IV. ENVIRONMENTAL DATA AND CONTROL

Methods for control of occupational exposures to heat must be adapted to the nature of the heat stress, and if chosen properly, can be expected to ameliorate resulting physiologic strains. Control of heat hazards has been discussed in several publications. Engineers may wish to consult a comprehensive monograph issued by the American Industrial Hygiene Association [60] which offers some details not provided here, in particular on thermal control of large factory spaces by ventilation. Engineering aspects of ventilation are also given in the ASHRAE Guide and Data Book.[61]

Earlier, Hertig [62] and Hertig and Belding [63] discussed methods of heat control. Wason [64] provided a comprehensive treatment of many aspects of the subject.

The ultimate goal of heat control engineering may be to create a climate of work in which true thermal comfort prevails. However, this seldom is achievable when large furnaces or sources of steam or water are present in the work area. In compromising with his ideal of providing comfort, the engineer may rationalize his shortcomings with the knowledge that man evolved as a tropical animal; he is well-endowed with physiologic mechanisms to cope with substantial levels of heat stress, particularly if he is acclimatized. It has been suggested that some exercise of these natural mechanisms among healthly individuals may, as in the case with physical exercise, have beneficial effects. This type of justification of hot working conditions is less warranted when jobs demand use of mental or perceptual facilities or of precise motor skills. In such cases thermal discomfort can distract attention; also, heat tolerance of physically inactive workers is less in some respects than for those whose duties require physical activity.

Analysis of the Problem and Options for Control

Before initiating control measures the engineer will wish to identify the components of the heat stress to which the worker is exposed in current operations or is expected to be exposed in new operations. This information can be used as a basis for rational selection of the means of control, and together with similar data obtained following adoption of control measures to demonstrate the effectiveness of corrective actions that have been taken.

Heat stress for the individual worker depends on: (a) the bodily heat production, or metabolic heat, M, of the tasks which he performs; (b) the number and duration of exposures; (c) the heat exchanges as affected by the thermal environment of each task; namely, (R) (Radiant Heat Exchange), (c) (Convective Heat Exchange), and (E) (Evaporative Heat Loss) as affected by tw (temperature of surrounding objects), v (air velocity), ta (air temperature), Pa (vapor pressure in the air) and Ps (vapor pressure on the skin); (d) thermal conditions of the rest area, and (e) the clothing that is worn.

Items (a) and (b) represent elements of behavioral control; (c) and (d), environmental control; and (e) may be regarded as a combination of both.

The approach toward control may involve modification of one or more of these determinants of heat stress. The challenge is to select specific methods for attack which will be both feasible and effective. Serious errors can result from resorting to some single pet engineering solution.

Consider the consequences of ducting outside air to the task site. This air usually is blown at the worker at a temperature as warm as the upper reaches of the shed where the ducts have been installed. This will enhance cooling by evaporation of sweat, but if the air is warmer than the skin (35°C, 95°F), it will increase the convective heat load. Consideration of the trade off between needed heat loss and increased heat gain is essential. The same goal might be achieved less expensively with portable fans.

In some situations the real mistake may be the failure to recognize that the heat problem derives from radiant load from a furnace which is not decreased by air movement. This mistake has been made less frequently in recent years, but elaborate ducting across the ceilings of older plants exist as testimony to use in the part of this inappropriate action.

Effectiveness of means used to control the five listed determinants of heat stress can be compared.

First to be discussed is decreasing the physical work of the task. Metabolic heat, M, can comprise a large fraction of the total heat load. However, the amount by which this factor may be reduced by control often is quite limited. This is because an average sized man who is simply standing quietly while pushing buttons will produce heat at a rate of 100 Kcal/hr whereas one who is manually transferring fairly heavy materials at a steady pace will seldom have a metabolic rate higher than 300 Kcal/hr and usually not more than 250 Kcal/hr.[65] Obviously, control measures, such as partial mechanization, can only reduce the M component of these steady types of work by 100 to 200 Kcal/hr; nevertheless, mechanization can also help by making it possible for the worker to be more isolated from the heat source, perhaps in an air conditioned booth.

