have reduced analytically differences in apparel and neutral temperature sensation votes to make them comparable to the ASHRAE ET* recommended comfort zone bounded by 22.2 and 25.6 ET* as seen in Fig. 3. This approach was used in earlier work (13) in which subjects do not wear similar clothing. We have used Standard Operative Temperature (STO) because STO more clearly defines the present conditions since skin wettedness was not actually measured in all our subjects. In brief, STO is defined as the uniform

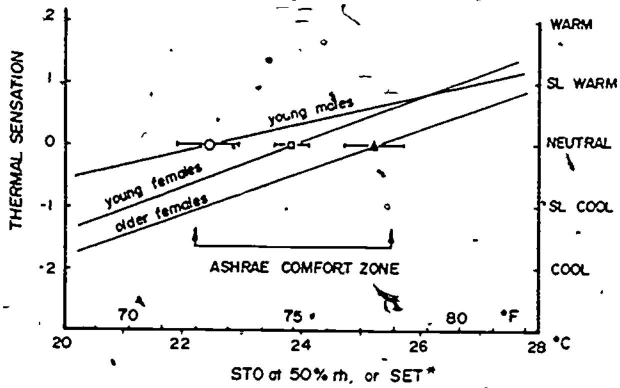

Figure 3. Estimating equations for average thermal sensation estimates as functions of standard effective temperature (SET*) or STO at 50% rh and the optimal SET* point (± 1 SD) for neutral thermal sensation for males (open circle), young female group (open squares) and older female group (open triangle). The regression equations are:

Males:	TSENS = 0.23 (SET*) - 5.15
Young females:	TSENS = 0.36 (SET*) - 8.57
Older females:	TSENS = 0.318 (SET*) - 8.01

temperature (T_a) at 50% humidity of a standard sea level environment (air movement 20 to 35 fpm) in which a subject wearing standard clothing (0.6 clo) loses the same heat by evaporation, radiation, and convection as in the actual complex environment. The "standard" environment at sea level (760 mmHg) is the same as the one in which ASHRAE ET* (2) is determined: i.e., in which a subject wears 0.6 clo and the air movement renders a convective heat transfer coefficient (h_c) of 2.9 W/(sq m °C) and a combined heat transfer coefficient (h_s) of 8.0 W/(sq m °C).

For our summer experiments, STO was determined by the following relationship:

$$STO = [hF_{cl}/h_sF_{cls}]T_a + [1 - hF_{cl}/h_sF_{cls}]\bar{T}_{sk} \quad (1)$$

where:

T_a = operative temperature T_o, $h = h_c + h_r$ and equalled 8.3 W/(sq m °C) in our experiments; and F_{cl} is the Burton clothing efficiency factor determined by the relation:

$$F_{cl} = 1/(1 + 0.155h \cdot I_{clo}) \quad (2)$$

I_{clo} is the clothing insulation in clo units (1 clo = 0.155°C · sq m/W) and

F_{cls} is the standard clothing efficiency factor for a subject wearing 0.6 clo and equals 0.58, using h_s = 8.0 W/sq m °C) from Eq (2).

Since the relative humidity in these experiments was 50%, then by definition (10) STO equals the Standard Effective Temperature (SET*).

Figure 3 presents the estimating equations for thermal sensation determined from analysis of the corresponding thermal sensation votes and SET* (or STO at 50% rh) from the same data as used in Table 1. Two observations can be made from this plot. One is that the SET* (i.e., STO at 50% rh) preferred temperature determined for the subjects in our study, although within the ASHRAE comfort zone, is significantly different ($P \leq 0.01$) between the young male and both female groups. Secondly, the T_a preferred temperature for younger females (Table 1) when normalized by SET* (STO at 50% rh) in respect to $\bar{T}_{sk}$ and clo, is lower in terms of SET* (STO at 50% rh) compared to the older female group. On the other hand, it can be inferred that the tendency for older females to prefer warmer T_a's may be a result of lower metabolic heat production in these individuals (26).

There was a significant difference in the subjects' sensitivity in judging thermal sensation as determined by statistical analysis of the regression coefficients. Young females and older females had significantly higher warmth sensitivity than the male group ($P \leq .005$). However, there was no significant difference ($P \geq 0.05$) in warm sensitivity between the young and older groups. The data suggest that a change in 4.34 °C in ambient temperature caused one category change in warmth sensation in the male group (i.e., reciprocal of the regression coefficient) while a 2.8 °C and 3.1 °C change in T_a would result in a similar category change in the young female and older female groups, respectively.

The results of the preferred optimum T_a levels, derived by our swing method for the winter laboratory study, in which subjects were allowed to wear typical winter indoor clothing, can be compared to the values obtained during the summer study. In the summer laboratory study described above, males' thermal-sensation neutral point (24.8° C) was significantly lower than the females; the thermal sensation sensitivity was also less. In the winter series (Table 1), however, the temperature for neutral thermal sensation was not significantly different within the groups, but was significantly reduced compared to summer values. In the winter study, the higher clothing insulation contracted the preferred air temperature for comfort and neutral thermal sensation about 2° C compared to the zone observed for the summer study. The thermal sensitivity values ($\Delta T_{sens}/\Delta T_a$) were in line with Fanger's predicted ($\approx .4$) but were higher, as a group, then for the summer series. The lower displacement in winter preferred temperatures for comfort is in itself interesting and has been also shown in the survey findings by Dr. Gagge discussed in this Symposium.

Effect of Level of Humidity on Comfort and Thermal Sensation in Summer

The results of the experiments in which humidity was elevated each hour for 3 hr at 27°C are shown in Table 2, and these discomfort and thermal sensation judgments are plotted in relation to ET* in Fig. 4. Each comfort and thermal sensation value is the average terminal judgment of a 1-hr exposure.

No significant differences were evident between thermal sensation values for the groups, or for individual changes within a group, at each humidity level (Table 2 and Fig. 4). In the male and female subject in which skin temperatures and core temperatures were measured, a humidity level of 40%, 60%, and 80% rh at 27°C T_a did not affect mean skin temperature which stayed constant within ± 0.2°C throughout a 3-hr period. Core temperature was also not elevated more than ± 0.1°C. This is direct evidence that temperature sensation, as judged psychophysically by the subjects, is associated with skin temperature, which is governed by ambient temperature rather than

Table 2. Comfort and thermal sensation values at the end of a 1-hr humidity exposure at 27°C T_a. Activity level at 1.2 met.

	COMFORT			THERMAL SENSATION		
Relative humidity (%)	40	60	80	40	60	80
P_a (Torr)	10	15.9	20.7	10	15.9	20.7
Males, n = 7 (22-32 yr)	0.57	0.82	1.57	0.50	0.81	0.54
± sem	0.19	0.24	0.12	0.33	0.08	0.33
Females, n = 5 (18-24 yr)	0.60	0.40	0.60	0.50	0.25	0.10
± sem	0.36	0.22	0.38	0.14	0.18	0.38
Females, n = 6 (33-60 yr)	0.42	0.33	0.83	0.33	0.42	0.58
± sem	0.30	0.15	0.25	0.33	0.30	0.27

n is number of individuals in each group; sem is the standard error of the mean.

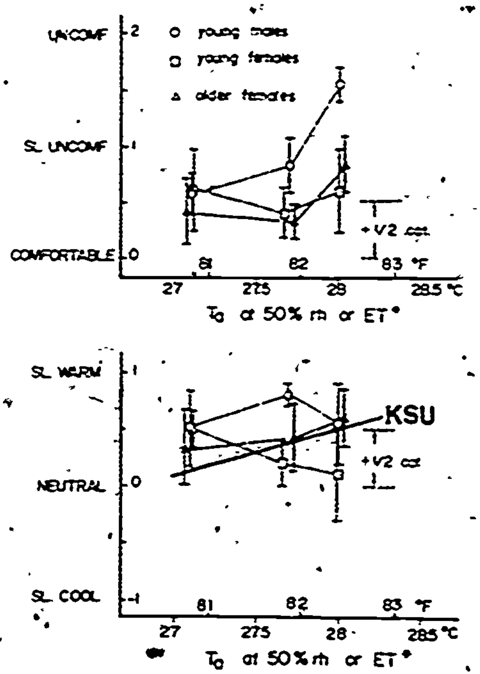

Figure 4. Average discomfort estimates (upper ordinate) and thermal sensation estimates (lower ordinate) as functions of ET* for humidity experiments. Solid line is combined Kansas State Univ. (KSU) regression equation: $Y = 0.151T + .010H - 8.371$ where T (T_a, °F); H (% RH) (Rohles et al, 1973).

modified by humidity level as long as skin temperature is higher than dew-point temperature. This response would be expected since relative humidity exerts little effect on the loss of heat by evaporation when the body is in the zone of vasomotor regulation (26). It also serves to show that one would not be able to predict accurately the clear effect of humidity on thermal affective responses by merely using an equation shown in Fig. 4. As evident in Fig. 4, humidity level affected judgments of discomfort, which varied markedly within the groups. There was a significant increase in discomfort, (using paired sample analysis, $P \leq 0.05$) for the male group from 60 to 80% rh level (Table 2, Fig. 4). However, for the younger female group or older female group, no significant increase in discomfort occurred during the 60% to 80% relative humidity increases. The mean discomfort value at 80% rh for the male group was significantly higher than the discomfort values for the younger female group ($t = 2.43$, $P \leq 0.05$) and for the older female group ($t = 2.52$, $P \leq 0.05$). Analysis at variance for repeated measures of unequal group size (Winer, p. 599)(27) confirmed the fact that humidity level was the significant main effect on subjects' discomfort votes.

Thus we can surmise that all groups were not affected at all by the 40% rh level at constant 27°C T_a. Males sensed a greater discomfort with increases in humidity level from 60% to 80% ($\approx$16 to 21 Torr) at an activity level of 1.2 met in 27°C T_a, while females did not. Furthermore, the discomfort at 80% rh was significantly higher in males than the discomfort felt by the younger female and older female groups. In terms of discomfort a change of 1 category Disc per change of 10.7 Torr is balanced by a change in 1.1°C T_a level in males. Griffiths and McIntyre (28) also found that at 28°C a low humidity was preferred and 50% and 75% rh were considered by their subjects as "more oppressive and uncomfortable." All these studies indicate that the minimum acceptable humidity conditions in summer months for a dry-bulb temperature of 27°C (80.6 F) appear to be at 60% rh ($\approx$ 16 Torr), corresponding to a ET* of about 27.7 or 2 °C ET* above the optimal ASHRAE neutral/comfort zone. However, further studies are needed at higher ambient temperatures and humidity levels. Males, engaged in office-type activity (1.2 met), as shown in this study, appear to be very sensitive to elevations in humidity; and level of skin wettedness, determined by the ratio of evaporation of sweat to the maximum evaporative capacity of the environment, probably plays an important role in adding to the warm discomfort as shown in earlier studies (7 and 13). Decrements in performance of light physical and mental tasks may occur at increasing levels of humidity ($\geq$ 60% rh at 27°C, as in our study) and higher ambient temperature for longer exposure periods.

Based on the present study (Table 2, Fig. 4), at the upper T_a of the FEA guideline (26.7°C) thermal discomfort and sensations (at $\leq$ 1.2 met) would not be appreciably elevated for humidity levels $\leq$ 60% rh (16 Torr) regardless of clothing ensemble if $\leq$ 0.6 clo. Higher humidities than these at the required summer ambient temperature conditions in office buildings may result in significant increases in warm discomfort and indicate a need for some humidity control.

Special consideration should be given to elderly office workers. As shown in this study, older females after 1-hr exposure were not excessively disturbed by the 80% humidity level at 27°C. However, because of the general lower physical fitness and resulting lower sweat secretion and poor skin circulation, level of skin wettedness does not serve as an early cue for thermal discomfort in the elderly as it does for more fit individuals (17). Other symptoms of distress (syncope, headache, etc.) are less ostensible and can occur at higher levels of humidity and ambient temperatures.

Effect of Level of Ambient Temperature on Thermal Acceptability in the Winter

The basis of this study was that subjects were allowed at will to increase their clothing insulation (by addition of sweaters). As such, behavioral thermoregulation would be the major way to avoid displeasure from cold aided also by vasoconstriction. We limited our exposures to 1-hr so that excessive heat loss would not be a major factor and decrease core temperature. In other studies we have done (19) at similar time periods, esophageal temperature was maintained constant ($37 \pm 0.2^\circ$ C) in sedentary individuals ($\approx$ 0.6 clo) even at ambient temperatures of 5°C and 10°C. In the present study, we were also interested in evaluating how cold discomfort varies over different body segments among males and females of different age groups.

A plot of the whole-body discomfort, thermal sensation, and effective clothing insulation (17) is shown in Fig. 5 for each group. The most significant observation is that at neither of the two T_a levels did the subjects manage to avoid discomfort totally by use of extra clothing (shown by the effective I_{clo} increase). Young females always had a significantly higher effective clo increase from comfort conditions compared to the other groups (roughly a change of 0.3 clo) from baseline comfort conditions. What is apparent in this figure is that subjects, for some reason, never added sufficient clothing which would bring them close to the intrinsic I_{clo} of 1.4, (about 0.9 effective clo), which Fanger (3) has recommended as a clo value for a 20°C preferred temperature at 1.1 met. Humphreys (29) has pointed out that an individual may find it more acceptable to function by intermittent activity levels, of rest and work, if he/she is lightly dressed in a comfortable environment than if he/she is heavily dressed in a cool one.

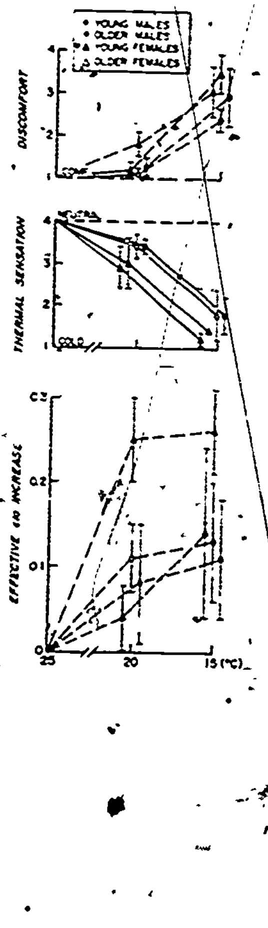

Figure 5. Whole body thermal discomfort, thermal sensation, and increase in effective I_{clo} at 20°C and 15°C.

A plot was made of whole body discomfort and arithmetic means of the local regional thermal sensation votes at 20° C and 15° C as shown in Fig. 6.

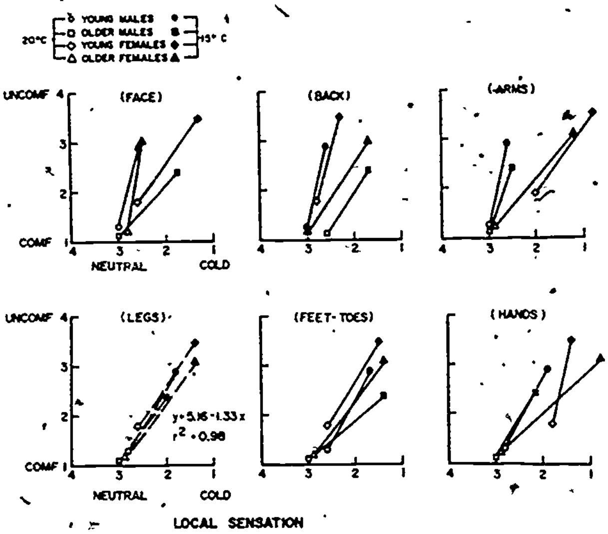

Figure 6. Relationship between whole body thermal discomfort and local thermal sensation from various body segments.

Clearly, what this figure indicates is that thermal sensation votes over the face, back, arms and hands tended to be distributed unevenly. The assessment of thermal sensation from the covered legs for the two T_a levels proved a good predictor of the total cold discomfort for all groups regardless of clothing insulation. Thus, every increase in local cold sensation from the legs (and possibly also feet and toes) away from a thermally neutral point may be a reasonable indication of total cold discomfort and by inference - thermal dissatisfaction for all individuals.

