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RESEARCH INST OF ENVIRONMENTAL MEDICINE NATICK MA
W R SANTEE ET AL. OCT 87

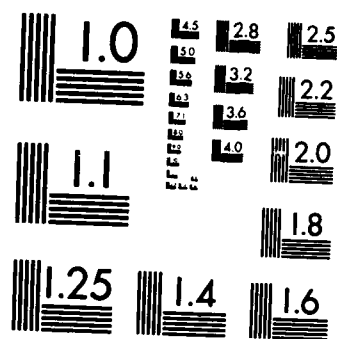
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This chapter concerns how the environment impacts on humans in terms of the environmental components of the net energy balance: radiation, conductance, convection and evaporation. The fundamental relationship between each of these environmental factors and the exchange of energy between man and his environment is presented in detail in the first section. The second section describes the instrumentation required to quantify the environmental parameters: temperature, wind, radiation and pressure. These determine the rates of energy exchange. Section three discusses methods for assessing the total impact of the separate environmental components as a single, net effect. <i>Keywords</i>			
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CHAPTER 1

CHARACTERISTICS OF THE THERMAL ENVIRONMENT

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THE THERMAL ENVIRONMENT...PATHWAYS OF HEAT EXCHANGE

Broadly defined, the environment consists of everything external to an organism's surface. Not all environmental parameters have a significant impact on physiology or human performance. In terms of the impact of the physical environment on an organism's physiology, the primary effect of the environment is that it determines the potential for heat exchange between a person and the environment. The actual heat exchange is determined by the interaction of the environment, certain physical characteristics of the organism such as posture and surface characteristics and internal physiology. The environmental parameters which determine the potential for heat exchange constitute the "thermal environment". Although the references to the thermal environment are common in the literature, a formal definition is rarely presented. Tracy, et al. (1986) defined the thermal environment as "a biophysical aggregate of air temperature, wind speed, relative humidity, and radiation".

The overall impact of the environment on an individual during the course of a single day is difficult to establish because people do not usually occupy a single, simple, homogeneous environment. In the course of a day, we move between environments; from room to room and indoors to outside. Even in a single outdoor location, environmental conditions change; daylight to night, calm to windy, warm to cold.

A triathlon event (62) is an example of how complex the interaction between individuals and their environment can become. An athlete in a triathlon typically starts with a morning swim. In cold water, heat loss is rapid, but the response is partially offset by the intense muscular activity. The participants emerge from the water, and begin the bicycle stage, perhaps along a winding coastal highway, alternating exposure to sun and shade, wind and calm as well as the air flow created by the speed of their

own motion. As the morning progresses, the sun rises higher in the sky, increasing both air temperatures and solar radiation. As the ground heats, wind movement, directed as up and down slope breezes and more general winds change in strength and direction. Along the coast, the air tends to be humid, limiting the cooling value of body sweat. At the end of the cycle ride, the participants begin a marathon, generally running on more level terrain under the afternoon sun as air temperatures reach their daily maximum. In the warmer air, away from the ocean moisture, sweat evaporates more readily, allowing more heat to be lost. For the slower participants, the sunlight wanes at sunset and they will continue their run into the night, either benefiting from the absence of direct sunlight and cooler air temperatures, or becoming chilled due to the combination of colder air and radiant heat loss.

From the preceding account, it should be apparent that, quantitatively, the environment involves a measurement of a number of variables. In the hypothetical triathlon, the participant's environment changed with time and place as the race progressed from morning to night and out of the ocean, along the coast and out across the flats. Our environment, therefore, has both a temporal aspect related to daily and annual cycles and a spatial aspect. Even a laboratory physiologist must take environmental variation into account if an attempt is made to select laboratory conditions which approximate a "representative" environment.

In order to characterize the environment, it is first necessary to understand the basic pathways of heat exchange between individuals and their environment. Once we have established how the environment impacts on an individual, then the question becomes which environmental parameters do we need to measure and what meteorological instruments can be used to collect the necessary data. In collecting any data, environmental or physiological, it is necessary to consider the cost and other limited resources, such as time or technical expertise relative to the utility of that information. In this chapter we will present a variety of methods.

Energy balance equation

The basis for measuring the effects of the environment on an organism is derived from the First Law of Thermodynamics used in the heat balance equation:

$$S = M - (\pm W_k) \pm E \pm R \pm C \pm K \quad [W \cdot m^{-2}] \quad (1)$$

Internal heat production is represented by metabolism (M). Heat exchange occurs by evaporation (E), conductance (K), convection (C) or radiation (R). The remaining energy is either work (W_k , where + is positive work representing energy leaving the system and - is negative or eccentric work) or heat storage (S).