Tasks such as shovelling which involve metabolic heat production at rates as high as 500 or 600 Kcal/hr require that rest be taken one-half to two-thirds of the time simply because of the physical demands of the labor. Thus, the hourly contribution of M to heat load will seldom exceed 300 Kcal/hr. It is obvious that mechanization of such work can increase worker productivity by making possible a decrease in the time needed for rest.

The second modifier warranting discussion is modifying the number and duration of exposures. When the task in a hot environment involves work that is a regularly scheduled part of the job, the combined experience of workers and management will have resulted in an arrangement which makes the work tolerable most of the time for most of the workers. For example, the relief schedule for a task which involves manual transfer of hot materials may involve two workers only; because of the heat and depending on the duress, these two workers alternate at intervals from five minutes up to an hour, which have been determined empirically. Under such conditions overall strain for the individual will be less if the cycles are short.[66] Where there is a standardized quota of hot work for each man, it is sometimes lumped at the beginning of the shift. This arrangement may be preferred by workers in cooler weather; however, there is evidence that the strain of such an arrangement may become excessive on hot days. The total strain will be less, evidenced by fewer heart beats, if the work is spread out. Significantly large variations in work site temperature usually occur during the work day. A typical continuous recording is shown in Figure 4.

The stress of hot jobs is also dependent on vagaries of weather. A hot spell or an unusual rise in humidity may create overly stressful conditions for a few hours or days in the summer. Non-essential tasks should be postponed during such emergency periods, in accordance with a prearranged plan. Also, assignment of an extra helper can importantly reduce heat exposure of members of a working team. However, there is danger in this practice when novices are utilized.

Many of the critically hot exposures to heat faced by employees in industry are incurred irregularly, as in furnace repair or emergencies, where levels of heat stress and physical effort are high and largely unpredictable, and values for the components of the stress are not readily assessable. Usually such exposures will force progressive rise in body temperature. Ideally, such physiologic measurements as body temperature and heart rate would be monitored and used as criteria for limiting such exposures on an ad hoc basis. Practically, however, the tolerance limits have been based on experience of the worker as well as of his supervisor. Fortunately, for most workers, perception of fatigue, faintness, or breathlessness may be relied upon most of the time for bringing individual exposures to a safe ending.

The highly motivated individual, particularly the novice who desires acceptance, is at greater risk. In the same spirit, foremen should respect the opinion of an employee when he reports that he does not feel up to work in the heat at a particular time. Non-job personal factors such as low grade infection, a sleepless night, or diarrhea (dehydration affects sweating) which would not affect performance on most jobs, may adversely affect heat tolearance.

Perhaps the best advice that can be offered for control of irregular exposures is (a) that formal training and indoctrination on effects of heat be provided both supervisors and workers, and (b) that these include directions to the effect that each exposure should be terminated before physical distress is manifest. There is abundant evidence that the physiological strain of an exposure which raises body temperature above 38°C is such as to contraindicate further exposures during the same day; it may take hours for complete recovery. More work can be achieved during several shorter exposures and with less overall strain.

The third modification to be discussed is modifying the thermal environment. The environmental engineer will usually identify important sources of heat stress in a qualitative sense, without resort to elaborate measurements. Thus, his experience will suggest that when air is static and the clothes of the workers become wet with sweat, it will help to provide a fan.

Nevertheless, we reiterate the advantages in making a quantitative analysis of the heat stress (and where possible the resulting strains) on workers. The effects of various approaches to control can be predicted, and improvements in thermal conditions at the workplace can be documented for higher levels of management based on measurements made before and after action has been taken.

We cite concrete examples to illustrate how the quantitative analytic approach may be used.

Case I. A case which is encountered frequently under ordinary conditions of hot weather.

Let us assume a laundry where the humidity is high (Pa = 30 mm Hg) despite the operation of a small exhaust fan on the wall. There is no high level heat source so the temperature of the solid surround (reflected in Tg) is about the same as that of the air.