Fanger has shown (3) that even within the level of ASHRAE's Comfort Standard (2), which is rigidly specified for both winter and summer conditions, 5% of the people will still be dissatisfied with the environment. In our study it was possible to directly compare the frequency of votes (5 subjects/group over 3 sessions), each subject checked as acceptable or not acceptable, over the two dry bulb temperatures. The results are shown in Table 3a. The hypothesis was tested of no difference between groups (i.e., equal acceptability among young males, older males, young females and older females). The χ^2 analysis gave 10.84 (df 3) which shows a highly significant difference in acceptability. Young females had the most dissatisfaction at 20° C environment despite a higher clo value (0.9 clo). As expected, at 15° C all groups had similar dissatisfaction with the environment (viz: $\chi^2 = 1$, df 3, $P \approx .05$). Interestingly, when Fanger's criteria (3) are used to estimate acceptability (i.e., all votes + 1 or - 1 from neutral, acceptable), the percentages are somewhat lower (70%) compared to our direct group votes as seen in Table 3b.

In our winter study it was found that at 20°C, the effect of added clothing by the subjects (generally done by adding sweaters and determined by the effective clo increase (17)) did maintain 3 of the groups in the comfort range. In this respect, our results concur with the observations of McIntyre and Griffiths (30) in which donning of a sweater (≈0.3 clo) increased feelings of warmth. Differences between males and females were again observed in the winter study. Local sites producing the highest cold sensation votes at

Table 3-A. Directly observed acceptability of 20°C.

	Young males	Older males	Young females	Older females	Total
Acceptable	13	12	8	15	48 (80%)
Not acceptable	2	3	7	0	12 (20%)
	15	15	15	15	60

$X^2 = 10.84$; df 3 ($P \leq 0.001$)

Table 3-B. Fanger's criteria of acceptability for same data.

	Young males	Older males	Young females	Older females	Total
Acceptable votes*	13	13	8	8	42 (70%)
Non-acceptable	2	2	7	7	18 (30%)
	15	15	15	15	60

$X^2 = 8.08 \geq 7.8$; df = 3 ($P \leq 0.05$)

*Acceptable votes according to Fanger include all votes + or - 1 category from 0 or neutral.

20°C showed a similarity to others' results (26, 30). However, the areas constantly exposed to cold such as the face and hands were not consistently sensed as the coldest by every group (variable heat loss in the face) (Fig. 6). The cold sensation votes from the uncovered legs, however, were highly correlated with total cold discomfort for all groups (Fig. 6) and may be a good predictor for both thermal sensation and discomfort.

Another factor which should be considered in judging thermal acceptability at 20°C and above is body weight-to-DuBois surface area ratio or the ponderal index of Fanger (e.g. $\sqrt[3]{wt/A_D}$), which factor is a relative indication of body build and amount of subcutaneous fat (in lieu of skin fold measurements). This factor is another way of aiding thermal insulation and, thus, enhance cold resistance (26). In this respect, young females had the lowest weight-to-surface area ratio, but were more dissatisfied at 20°C despite a higher calculated I_{clo} than the other groups. The combination of increased local air movement around extremities while walking and increased dry heat loss around these specific body segments may have also contributed to the dissatisfaction apparent in young females. In the winter study it was found that older individuals complained less of the cold than did younger females and they had less cool discomfort at both 20°C and 15°C (Fig. 6). Such response has been shown in other studies on elderly persons by Watts (31) and by Horvath et al (32). Horvath et al (32) noticed that although older subjects (male and female) did not make discomfort complaints (at 10°C), they were less able to maintain core temperature than the younger subjects. We are especially concerned with responses from the elderly age group because in older individuals metabolism is generally decreased compared to young individuals and problems of adequate circulation may occur, especially in the inactive. Cold discomfort, however, may not serve as an adequate cue as shown in the study by Watts (31), Horvath (32) and ours.

In summary, as shown in these laboratory experiments, a 20°C environment, of possible interest nationally as an energy conservation strategy, may never be wholly accepted by a significant percentage of all individuals despite added clothing or doing light office work with increased activity. When occupant comfort and acceptability of such an environment is considered, local cold discomfort from peripheral extremities, such as arms, legs and feet, surface area-to weight ratio, sex and age, duration of occupancy, as well as level of activity, must all be considered. All the problems, introduced by these factors, certainly will not be remedied by merely adding extra clothing. However, an awareness of which groups of subjects are the most likely to be dissatisfied is a step in the proper direction. Even while left free to increase clothing at 20°C, only 80% of the subjects in our laboratory winter study found the conditions thermally acceptable.

Special Study: Seasonal Acclimatization

Despite extensive research in this field, little is known about the effects of long-term heat exposures for subjects working and living in hot climates on their thermal comfort response and on their thermoregulatory system. Equally unclear is human acceptability of such an environment even though many spend whole lives in warm regions. For example, a sedentary office worker in a hot climate is not necessarily acclimated to moderate or hard work in that climate. Thus, both physiological and sensory responses may be clearly different in the same individual depending on the task he performs. Whether at rest or active, heat acclimated subjects, both clothed and unclothed, should have an upward displacement in preferred T_a (or acceptability of a given warm environment) compared to an unacclimated state. However, Fanger (24) has never observed this in individuals brought to Denmark from tropical areas. Additional basic studies are necessary, however, because Nicol (33) has analyzed the field studies made by Webb (34) and found that natives of certain hot-wet regions, with varied occupations and presumably heat acclimatized, do prefer warmer ambient conditions (up to 32-33° C) in summer seasons. Humphreys (29) has compared results of extensive field studies in various climates around the world and concludes that "Fanger's results which suggest that acclimatization does not affect thermal comfort requirements, may need some qualification."

A just-completed study (25) explored the physiological and affective changes occurring during seasonal heat acclimatization in 20 young males attending Yale Summer School sessions. Subjects rested or did light exercise (≈ 2 met) while exposed to ambient temperature changes, either unclothed or heavily clothed. The conditions were done in early June and repeated in late August. Results of the study are shown in Table 4.

In general, the affective responses for resting subjects, both clothed and unclothed showed no statistically significant difference between June and August. This confirms McNall's et al (6) early studies in resting subjects. However, the light exercise was, in fact, instrumental in changing affective responses. Exercising subjects in August preferred a warmer temperature (Scale 1), thought they were sweating less (Scale 3), had lower internal temperatures (oral), and felt cooler (Scale 5). Figure 7 shows that, for subjects in which sweat loss was directly measured, a displacement occurred towards lower internal body temperature without a change in the proportional control coefficient for evaporative heat loss.

Table 4.

Summary of Differences Between June and August

Scale	Conditions	Test (n)	Mean difference	
1 (Preference)	Rest	Sign (9)		N.S.
	Exercise		16+, 6-	$p \le 0.05$
2 (Discomfort)	No test significant			
3 (Sweating)	Resting (1 & 2)	Paired t (9)	-0.1	N.S.
	Exercise (3 & 4)	Paired t (9)	0.9	$p \le 0.01$
4 (Estimate)	No test significant			
5 (Warmth)	Resting (1 & 2)	Paired t (9)	-0.1	N.S.
	Exercise (3 & 4)	Paired t (9)	0.7	$p \le 0.01$
6 (Hands)	No test significant			
7 (Feet)	No test significant			
8 (Face)	No test significant			
Mean skin	Clothed (2 & 4)	Paired t (5)	0.5	$p \le 0.01$
	Unclothed (1 & 3)	(4)	0.1	N.S.
Internal	Resting (1 & 2)	Paired t (9)	0.1	N.S.
	Exercise (3 & 4)	(9)	0.2	$p \le 0.01$

A positive difference implies a lower value in August. In scale 1, more people requested a warmer environment in August than in June.

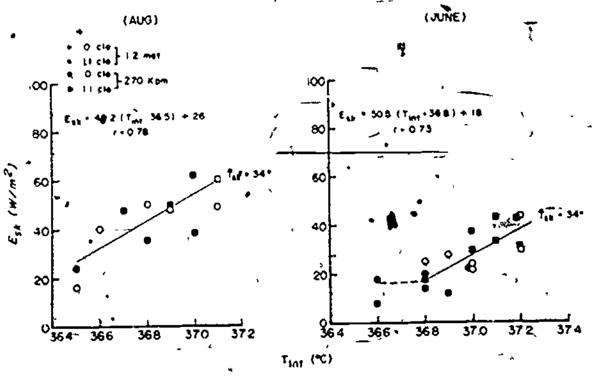

Figure 7. Relationship between evaporative heat loss (E_{sk}) and internal body temperature.

These experiments have broad relevance to energy conservation requirements in summer months. For one thing, if subjects' thermal preference is for higher ambient temperature in late August, the thermal acceptability criteria (2) may in fact be changed. Building environments (T_a and rh) could be allowed to rise during the day in summer months with only minimal dissatisfaction. Essentially, physiological processes (improved skin blood flow, evaporative heat loss) occurring during normal heat acclimatization could compensate for the reduced air conditioning necessary for conservation of energy. However, our results have to be confirmed by more extensive field surveys.

CONCLUSIONS

The present review has focused on some physiological and subjective factors which will be important in Energy Conservation practices in the future. Throughout this paper the emphasis has been that, before we consider engineering applicability in built environments, we must first consider physiological consequences. It is an easy matter to lower thermostat settings in the winter or raise temperature settings or eliminate humidity control in the summer. As we have shown in these laboratory studies, such practices will involve a measure of discomfort. Thermoregulatory and heat exchange models can offer a useful first order prediction of the degree of thermal discomfort; but, we need to realize that such model predictions have to be compared with actual experimental data which may not necessarily involve thermal steady-state conditions. It is not the physiological comfort point where we need additional studies - it is at displacements from this point. Such studies in the future should focus on a disinterested resolve to such factors as sex, age effect, frequency and direction of dry bulb and humidity and possibly any changes in human comfort criteria caused by normal physiological acclimatization.

Acknowledgments

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RATING OF ENVIRONMENTS FOR HUMAN THERMAL COMFORT BY "RESULTANT SURFACE TEMPERATURE"

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ABSTRACT

A concept is introduced for rating thermal environments on their potential for human comfort. It involves the measurement of the surface temperature (designated Resultant Surface Temperature) of an object placed in a building environment and producing heat per unit surface area at a rate equal to that of a human body. A detailed description is given of a prototype RST-Meter that has been built. The intended applications for the instrument and how it could be used for rating environments is described.

Key Words: Indoor Environmental Measurement, Rating of Indoor Environments, Thermal Comfort

INTRODUCTION

It is generally accepted that there are six primary variables that govern the "feeling" of comfort or discomfort on the part of occupants of any given structure (1, 2)*. The variables are air temperature, relative humidity, air velocity, mean radiant temperature, the level of activity of the occupant, and the amount of clothing worn. Experimental work has been done over the past fifty years to determine the interrelationships among these variables and how a change in one, with given fixed values of the others, affects comfort (3,4,5,6,7,8,9). More recently, mathematical models, which have been verified by some of the past experiments, have been used in these studies (1,10,11,12).

In making measurements to determine the acceptability of indoor environments from a thermal standpoint, the air temperature, relative humidity, and velocity are most often measured with conventional instruments and the mean radiant temperature (MRT) determined by using a globe thermometer. However, it is difficult to accurately measure the air velocity because of the relatively small air movement in most occupied spaces of buildings. In addition, the accuracy of determining MRT with the globe thermometer is a function of the accuracy of determining the air velocity. The globe normally is a 15 cm (6 in.) diameter hollow copper sphere coated with flat black paint and having a thermometer at its center. The temperature assumed by the globe at equilibrium is a result of a balance between the energy gain or loss by radiation and the gain or loss by convection. The MRT is then calculated using the air temperature, air velocity, and globe temperature. There have been a number of instruments built over the last decade to determine MRT more directly. They are reviewed in a separate paper presented at this symposium (13).

There have been very few instances where the measurements of all the variables or at least the effect of all the variables have been combined into a single instrument. Two of the most significant attempts at doing this have resulted in the so-called "Thermal Comfort Meter" (14,15,16) and the "R-Meter" (17).

The "Thermal Comfort Meter" consists of an ellipsoidally-shaped sensing body and an associated control circuit and calculating device. The size, shape, and surface properties of the sensing body were chosen so that the relationship between the energy exchange by convection and radiation is the same as that for a human. The control circuit maintains the surface temperature of the sensing device at a prescribed level (chosen by the instrument user and depending upon the occupant's metabolic rate and nature of the clothing specified) and the amount of energy required to maintain this temperature (i.e., the heat loss from the sensing body) is then used in the calculating device to give a direct readout in terms of relative position on a comfort scale.

* Numbers in parenthesis indicate references at the end of the text.

The R-Meter consists of a sensor unit which is a 0.5 cm (2 in.) diameter skin-colored sphere formed by No. 36 enamel copper wire, bifilarly wound as two hemispheres. The wires are held as a rigid sphere by a thin epoxy coating. The sphere serves not only as a sensor but also as a uniform and rapid heating element. The sensor and associated control box can be operated to determine the operative temperature (18,19), defined as the uniform temperature of an enclosure surrounding the subject in which he would have the same heat exchange by radiation and convection as he does in the actual environment.

The major advantages of such instruments are their ease of use and the fact that the individual environmental variables need not be measured. This latter advantage however is also a disadvantage. Whereas the instrument will give an indication of the relative feeling of discomfort to be expected, it is not possible to determine the reason for discomfort without additional measurements. The exception is with the use of the R-Meter, where it can also be used to measure MRT and equivalent "free-stream" air velocity.

The subject of this paper is new instrumentation and the experimental approach which should allow a thermal environment to be fully characterized including the asymmetrical aspects of low temperature radiation and air motion.

RESULTANT SURFACE TEMPERATURE (RST)

The task of characterizing and rating a given environment on its potential for human thermal comfort could be resolved in an ideal manner, if there existed one measurement that would reflect, and be responsive to, all factors of the thermal environment, in the same way as a human body is affected and induced to respond. It is proposed that a measurement of surface temperature (to be called resultant surface temperature (RST)) of an object, producing heat per unit surface area at a rate the same as the heat production of a human body and placed in the position where the occupant of the environment would place himself, will satisfy the requirement.

Inherent in the concept of RST are the following assumptions:

1. Whenever, at a given rate of heat production, any factor of the thermal environment changes, the RST must also change in order that the equilibrium between production and loss of heat can be restored. In other words, whenever the MRT rises, and everything else stays the same, the RST must rise. Whenever air temperature falls, and everything else stays the same, the RST must fall. Whenever air motion increases and everything else stays the same, the surface temperature of the heated object must go down.

2. There is, in any one environment at a specified location, at one time, and in one direction of space, only one RST that can fulfill this condition.

"RST" is therefore chosen to be the variable to rate thermal environments objectively and unequivocally with respect to their effects on human occupants in given places. Moreover, unlike ratings obtained by means of the state-of-the-art indices, the measurements of RST would be independent of any study or findings, past, present or future, on the reactions of human subjects, their physiological (pheripheral or central) temperatures and their subjective sensations, behavioral reactions, or votes of comfort. The essential physical characteristics of a given environment would be measured in an exactly reproducible manner.

DESIGN AND CONSTRUCTION OF AN RST-METER

Some work has been done to design and build a prototype RST-Meter. This work will be described herein.

Since two of the four physical factors involved in the heat exchange process between the occupant and space, radiant heat transfer and air motion, have directional characteristics, it was decided to construct a sensor that could be used to "scan" the environment. In this way, the directional characteristics of RST could be determined. Since a scanning radiometer had already been built (20) for determining directional radiant temperature (DRT) (see Figure 1), it was tentatively decided to incorporate the prototype RST-Meter onto the top of the existing scanner head.

A schematic of the proposed RST-Meter construction as originally conceived is shown in Figure 2. It consists of a tightly bonded lamination of several components. The center is an insulating base which serves to unite mechanically, yet separate thermally, the two heaters supplied with identical amounts of energy per unit time and surface area. External to the twin heaters are twin thermometers bonded to the heaters by a thin layer of electrically insulating material. The outermost layers are coated with some material absorptive to low-temperature long-wave radiation.