The heat exchange pathways, evaporation, conductance, convection and radiation can be subdivided into two categories, mechanisms of dry or sensible heat exchange and insensible or wet heat exchange. The potential for dry heat exchange is determined primarily by the environment whereas evaporative heat exchange is strongly influenced by sweating rate, a physiological function, as well as the limits imposed by the external environment.

Sensible or dry heat exchange:

Dry heat exchange (or non-evaporative heat exchange) does not involve the evaporation of water from the body surface and can be determined directly as a function of the measurable (sensible) difference in temperatures between the organism and its environment. Dry heat exchange is particularly useful when the ability to sweat is inhibited, such as by individuals wearing impermeable clothing. When evaporative heat loss cannot occur, the potential for dry heat exchange represents the variability in the thermal environment.

Convection

Convection is heat exchange between a surface and a fluid, normally air or water. The rate of convective heat exchange is dependent on the density of the fluid, the temperature gradient between the surface, the area of exposure and fluid and the flow rate and turbulence of the the fluid. Equation 2 is an equation for convective heat exchange:

$$C = h_c (T_a - T_s) \text{ [W}\cdot\text{m}^{-2}] \quad (2)$$

The variables are the temperatures of the surface and the fluid ($T_s - T_a$ in K), and the convective heat transfer coefficient (h_c in $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$). Determination of h_c is not an easy step in calculating convective heat loss as it is a complex function of fluid density, flow and shape or posture. There are two type of convection, free and forced convection.

"Free" convection is primarily a function of fluid density and is important only in fluids that are still or moving at very low velocities or flow rates. Free convection results from density gradients forming in the fluid surrounding the subject due to the warming/cooling of fluids which are in close proximity to the body surface. Free convection creates a stable, static gradient of fluid surrounding the surface and in effect altering the rate of heat exchange between the surface and the environment.

"Forced" convection is a function of fluid velocity in addition to fluid properties and is important at higher wind speeds. Fluid movement disrupts the static layering responsible for free convection. The flow characteristics of the fluid are important because a smooth, turbulent free (laminar) flow creates a series of layers of fluid of increasing velocity above the surface. The higher the velocity of the fluid, the thinner the layers. The thickness and velocity present within these layers affect the rate of

heat transfer between the surface and the surrounding fluid. The faster that fluid flows over the surface, the less time there is for heat transfer to a given volume of fluid. As a consequence, the slower moving fluid layer which is closest to the surface is directly mixed with the temperature of the surface (14.17.47). Turbulence in the fluid flow disrupts the layers or lamination, bringing warmer/colder fluid into proximity to the surface. Turbulence can also be caused by surface texture or roughness and irregular surfaces (14.30.49).

The rate of heat exchange by convection is given by the heat transfer coefficient (h_c). To calculate h_c , a series of empirically derived dimensionless variables are used: the Nusselt number (Nu), the Grashof number (Gr), the Prandlt number (Pr), and the Reynolds number (Re). The Nusselt number is related to h_c by the equation:

$$h_c = Nu k_f / L \quad [W \cdot m^{-2} \cdot K^{-1}] \quad (3)$$

where L is the characteristic dimension or shape factor and k_f is the thermal conductivity of the fluid: for air (14.49) it is a function of air temperature ($^{\circ}C$):

$$k_a = 2.41 \cdot 10^{-2} + 7.8 \cdot 10^{-5} \cdot T \quad [W \cdot m^{-1} \cdot ^{\circ}C^{-1}] \quad (4)$$

The Grashof and Prandlt non-dimensional (N.D.) numbers are used to calculate the Nusselt number for free convection. In air (T_a 10-50 $^{\circ}C$ [55]), the Prandlt number is a constant (0.72). The Grashof number can be calculated according to the following equation:

$$Gr = a \cdot g \cdot L^3 (T_s - T_a) / \nu^2 \quad [N.D.] \quad (5)$$

The variables are the coefficient for the thermal expansion of air (α), the acceleration due to gravity (g) and the kinematic viscosity of air (ν). Temperatures may be expressed either $^{\circ}\text{C}$ or K in equation 4 provided both T_s and T_a agree in scale. The latter term can be calculated from T_a ($^{\circ}\text{C}$):

$$\nu = 1.33 \cdot 10^{-5} + 9.0 \cdot 10^{-8} \cdot T_a \quad [\text{m}^2 \cdot \text{s}^{-1}] \quad (6)$$

The equation for the Nusselt number for free convection is:

$$\text{Nu} = c \text{Gr}^a \text{Pr} \quad [\text{m} \cdot \text{s}^{-1}] \quad (7)$$

But, substituting a constant value (c') for $c\text{Pr}$ in air, the equation becomes:

$$\text{Nu} = c' \text{Gr}^a \quad [\text{N.D.}] \quad (8)$$

A value of 0.50 for c' was derived from Campbell (1977) for cylinders, spheres and flat surfaces.