In the simplest situation we take Ta and Tg equal to the temperature of the skin, which may be assumed to be 35°C (95°F). This means heat exchange by R and C is zero. Let us examine the case on the basis that exposure is continuous and the average physical work is moderate (M = 200 Kcal/hr). The heat load, EREQ, is then,

$$M + R + C = EREQ$$
$$200 + 0 + 0 = 200$$

The workers wear minimum clothing. The air speed is low, 15 m (50 ft) per minute. Analysis for the seminude condition yields an indication of maximum evaporative capacity:

$$EMAX = 2.0\ V^{0.6}\ (42 - Pa)$$, where 42 mm Hg is Ps of completely wetted skin at 35°C.

$$EMAX = 2 \times 8.7\ (42 - 30) = 200\ \text{Kcal/hr}$$

Nominally, a worker under these conditions is just able to maintain bodily heat balance if he keeps his skin completely wet. To do this he must sweat extravagantly, which means some dripping. It is easy to see why the workers wear as little clothing as possible. Wearing a long-sleeved work shirt and trousers would reduce EMAX by about 30% or 13 Kcal/hr. The resulting excess of heat load over EMAX would result in rise of body temperature and it can be estimated that the limit of tolerance would be reached in about an hour.

When, as in this case, the heat load is itself moderate, the attack of the control engineer should be aimed at increasing EMAX. In most such situations the management or the workers might find it expedient to bring in fans for spot "cooling." Note that since EMAX is 0.6 root function of air speed, tripling of air movement across the skin would result in doubling of EMAX. In this case an increase from 15 m/min to 45 m/min is easily achieved and it is predicted that such air speed will raise EMAX to 400 Kcal/hr. Sweat required would be reduced to about 0.35 liters/min and would be evaporated at nearly 100% efficiency; the skin will no longer be dripping wet. It is clear that this control measure has limitations. If air speed were already 45 m/min, tripling would produce a wind which could disrupt operations.

A more effective permanent approach would be to replace the small exhaust fan with exhaust hoods opening over the moisture source. Adequate make-up air would have to be provided.

If outside high humidity rather than a large inside source of hot water were creating inside conditions similar to those of this case, the obvious solution would be installation of mechanical air conditioning. This would be an expensive solution for Case I.

Case II. Selected to show how the wearing of clothing can be advantageous and the presence of high air speed a liability under very hot, dry conditions.

Assume Ta = 45°C (113°F), Tg = 48°C (118°F), v = 100 m (330 ft) per minute, and Pa is low, 10 mm Hg. We use the same M as in Case I.

Long-sleeved shirt and trousers are worn.

$$M + R + C = EREQ \quad EMAX$$
$$200 + 132 + 96 = 428 \quad 615 \text{ Kcal/hr}$$

Suppose the worker wore only shorts under these circumstances. R, C, and EMAX would be increased:

$$M + R + C = EREQ \quad EMAX$$
$$200 + 220 + 160 = 580 \quad 1020 \text{ Kcal/hr}$$

The total heat load is increased about 150 Kcal/hr. This means an increase in the requirement for sweating of about 0.26 liter per hour, making a total requirement of 1.0 liter per hour as compared with 0.74 liter/hr when wearing shirt and trousers.

Thus, under conditions where Tw and Ta are above 35°C and Pwa is low the wearing of full clothing can provide a thermal advantage; the extent of this advantage must be assessed. In examining the above model it will be apparent that there is an optimum amount of clothing in such situations. This is the amount which reduces EMAX to a value slightly in excess of EREQ. The long shirt and trousers are just about right for this purpose under the given conditions of forced inlet air.

With low Pa as in a semi-arid area, a more satisfactory solution probably could be reached through installation of an evaporative cooler. In Case II, inside temperature was usually 5°C hotter than outside, due to process heat and insulation on the roof of the shed. Assuming outside Ta does not exceed 40°C (104°F) and Pa is about 10 mm Hg, the temperature of the outside air drawn through a water spray washer in large volume could be reduced to approximately the prevailing out-of-door Twb, namely 22°C (72°F). Most of the wash water could be recycled. Pa of the conditioned air would be raised from 10 to 20 mm Hg. If temperature of the work space were reduced by this means to 30°C, a conservative estimate of the components of heat stress for clothed workers would be about

$$\begin{array}{c} M + R + C = EREQ\ \ EMAX \\ 200 + 100 - 200 = 100\ \ 400\ \text{Kcal/hr} \end{array}$$

Case III. Chosen to illustrate the dramatic reduction in heat load achievable by provision of appropriate shielding when radiation from a furnace is substantial.