When the instrument was first conceived, it was planned to build the sensor head by depositing thin layers of metal on opposite sides of a thin "Mylar" sheet. Each sheet was then to form one half of the symmetrical instrument sensor of Figure 2. On one side of the sheet, the metal was to be reference grade platinum which would serve as the resistance thermometer and on the other side, a metal alloy (called LTC) of gold, chromium, and nickel with an extremely low temperature coefficient of resistance for the heating element. It was planned to bond the resistance heater directly to the central insulating panel. In turn, the resistance thermometer deposited on the opposite of the "Mylar" sheet was to be covered by an overlapping layer of silicon monoxide (also accomplished by deposition) allowing a covering metal foil to be applied for an outer surface. It was recognized that the only disadvantage of such a design was the relatively low resistance (on the order of ten ohms) obtained for square layers that were thick enough to be uniform. However, the resistance could be increased to the order of 200 ohms by dividing the square into a continuous ribbon. Figure 3 shows the basic pattern for both the resistance heater and resistance thermometer. It was planned to accomplish the pattern by placing certain "masks" over the substrate during the deposition processes.

After several months of experimentation, the basic design described above had to be modified for two main reasons. First, it was not possible to accomplish a uniform comb pattern as shown in Figure 3 by deposition even though two different techniques were used for "masking" the substrate. Secondly, it was found that the resistance thermometers could not be electrically isolated from the covering metal foil by the deposition of the silicon monoxide layer. A microscopic investigation of the deposits revealed innumerable pinholes which resulted from not being able to obtain a completely dust-free substrate.

As a result of the above efforts, a change in design was made. It was decided to use a substrate of synthetic sapphire and to deposit the same metals as initially selected but to do it by the technique of "sputtering". The facility for sputtering (in this case at the National Bureau of Standards) had a size limitation on the target. Consequently, the size of the prototype sensor which was actually built was reduced somewhat from the original design.

Figures 4 through 7 are schematic diagrams showing the essential features of the prototype that was finally built. The substrate of sapphire that was used had a thickness of 0.2 mm. Figure 4 is a front view of the sensor head showing the essential dimensions. The surface of the sensor measures 1 cm^2. The two deposits, gold for the resistance thermometer and LTC for the heater, are on opposite sides of the substrate with the slicing patterns rotated by 90^o. This rotation was done to insure a uniform temperature distribution across the surface of the sensor. The figure also indicates the wires required for connection to either a linear bridge (thermometer) or a power supply (heater). The five shown are for the thermometer and heater in front. A total of ten were required for both thermometers and heaters and were fed down through stainless steel tubing having an inside diameter of 6 mm as indicated in Figure 5.

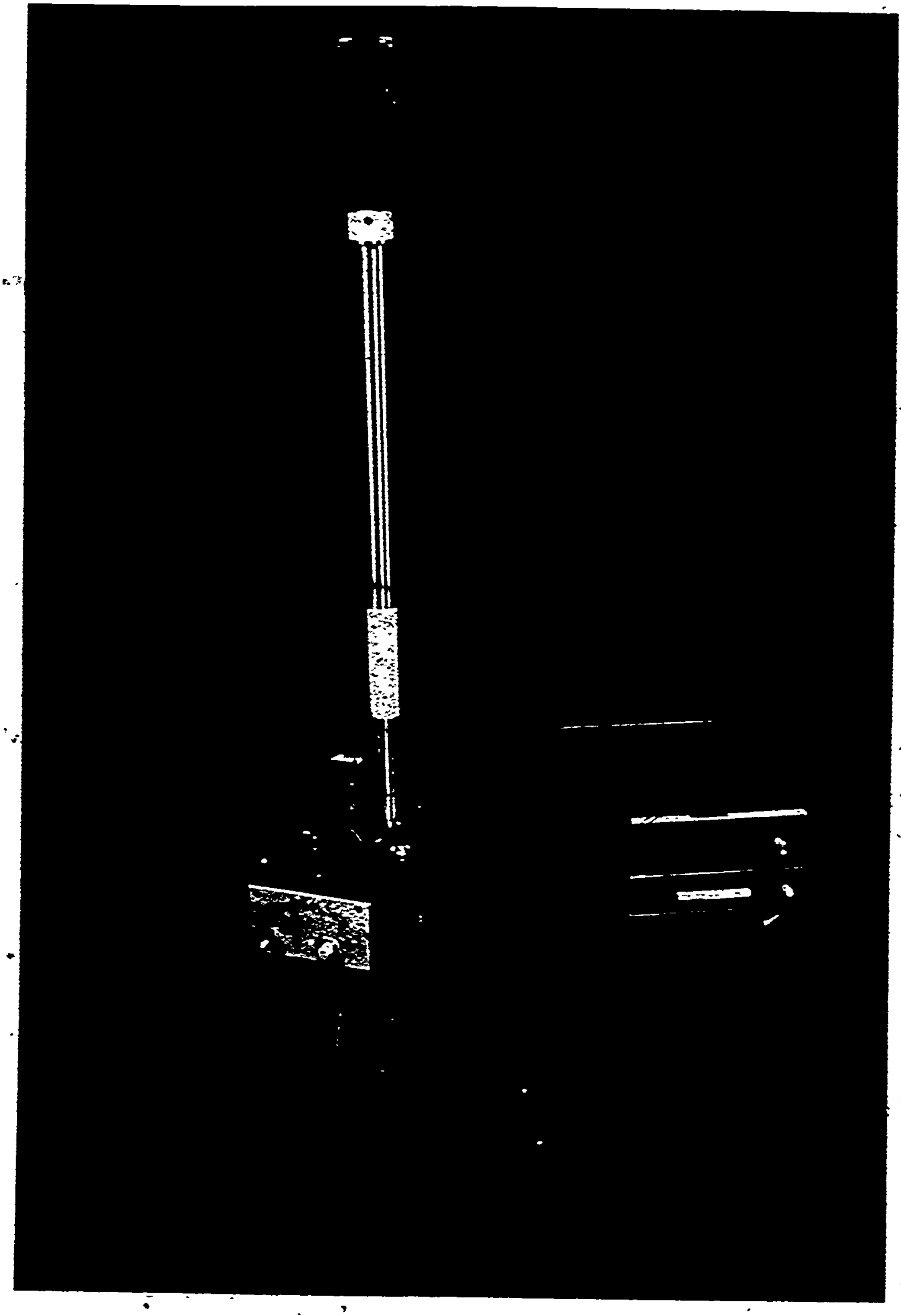

Figure 1. NBS Scanning Radiometer (20)

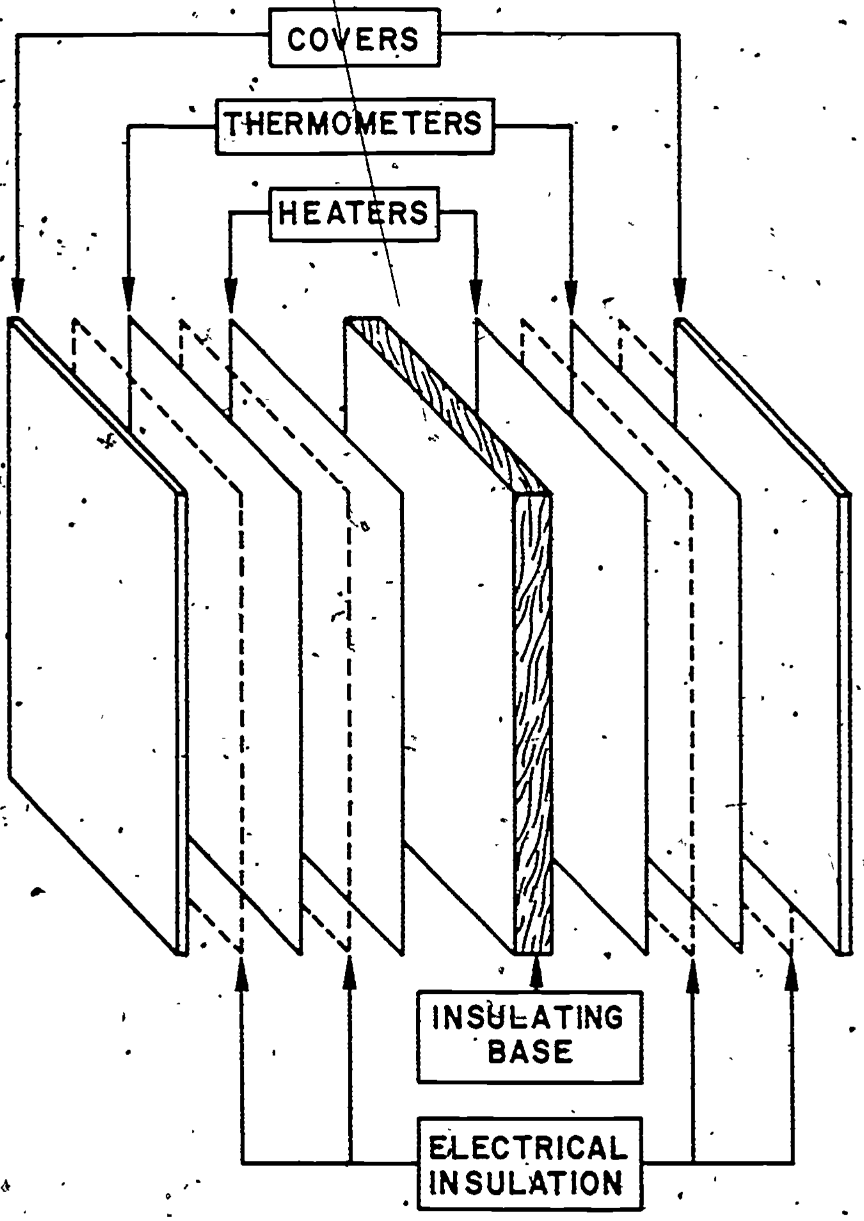

Figure 2 Schematic Diagram of the Major Elements of an RST-Meter

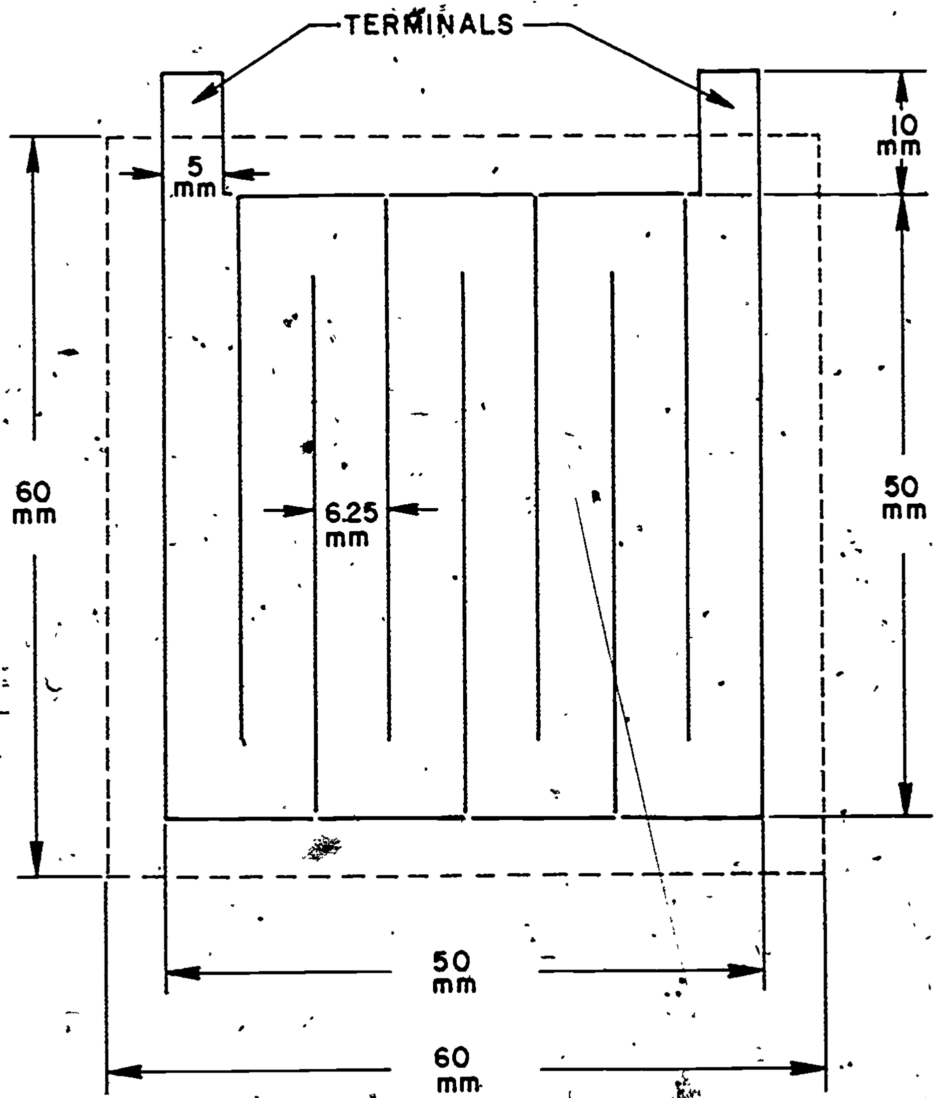

Figure 3 Comb Pattern Proposed for the Resistance Thermometer and Heating Element of the RST-Meter

