CHAPTER 6

Thermal Management Perspectives
Local habitat of tropics is most of the time exposed to natural hot climate. Industrial population in this region, in addition to natural hot environment, burdened with the factor of occupational heat load (wherever applicable). This heat burden affects human performance, industrial productivity, health and safety. However, enormous potential of physiological and behavioral adaptations of human beings helps to cope with the combined demands of physical work and environment. The present contribution examined the process of human adaptability to extreme hot climates based on the classical biophysical analysis of heat exchanges.

The study primarily dealt with the complexity of biophysical reactions that regulates heat balance, including heat gain from external influences and internal heat production through metabolism. The biophysical derivation evolved in the study was based on the foundation of heat exchange mechanism (i.e., thermal equilibrium and zero heat storage), which primarily dealt with temperature difference between body segments and
across compartments. These exchanges are influenced by the classical physical laws and energy transformation due to physiological manifestation.

1) Utility of the Biophysical Derivation

The 320 steps spreadsheet derivation brought out several biophysical parameters of academic interests and practical importance towards heat stress management. The expression given in chapter 3 and in flow sheets (Fig. 3.2 A to E) explained the contribution of segments and compartments in heat exchange, with reference to external environment.

- Core – Shell concept

Based on the analysis of heat transfer between segments and compartments of the body, the present study noted that temperature profile of the skin and fat layers demonstrated similar trend and tended to diverge beyond a threshold point, which we demonstrated as divergence point. Similarly core and muscle layers showed a converging tendency. The point at which both of these compartments converged was called converging point. This characteristics of the pairing layers (i.e., core-muscle and fat-skin) might be a reconfirmation of core-shell concept described by gagge et al. (1986).

- Segmental Triggering

Each segment had different divergence and convergence point of its compartments as shown in Table 3.8. The study revealed, that
characteristics of different segments appeared to have a characteristic gain and a threshold above which segmental temperature triggered to increase. This triggering response was found to be primarily because of compartment temperature increase, and these triggering responses were found to vary from segment to segment.

It was noted that (refer to Fig. 3.8, 3.9, and Table 3.8) segmental triggering of human head started first compared to other segments (at 36.4°C of body core temperature, the temperature of skin and fat layers show diverging trend) and convergence of core and muscle layers (at 39.17°C body core temperature) was also faster than other part of the body. This reconfirms the sensitive nature of head segment. The corresponding span of body core temperature of 2.77°C, is likely to have criticality in human thermoregulation.

- **Compartmental Conductance**

The study revealed higher conductance of inner layers, *i.e.*, core-muscle, and muscle-fat, compared to the peripheral layers, *i.e.*, fat-skin. The conductance of the compartments in trunk and leg were found higher than other body segments (Fig. 3.7). The conductance patterns of the segments and layers probably reflect the inherent tendency of human body of isolating itself from environmental changes and conserving the energy within, as a mechanism to maintain thermal equilibrium.
• **Heat Sink**

The segmental and compartmental heat exchange mechanism suggested trunk, instead of head (as observed by Rasch *et al.* 1991) as the heat sink of the body. Because of its large body surface area, the trunk segment exchanged larger amount of heat, compared to other segments. Refer to Fig 3.3, the hand segment also seemed to be a useful heat exchanger, in dissipating heat from the body, as it has uniform heat conductance from innermost to outer body compartment (refer Table 4.3). These observations need to be further examined to elucidate the role of peripheral segments in total heat transfer between the human body and environment.

• **Limit of Tolerance**

The biophysical derivation has practical utility in assessing the rate of change in body core temperature from any given initial condition. Thereby, the build up of the body core temperature can be predicted from the exposure duration. In other words, by making the criteria limit of maximal heat tolerance limits, e.g., 39°C, one can arrive at the tolerance time of an individual.

However, this rate of change was observed differently in different biophysical environment and with the state of acclimatization of the subjects. There was a lower increase in body core temperature in hot-
humid group compared to hot-dry and unacclimatized group. The regression equations drawn are given below:

Unacclimatized men: \[ \frac{dT}{dt} \ (\degree C/min) = 0.002 \times \text{WBGT} - 0.003; \]
\[ (r = 0.304; \ p < 0.05) \]

Acclimatized (Hot-dry): \[ \frac{dT}{dt} \ (\degree C/min) = 0.007 \times \text{WBGT} - 0.193; \]
\[ (r = 0.471; \ p < 0.01) \]

Acclimatized (Hot-humid): \[ \frac{dT}{dt} \ (\degree C/min) = 0.005 \times \text{WBGT} - 0.166; \]
\[ (r = 0.613; \ p < 0.01) \]

The validity testing of the biophysical derivation was done against the experimental data, and the prediction has an error of about 6-24%, based on the experimental condition. With reference to environmental conditions selected in the present study (refer to heat exposure programme described in Chapter 4 — Process of Acclimatization), the error in prediction was relatively less in hot-dry conditions, compared to hot-humid environment. Therefore, the expression may be useful for industrial work scheduling and utilization of manpower by specifying the thermal environment and/or exposure duration, thereby to ensure health and safety of workers in hot working environment.

