CHAPTER 2

Review of Literature
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REVIEW OF LITERATURE

The hazards associated with work in hot environment have long been recognized as an important area of occupational health research. Hot environment can produce stress and strain on the human body, leading to discomfort and illness. The concepts of heat stress and heat strain assessment have been originated from the basic understanding of heat exchanges through multiple routes (e.g., convection, conduction, radiation, evaporation) and the internal metabolic heat production. Heat strain represents the physiological changes due to heat stress. Thermoregulatory responses including cardiovascular responses interact to attain the body's thermal equilibrium. These responses can be regarded as the indicators of heat strain.

Heat stress may be natural or artificial. Natural exposure occurs in tropical areas, whereas artificial exposure may occur in industrial or other situations. While the advances in air-conditioning technology have greatly reduced the need for human exposure to extreme hot environment, particularly with reference to indoor environment, the tropical heat for the community environment is unavoidable. For example,
- Exposure to hot weather, working in open sunlight during summer, as in case of construction jobs, stockyards, and the like;
- Workplaces near the boilers, furnaces, heat treatment tanks, steam pipes and hot processes; areas like foundries, forge shops and rolling mills;
- Operations like welding, glass manufacturing, hot metal cutting, etc;
- Working in sheds/workshops and exposure to radiant heat; and
- Confinement in hot areas and poorly ventilated areas.

The miners are exposed to hot working conditions due to increase in temperature with depth, and partly due to lack of ventilation. The textile workers are subjected to hot-humid condition that is required to maintain optimum conditions for cotton weaving. The steel and aluminium workers are exposed to intense radiative loads from open hearth furnaces and refractory ovens. Such industrial conditions often exceed the climatic stresses found even in most extreme naturally occurring climates.

When humans are exposed to extremely hot environment, the physiological and other sensory responses may elevate to such an extent that they are unable to continue exposure and are likely to face possible heat collapse (Avellini et al. 1980). The usual limiting value of $T_{cr}$ for day to day exposure is about 38°C. Under hot ambient condition, such a steady state may not be possible and therefore, experts opined a 1°C rise in $T_{cr}$ as the upper limit for 1-2 hour exposure (NIOSH 1972; WHO 1969). This value
represents a heat storage of approximately 6.0 kcal. Immietro and Goldman (1965) suggested a realistic upper limit for $T_{tr}$ as 39.2°C and $T_{tr}$ at a level of 39.0°C has been taken as tolerance limit for persons at rest and work for a short duration (Pandolf and Goldman 1978). The basic physiological reason for this limit is probably that the main avenue of heat loss (sweating) becomes saturated at about this value.

As schematically shown in Figure 2.1, the $T_{tr}$ is in dynamic equilibrium as a result of a balance between the factors that add and subtract body heat. This balance is maintained by the interaction of mechanism that allows heat transfer to the periphery or shell, regulates evaporative cooling, and varies the body's rate of heat production. When heat gain outstrips heat loss, as readily occurs in vigorous physical activity in hot environment, the $T_{tr}$ rises; in the cold environment, on the other hand, heat loss often exceeds heat production and the $T_{tr}$ falls. The upper limit of tolerance, therefore, depends on the environment, characteristics of the persons exposed, and one's thermal state on the initiation of heat exposure and one's ability to thermoregulation.

The climate physiologists has often been called upon to prescribe tolerable levels of heat stress, for its application in industry and other occupational sphere. Leithed and Lind (1964) suggested three catagories of hot environment, i.e., easily tolerable (comfortable), just tolerable conditions, i.e., tolerable for intermittent exposure only and intolerable conditions. Belding and Kamon (1973) described a physiological method for determining
the upper limit of the prescriptive zone. The American Society for Heating, Refrigerating and Air-conditioning Engineers (ASHRAE 1981) formulated tolerable temperature for different occupational settings. For different metabolic levels and clothing factors, minimum and maximum tolerable temperature were defined, assuming a relative humidity of 50% with air velocity in the free convection zone. Several studies have observed the length of tolerance time during work in hot environment (Wyndham et al. 1965; Goldman et al. 1965). Montain et al. (1994) determined the influence of exercise intensity, protective clothing, and climate on physiological tolerance to heat stress. Under these conditions individuals are unable to achieve thermal steady state (Sawka et al. 1992). Davies (1993) examined the physiological responses in severe-prolonged heat exposure to the limit of tolerance. Therefore, it is important to understand the magnitude of physiological strain that humans can tolerate (Pandolf et al. 1986).

Complications From Excessive Heat Stress

Excessive exposure to a hot environment can cause serious ill-effects of varied nature (Grandjean 1988).