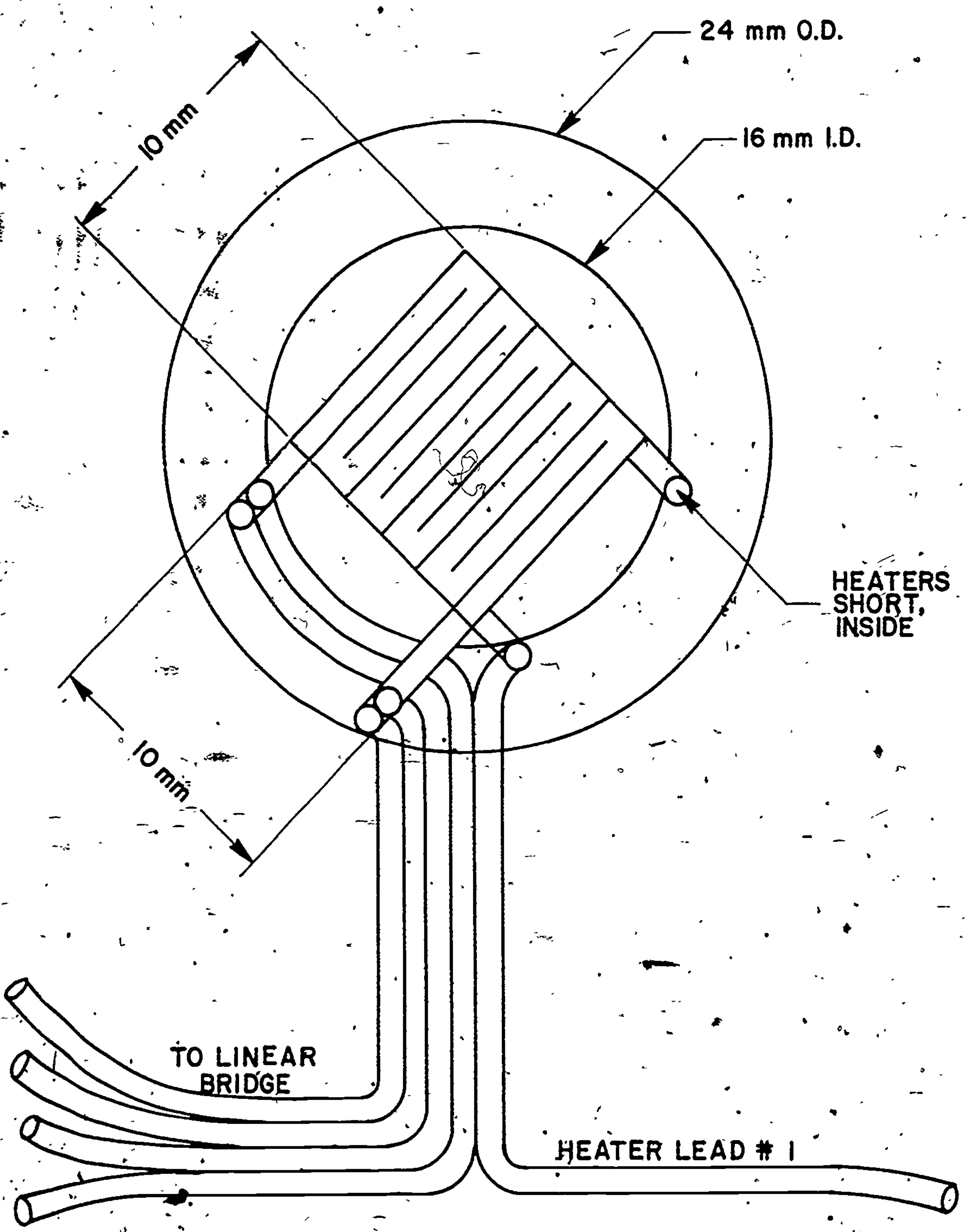

Figure 4 Front View of the Prototype RST-Meter Sensor

RST-METER SENSOR

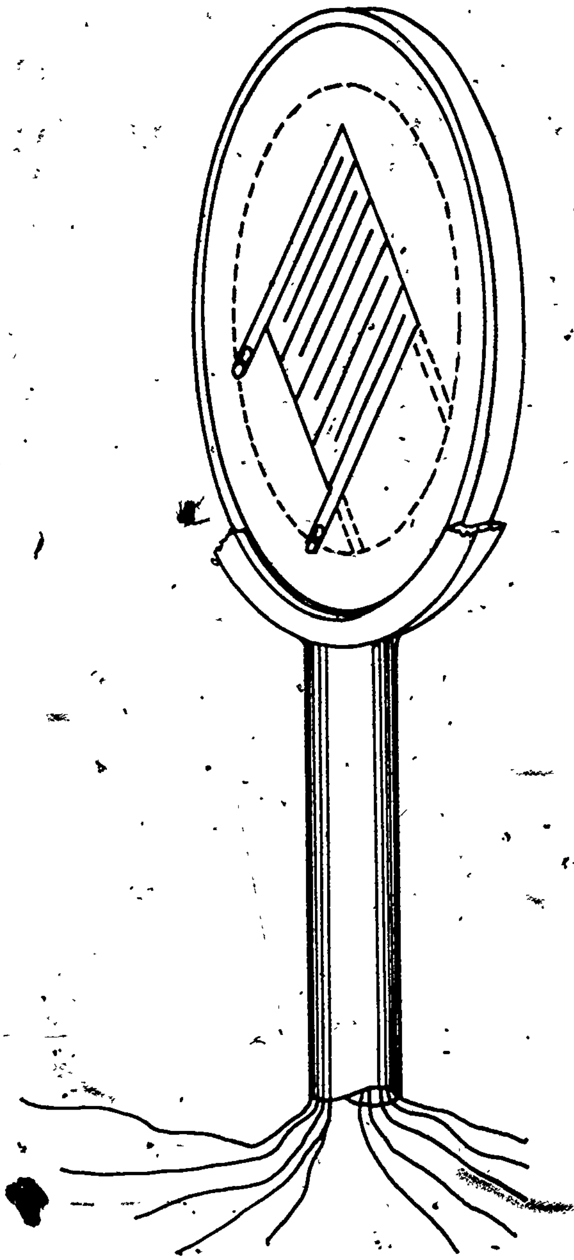

Figure 5 Isometric View of the Prototype RST-Meter

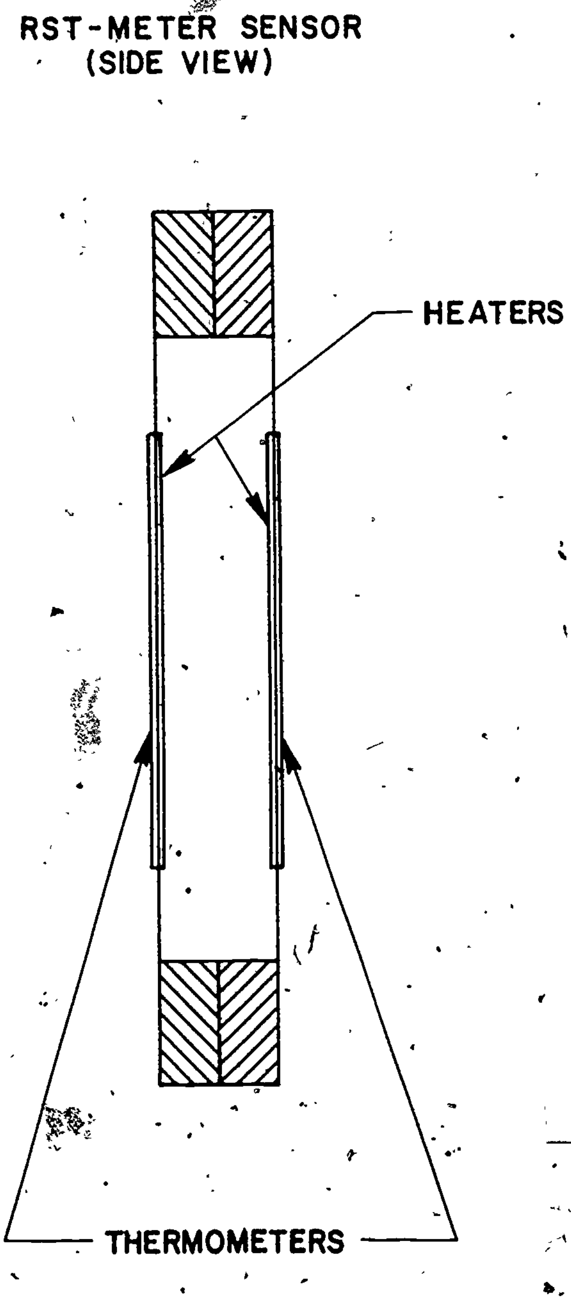

Figure 6 Side View of the RST-Meter Sensor

RST-METER SENSOR
(CUTAWAY VIEW)

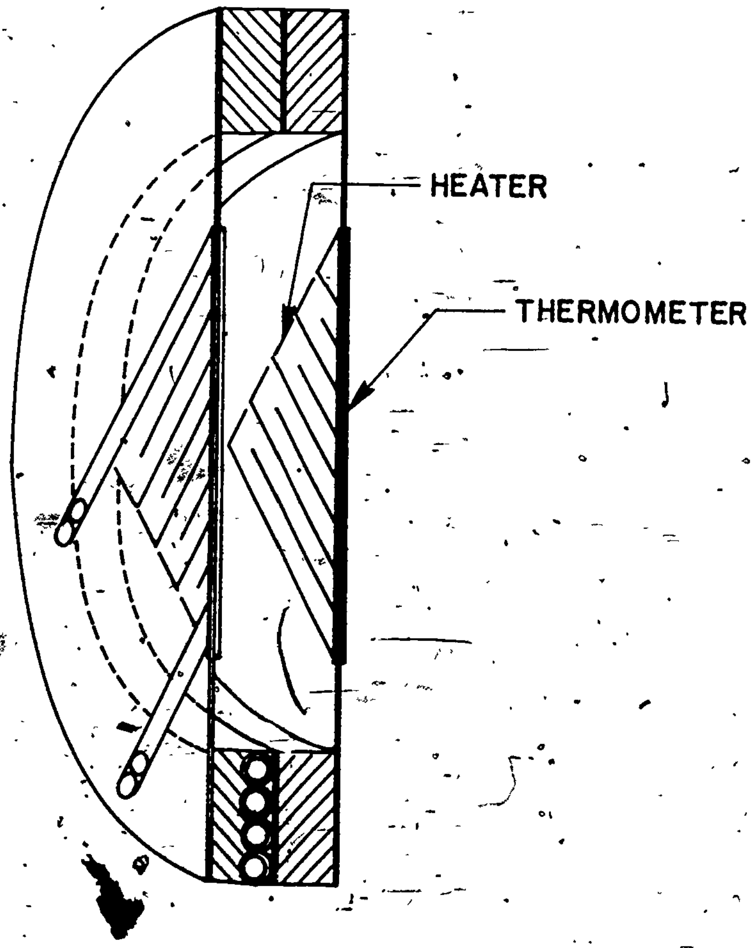

Figure 7 Cutaway View of the RST-Meter Sensor

Figures 6 and 7 show a side view and cutaway view, respectively, of the sensor head. The air space between the two heaters was left open. After further analysis, the space could be filled with an insulating material. The prime considerations will be the required speed of response to changing environmental conditions as well as having the measurement in one direction not influence the measurement in the opposite direction. As can be seen, the outer ring of the sensor head serves as a carrier for the lead wires. The wires of 1 mm in diameter run in separate grooves rather than in one 4 mm conduit. This allows the wires to be separately and securely located.

Figure 8 shows one thermometer and heater unit prior to assembly in the sensor head. The comb pattern shown was not obtained during the deposition process as originally planned; instead, it was made after deposition by a special scribing process. The substrate was fastened to a movable table fitted with a low-magnification microscope and a special cone-shaped carballoy stylus. In such a rig, it was possible to form lines of less than 0.05 mm in width.

Figure 9 shows the completed prototype sensor head. It has been assembled in the metal ring and silver epoxy resin was used to attach the lead wires to the terminals of the resistance thermometers and heaters. The necessary bridges and power supplies have been added to the table of the existing scanning radiometer shown in Figure 1. Some preliminary calibration work has begun to determine the characteristics of both the thermometers and the heaters. Further development work is planned to examine alternate and better ways of making such an instrument.

APPLICATION OF THE RST-METER

A brief description will be given of the intended uses for the RST-Meter.

An Environmental Physiological Temperature Scale

As evidenced from the description of the instrument principles, RST measurements could be considered measurements on a "physiological scale" and should allow one to determine which one of several environments would be "warmer" or "cooler" for occupants and by how many "degrees". This should be so regardless of whether the air motion, air temperature, or radiant temperature is the predominant determining physical factor. Although humidity level over a wide range has only a minor effect on preferred thermal conditions, a complete evaluation of the environment would require an additional independent measurement of the humidity level.

Once environments have been evaluated or rated on the RST scale, predicting how different individuals would react to those environments is a completely different subject requiring independent analysis. A great deal of research has been done in determining human subjects' "preference" for different environmental conditions. References (3-9) have already been cited and a complete review paper has been devoted to this topic at this symposium (21). However, it is felt that in conjunction with the use of an RST scale, a significant sample of the population should be subjected to controlled experiments in which not only their verbal or written responses are recorded and analyzed, but detailed physiological measurements made as well. This would enable a solid body of knowledge to be established on optimal environments and zones of comfort as a function of the individuals' own "human thermostat".

In recent decades, sensory physiology has made extraordinary progress due to recordings of single-unit nerve action potentials. As a result, we now know that more than a single measured body temperature is needed to characterize the humans' state of thermal equilibrium. Research has shown (22, 23) that the reaction of an occupant to his thermal environment is a unique function of the temperature in the anterior portion of the hypothalamus region of the brain as well as on the skin. When the hypothalamus temperature rises above a sharply defined set point for the individual (varies from person to person), warm sensitive neurons

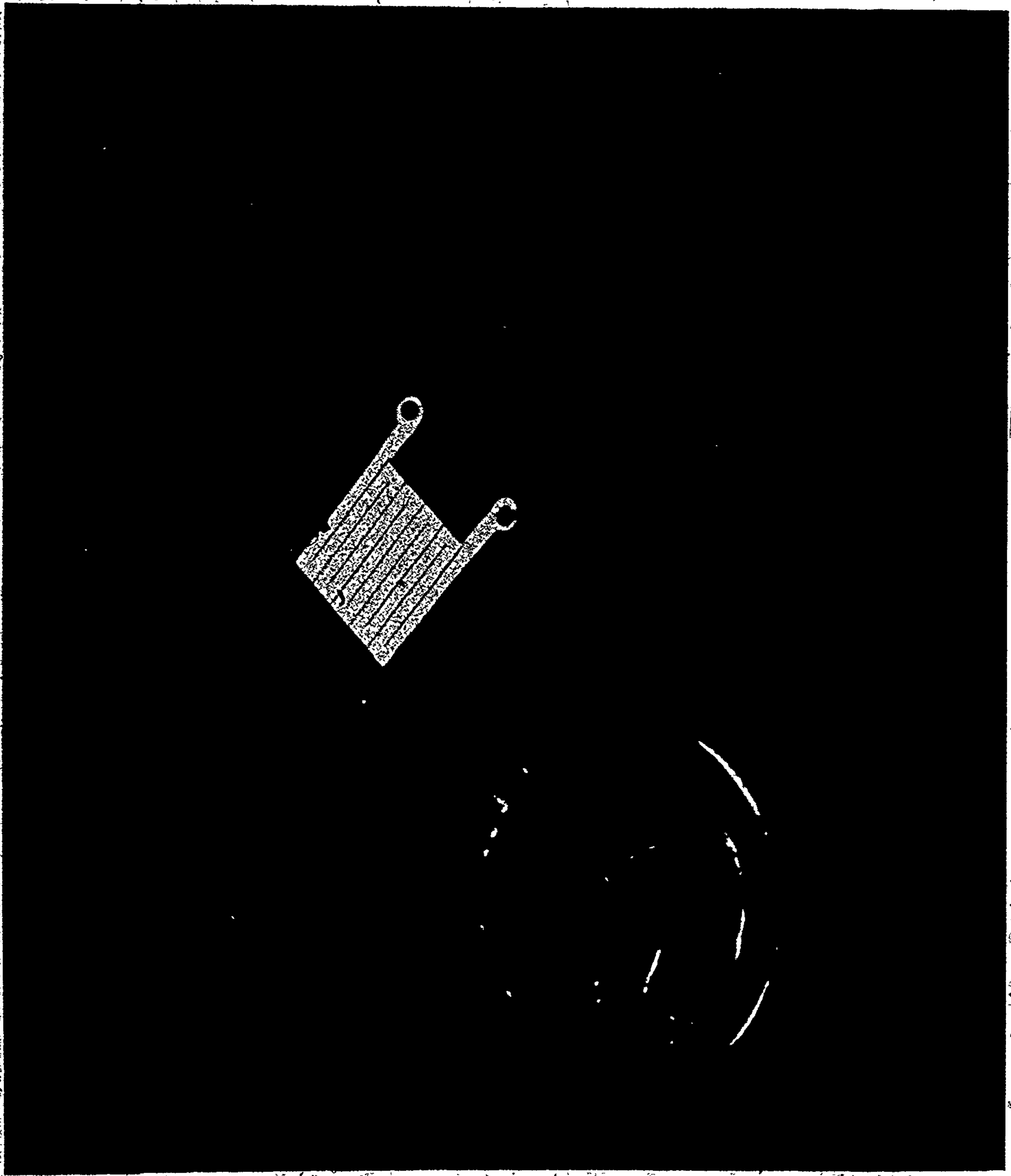

Figure 8 Complete Sensor of the RST-Meter Showing the Resistance Thermometer (on top) and Heating Element (underneath)