2) Classification of Biophysical Environment — a tool for possible Management of heat adversities

The reduction of adverse health effect can be accomplished by classifying the working environment and selecting suitable people easily adaptable
and tolerable to the situation. As management strategy, the heat adversities can be controlled through proper application engineering in work place, work practice control, worker training and acclimatization, medical supervision and proper use personal protective equipments. The present study (Chapter 4) observed that despite greater physiological demand in hot-humid environment, human adjustment to consecutive exposures to hot-humid environment was much better compared to dry-heat condition. Daily brief exposures of about 1.5 to 2 hours working in the humid heat for about 5 days resulted in short term acclimatization. Whereas, the subjects exposed to hot-dry environment took longer time of adjustment. Acclimatization in dry heat required higher duration of training (>8 days). Slower thermoregulatory responses in dry heat group were suggestive of delayed acclimatization.

The present study reconfirmed that sweating rate and body core temperature were critical to acclimatization, however, the relationship of the core and skin played a critical role in both sweating response and heat dissipation mechanism to achieve a state of acclimatization. Heat conductance in all segments was found to be better in hot-humid group, compared to the hot-dry group. This invariably supported the observation that the humid group had a constant effort to adjust the body demand to dissipate heat in hot environment.
Table 6.1 shows the influence of combined heat exchange (C plus R) through segments. About 28.5% surface area (hand, leg and feet) of the human body was responsible in receiving 56 to 64% of total combined heat coming from the hot environment. The body heat accumulation due to environmental factors (C plus R) was found negatively correlated with body mean skin temperature and this was more evident in case of humid group. Therefore artificial increase of skin temperature could be an avenue to withstand heat severity. Ogawa et al. (1982) suggested about sweat gland training by repeated local exposure to heat, especially by daily hot water bath of a limb area. Or, properly designed clothing could stop the entry of such a large quantity of heat thus reducing the body heat load.

The present study also observed that heat conductance of the hand segment was uniform from "core" to "shell", therefore, special attention

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>STATUS</th>
<th>HEAD</th>
<th>TRUNK</th>
<th>ARM</th>
<th>HAND</th>
<th>LEG</th>
<th>FEET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid Acclimatized</td>
<td>Resting</td>
<td>12.8</td>
<td>13.5</td>
<td>17.1</td>
<td>18.7</td>
<td>17.3</td>
<td>20.6</td>
</tr>
<tr>
<td></td>
<td>Working</td>
<td>10.7</td>
<td>12.3</td>
<td>13.0</td>
<td>18.5</td>
<td>23.6</td>
<td>21.9</td>
</tr>
<tr>
<td>Dry Acclimatized</td>
<td>Resting</td>
<td>12.1</td>
<td>15.3</td>
<td>16.9</td>
<td>18.7</td>
<td>17.7</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>Working</td>
<td>11.0</td>
<td>13.4</td>
<td>12.2</td>
<td>12.2</td>
<td>26.5</td>
<td>24.7</td>
</tr>
</tbody>
</table>

should be taken to use this avenue as the best segment for dissipating heat from the body. At the same time, attention may be required to stop
entry of heat through the segment. This observation has academic interest for future research on peripheral cooling (Heising and Werner 1985, 1987; Nag and Pradhan 1993).

3) Work Practices and Physiological Adjustment

Work practices and physiological adjustment has a wider applicability when environment control measures fails. Apart from acclimatization, one of the most effective option under heat stressed condition is work time scheduling which along with human resource management takes care of the time alloted for breaks in the work schedule (Nag 1991). It is a demonstrated fact of favorable effect of resting in cool environment (Brouha 1967). Ohnaka et al. (1993) proposed “cool room” inside the work place where intermittent rest could be taken. One approach to enhance total work capacity is to carefully schedule work-rest cycles (Constable at al. 1994). In order to examine this approach, a sample case study was designed with two volunteers (Sub. 1: Body weight 48 kg, Body height 156 cm, BSA 1.45 m²; Sub. 2: Body weight 45 kg, Body height 153 cm, BSA 1.35 m²). The subjects were exposed to three hot conditions as below:
Condition 1: $T_a = 38 - 39.5$ (°C), RH 45 – 50%
Condition 2: $T_a = 38 - 40$ (°C), RH 71 – 73%
Condition 3: $T_a = 43.2 - 45.1$ (°C), RH 44.2 – 50.5%

The subjects were exposed to each of these climatic conditions for four times:

- Firstly to determine the heat tolerance time of the subjects for each of the climatic conditions, when the subjects continued ergometric work without any interruption.