Practical examples of the reduction in radiant heat load achievable by these means are provided by Lienhard, McClintock, and Hughes[67], by Haines and Hatch[68], and by others[64,69]. This case is chosen from the first of these references because the situation is real and physiological as well as environmental data are available. The task is that of skimming dross from molten bars of aluminum.

The worker stands at the task. Manipulation of a ladle involves moderate use of shoulder and arm muscles and requires an M of about 200 Kcal/hr. The environmental temperatures before the corrective action were reported as Tg = 71°C (161°F), Ta = 47.8°C (118°F), and Twb = 30.5°C (87°F). The air speed was 240 m/min (800 fpm) as a result of forced ventilation directed at the worker from an overhead duct. Note that the humidity was very high (Pa = 24 mm Hg) which is characteristic of the local climate. In terms of heat load and EMAX the situation was:

$$\begin{array}{c} M + R + C = EREQ\ \ EMAX \\ 200 + 830 + 210 = 1240\ \ 580\ \text{Kcal/hr} \end{array}$$

It is obvious from the deficiency of evaporation and the enormous load that the workers, despite full clothing and a face shield, were able to perform this task only for a few minutes at a time. Heat exhaustion was not uncommon (and might partly be attributable to the difficult hot conditions prevailing in the nearby rest area).

Engineers undertook control of this heat exposure by interposing finished aluminum sheeting between the heat source and the worker. Infrared reflecting glass at face level permitted seeing the task and space was left for access of the arms in using the ladle. As a result of these measures it was recorded that both Tg and Ta were reduced to 43°C (110°F). The same air speed was present as before and if we assume the same Pa we obtain:

M	+ R	+ C	=	EREQ	EMAX	
200	+ 53	+ 130	=	383	580	Kcal/hr

By this action to reduce R, the heat load was brought to a level that is reasonable for prolonged work, but did not completely eliminate the heat stress. The predicted requirement for sweating to maintain heat balance was reduced to about 0.7 liter/hr from the previously impossible-to-sustain level of 2.1 liters/hr. (The before and after average levels actually observed for two workers were not far from these predictions, namely 1.1 and 2.1 liters/hr. The same two subjects also showed a marked reduction in heart rate, as a result of the changes, from an average of 146 to 108 bears/min.)

The percent reduction of the radiant load can be taken as a measure of the effectiveness of the reflective shielding, and in this instance approximates 85%. Large errors in the stimate of R are possible at extremely high globe temperatures, but in this case it appears that the maximum relief that could be expected from shielding was achieved. Haines and Hatch reported smaller reductions in R of 51 to 74% from interposing a sheet of aluminum at eleven different work sites in a glass factory. Others have shown reduction of 90% or more under ideal conditions not likely to prevail on the plant floor.

While in Case III we have dealt with some aspects of control of R by shielding, the two other classical approaches of industrial hygiene engineering, namely, control at the source and control at the man, offer possibilities which must be considered.

Application of insulation on a furnace wall can reduce its surface temperature and thereby the level of R. A by-product of such treatment is a saving in fuel needed to maintain internal furnace temperatures. Application of a polished metallic surface to a furnace wall will also reduce R. However, a polished metallic surface will not maintain its low emissivity if it is allowed to become dirty. A layer of grease or oil one molecule thick can change the emissivity of a polished surface from 0.1 to 0.9. And the emissivity of aluminum or gold paints for infrared is not necessarily indicated by their sheen. If the particles are smaller than about one micron they emit almost like a black body. (The same is true for fabrics coated with very fine metallic particles.)

Equal or even more effective reduction of R is achievable with nonreflective barriers through which cool water is circulated.

The engineer is frequently baffled in shielding by the fact that access to the heat source is required for performance of the task. We have seen various solutions to this problem. One is a curtain of metal chains which can be parted as required and which otherwise reduces emission like a fireplace screen. Another is a mechanically activated door which is opened only during ejection or manipulation of the product. And finally, remotely operated tongs may be provided, taking advantage of the fact that radiant heating from an open portal is limited to line of sight and falls off as the reciprocal of the square of the distance from the source.