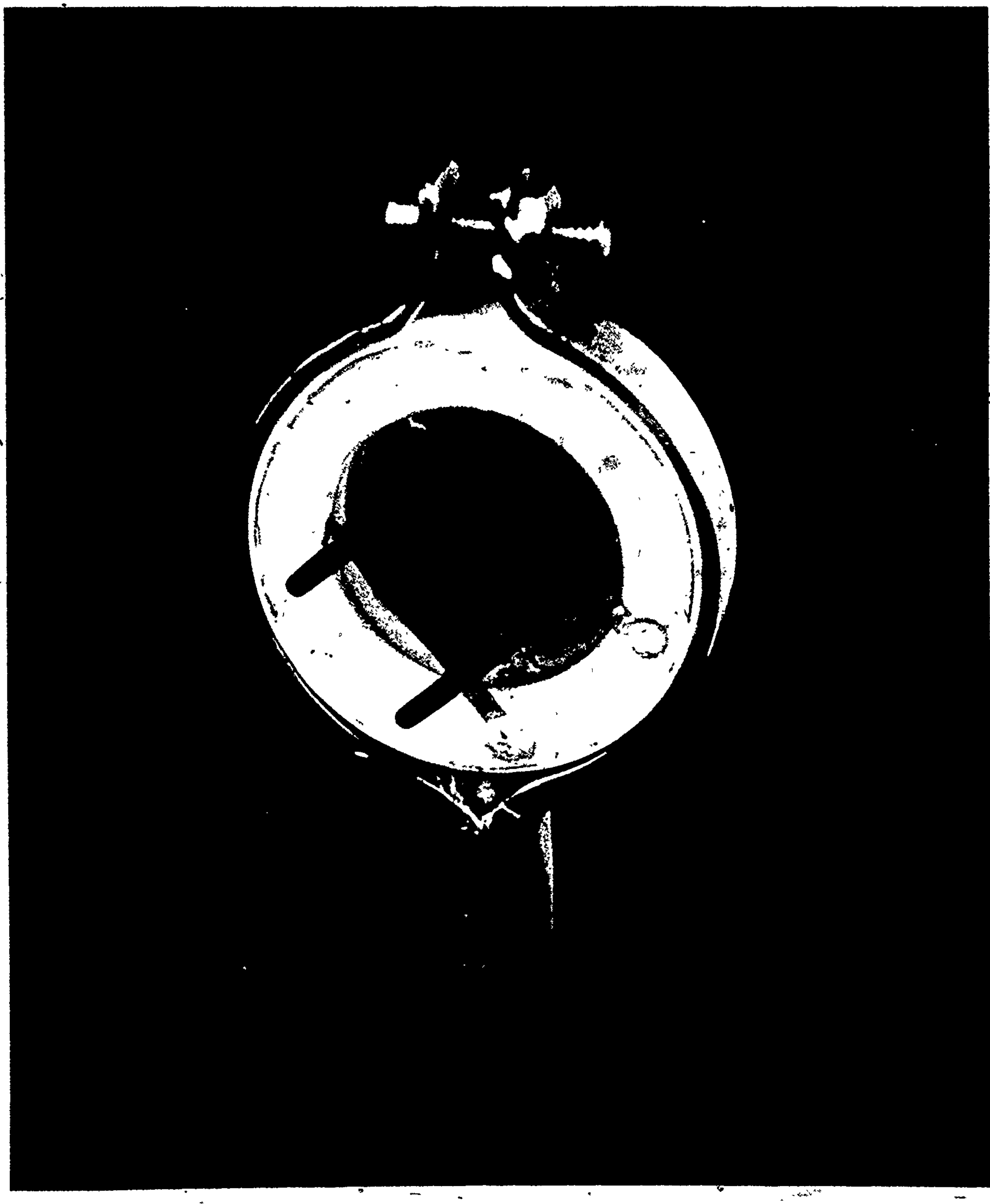

Figure 9 Completed Prototype RST-Meter

begin to fire and excite sweating such that the rate of sweat production is directly proportional to the deviation beyond the set point. The skin temperature can cause an effect of inhibition on the sweating (if it is occuring) as well as result in a feeling of cold by the individual if its value is below 33°C.

Partition of Body Heat Loss

The human sensory system has no means to distinguish between radiant and oonvective heat loss. Determination of RST will therefore be sufficient in stating the degree of comfort or discomfort to be expected in a given environment. However, to the thermal engineer, it is critically important to know why a given environment is inadequate. Are there sources or sinks of radiant heat, low or high air temperatures, or directional air currents? To answer these questions, the measurement of RST could be combined with measurements of the radiant temperature.

As mentioned previously, it is the intent to use the RST sensor in conjunction with the scanning radiometer of Figure 1. As a result, integrating the results of one complete scan with both instruments would allow the simultaneous determination of MRT as well as an integrated RST. Recognizing that this value of RST represents the surface temperature of a heated object or non-sweating human of specified metabolic heat production exchanging heat with his environment, it is possible to calculate the heat exchange by radiation*:

$$q_r = \sigma (T_s^4 - T_e^4) \qquad (1)$$

where

q_r = rate of heat transfer per unit area by radiation between the RST sensor and the environment, W/m^2

σ = Stefan-Boltzmann constant, W/(m$^2\cdot$ K)

T_s = surface temperature of RST sensor, K

T_e = mean radiant temperature of the environment, K.

Since the total rate of heat input to the sensor is known and specified, one simply subtracts the radiant portion computed above to determine the heat loss by convection.

Prediction of Body Skin Temperature

One can consider heat transfer from the surface of the human body through the clothing to the environment to be described by the simple steady-state heat transfer equation:

$$\dot{q} = \frac{(t_{sk} - t_{co})}{R} \qquad (2)$$

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* Assuming the RST sensor is small in comparison to the environment it faces and that its surface emissivity = 1.

where

q = total rate of heat loss per unit area from the human body, W/m^2

t_{sk} = skin temperature, ^{o}C

t_{co} = outer surface temperature of the clothing, ^{o}C

R = overall resistance of the clothing to heat transfer, $(m^2 \cdot {}^{o}C)/W$

It should therefore be possible to use equation (2) to predict the body skin temperature once the Resultant Surface Temperature has been measured (t_{co}) for a given metabolic heat production ($\dot{q}$). References (24-27) give detailed data on or methods of predicting the resistance or insulating value of a variety of clothing ensembles.

Once the skin temperature has been computed, its value could then be used to state the degree of discomfort due to cold (a skin temperature below 33°C). In addition, using a mathematical model of the human body (11,12), it would be theoretically possible to predict a central body temperature and hence predict the exact state or condition of the person in that given environment. It should be noted though that for this prediction to be meaningful, the central body temperature would have to be correct within very narrow limits. Since the thermal conductance between the skin and core of the body varies widely due to vasomotor responses and variable rates of blood flow between these two areas, it is felt that predicting central body temperature from the measurements could not be done accurately.

Accounting for Evaporative Heat Loss

Man maintains thermal equilibrium with a hot environment partially by evaporative heat loss or secretion of moisture at the sweat glands. In order to properly account for this in the measurement of RST and rating of the environment, it is proposed to reduce the heat input per unit area to the sensor by an amount equal to the evaporative heat loss. This "negative metabolism" could be based upon studies done on sweat rates of individuals and could be automatically accounted for in the control and operation of the instrument.

Equivalent Ideal Temperature (EIT)

When exposed in air to an environment and heated at an appropriate rate per unit area, the value of "temperature" indicated by the RST-Meter will always be higher than the air temperature and what a conventional room thermostat would indicate. In order for the readings of the RST-Meter to bear some resemblance to the temperature building occupants are most familiar with, it is convenient to introduce the concept of equivalent ideal temperature (EIT).

While any number of environments of widely varying air temperature, air motion and mean radiant temperature may yield exactly the same reading of RST, there is in theory one that is most readily defined; an "ideal" room in which the mean radiant temperature is identical with the air temperature, and the room is free of any air motion beyond the inevitable thermal convection occuring around the instrument. The integrated RST of this room is designated as its EIT. It is proposed to "calibrate" the RST-Meter in a special "ideal" chamber so that all rooms in which the RST-Meter is used could be rated on an EIT scale.

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ASPECTS OF INDOOR ENVIRONMENTS: TOLERABLE VS COMFORTABLE THERMAL ENVIRONMENTS

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ABSTRACT

Thermal comfort depends on a variety of factors including the level of physical activity, clothing worn and how the occupied space is heated, cooled or ventilated. Sufficient attention has not been paid to the importance of physical activity or the types of jobs workers need to perform in a given environment. Their metabolic heat production and modes of heat loss are important modifiable components in the energy balance equation. Both relatively cool and warm environments can be tolerated by the physically active worker. Similarly, modification of clothing ensembles can extend the tolerable range depending on the type of task performed. Comfort and tolerable conditions can be quite different, but when energy must be conserved maintenance of tolerable conditions will, of necessity, take precedence over "comfort." The limits of tolerable conditions for various tasks remain ill-defined and largely a happening of the work place. Use of tolerable conditions may provide thermal stress and result in physiological and psychological strain. Thus, research is needed to provide guidance regarding tolerable conditions and their periodicity, physical activity, clothing worn, work-rest cycles and productivity. The cumulative effects of prolonged thermal stress and the resultant strain need to be assessed.

KEY WORDS

Thermal comfort, thermal sensation, thermal tolerance, work conditions, temperature control, environmental control, temperature and performance.

The concept to be treated in this hopefully provocative paper is that there are important aspects of the thermal environment of consequence to workers and their employers other than comfort or thermal sensation considerations. Acceptable work can be performed within environments encompassing a relatively wide range of environmental conditions.

Thermal comfort has been defined as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE Standard 55-74)(1) or more recently in terms of thermal sensation, "A sensation that is neither slightly warm or slightly cool" (ASHRAE Handbook of Fundamentals, 1972)(2). As the more recent version suggests, a thermal evaluation scale and a comfort scale should probably not be combined as has been the traditional practice, but the scales should be separated to better utilize their independent contributions. A thermal sensation rating is a function of the surrounding environmental conditions described by: dry bulb temperature (T_{db}), wet bulb temperature (T_{wb}), water vapor pressure, mean radiant temperature, and air velocity, plus such behavioral modifications as the wearing of different types of clothing, utilization of protective strategies or the modification of physical activity so as to change the heat generated by metabolism within the body. All of these relatively discreet yet interdependent variables affect the body with respect to comfort and thermal sensation. In terms of traditional usage, the temperature and humidity range which provides high probability of comfort has been set forth as the "comfort envelope." Research, primarily on college students, has provided definitive data on the "comfort" of interior environments for subjects wearing approximately one "clo" uniforms and who are either resting or working at very low metabolic rates.

The point is that comfort and thermal sensation scales while providing useful information, omit important inputs from the complex environments, that are probably acceptable to those in the occupational world. People must work within the environment but they can perform well in uncomfortably hot or cold environments. A partial list of some of the important factors to consider in an analysis of performance in relation to thermal tolerance is presented in Table 1.

Table 1

Some Factors of Importance in Establishing the Range of Environmental Conditions Acceptable in a Given Occupation Area

Personal	Behavioral	Environmental
Age	Meal Pattern	Distractions
Sex	Clothing Worn	Noise, vibration, odors
Body Composition	Thermal Antecedents	Lighting
Body Build	Physical Activity Antecedents	Decor
Diurnal Variation	Mental Concentration	
Metabolic Rate		
State of Acclimation		

Synergistic as well as inhibitory interactions are not only possible but probable.

Because of the spectre of a long-term energy shortage, one must assume that energy for heating and cooling will be available in the future only at a premium and, therefore, must be conserved. Thus, the concept of tolerance in relation to acceptable productivity assumes added importance. To accommodate the tolerance/productivity concept the intrapersonal, behavioral, occupational and environmental complex should be assessed in some detail in order to provide an acceptable compromise for buildings and their environmental control systems.

Thermal limits within the range of physiological temperature regulation for man have been defined as the extreme environmental conditions which induce physiological responses that reach "steady state" values and which are reversible once the thermal stress has been removed (3). Other less severe criteria for thermal strain limits include those used to establish safe working conditions for a wide range of occupational activities (4). The variables described which affect comfort are also the ones used to establish thermal limits, i.e., T_{db}, T_{wb}, radiation and air movement. "Physiological" thermal limits have generally been defined utilizing laboratory or occupational environments. Emphasis has usually been placed on the limits of thermal regulation, principally body heat storage and core temperature rise.

Tolerable thermal limits or tolerance limits are somewhat difficult to define, partially due to the wide variability in individual thermal tolerance in relation to specific environmental conditions and work practices. For purposes of discussion, tolerance limits may be defined as those extreme environmental conditions which produce no significant degradation of performance within an allowable period of time. The performance may be measured in physical, mental, physiological, or other appropriate quantifiable terms and evaluated with respect to environmental conditions. Thus, the environmental limits are "tolerable" both with respect to the workers demonstrated physiological strain and an acceptable level of performance or productivity. Of concern, of course, is the political necessity to recognize worker acceptability as a modifying variable. Hopefully, however, scientific guidance as to possible solutions will remain unbiased by political considerations, at least initially.

Some of the problems related to utilization of comfort scales are illustrated by the following examples. It is interesting that the temperature which man rates as comfortable has risen about 5.5 °C (10 °F) in the last 60 years of documented comfort research (5). This trend has been associated with increased body size, reduction in "standard" clothing worn in indoor environments as well as to differences in comfort assessment techniques. It is also possible that adaptive trends have played a role, i.e., brought about by changed living patterns and better heating and cooling systems, including control systems. It has been demonstrated that subjects at rest who were studied during a one hour exposure at 23.3 °C (74 °F) effective temperature following an environmental antecedent exposure at 60 or 90 FET gave similar comfort scale ratings within the first hour following exposure (6). Thus, short term antecedent temperature history was deemed of no consequence. Antecedent exposures of longer duration or in hotter or colder environments were not utilized nor were the effects of a 25 yard walk or a toilet stop evaluated. The latter occurred between the antecedent exposure and the exposure of record and, of course, involved undocumented thermal transients.

An evaluation of student performance in three air-conditioned schools compared with student performance in three non-airconditioned schools provided unexpected results. The students within the climate controlled schools showed a significant reduction in classroom performance with lower temperatures ($p<0.01$). The range in conditions studied was only 2-3 °F and in the vicinity of 74 °F. The students at the non-climate controlled schools showed no significant correlation between performance, even within an 8-10 °F range in environmental conditions, and environmental temperature. Further, the students in the non-climate controlled schools gave predominantly "neutral" thermal comfort ratings over a wider temperature range than students in the climate controlled schools (7). The implication is that the students in the schools with no temperature control did as well as those with relatively precise temperature control within the temperature ranges studied. Perhaps prior thermal acclimation was responsible for the rating of neutral to the wider range of environments.

When the metabolic rate is high and mental involvement intense, ready acceptance of cool environmental conditions is possible, e.g., a lightly clothed basketball player (approximately 0.13 clo) will tolerate a cool environment 15 °C (60 °F) whether on the court or on the bench, even with a tenfold difference in metabolism. The mental involvement with the contest overwhelms the comfort or thermal sensation evaluating mechanisms. The player may be sweating profusely when he begins to rest and cool rapidly but not notice because of the competition. It is only with a break in the action that perception of the thermal conditions of the environment return and protective clothing is donned. Even then an assistant may have to remind him by handing him a sweatshirt or jacket to put on.

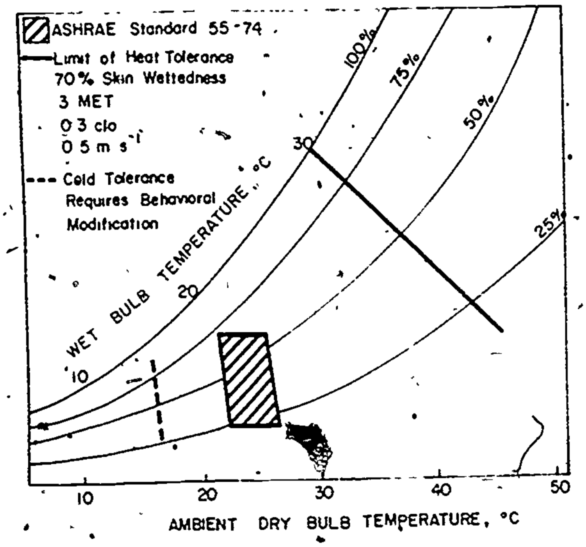
The examples illustrate that comfort rating or thermal sensation rating is imprecise at best, particularly when related to performance criteria. Thus, it is proposed that the literature be restudied and that new experiments be designed to utilize the tolerance/productivity concept with a view toward total design of buildings and facilities to include major consideration of energy conservation principles.