- When the human body has to cope up with high temperature, blood circulation has to increase which necessitates the heart to work harder. By itself, blood plays an important role in heat regulating process. Since the
cardiovascular system links with most of the body functions, the overexposure to heat results in other physiological disturbances.

- At high temperatures, there is an increased secretion of sweat, with simultaneous loss of water and salts from the body, which lead to exhaustion and impairment of body functions (Holmer 1992).

- In the process of thermoregulation, physiological changes take place to prevent muscles from producing heat. These changes are associated with tiredness, tendency to sleep and fatigue, leading to performance decrement, errors and accidents (Maughan 1994).

Excessive heat exposures often culminate to heat related illnesses or disorders. These occur when the body can no longer maintain $T_e$ within a reasonable range, via the usual thermoregulatory mechanism (Wildeboor and Camp 1993). The changes in $T_e$ affect cellular structures, enzyme systems, and numerous chemical and physical processes that take place in the body. The risk factors for HRI are, for example, lack of acclimatization, dehydration, lack of sleep, poor physical status and working capacity, being overweight, alcohol use, age, medications, exposure to high ambient heat and prolonged physical exertion (Ramsey et al. 1983). NIOSH (1986) issued revised criteria as below:

(i) reaching $T_e$ of 40°C, is a risk of developing heat stroke if the exposure continues for some hours;
(ii) suffering from repeated attacks of heat collapse prevents a person from standing erect because in such circumstances the person might not be able to look after his own safety; and

(iii) suffering a change in temperament and being no longer responsive to instructions.

Since the long term effects of repetitive heat exposure and its impact on health and safety are multi-factorial, defining comfortable thermal environment or tolerability are extremely important to determine safe exposures for persons to work in hot environment.
Figure 2.1 Factors that contribute to the body’s heat gain and loss, and related precautionary measures to minimize health hazards.
Thermal Indices in Relation to Human Heat Tolerance Assessment

The hot environment consists of a combination of multiple factors, e.g., ambient air temperature ($T_a$), air velocity ($V_a$), water vapour pressure, and radiative temperature from surrounding environment. A thermal index essentially integrates various thermal, physical and personal factors into a single number to define a hot environment (Malchaire and Mairiaux 1991). A number of heat stress indices have been introduced in the past decades that are supposed to reasonably mirror the heat load on the individual (Beshir and Ramsey 1988). Accordingly, these indices can be classified as stress or strain indices, based on physical factors of the environment, thermal comfort assessment, rational heat balance equation, and physiological strains (Beshir 1981). These indices provide a necessary procedure to measure the thermal environment for different application, such as establishing safe heat exposures and regulatory rules (NIOSH 1986), considering human performance and safety (Hancock 1982; Ramsey et al. 1983). Some of the frequently used thermal indices are grouped as empirical indices and rational indices, as below:

Empirical Indices (Based on Subjective Preference)

- Effective Temperature (ET) (Houghton and Yaglou 1923)
- Corrected Effective Temperature (CET) (Bedford 1945)
- Wet Bulb Globe Temperature (WBGT) (Yaglou and Minard 1957)
- Wet Globe Thermometer (WGT) (Botsford 1971)
• Oxford Index (WD) (Lind and Hellon 1957)
• Operative Temperature (OT) (Gagge et al. 1967)

Rational Indices (Based on Analysis of Heat Exchange)
• Predicted Four Hour Sweat Rate (P4SR) (McArdle et al. 1947)
• New Effective temperature (ET*) (Gagge et al. 1971)
• Standard Effective Temperature (ASHRAE 1972)
• Heat Stress Index (HSI) (Belding and Hatch 1955)
• Heat Stress Index (HSI BC) (Brief and Confer 1971)
• Index of Thermal Stress (ITS) (Givoni and Berner-Niv. 1967)
• Skin Wettedness (W) (Gagge 1937)
• Required Sweat Rate (SW<sub>req</sub>) (ISO 7933 1989)
• Predicted Mean Vote (PMV) (ISO 7730 1994)
• Predicted Percentage of Dissatisfied (PPD) (Fanger 1973).