The fourth modification to be discussed is that of thermal conditions of the rest area. Brouha[66] states "it is undeniable that the possibility of rest in cool surroundings reduces considerably the total cost of work in the heat." There is no solid information on the optimum thermal conditions for such areas but there are laboratory data which support setting the temperature near 25°C (77°F). This feels chilly upon first entry from the heat, but adaptation is rapid.

The placement of these areas is of some importance. The farther they are from the workplace, the more likely that they will be used infrequently or that individual work periods will be lengthened in favor of prolonged rest periods.

Incidentally, the same principle applies for positioning of water fountains. When they are remote from the worker, substantial dehydration is more apt to occur. The proper temperature for drinks under hot conditions is often asked. There is no scientific answer, but most men will not willingly drink fluids that are close to body temperature. They welcome chilled water and recognize that frequent small drinks are better than large draughts.

The final modification to be discussed is clothing. Heat stress usually may be altered substantially through selective wearing of clothing. In the heat, as in the cold, the thermal function of clothing is to reduce heat transfer between the individual and his environment.[14] Clothing may reduce transfer by radiation, by convection, and by evaporation of sweat.

Whether clothing will represent an advantage depends not only on its design but on the characteristics of the particular thermal environment in which the work is being performed.

1. Conventional work clothing:

We first examine what is known about the effects of ordinary work clothing consisting of work shirt and trousers. These will be of flame retardant material if fire or sparks are in the working area. Other items normally will include cotton underwear, socks (which in hot weather are better if of medium to heavy weight), perhaps gloves, and perhaps a hard hat. The wearing of long underwear, woolen or cotton, represents a special case which is dealt with later.

The effect of such clothing in interfering with heat loss by R+C is substantial and can be illustrated. For a man doing moderately hard physical work (1200 Btu/hr) and wearing only shorts, comfort temperature would be about 70°F. In work clothing comfort temperature might well be 55°F. If the environmental temperature actually was 70°F, the cost of wearing clothing, in terms of heat stress, would be equivalent to an added sweat rate of at least one-half pint per hour.

Laboratory studies clearly indicate that ordinary work clothing will reduce radiant heat transfer by 30 to 40 percent.[70] Theory yields a similar reduction for transfer by convection. And recent studies demonstrate that this clothing will reduce the potential for evaporating sweat by about 40 percent.

There are two important implications of these findings. Only the first is common experience. In warm environments, below skin temperature, wearing of clothing decreases heat loss and comfort. This is particularly true when humidity is high or the air is static. This disadvantage may become an advantage when air temperature and/or radiant temperature exceeds skin temperature. Then clothing reduces heat gain to the body. For example, on a 95°F day the radiation from the sun under a clear sky can represent the equivalent of a 20°F increase in air temperature for the seminude body.[14] This load can be reduced to the equivalent of 8°F by conventional work clothing (to even less with near-white clothes). Heavier clothing would reduce R even more, but this advantage is nulified at the point such clothing interferes with evaporation of sweat. In arid climates adequate evaporation seldom is a problem, particularly with good air movement, but in an industrial plant with the high radiant heat from a furnace the limits on evaporation may preclude heavy clothing for prolonged tasks.

The implication of the above is that radiant heat which was tolerable for a worker wearing shirt and trousers would be excessive for a man in shorts. This has been demonstrated in the laboratory.[70] A mean radiant temperature of 205°F was used in simulation of a task involving four-minute exposures interspersed with two-minute relief periods. This was tolerable when clothes, but intolerable when nude. The radiant load became just tolerable when reduced in intensity by about 30 percent. As mentioned in the preceding section, the color of skin or of clothing is immaterial in these exposures; they are black to infrared heat.