If it is true that man's range of adaptability to thermal changes may be reduced by limiting exposure to environmental swings through utilization of modern HVAC systems, such utilization may be counterproductive. Consideration of the present trends in energy costs and the requirement for energy savings makes it mandatory to attempt to extend the range of man's limits rather than shorten them.

The tolerance limits for acceptable human performance and productivity are poorly understood although some experimentation has been recently performed (8). Comfort at lower indoor temperatures, 15-20 °C (60-68 °F), may be enhanced by selection of appropriate clothing with insulation values in the range of 0.5 to 2.0 clo depending on the quantity of metabolic heat generation by the requirements of the job. The critical body parts are the hands if manual dexterity is important to preserve. The acceptable environmental limits become a function of all the factors that were pointed out in Table 1 plus acclimation, adaptation which includes familiarization, and work rest schedules that favor maintenance of acceptable performance. It is conceivable that studies of behavioral modification, such as accommodation to reduce temperatures in the home, may reveal positive correlations, i.e., in this instance acceptance of cooler conditions in the work place.

The range in tolerance in relation to the ASHRAE thermal comfort envelope is illustrated in Figure 1. The arbitrary tolerance limit at the cool end was established using the criteria of maintenance of acceptable hand-finger dexterity. The arbitrary tolerance limit at the hot end (see reference 9) was based on the wearing of a minimum of socially acceptable clothing, while performing a job requiring 3 Mets of metabolism and where sweating would not be objectionable either to the worker or fellow employees. The limits constitute an example based on cursory perusal of the literature and not specific job-related experimental evidence.

Figure 1.



Thus, the purpose for which a building or work space will be used becomes all important for consideration in the design process. Accurate definition of purpose requires thorough knowledge of the job and the worker's interactions with his equipment as well as the environment within which the work will be performed. To gain insight into acceptable design criteria, it will be necessary to conduct a variety of thermal tolerance/productivity types of studies in suitable laboratories or acceptable work places that can serve as laboratory substitutes. One needed type of experiment would be study of the hand-finger dexterity problem in cool environments for a commonplace job such as typing. Conceivably, one could start these experiments at the cool end of the scale using skilled typists working on difficult typing projects at temperatures around 10 °C (50 °F). Various types of heating or air-conditioning could be employed, clothing could be modified, and the work-rest schedule altered. Environmental temperature increments of about 2.5 °C could be utilized to cover the temperature range of interest. The experimental periods should be long enough to facilitate discrimination between accepted differences in productivity.

Another type of experiment would involve utilization of ramp changes in environmental conditions, with environmental control modified by the worker. Using the example of the typist, the environment in which the typist was working could be cooled at a rate of about 5 °C/hour. The typist could warm the environment by changing a convenient control setting. The typing task would be real and require sustained concentration. Perception of the environment would be measured by the frequency and extent of environmental control manipulation. Variation of this experiment could include provision of graded clothing layers to substitute for environmental control, use of a small auxilliary heater, use of a sham environmental control system, or using ramp changes involving different slopes. The list of possible experiments could be quite lengthy, but the point is that these types of experimentation should be performed to complement our knowledge of thermal comfort and sensation.

Considerable energy savings can be realized if the controlled environment is allowed to fluctuate within tolerable limits while responding to ambient variations. It is acknowledged that most present systems are neither designed or capable of sensing ambient conditions far enough in advance or appropriately to affect accurate control changes, knowing the heat storage and exchange characteristics of the building or work space.

While designs for heating, and air-conditioning systems should in the future consider acceptable tolerance/productivity criteria, it would be inadequate and unjust to design environmental systems to meet near survival limits. Long-range acceptance of more spartan conditions than we are currently accustomed to will undoubtedly require pertinent education programs for the affected workers that are based on some scientific input. Thus, both comfort thermal sensation criteria as well as tolerance/productivity criteria may well have to be considered to develop more realistic environmental designs. The acceptable interactions among criteria remain to be determined. Thus, we currently disagree with R. G. Nevins,(10) our departed colleague and one of those who has contributed substantially to the literature on thermal comfort, that "there is no spartan virtue in being uncomfortable. Indeed, it is believed reasonable, but difficult to prove, that people perform better, learn better, and accomplish more when comfortable rather than when too cool or too warm." The definition of "too cool" and "too warm" should be redetermined utilizing tolerance/productivity criteria. The ASHRAE thermal comfort envelope should be expanded and a variety of thermal envelopes constructed based on our knowledge of the complex of personnel, job, and environmental interactions.

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ASSESSING PRODUCTIVITY DECREMENTS IN HEAT AND COLD: ON-SITE SIMULATION OF INDUSTRIAL WORK IN A MOBILE CLIMATE CHAMBER

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ABSTRACT

This paper describes the establishment in Africa of a major research project whose aim is to quantify the effects on productivity of heat and cold stress in factory buildings. The intention is to provide design criteria for the intermediate levels of thermal stress - beyond comfort but not involving any risk to health - which are likely to occur in the industrialization of developing countries with warm climates and limited resources. The background to the project is given, and relevant published work is summarized. On-site simulation of industrial work in a mobile climate chamber was chosen in preference to conventional field or laboratory studies. The development and construction of the mobile climate laboratory, including the performance testing equipment, is described. The currently proceeding research program is given. It is suggested that the rationale and methods of this project are appropriate for energy conservation research elsewhere.

INTRODUCTION

The main function of any building is to transform the outdoor climate to an indoor climate that promotes the human activities it contains. Criteria derived from these activities should therefore be used to optimize the design of the building and to justify the allocation of resources for its construction and operation. Where resources are limited, the criteria must be 'hard', not based on preference, but objective, demonstrably relevant to the stated purpose of the enterprise, and quantitative. Such criteria are difficult to define for some categories of buildings, notably for dwellings. It is usually assumed in the case of dwellings that comfort criteria fulfil the above requirements. Comfort may perhaps be defined as a necessary criterion for the indoor climate of dwellings; particularly when adequate resources are available, but it is surely not a sufficient criterion; even in dwellings other criteria can be derived, more relevant to the purposes of the human activities performed there, and more objective than those of comfort. In a factory building, whose purpose is to increase production, comfort criteria are neither necessary nor sufficient. Resource allocation must be guided by criteria of productivity. This is especially true in developing countries, and in countries with a stressful climate. It is especially true in Africa.

Africa has embarked upon a course of industrialization. Every African country now welcomes foreign investment and the establishment of new industries. Countless new factory buildings will be erected in the near future, many of them in harsh climates where no such building has existed before. Their viability depends upon correct resource allocation. If environmental standards are set unrealistically high, the factory building and its services would use too big a proportion of the available resources, and may be built elsewhere. If standards are set too low, productivity may be so adversely affected that the enterprise will fail. This may occur even if minimum standards that safeguard health are strictly observed. A rational allocation of resources requires that environmental standards should be set between these two extremes. It is not a technical problem; buildings can easily be designed to provide the required conditions, either passively, as when a massive building structure is used to reduce the extremes of an arid climate or actively, when conventional heating or cooling equipment is installed. The problem lies in determining the returns for providing such design features, and thus increasing the cost beyond that of a basic shell construction. In most factories the production machinery is designed to operate well beyond the climatic extremes likely to be encountered. Only in rather special cases can climatic control be justified for machine or product. Examples are where computing machinery and food production require specific temperatures, weaving requires controlled humidity, and electronic assembly requires a dust-free atmosphere. In most cases the returns to be expected are in terms of the effects upon human efficiency, and therefore upon productivity. Criteria derived from a study of these effects are therefore urgently required for the industrialization of Africa.

THERMAL CONDITIONS IN FACTORY BUILDINGS

This paper is concerned with the derivation of criteria for optimizing thermal conditions in factory buildings, i.e., with the comfort and moderate stress region. It does not deal with limiting criteria for extreme thermal stress. Hazardous exposure to extreme heat or cold occurs only in hot or cold process industries for which special studies must be made in each case to determine the trade-off available between process and operator safety and efficiency. The only exception is where heavy manual work is to be performed under what would otherwise be only moderate heat stress. In this case the work itself usually contributes the major heat load, the criteria appropriate are those of thermal physiology, and a solution is available in increased mechanization of the task. In the vast majority of factory buildings, thermal conditions for light manual work are no more than moderately stressful; the criteria appropriate are those of comfort and productivity, and improvements can only be achieved by increasing the cost of the building and its services.

PUBLISHED WORK

An assessment of published work relevant to the optimization of thermal conditions in factories was recently made by the present author [1]. In view of its limited circulation, a short summary of the conclusions will be given here.

1. Thermal conditions providing optimum comfort may not give rise to maximum efficiency. In an experiment by Pepler and Warner [2], normally clothed young American subjects performed mental work at different temperatures. They were most comfortable at 27°C, at which temperature they exerted least effort and performed least work. They performed most work at 20°C, although most of them felt uncomfortably cold at this temperature.

2. The effects of heat stress on human efficiency are not linear. In the above experiment, rate of working showed a minimum at 27°C, although naturally it would have declined below this value in extreme cold or heat. A similar reversal of the effects of moderate heat stress on performance was demonstrated by Wilkinson, Fox et. al. [3] under conditions of controlled hyperthermia, and also by Wyon [4] in a simulation experiment with Swedish school children. No corresponding data are available for cold stress. Manual dexterity has usually been found to decrease monotonically if not linearly with cold stress, but Clarke et. al. [5] have shown that muscular strength increases to a maximum in moderate cold stress before declining at more extreme levels. These non-linear effects are in marked contrast to the orderly decline of comfort below and above a maximum at some optimum temperature.

3. The above conclusions together invalidate the usual assumption that performance effects can be deduced from studies of comfort alone. Unfortunately, very few field studies of performance under moderate heat and cold stress have been reported, and there are many unknown factors involved in the application of laboratory results. However, the following conclusions are drawn from the available evidence.

4. The critical temperature for performance lies at about 30°C for normal humidity levels. This conclusion was reached by Pepler [6], citing studies made in weaving sheds and coal mines by the Industrial Fatigue Research Board in England over 50 years ago.

5. Accident rates are lowest at 20°C, increasing by over 30% below 12°C and above 24°C [7]. This study was carried out in three munitions factories, over periods of 6, 9 and 12 months, by the Industrial Fatigue Research Board (see figure 1).

6. Moderate heat stress has an adverse effect upon the accident rate for men, but a much smaller effect on women. Accident rates were closely similar for men and women at and below the optimum temperature, suggesting that the difference was not due to differences in the tasks performed by each sex. This conclusion derives from the above study of munitions factories, and the effect is clearly apparent in figure 1.

7. Moderate heat stress and fatigue interact to increase accidents. This conclusion is derived from studies by Vernon [7] of 18,455 English coal miners at work. Figure 2 shows clearly how accidents increased with the number of hours worked in a shift, but progressively more rapidly at temperatures of 18, 25 and 28°C.

8. Moderate heat stress increases the dependence of accident frequency upon age. This conclusion is again derived from the studies by Vernon and his colleagues [7] of coal face workers over a 4-year period. Figure 3 shows that age was barely a factor in accident causation below 21°C, while increasing the relative accident frequency by up to 40% for older men above 21°C.

9. Performance of simulated work is worse at 10°C than at 17°C, and worse at 24°C than at 20°C. These conclusions are drawn by Pepler [6], from the Industrial Fatigue Research Board experiments, and by Wyon [8], from the New York State Commission on Ventilation Report [9], respectively. Note the excellent correspondence of these performance data with the field accident data. Both experiments were carried out under realistic working conditions, subjects working a full eight-hour day for several weeks.

10. Laboratory tests of rapid skilled arm movement indicate performance decrement at 13°C and 29°C, below the level achieved at 21°C. A further and more marked decrement takes place between 29°C and 38°C, according to the result obtained by Teichner and Wehrkamp [10]. Again, the correspondence with field accident data is good. Similar results were obtained by Pepler [11] with heat-acclimatized Europeans living in Singapore, although the optimum temperature in this case appeared to be at least 5°C higher than the expected influence of the reported differences in clothing, humidity and air velocity between the two experiments. It is possible that this difference represents the effect of heat acclimatization.

11. Physiological studies imply substantial sex and race group differences in the effects of moderate cold stress on manual dexterity. Wyndham et. al. [12] found that black males showed greater peripheral vaso-constriction than white males in moderate, but not in extreme cold stress. Numerous studies indicate that manual dexterity is a function of hand skin temperature, but as no direct performance studies are available and the physiological studies were carried out on nude, inactive subjects, not quantitative estimates of group differences in performance in the cold can be made. Wyndham et. al. [13] found that black males tolerated heat stress better than white males unless both groups were artificially acclimatized, and there is similar evidence (Wyndham et. al. [14], [15], Fox et. al. [16]) that female tolerance of both heat and cold stress is lower than that of males. Only in the case of cold stress, however, can these group differences be confidently expected to produce differences in performance.

12. Heat and noise stress act on performance in similar ways and can be expected to interact. The main evidence for this conclusion (Bursill [17], Hockey [18]) has recently been criticized by Poulton [19]. However, evidence for such an interaction may also be derived from Viteles and Smith [20]. Significant effects of heat stress on performance can be shown to have occurred at 72 and 90 dB, but not at 80 dB, in the data published by these workers. This suggests a complex, non-linear interaction of noise and heat stress.

The above conclusions are subject to the special conditions under which each study was carried out - i.e., the field studies must be considered specific to the particular industry, country and historical period in which they were carried out, and the laboratory studies were of short duration, with an artificially high level of motivation, and subjects who were highly selected fit young men, usually students or servicemen. Their validity for factory building design cannot be assumed without verification, but they are indicative of the operative factors.

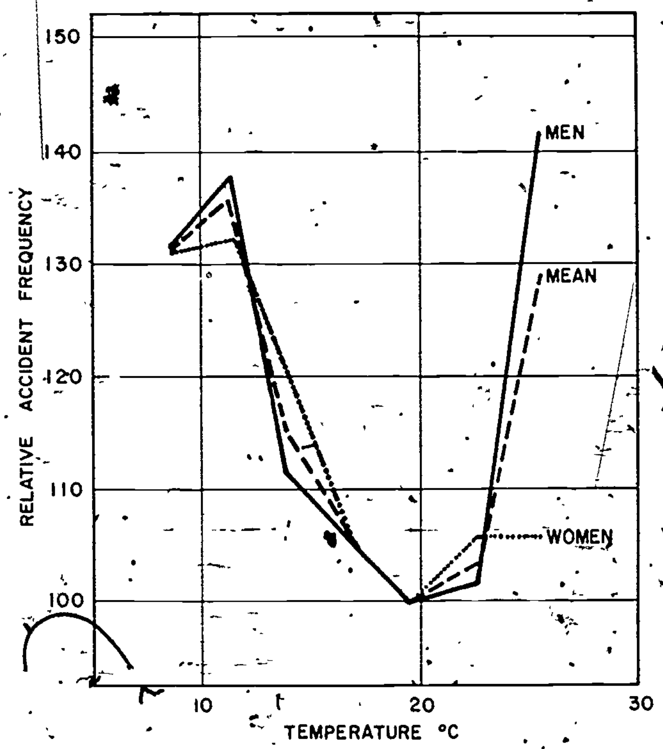


Figure 1. Accident Frequency in Relation to Temperature (Data for English Munitions Factories from Vernon [?]).