Analysis of the indices indicate that various indices differ in the basic approach, the units used to express the effects of various factors, the range of application and the relative importance attributed to different factors, including their mutual interdependence (Pulket et al. 1980). A brief review of the commonly used thermal indices is summarized in Table 2.1.
Figure 2.2 A schematic diagram for heat stress and strain evaluation.
Since evaluation of heat stress and strain involves complex influences of multiple factors (as schematically shown in Figure 2.2), limitations exist with the applicability of the heat stress and strain indices. Mutchler and Vecchio (1977) studied and developed empirical relationships between several indices of heat stress derived from a series of studies in 14 representative hot industries. Freivalds (1987) observed that a stressful environment is created by the demand of a particular work. Certain indices such as ET (B) are more appropriate for easily tolerable conditions in which human can easily maintain thermal equilibrium for a long period of time. Other strain indices like PaSR and HSI may be appropriate for just tolerable conditions in which thermoregulatory capacity is stretched to the limits. Malchaire (1990) studied the principle indices in real situations in industry, and examined their limitations. Several heat stress criteria documents (e.g., ISO 7243, 1989; ISO 7933, 1989; NIOSH 1986) have been published with the objective of minimizing the risk of heat illness in industry. The Swreq and WBGT indices, on which ISO standards 7933 and 7243 are based, provide virtually identical results for the limits of an 8-hour exposure. The utility of ISO 7933 analytical model is under investigation for its wider application. Kahkonen et al. (1992) noted that the ISO 7933 is applicable only for moderate climatic conditions. Needless to mention that any recommendations such as the prescriptive thermal zones, upper permissible limits for work, etc., which are suggested for the temperate climate may not be suitable for application in the tropical
climate, due to extremely hot environment and differences in the population characteristics.

In spite of the difficulty to derive a universally acceptable heat stress or strain index, by virtue of the relative simplicity of prediction in most cases, the industrial practitioners and researchers will continue to use the indices in their area of interest. What it essentially demands is in-depth analysis of the indices to identify its utility and range of application, with special reference to its utility in heat tolerance assessment. Further, hypohydration of an individual reduces human ability to tolerate heat; the applicability of the thermal indices needs to be examined with reference to the hydration state of individuals.

**Hyperhydration and Human Heat Tolerance**

Greenleaf, (1979) noted body fluid levels as (a) Euhydration, referring to "normal" body fluid content, (b) Hypohydration refers to body fluid "deficit" and (c) Hyperhydration refers to body fluid "excess". The primary objective of fluid replacement is to maintain a state of euhydration and avoid dehydration. The water balance of human body is schematically shown in *Figure 2.3*.

Under heavy physical work and/or high environmental heat load, where the demands for sweating are high, the voluntary intake of fluid may not be sufficient to keep pace with the water loss and dehydration may ensue (Gisolfi 1983). Moreover, feeling of thirst is not an adequate guide for water replacement. Further, it has been recognized that active humans do not
voluntarily replace all the water lost during prolonged exposure to heat (Hubbard et al. 1990). Even when fluid is consumed during physical activity, the persons frequently become dehydrated because the rate at which fluid is lost as sweat can be as much as twice the rate at which fluid can be absorbed after ingestion. The kidney rapidly excretes any excess fluid, and the plasma volume is not apt to be expanded after fluid intake (Candas et al. 1988).

The detrimental effects of hypohydration have been extensively studied, including descriptions of decreased blood flow to the skin (Fortney et al. 1984); increased $T_c$ and muscle temperature during heat exposure (Nielsen 1974), increased heart rate (Candas et al. 1986; Sawka et al. 1985), decreased sweat rate, decreased tolerance for acceleration and decreased overall performance (Sawka 1988). Attempts have been made, therefore, to minimise these disturbances by various regimens of fluid intake before, during and after physical activity. Different means of rehydration by hyperhydrating agents such as water, carbohydrate and electrolyte supplements and glycerol solution have been practiced (Lyons et al. 1990; Armstrong et al. 1997; Coyle and Montain 1993) to attenuate some of the disturbances, enabling the subject to undertake work at a lesser risk of hyperthermia. Armstrong et al. (1997) examined the distinct and interactive effects of initial hydration state, exercise-induced dehydration, and water rehydration in a hot environment. Similarly, Kristal et al. (1988) showed that subjects increased their exercising periods after forced water loading. Gruca et al. (1987) demonstrated that
hyperhydration influences thermoregulatory function in exercising men by shortening the delay in onset of sweating and by decreasing the quantity of dripped sweat. As a result, the increases in $T_{\infty}$ in hyperhydrated exercising men are lower than in normally hydrated individuals. Greenleaf and Harrison (1985) suggested to encourage individuals to drink water or low sodium noncarbonated beverages every 15-20 min, while working in hot environment.

Murray et al. (1989) demonstrated that carbohydrate supplements containing as much as 15% carbohydrate do not differ from water in its ability to effectively support thermoregulation. Takamata et al. (1995) provided an evidence that drinking generally inhibits osmoregulatory response and there exists a vital interaction between the osmoregulatory and thermoregulatory centres in humans. Montain et al. (1995) showed that fluid ingestion at the onset of physical activity transiently attenuates the rise in $T_{\infty}$ and heart rate that occurred if rehydration was began later in exercise. Nose et al. (1990) also suggested that a partial restoration of the lost plasma volume during exercise is useful to suppress the drift in heart rate and to promote better heat transfer from the body core to the skin surface in a warm environment.