- In separate days, the subjects were asked to perform ergometric work in the specified climatic conditions at different sequence of work and rest. Each spell of work-rest cycle was of 10 min duration, e.g., work-rest ratio as 5:5, 4:6 and 6:4. The physiological measurements were recorded, similar to Chapter 4 and 5.

Table - 6.2 shows the physiological responses and tolerance time of subjects in different environmental conditions (with work—rest scheduling). The tolerance time was determined on the basis of the attainability of body core temperature of 39°C. The number of subjects involved in the study was small but the trend of the data was suggestive of improvement in tolerance time, compared to no rest condition.
Table 6.2: Physiological responses and tolerance time in different work-rest cycles in heat exposures

<table>
<thead>
<tr>
<th>Condition</th>
<th>Work/Rest Pattern</th>
<th>VO₂ (l/min)</th>
<th>Tₚ (°C)</th>
<th>Tolerance Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sub. 1</td>
<td>Sub. 2</td>
<td>Sub. 1</td>
</tr>
<tr>
<td>Ta = 38 – 39.5 (°C)</td>
<td>No Rest</td>
<td>1.043</td>
<td>1.523</td>
<td>36.45</td>
</tr>
<tr>
<td>RH = 45 – 50%</td>
<td>5 : 5</td>
<td>0.883</td>
<td>1.623</td>
<td>35.85</td>
</tr>
<tr>
<td></td>
<td>4 : 6</td>
<td>0.803</td>
<td>1.443</td>
<td>36.85</td>
</tr>
<tr>
<td></td>
<td>6 : 4</td>
<td>0.923</td>
<td>1.703</td>
<td>36.85</td>
</tr>
<tr>
<td>Ta = 38 – 40 (°C)</td>
<td>No Rest</td>
<td>0.923</td>
<td>1.383</td>
<td>37.95</td>
</tr>
<tr>
<td>(RH = 71 – 73%)</td>
<td>5 : 5</td>
<td>1.423</td>
<td>1.703</td>
<td>37.05</td>
</tr>
<tr>
<td></td>
<td>4 : 6</td>
<td>1.803</td>
<td>1.803</td>
<td>37.95</td>
</tr>
<tr>
<td></td>
<td>6 : 4</td>
<td>1.815</td>
<td>1.703</td>
<td>37.85</td>
</tr>
<tr>
<td>Ta = 43.2 – 45.1 (°C)</td>
<td>No Rest</td>
<td>1.303</td>
<td>1.383</td>
<td>37.45</td>
</tr>
<tr>
<td>RH (4.2 – 50.5%)</td>
<td>5 : 5</td>
<td>1.443</td>
<td>1.303</td>
<td>37.05</td>
</tr>
<tr>
<td></td>
<td>4 : 6</td>
<td>1.223</td>
<td>1.703</td>
<td>37.45</td>
</tr>
<tr>
<td></td>
<td>6 : 4</td>
<td>.923</td>
<td>1.077</td>
<td>37.95</td>
</tr>
</tbody>
</table>
Fig. 6.1: Minute to minute heart rate of the subjects in work-rest cycles during exposure to condition 1 and condition 2.
Fig. 6.2: Minute to minute heart rates of the subjects in work-rest cycles during exposure to Condition 3
Fig. 6.3: Rate of change of body temperature at different work-rest cycles in Condition 1, 2 and 3
Data given in Fig 6.1 and 6.2 show that the cardiovascular load (heart rate response) decreased with the introduction of rest cycle. Apparently, equal work and rest seemed to have positive impact for better heat tolerability, in terms of physiological responses and work performance. It was noted that in each cycle of work-rest schedule, the base line of previous heart rate tended to shift upward. The trend suggests that the success of this kind of physiological adjustment for better heat tolerance and increased productivity requires a very fitting work-rest scheduling, which can improve the stressed condition favourable towards better work capacity and improved productivity. Fig. 6.3 showed that the rate of change of body temperature have different response characteristics with the environmental conditions in different work-rest pattern. The figure showed a trend of more effectiveness of this kind of scheduling in higher environmental warmth as condition 3. But this trend requires to be substantiated with more number of subjects.

Since the management of tropical heat is a major concern for industrial as well as community environment, the present longitudinal study bears importance in framing guidelines of human exposure to hot environment, and in preventing heat-related adversities. With due recognition of the limitations of the thermoregulatory models and sources of variations, the author expresses that the suggested biophysical derivation was useful to understand the heat exchange phenomena between segments and across
different compartments of the body. The findings may be suitably applied in industrial surveillance of heat-induced health effects. Taking into account of the prevailing work environment conditions, the heat acclimatization procedure may be adopted in the industry for better adaptability and tolerability to hot environment. However, one may not ignore the specificity of the environment in terms of human adjustment. The present study supports the view point that heat training may be more effective in hot-humid environment than in hot-dry environment, and this will consequently influence in improved working capacity of people of tropics.