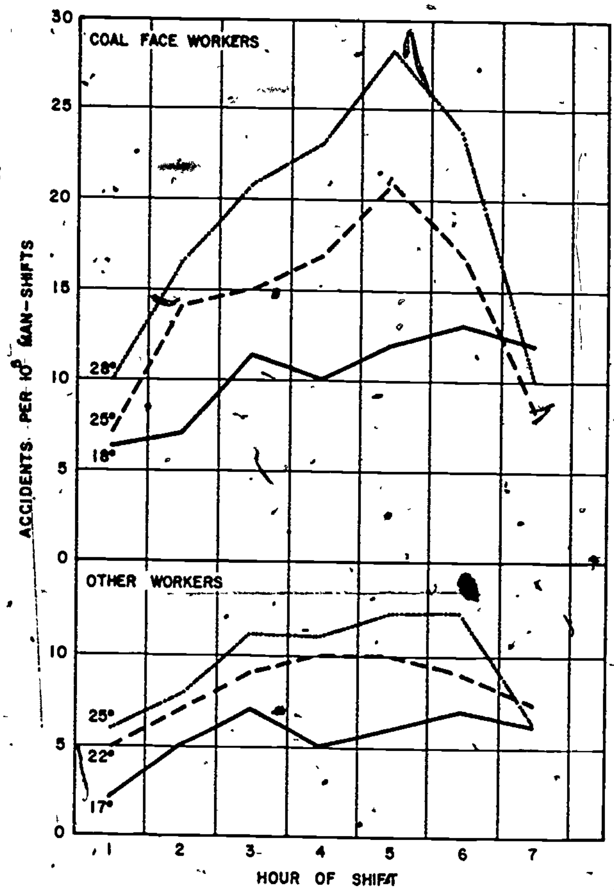


Figure 2. Accident Frequency Underground in Relation to Fatigue and Temperature (Data for English Coal Mines from Vernon [7]).

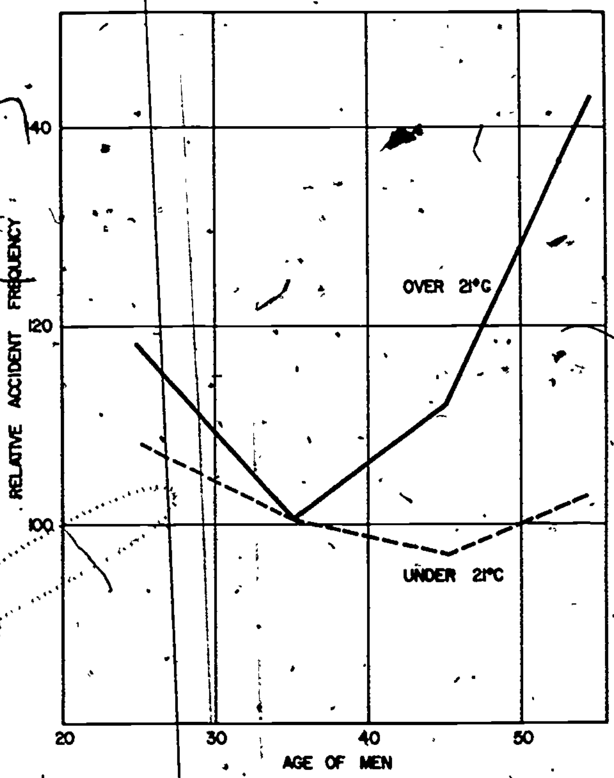


Figure 3. Accident Frequency Underground in Relation to Age and Temperature (Data for English Coal Mines from Vernon [7]).

THE PRETORIA EXPERIMENTS

BACKGROUND

The National Building Research Institute (NBRI) in Pretoria, South Africa, is engaged in studies of factory building design for African climatic conditions. The influence of various design features on the resultant indoor thermal conditions is being studied in a number of different climatic zones (van Straaten and Wenzel [21]). The building physics involved is relatively well understood (van Straaten [22]). In 1974, the present author was invited by NBRI to initiate a further aspect of this project to provide criteria for thermal effects upon productivity, without which cost/benefit analyses of factory building design alternatives could not be carried out. Research proposals based upon the above assessment of published work were made and construction of the experimental facilities began in 1975. The work has begun and is scheduled to continue over a period of several years.

RESEARCH STRATEGY

The information requirement is for valid and quantitative estimates of the effects of various attainable levels of heat and cold stress upon productivity, for immediate application in factory building design. The above assessment of published work indicates that long-term accident rate studies would probably provide the most valid and reliable evidence for the existence of undesirable thermal effects at low levels of stress. However, the time factor and the requirement for quantitative estimates of productivity decrements eliminate this option. It is true that modern loss-control evaluation studies currently assume a fixed ratio between disabling injuries, minor injuries and damage incidents (1 : 50 : 500 is not uncommon) and that this, if valid, provides an attractive means of estimating this aspect of productivity decrement from registered injury statistics. However, there is no general agreement, and certainly no conclusive evidence, as to the ratio or the cost of damage incidents. Both must be presumed to vary between industries and may even be functions of thermal stress. To study damage incidents directly requires a very high degree of co-operation at all levels of factory management, and is difficult to carry out reliably even within a company. Numerous studies in different industries would be necessary, and only one aspect of productivity decrement would be accessed.

In view of the numerous operative factors indicated by the assessment of published work and the impossibility of controlling a sufficient number of them in the field, straight productivity studies are judged feasible only as point validation of firm, existing, quantitative hypotheses. Such hypotheses cannot yet be put forward on the basis of published work. Conventional laboratory experiments serve mainly an exploratory function, and in view of their short duration and artificial circumstances cannot be said to supply a sufficiently valid basis for such hypotheses. The above assessment of published work amply illustrates the complexity of the relationships and the number of factors involved; there seems little need to perform further exploratory studies. Only realistic simulation studies, in which the main factors known to be operative are strictly controlled while the realism of field work is as far as possible maintained, seem able to fulfil the information requirement. It was therefore proposed that simulation studies should provide the link between laboratory and field, enabling subsequent point-validation studies to be made in the field as a final stage.

EXPERIMENTAL DESIGN

Groups of four subjects will perform simulated industrial work for a full working day under controlled environmental conditions. Each group will be exposed to only one level of thermal stress, i.e. thermal effects will be tested between rather than within groups. The subjects will be volunteer industrial workers, and the exposures will take place on the factory site where they work. However, the need for a controlled thermal environment necessitates that they work that day in a mobile climate chamber. They will change into standard clothing and footwear typical for the industry and time of year. The simulated work will consist of set tasks performed in rotation during the exposure, each designed to represent some component skill directly relevant to industrial work. In subsequent application of the results to a specific work situation, the component skills critical for productivity in heat and cold stress will be identified. The tasks were chosen to provide directly a small number of simple and well-defined measures, usually of work-rate and percentage error. The registration of these measures is automated where this is feasible. Some have been used before in the assessment of thermal effects, some have been used in other connections, and some are new. Complex, multi-skilled tasks have been avoided, and they are all sufficiently simple to be learned quite quickly. Skin temperatures and heart rates are monitored. Thermal comfort assessments are recorded continuously from dial voting equipment. The main factors in the experiments are temperature, sex, ethnic and regional differences in acclimatization. In a reduced parallel series, the influence of clothing and activity on heart rate, skin temperature, sweat rate and thermal comfort are to be assessed under otherwise identical conditions, but in repeated measures (within groups) design.

THE NBRI MOBILE CLIMATE LABORATORY

CLIMATE CHAMBER

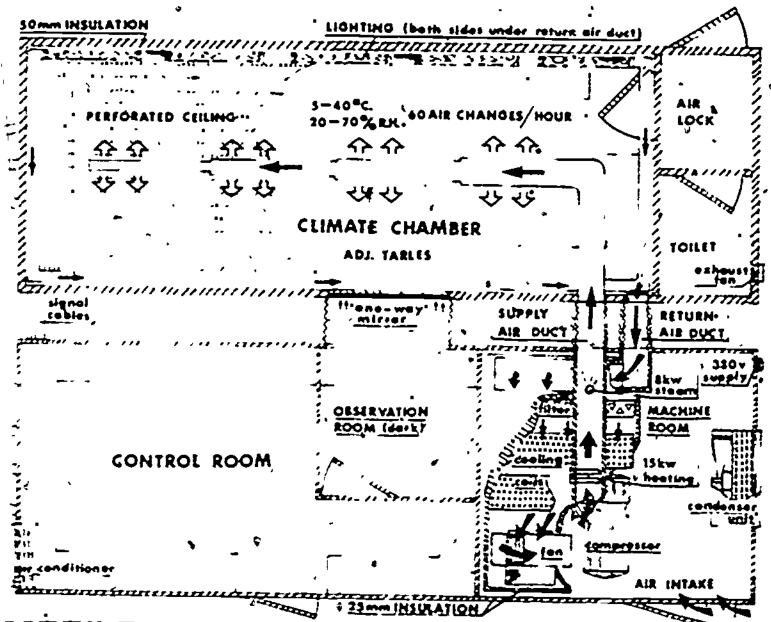
The mobile climate laboratory consists of two double-axle caravans, each 8 m long, 3 m wide and 3 m high. These are parked 0.5 m apart and linked together on site. Figure 4 shows the plan and section of these caravans. The climate chamber unit weighs 2500 kg, and contains a 6.5 x 2.7 m exposure chamber, an air lock (entry lobby) and a toilet/washroom. The service unit weighs 3500 kg and contains a plant room with the air conditioning machinery, and a control room for the instrumentation. Within the control room is a darkened observation booth, providing a one-way view through a half-silvered screen to the climate chamber. The screen is mounted as a window in the middle of the long side of the climate chamber, immediately opposite the observation booth window. A light-tight bellows is mounted between the caravans to exclude daylight from these windows.

Flexible insulated air ducts are mounted between the caravans at roof level for supply and return air from the air-conditioning plant. Supply air at controlled temperature and humidity passes through one flexible duct to a ceiling plenum, entering the climate chamber through a perforated metal ceiling. This ensures a low entry velocity and even distribution over the entire floor area. Up to 60 air changes per hour can be supplied by the variable speed main circulation fan, of which 70-100% is recirculated. The climate chamber is maintained at positive pressure, and controlled leakage through the door maintains the air-lock at a similar temperature. The toilet is maintained at a negative pressure by a separate exhaust fan venting to outside air. Return air from the climate chamber is drawn up behind hollow metal walls to a duct extending right around the chamber above the ceiling, connected through the other flexible duct to the plant room air intake.

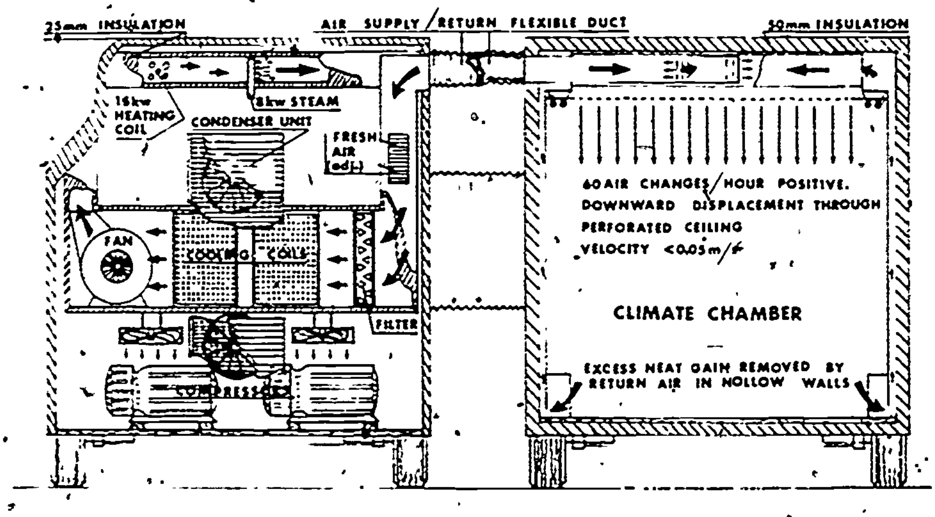
Polystyrene insulation 0.05 m thick is mounted directly inside the external metal skin of the caravan walls and roof, vapor-sealed on the inside surface. Local heat loss or gain through this small amount of insulation due to strong sun or wind is removed by the exhaust air and taken up by the air conditioning plant, while the hollow metal walls remains at the intended temperature. Thermal radiation errors are thus effectively eliminated without either massive walls or prohibitively thick insulation. Two further advantages of this lightweight 'hypocaust' construction are that the time constant of the climate chamber is very low, and the acoustics are exceptionally good. There are no rigid connections between the caravans, and hence no vibration is transmitted from the plant room.

INSTALLATIONS

The air-conditioning system was designed by the National Mechanical Engineering Institute (NMERI), Pretoria, and supplied by Bronsair (Pty) Ltd. It is simple over-cooled, over-dehumidified system. Two compressors transfer reject heat to air-cooled condensers with variable speed fans. The return air from the climate chamber is mixed with a manually-set 0-30% proportion of fresh air, filtered, and drawn over a series/parallel arrangement of direct expansion cooling coils providing five manually selected levels of cooling effect. This ensures that the temperature and moisture content are reduced to below the required levels. It is then blown past thyristor-controlled electrical elements providing 0-15 kVA of proportionally-controlled heating effect with a rapid response. Steam is subsequently added at atmospheric pressure from an 8 kVA electrolytic boiler with proportional output. The temperature and humidity sensors for the proportional control units are located in the exposure chamber. A sample of air from ceiling height is drawn across them by means of a small fan, thus ensuring a rapid response. This was found to work well at high temperatures.



N.B.R.I. MOBILE CLIMATE LABORATORY



N.B.R.I. MOBILE CLIMATE LABORATORY

Figure 4. Plan and Section of the Mobile Climate Laboratory Described in the Text, Housed in Two Caravans, National Building Research Institute, Pretoria.

Stability problems occurred only when very cold air was to be supplied to the chamber, as the time constant of the feed-back circuit was slightly increased by the altered air-flow pattern. In this case a variable proportion of air taken directly from the ceiling plenum is added to the control sample. This simple 'quickening' of the feed-back circuit has been found to restore stable operation without introducing measurable bias to the resulting set-point temperature or humidity. Temperature control stable within ± 0.1°C is routinely achieved over the range 6-40°C, and variations between different points in the chamber are below 0.5°C. Humidity control to within 1% relative humidity in the range 20-70% is achieved between 15 and 35°C. System limitations reduce the maximum relative humidity attainable to 50% at 40°C, and increase the minimum to 50% at 6°C. Air velocity in the climate chamber is below 0.05 m/s, and globe temperatures are within 1°C of air temperature. Tyristor-controlled fluorescent tubes recessed into the ceiling provide controlled lighting intensity from 0-1200 lux at working height. A remote control panel for the air-conditioning plant is located in the control room.

POWER AND WATER SUPPLY ON SITE

The mobile climate laboratory requires a maximum power supply of 30 kVA. This is ~~provided by cable from a~~ standard 3-phase, 380 V factory outlet at each site. From this, single-phase 220 V power supplies are provided in both caravans, together with 1 kVA of stabilized 220 V for sensitive instrumentation. If the laboratory is to be used where no 380 V supply is available, a standard diesel generating set will be hired by the week. These are readily available from local builders' plant-hire firms. Water must be supplied by 1-inch hose for the steam generator and washroom.

TOW VEHICLE AND CARAVAN FITTINGS

The caravans are towed, one at a time, by an International V-8 2-ton truck with hard canopy. This is fitted as a 10-seat bus and equipped with gas rings and refrigerator for food preparation and storage, and a folding table. This serves as a staff room. Subjects change in a large tent extending along the whole of the exposed side of the climate-chamber caravan, enclosing the door and serving also as an entrance lobby. Solar heat gain to the climate chamber is thereby reduced. A sun canopy is likewise fitted to the exposed side of the service caravan. An intercom links tow vehicle, changing room, entrance lobby, climate chamber, plant room and observation room to the control room, and a hand-set pair between observation room and climate-chamber enables experimenters to communicate confidentially during an exposure. Up to 12 work surfaces, 0.9 x 0.4 m, can be suspended from the walls of the climate chamber as required, and adjusted individually to the correct height for each seated or standing subject. Metal cable ducts run along each wall, well separated from the power supply circuit, taking signal cables from each such work-station to a cable box at one corner. A canvas cable duct is mounted between the caravans to enclose cable ports in the cable box and the control room. Signal cables are extended through the duct to the control room on site to connect with instrumentation, and are withdrawn to the cable box in transit. A motor-driven belt with variable speed and gradient can be installed transversely at one end of the climate chamber for controlled exercise. The control room is fitted with work surfaces, cupboards and drawers for storage, and a standard 3.5 kVA room air-conditioner. The observation room is similarly fitted and is positive-pressure ventilated with conditioned air from the control room. A small work bench for repairs is fitted in the plant room.