For forced convection, the Nusselt number is calculated from the Prandlt and Reynolds numbers:

$$\text{Nu} = c \text{Pr}^a \text{Re}^b \quad [\text{N.D.}] \quad (9)$$

The constants, a, b and c , are dependent on shape factors. As noted, the Prandlt number can be treated so as in the case of free convection, the equation can be simplified by substituting a constant value for Pr^a :

$$Nu = c'' Re^b \quad [N.D.] \quad (10)$$

Nishi et al. (1970) cites "compromise" values of 0.33 and 0.55 for c'' and b , respectively, for a cylinder.

The Reynolds number can be calculated from the equation:

$$Re = vL/\nu \quad [N.D.] \quad (11)$$

where v is the wind speed. The characteristic dimension (L) is determined by the shape and actual dimensions of the subject. For a cylinder, the usual model for a standing human, L is the diameter.

The original relationships were derived in wind tunnels (laminar flow). In natural environments, however, air flow near the surface often is turbulent. Also, the geometry of human and animal forms is complex compared to the models used to derive the original relationships. Mitchell (1976) presents alternative equations for calculating the characteristic dimension and Nusselt number for small animals and humans in outdoor environments.

Nishi et al. (1970) proposed the use of an adjusted heat transfer coefficient, $\bar{h}_c$, to adjust for the activity of the subject. The sublimation rate of naphthalene spheres fixed just above the body surface were used to estimate the convective heat transfer rate. For a subject resting on a stationary cycle they calculated h_c at 3.1, but for a subject cycling at 60 rpm, $\bar{h}_c$ was 6.0 (wind speed $\sim 0.15 \text{ m}\cdot\text{s}^{-1}$).

Conduction

Conduction (K) is heat exchange between two solid surfaces in direct contact. The rate of conductance is dependent on the temperature difference between the two surfaces, the thermal conductivity of the surface materials (k_c). The distance through which the heat is conducted is l.

$$K = (k_c/l) (T_a - T_s) \quad [W \cdot m^{-2}] \quad (12)$$

For a standing human with adequately insulated feet, conductance is of very limited importance in calculating the total heat exchange. Standing bare-footed on ice or holding a cold-soak wrench will cause significant local heat loss or even cold injury, but generally we avoid long-term or extreme exposure of the extremities to conductive heat loss. Lying uninsulated on ground that is significantly hotter or colder than the body will result in significant heat exchange. The daily activity of greatest continuous duration is usually sleep. Participants in winter camping are well aware of the importance of insulation from the ground. More than one winter camper has awakened in the morning to discover they are lying in a depression created by body heat melting the packed snow beneath the tent floor.

Radiation

The radiation term in the energy balance equation is a complex variable representing the net effective radiation balance of an individual. Six radiation terms determine the radiation exchange between an object and its environment. There are five incoming radiation variables; three solar terms and two thermal or "heat" terms. The sixth term is radiation emitted or radiated by the subject out into the environment.

In most biometeorological studies, solar radiation refers to radiation in the 400 to 750 nm wavelengths emitted and received directly from the sun. Thermal radiation is in the near infra-red range from 800 to $8.0 \cdot 10^4$ nm. Solar radiation may be received directly from the sun as "direct" solar radiation, scattered, sky or "diffuse" solar radiation, and solar radiation "reflected" from the ground. Incoming thermal radiation consists of "sky" and "ground" thermal radiation. In SI units, all radiation intensities are expressed in $\text{W} \cdot \text{m}^{-2}$ and the radiation terms for the net radiation equation are calculated by multiplying the radiation intensity by the correct surface area. In the case of direct solar radiation, the calculation of the correct surface area presents a rather interesting problem.

[INSERT FIGURE 1 HERE]

The amount of direct solar radiation received depends on the intensity of the solar radiation and the posture and position of the subject relative to the direct parallel beams of solar radiation. Although direct solar radiation falls across the entire body surface area exposed to direct sunlight, the amount of direct solar radiation received is equal to the full intensity of the sunlight measured (or corrected) normal to the solar beam times the cross-section area of an object normal to the solar rays (A_p). This relationship is known as Lambert's cosine law (2.14.65). To clarify further, assume that a subject is represented by an upright cylinder.