Recent studies have focused on the use of glycerol solution with its possible effects to achieve hyperhydration (Freund et al. 1995; Lyons et al. 1990; Montner et al. 1996). Riedesel et al. (1987) demonstrated that the ingestion of glycerol (1 and 1.5 gm/kg body weight) reduces the urine volume during the 2nd and 3rd hour of ingestion, suggesting that glycerol may delay
excretion of the excess fluid and thereby prolong the hyperhydration state. Lyons et al. (1990) and Koenigsberg et al. (1991) confirmed that glycerol/water hyperhydration has dramatic effects in improving a person’s ability to thermoregulate during heat stress. This is achieved by greater fluid retention after hyperhydration with glycerol and water than with water alone.

Other studies (Sawka et al. 1997, Latzka et al. 1997; Murray et al. 1991) have reported noted that the fluid ingestion regimens are influenced by multiple factors, such as the timing of fluid intake, composition of the fluid ingested, the nature, intensity, and duration of physical activity and heat exposure regimen studied, including the physical condition of the subjects. Findings generally emerge that ingestion of glycerol may result in increased plasma osmolality with peak levels achieved within 60 minute, and expanded plasma volume, reduced Tcr and increased sweat rate during work in the heat. Gleeson et al. (1986) indicated that glycerol ingestion soon before or during exercise might provide a transient osmotic impetus to temporarily retain fluid in the vascular spaces. However, it remains inconclusive whether multiple dosages of glycerol and water can extend the state of hyperhydration for many hours or even days. This demands longitudinal studies with ingestion of different mix of glycerol and water. The strategies that facilitate hyperhydration will certainly be beneficial to minimize physiological strain and enhance work performance for persons exposed to high heat. These would ostensibly be of considerable benefit to athletes, workers and military
personals who exercise in the heat. Therefore, assessment of human heat
tolerance under different state of hydration has practical utility to categorise
physiological strain in relation to combined environment warmth (i.e., thermal
indices).

Figure 2.3 Schematic body water balance.
<table>
<thead>
<tr>
<th>Empirical Indices (based on subjective preference)</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFECTIVE TEMPERATURE (ET): Houghton and Yaglou (1923). A sensory index that combines the $T_e$, $T_{wb}$ and $V_e$ into a single value. Normal scale (men wearing ordinary summer clothing); Basic scale (men stripped to the waist).</td>
<td>Simple, easy to measure and fast responding, very widely used as a steady index for measurement of heat stress.</td>
<td>Radiant heat effects and work rates are not included.</td>
</tr>
<tr>
<td>CORRECTED EFFECTIVE TEMPERATURE (CET): Bedford (1945). Globe temperature ($T_g$) is used in place of $T_e$, otherwise it is same like ET</td>
<td>Integrate four climatic factors ($T_e$, $T_{wb}$, $T_p$, $V_p$) in a single reading; simple and easy to use (WHO 1969); useful index for engineers (Fuller and Smith 1981).</td>
<td>Does not take into account the effects of clothing and metabolic heat.</td>
</tr>
<tr>
<td>NEW EFFECTIVE TEMPERATURE (ET*): Gagge et al. (1971). Reference to $T_i$ and 50% RH, determines total heat exchange from skin surface, as is the actual environment. Derived from ET*, ET100 —standardized for 100% saturation of vapour pressure is included in the present study.</td>
<td>A good indicator of physiological strain and warmth assessment; estimates human heat transfer (Gagge et al. 1971) and useful for calculating ventilation or air-conditioning requirements.</td>
<td>Difficult to apply, requires elaborate measurements and computations; usefulness is limited for exposure times shorter than an hour (Gagge et al. 1971).</td>
</tr>
<tr>
<td>WET BULB GLOBE TEMPERATURE (WBGT) Yaglou and Minard (1957); ISO 7243 (1989). Combines $T_e$, $T_{wb}$, $T_i$ and $V_e$. WBGT ($T$) = 0.7 $T_{wb}$ + 0.3 $T_i$; WBGT ($O$) = 0.7 $T_{wb}$ + 0.2 $T_i$ + 0.1 $T_e$.</td>
<td>Simple to measure, practical for industrial purposes and reliable; correlates well with the physiological reactions due to heat exposure (Ramsey 1976).</td>
<td>Poor under low humidity conditions (Ramsey 1976). Separate graphical presentation to consider metabolic workload (Ramsey and Beshir 1985).</td>
</tr>
<tr>
<td>WET GLOBE TEMPERATURE (WGT): Botsford (1971), combine the effects of four main climatic factors into a single reading.</td>
<td>Simple and reliable index, small size unit, practical for industrial purposes; high correlation between WGT and other indices (Beshir 1981).</td>
<td>Correlation with physiological responses not well established; does not consider the metabolic workload (Ramsey and Beshir 1985).</td>
</tr>
<tr>
<td>OXFORD INDEX (WD): Lind and Hellon (1957) W.D. = 0.15 $T_e$ + 0.85 $T_{wb}$ where WD is the weighted value and $T_e$ and $T_{wb}$ temperature.</td>
<td>Accurate and specifically used in high levels of heat stress. Useful for heat tolerance assessment.</td>
<td>Effects of clothing and metabolic heat are not considered.</td>
</tr>
<tr>
<td>PREDICTED 4-HOUR SWEAT RATE (P,SR): McArdle et al. (1947). Predicts total sweat loss (liters) during a 4-hour exposure.</td>
<td>It takes into account the metabolic energy expenditure; considered as one of the most valid indices; estimates actual average sweat loss of a group, particularly fit for acclimatized men.</td>
<td>Complicated to use, inaccurate at low humidity. Several corrections for work rate, clothing and radiant heat are applied in $P_{SR}$ calculation.</td>
</tr>
</tbody>
</table>
### Rational Indices (based on analysis of heat exchange)