INSTRUMENTATION

COMPUTER SYSTEM

Data requisition is based on a 16 kbyte desk computer (Hewlett-Package 9830) in the control room. This unit has a hard-wired BASIC compiler and peripheral control unit, and is thus equivalent to a conventional computer with at least twice the memory and a software compiler and operating system. It serves 11 peripheral units: printer, two magnetic tape stations, mark-sense card reader, paper-tape reader, scanner, digital voltmeter, calendar clock, telemetry receiver control, skin temperature telemetry output and ECG telemetry output. This system performs most of the data acquisition, processing and storage required in the industrial experiments. It acquires physical and physiological data on-line, but no attempt has been made to acquire human performance data on-line. This is primarily because of the queuing problem - two or more subjects may respond at the same time, requiring a computer several orders of magnitude faster, and thus more expensive. However, the diversity of the performance testing equipment, and the need to retain flexibility of choice and test sequence, and the inherent unpredictability of working with several subjects at once, greatly increase the difficulty and expense of on-line data acquisition. Instead, each performance testing unit is independent.

PHYSICAL DATA LOGGER

Temperature measurement to an accuracy of 0.1°C is achieved using thermocouples with a heated reference junction at 44°C. Measurements are initiated by the computer under program control by selecting one of 30 channels on the scanner. The sequence is paced by the calendar clock, but the computer has 'random access', i.e. can select channels in any order and repeat measurements if they fall outside preset guard values. The measurement is made by the digital voltmeter with microvolt resolution, and transmitted to the computer. Conversion to a calibrated temperature value is then performed by the program, the measurement is repeated if necessary, and the value stored on magnetic tape. Measurement usually takes place at about 2 channels per second, with a scan at 5 minute intervals. Humidity is then measured in the same way using a heated lithium chloride sensor.

THERMAL COMFORT DATA

Subjects register their sensations of thermal comfort by adjusting a dial voting apparatus (Wyon et. al. [23]). Each subject is provided with a 270° dial resembling a thermostat, but bearing a thermal comfort scale with three 90° zones marked 'too cold', 'comfortable' and 'too hot'. They are asked to set the pointer repeatedly so that it always represents their thermal sensation during the exposure. The dial can be connected to sockets at each work station. Up to six dials can presently be identified by the computer, which registers the pointer settings at regular intervals as a percentage of full scale, using a simple bridge circuit and individual calibration equations for each dial. The computer lights a warning light in the climate chamber if any dial is disconnected during a measurement sequence. Dial facia bearing the labelling in any of the six most usual languages of South Africa can quickly be fitted to each dial unit.

COMPUTER CONTROL OF CLIMATE CHAMBER TEMPERATURE

In order to be able to expose subjects to simulated diurnal temperature changes in the climate chamber, provision has been made for computer control of the climate chamber temperature. Under steady-state operation, the control circuits are completely independent of the computer. However, a simple link may be established by switching in a motor-driven multiturn resistor in place of the normal set-point using the scanner relays. A sequence of set-point values is entered to the computer memory for execution at set intervals, paced by the calendar clock. Adjustment at five minute intervals has been found satisfactory, and an arbitrary temperature curve within the capacity of the plant can be achieved with full 0.1°C accuracy.

PHYSIOLOGICAL DATA LOGGER

ECG and four skin temperatures can be acquired from each of four subjects by telemetry with a range of 500 m. This is primarily intended for field studies, but greatly simplifies data acquisition in the climate chamber by ensuring that the data is continuously available to the computer even when subjects are moving between work stations. Any one of the 20 channels can be accessed by the computer, one at a time. Thermistors with a standard calibration within the required accuracy of 0.2°C are used for skin temperature measurement. ECG is acquired by the computer as a sequence of inter-beat intervals with millisecond accuracy. The system is not yet fully operational. Sweat rate will be measured as a total body weight change, using a mechanical beam balance with an optical scale and 5 gm accuracy; readings will be entered on mark-sense cards for computer compilation.

BACK-UP SYSTEMS

Key chamber temperatures and humidity are recorded on a 0-50°C sampling chart recorder with cold-junction compensation, completely independent of the computer system. This record also provides a visible review of temperature trends over a period of about an hour. Since, duct temperatures and outside air temperature are also included, this provides the operator with the information needed to run the plant correctly. The telemetry receiver can operate under manual control, independently of the computer. Should these systems also fail, a hand-held electrical thermometer enables direct measurements of dry and wet-bulb air temperature, room surface and skin temperatures to be made with an accuracy of 0.1°C.

PERFORMANCE TESTING EQUIPMENT

Performance tests are either scored manually, scored automatically onto counters or registered on paper tape for off-line analysis by the computer. In the first two instances, the experimenter enters the score onto mark-sense cards pre-punched with session, subject, time and test identification. After each session the cards are read by the computer and the scores automatically compiled with the physical and physiological data acquired by the computer during the relevant test. The link is made by the time reference, as physical and physiological records are filed against time on the magnetic tape record. The following brief notes summarize each test and give references to their previous use where appropriate. Unless otherwise stated, timing is performed manually using a stop-watch.

COLD-SENSITIVE TASKS

COLD-SENSITIVE TASKS

1. Tactual discrimination - 2 edges. A development of the V-test introduced by Mackworth [24], eliminating the possibility of subject bias. The subject feels the presence or absence of a gap between two edges 4, 3, 2 or 1 mm apart, using the pad of a forefinger. The test is semi-automated and scored on counters.

2. Tactual discrimination - raised letters and numbers. The subject feels raised letters or numbers on the surface of a drum and checks against a printed list containing discrepancies at random. The subjects' responses are entered manually from the list to the computer for scoring. This test appears not to have been used in the cold.

3. Finger dexterity - rolling movement. The subject rolls a pencil-sized shaft as fast as possible between his fingers, against retardation at two levels of torque. Rotations are registered on a counter. This is a development of a test found by Hellstrøm [25] to be very sensitive to cold.

4. Finger dexterity - peg test. The subject picks up three small pegs at once and inserts them one after the other in the same hold, using only one hand. This test is manually scored. It is described as the O'Connor peg test by Parker and Fleishman [26], but not as a cold-sensitive test.

5. Manual dexterity - block stringing. The subject strings wooden blocks using a blunt needle. The test is described by Gaydos [27] and has also been using in the cold by Lockhart [28].

6. Manual dexterity - knot tying. The subject ties the same knot repeatedly in lengths of string. The test has been used in the cold by Gaydos [27], Gaydos and Dusek [29] and by Clark and Cohen [30], among others.

7. Simulated assembly task-screw plate. The subject transfers small nuts and bolts between holes in a steel plate. The test was used by Baddeley et. al. [31] to test the manual dexterity of divers underwater. A similar test was used by Kay [32] in the cold.

8. Simulated assembly line task. The subject inserts small pegs into 3 holes in each transverse bar of an intermittently advancing assembly line. The speed of the line can be varied, and the test is scored onto 4 counters, using microswitches to detect the number of bars passing with 0, 1, 2 or 3 pegs inserted.

9. Skill diagnosis - track tracing. The subject traces a track in a vertical plate with a hand-held probe. Once inserted, it cannot be withdrawn until the whole track has been traced. An electronic counter records the error score as the total time in contact with the plate or the rear facia for a preset number of repeats. The task has been described by Fleishman [33] and by Parker and Fleishman [26] as the best predictor for a group of skills characterised by slow exact hand movements, but has apparently not been used in thermal experiments.

10. Skill diagnosis - steadiness precision. The subject slowly inserts and withdraws a hand-held 0.5 m probe into a narrow tube to touch a target at the end without touching the sides. The error score is recorded as for the track-tracing task, was described by the same authors as a predictor of a similar group of skills involving slow exact arm movement, and does not appear to have been used in thermal experiments.

11. Skill diagnosis - rotary pursuit. The subject tries to maintain a hand-held probe on a small target near the periphery of a rapidly rotating gramophone-type turn-table. Time on target is recorded on an electronic counter during five 20 sec. periods with 10 sec. rest periods between. The task was found to be sensitive to heat and cold by Teichner and Wehrkamp [10].

12. Skill diagnosis - motor judgment. The subject controls the speed of a rotating pointer to avoid moving obstacles using a 'joy-stick' control lever. The error score is recorded on an electronic counter during a pre-set automatically timed work period. An early version of this task is described by Parker and Fleishman [26].

13. Grip strength. The subject exerts maximum force for a period of several seconds, using both hand and finger grips. Performance is recorded on a paper chart, clearly visible to the subject to provide visual feed-back and encouragement. The dynamometer uses a strain gauge assembly developed by NMERI to compensate for the mechanical advantage obtained by applying the force at different points on the handle.

14. Integrated task simulation - 5 choice serial reaction. The subject holds a metal probe and touches five small targets in a continuous random sequence given by a 5-lamp display. Errors and serial reaction times are recorded. This task is described by Poulton [34] and has been used extensively to measure the effects of heat, noise, loss of sleep, alcohol, etc. upon perseverance and concentration. Two further aspects have been added, to measure aiming and vigilance respectively; responses initially missing the target are recorded, and the subject must press a hand-held button to report brief, barely visible delays introduced at random to the display change. Data relevant to each response are recorded on a paper-tape punch. The test simulates the skills using in typical work-bench tasks.

Heat-sensitive tasks

(Tasks 4, 7, 8, 12 and 14 will also be used in the heat stress series.)

15. Integrated task simulation - vigilance. The subject monitors a central display consisting of a rotating pointer on a dial, and a peripheral display consisting of an array of lights distributed from one extreme to the other of his visual field. This is a combination of the clock test used by Mackworth [35] and the vigilance aspect of the task used by Bursill [17]. Both authors found marked effects due to heat stress. Data relevant to each response or signal are recorded on a paper-tape punch. The test simulates the work of monitoring large instrument panels for process control. It is not yet operational.

16. Simulated inspection task - card sorting. The subject inspects a matrix of numbers printed on each card, rejecting those where any two of the numbers are the same. A paper and pencil version of the test was found to be sensitive to moderate heat stress by Holmberg and Wyon [36]. In the present version the test is automatically scored onto counters using magnetic labels on the target cards.

17. Simulated checking task - card sorting. The subject compares two 7-digit numbers on opposite sides of each card, rejecting those where the two numbers differ. The task is scored as above.

18. Memory Task. Subjects memorize a list of common words and must recognize them in a larger list containing other words as well.

19. Simulated spot-welding. The subject manipulates a heavy but counter-balanced welding caliper to close on five targets in a random sequence given by a 5-lamp display. Scoring is automatic onto electronic counters. The test measures perseverance in realistic heavy precision task. It is not yet operational.

RESEARCH PROGRAM

The experiments described above will be carried out during 1977 and 1978 by R. Kok, Mary Lewis and Dr. G. Meese. The results will be published in NBRI reports and in appropriate scientific journals. During 1976 the mobile climate laboratory has been commissioned, and the performance tests have been validated in extensive pilot studies as they became operational. A preliminary study of heat and noise interaction is currently being completed, using 240 subjects. It is intended to examine the changes in hand skin temperature occurring in response to various diurnal temperature changes, using the computer control of the climate chamber temperature described above. On a long-term basis, the climate laboratory is seen as a valuable resource for examining human response to the indoor environment expected to occur in proposed buildings of alternative designs.

RELEVANCE TO ENERGY CONSERVATION

The Pretoria unit was established to provide valid and quantitative data on the effects of alternative factor building designs upon productivity. The information requirement for energy conservation is the same - the effects of alternative energy conservation strategies must be quantified in experiments that are sufficiently valid and realistic to be accepted as a basis for important investment policy decisions. No new principles or extreme levels of stress are involved. Known principles derived from laboratory studies must be applied to the moderate stress region. Field studies are desirable, but would inevitably take much longer to perform. If possible, accident, loss control and productivity studies should proceed in parallel with simulation studies of the Pretoria type.

ACKNOWLEDGMENT

I would like to express my thanks and appreciation to Dr. T. L. Webb, Director of the National Building Research Institute in Pretoria, South Africa, and his colleagues, in particular Mr. J. F. van Straaten, who initiated the project and has continuing responsibility for it, and Mr. S. J. Richards, the chairman of the Steering Committee for Indoor Environment co-ordinating this and allied research, for affording me the opportunity of leading this important project in its initial stages and for continuing to contribute to it, and for NBRI's agreement to publish this paper. I am equally grateful to Messrs. J. M. Gouws, A. R. Dys and W. Smit for the mechanical and construction work associated with the performance tasks and the mobile laboratory and to Mr. W. Verhagen for developing and building the electronic circuitry.

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SUMMARY AND CLOSING REMARKS

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In these few remarks I shall attempt to summarize the apparent needs for further research on human response to the thermal environment which have been suggested by this symposium. In addition, comments will be made concerning the priorities of future research. Those of high energy savings potential will be suggested as high priority items and will be treated in that order.

1. Time-temperature relations of excursions outside the presently accepted comfort limits. The use of building mass as a "thermal flywheel" can save considerable energy, as well as shift energy use periods. The effects on comfort and performance need quantification as conditions deviate beyond "comfort" limits, and then are restored at some later time.

2. Clothing research. The immediate need is to identify and specify proper available clothing ensembles as functions of performance and comfort and to educate the public as to their availability. More long-range objectives would be to provide a technical base for thermal "labeling" of clothing articles for the public, as well as research into practical methods of adjusting the clo values of ensembles when worn in various environments, i.e., opening and closing vent flaps. A study of the life cycle cost of utilizing clothing would also be appropriate. Is it more economical of capital and energy to wear more clothing and save heating energy? An additional area of study would involve examining finger dexterity limits. Lowering temperatures and adding clothing might not be acceptable beyond a certain point because of this factor.

3. Spot heating and cooling limits. The use of localized heating and cooling in building environments, particularly for industrial applications, has potential for large savings in energy. The acceptability of such environments for comfort and performance should be examined.

4. Heated and cooled furniture. Comfort and performance limits when using heated or cooled chairs should be determined. Energy would be saved for example by using heated furniture and maintaining the surroundings at a lower than usual temperature. Increased activity when the person would leave the heated chair to move around might offset the additional cooling. Many interesting possibilities for this concept exists.

5. Energy efficiency of controlling the thermal variables independently. At present, air temperature appears to be the most practical of the four environmental variables to control; however the conditions under which it is more energy efficient to control mean radiant temperature, air velocity, or humidity and still maintain the same degree of "comfort" should be identified.

6. Cold sleep conditions. Research is needed to establish limits of acceptable sleepware and bedcovering for comfort and health consistent with lower temperatures for night-time energy savings.

7. Instrumentation. A cheap and simple comfort instrument still remains as a need.

All of the above research areas need special attention for children, the aged, and the infirmed for obvious reasons.

It does appear that the several human comfort mathematical models now being employed are accurate enough to be practically employed in many of the research areas. Better models per se do not seem to be high priority needs.

The specialized use of color, design, sound, and music do not seem to have great potential for energy saving, with one interesting long-range exception. Can the visual and acoustical environment be designed so that people can live and work comfortably in smaller spaces? The resulting energy savings would then be great.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

These are the proceedings of a symposium sponsored by the National Bureau of Standards and held in Gaithersburg, Maryland on February 11, 1977. The symposium was held for the purpose of exploring new aspects of indoor thermal environments, caused primarily by the impact of energy conservation in new and existing buildings. Included in these proceedings are eleven formal papers which were presented by leading researchers in the field of thermal comfort and heat stress. The contributed papers were from Denmark, Sweden, and several research institutions within the United States including the John B. Pierce Foundation at Yale University, Kansas State University, and Pennsylvania State University. Information was presented on a variety of approaches to determining human response to thermal environments. These included laboratory studies in environmental chambers utilizing instrumented human subjects, field studies involving surveys and questionnaires, mathematical modelling of humans, an analysis of some types of instruments used in assessing the quality of the environments, and a discussion of the relationships between productivity and the thermal environment.

17. KEY WORDS (six to twelve entries, alphabetical order, capitalize only the first letter of the first key word unless a proper name; separated by semicolons)

Energy conservation in buildings; heat stress; human comfort; indoor environment; mean radiant temperature; thermal comfort

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