The highest local skin temperatures readily tolerable under such conditions depends on the amount of body surface area affected. For large areas such as the back it is about 105°F; for smaller areas such as a hand it may be 110°F. As an average for the whole body of an individual at work for prolonged periods, 95°F is about the limit; with higher average skin temperatures, a rise in internal body temperature may be expected. Additional information on time-tolerance relationships appears.[71]

Long winter-weight underwear has been adopted by many workers who move in and out of very hot environments. This makes sense to the extent that the extra layer provides a substantial buffer against extremes of heat gain (and loss, which is a factor in open sheds in wintertime). In humid summer weather the practice is less justified, unless there is ready access to air conditioned areas for recovery, because the underwear interferes with evaporation of sweat from the skin. The ounce-by-ounce efficiency of evaporation of sweat from clothing is considerably less than from the skin, more sweat must be produced to maintain heat balance and little or no more can be evaporated.

It is obvious that ordinary work clothing itself moderates extremes of transient heat exposures, but this is to a lesser extent than when long underwear is worn.

2. Special Clothing:

This may take various forms. For example, the wearing of infra-red reflecting face shields may be indicated when radiant heat is high. In frequent handling of hot materials, it is good practice to provide several pairs of oversize insulative gloves, these having wide gauntlets for easy entry without using both hands.

For very hot exposures, as in relining furnaces, thick insulative clothing is appropriate. This acts as a heat "sponge." This sponge may be more effective if made of high density materials (asbestos in the recent past) because of the higher heat capacity, but insulation with minimum weight is best imparted by a thickness of trapped, still air. It is obvious that for relatively longer intervals of exposure, high density and highest feasible thickness should be sought. The protective value of such clothing is enhanced by aluminizing its surface and sometimes interlining foil between insulative layers.

3. Aluminized Reflecting Clothing:

When shielding against radiant heat loads cannot be accomplished by fixed barriers, aluminized clothing components may often be used to advantage. The aluminum is vacuum deposited on the surface of the fabric. Interposition of such coated fabrics between a 600° to 1100°F source and a black globe has resulted in reflection of 90% of incident energy.[60]

However, in a study using reflective clothing items while working in the 205°F radiant heat mentioned above, efficiency was found to be much less. Ordinary work clothing yielded 40 percent protection, an aluminized apron about 50 percent and a full aluminized suit about 60 percent. In intermittent work at high humidities the full suit proved a handicap because of its interference with evaporation of sweat. The use of full reflective clothing can sometimes be avoided. For example, fixed shielding to waist level may make possible use of only an aluminized jacket. Or a worker who faces the heat source may resort to a long metallic apron. When the coverage with reflective clothing is only partial, there is much more opportunity for evaporation of sweat.

It is obvious that an aluminum finish, as on the palmar surface of an insulative glove, will be of little use in handling materials.

4. Thermally Conditioned Clothing:

Numerous ideas have been incorporated in special clothing for maintaining comfort in extreme heat (or cold). Some systems supply appropriately cool air from a mechanical refrigerator to points under a jacket or coveralls. When air from a remote source is used, there are two problems. One is the gain of heat through the walls of the supply tubing. This problem has been solved in some cases by using porous tubing which will leak an appropriate amount of supply air to keep the walls suitably cool. The other problem is distribution of the air through the suit. With a simple, single orifice it is difficult to cool a sufficient area of skin and the area cooled may be too cold. Provision of several orifices, though better, will create bulk and restrict mobility.

In fact, the restriction of movement resulting from tethering the worker to a supply line will often contraindicate this type of system. When such a line is used, there should always be a simple quick disconnect for use in emergency.

The vortex tube source of cool air has been used successfully in some situations.[62] The device is carried on the belt. Air introduced tangentially at high velocity is forced into a vortex, which results in two separable streams of air, one cold which is distributed under the suit, the other hot which is discarded. Compressed air requirements to operate the vortex system are large.

Self-contained sources of conditioned air which can be backpacked have also been developed. One involves a liquid refrigerant which is sealed into a finned container. After being cooled in a deep freeze, the container is placed in the pack. A small battery-driven fan circulates air across the fins and into the suit. A single charging of this device may extend tolerance for relining furnace walls from several minutes to 30 or 60 minutes.

More sophisticated devices employ a closed system with liquid as the coolant and a fairly elaborate network of small tubes for distribution.

The nuisance factor must be considered for all such devices. Men will not go to the trouble of donning them unless they recognize more than a marginal advantage. On the other hand, with such devices, it has sometimes been possible to change hot tasks which required long rest pauses and multiple workers into single worker, continuous duty operations.