| **HEAT STRESS INDEX (HSI): Belding and Hatch (1955).** HSI = 100 x E<sub>aw</sub>/E<sub>max</sub> indicates the level of heat stress, with a value of 100 being considered as maximum. HSI (BC): Brief and Confer (1971) revised the HSI of Belding and Hatch using new coefficients of heat exchange and correlation for clothing. HSI (McKarns and Brief 1966) revised index for clothed subjects. | **Advantages:** Widely used as a tool for evaluating hot-work environments; takes energy expenditure in account; can be used under hot as well as cold conditions. McKarns and Brief (1966) modification also permits the calculation of allowable exposure time and rest allowances at different combinations of environmental and metabolic heat. | **Disadvantages:** Involves multiple steps of calculations and requires more instrument and time consuming. May not be applicable at very high heat stress conditions, both hot, hot-dry and hot-humid conditions. |
| **OPERATIVE TEMPERATURE (OT): Gagge et al. (1967).** Weighted sum of radiative and convective heat transfer in a uniform environment, as it would occur in an actual industrial environment. | **Advantages:** Can be derived from the heat balance equation, and used directly to calculate the heat exchange by radiation & convection. | **Disadvantages:** Factors of humidity and metabolic heat are not included. Limited use for industrial environment. |
| **INDEX OF THERMAL STRESS (ITS): Givoni (1969).** Incorporates cooling efficiency of sweat secretion; computes the sweat loss required for maintenance of thermal balance. | **Advantages:** Provides quantitative relationships of the factors involved; can be used in heat and cold. | **Disadvantages:** Calculations and the expressions are complicated. |
| **SKIN WETTEDNESS (W): Gagge (1937).** Ratio of the total skin evaporative loss (E<sub>aw</sub>) and the maximum evaporative loss from a fully wetted skin surface (E<sub>max</sub>) (i.e., W = E<sub>aw</sub>/E<sub>max</sub>). The minimum value of W is 0.06 when there is skin diffusion but no sweating, and the maximum value of W is 1.0 when the skin is fully covered by sweat (Gagge 1981). | **Advantages:** Considers the basic variables that are required for heat balance equation. | **Disadvantages:** The basic variables to heat balance must be measured. Time consuming and requires recording equipments. |
| **REQUIRED SWEAT RATE (SR<sub>req</sub>): ISO 7933 (1989). Index is based on heat balance equation and used to evaluate how stressful a given working environment is and whether it is acceptable for continuous work.** | **Advantages:** Most powerful and reliable index for organizing work and rest in hot conditions (Peters 1988); provides analysis of the effects of basic parameters of the thermal environment; computer program is provided for ease in calculation. | **Disadvantages:** Difficult to understand and calculate. |
| **PREDICTED MEAN VOTE (PMV): Fanger (1973); ISO 7730 (1994). PREDICTED PERCENTAGE OF DISSATISFIED (PPD): Fanger (1973)** | **Advantages:** Provides analysis of the effects of basic parameters of the thermal environment; can be used to determine the best control measures; computer program is provided for easy calculation. | **Disadvantages:** Not uniformly responsive. |