If the sun's rays came straight down from overhead, the full intensity of the radiation would fall only on the top of the cylinder, an area equal to the circular top of the cylinder (38.66.69). Now assume that the sun's rays are coming directly from the horizon. Although the radiation is spread over the entire half of the cylinder, the total amount of solar radiation received is equal to the full strength of the direct rays

times the area of a rectangle with height equal to the height of the cylinder and width equal to the diameter of the cylinder. If the source of the solar beam moves from directly overhead to the horizon, the cross-sectional area of the cylinder normal to the solar rays (A_p) goes from a minimum circular area to a maximum rectangular area. In between, A_p is an oval, with a short axis equal to the diameter of the cylinder and the longer axis lengthening from the diameter to the height of the cylinder as the solar source changes from vertical to horizontal relative to the subject cylinder. The longer axis height (ht') can be calculated by determining the angle between the sun and the horizon (solar elevation θ_s) or deviation from vertical (the zenith angle θ_z) and multiplying by the cosine or sine respectively of the solar or zenith angle. Underwood et al. (1966) presents the following equation to calculate the cross-sectional or projected area (A_p) of a cylinder normal to the beam:

$$A_p = \pi \cdot r^2 \cdot \cos \theta_z + 2 \cdot r \cdot ht' \cdot \sin \theta_z \quad [m^2] \quad (13)$$

Calculation of the zenith angle from the time of day, site coordinates, daily solar declination and other information is described in appendix A of this chapter.

[INSERT FIGURE 2 HERE]

Human shapes are a little more complex than simple cylinders and a more pragmatic method for determining the correct cross-section angle for a given zenith angle has been utilized. The basic method is to use a device that holds a camera at an equal distance from the subject while traversing an arc simulating the actual solar angle. A reference sphere which always presents the same cross-sectional area to the camera may also be photographed (10). By using a planimeter, or simply cutting out

and weighing the prints, the surface area of the model normal to light entering the camera aperture can be determined. The clothed surface area of an individual can be calculated from the DuBois nomogram for nude surface area (A_D) and proportional values for each zenith angle can be determined (20).

$$A_D = 0.202 \text{ wt}^{0.425} \text{ ht}^{0.725} \quad [\text{m}^2] \quad (14)$$

Height (ht) is in m and weight is in kg. Those derived proportional values can be applied to the calculated surface area of any subject in the same posture and orientation relative to the sun.

Underwood et al. (1966) presents a more specific equation for determining A_p , the body area normal to the direct solar beam for an "average man":

$$A_p = 0.043 \sin \theta_s + 2.997 \cos \theta_s \sqrt{(0.02133 \cos^2 \phi + 0.0091 \sin^2 \phi)} \quad [\text{m}^2] \quad (15)$$

The solar elevation angle (θ_s) is the complimentary angle of θ_z . The azimuth angle (ϕ) is the orientation of the object relative to the sun. An individual facing directly towards or away from the sun has a ϕ of 0° and sideways (shoulder towards the sun) has a ϕ of 90° .

Determining the amount of incoming diffuse solar, reflected solar, ground thermal and sky thermal radiation is not as difficult. All these radiation sources are treated as isotropic, that is the radiation is emitted in all directions from an area source. For diffuse or scattered solar radiation, the solar radiation strikes all surface areas exposed to the sky with equal intensity over their entire area. For a subject cylinder, the diffuse radiation would fall with equal intensity on all of the top and side surfaces of the cylinder. Only the bottom area of the cylinder is sheltered from the diffuse

radiation. Non-solar thermal radiation from the sky utilizes the same surfaces as diffuse solar radiation. Solar and thermal radiation reflected or emitted from the ground strikes only the sides of the cylinder in our model. For a different shaped model, such as sphere, some of the radiation will fall above the equator of the model.

One other physical characteristic of the subject determines how much incoming radiation is received. All light striking the surface of an object is reflected, absorbed or transmitted. The solar load of an object is a product of the total solar irradiance (direct, diffuse and ground reflected) and absorptivity (α); the percentage of light absorbed by the object. For human subjects, radiation that is transmitted through the clothing surface is generally absorbed by the body tissues, so "absorptivity" is calculated by subtracting the proportion of light reflected from 1.

All surfaces with a temperature above absolute zero emit thermal radiation. The Stefan-Boltzmann law defines the emission (R_b) of a perfect blackbody as:

$$R_b = \sigma T_s^4 \quad [W \cdot m^{-2}] \quad (16)$$

Sigma (σ) is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} W \cdot m^{-2} \cdot K^{-4}$) and T_s is the absolute surface temperature of the blackbody in degrees Kelvin ($^{\circ}K$). Emissivity (ϵ) is a proportional term for the amount of thermal radiation, relative to a black-body, that a surface emits. By multiplying the calculated R_b of a perfect blackbody by the emissivity (ϵ), the radiation emitted by an object can be determined. A perfect blackbody is defined as a body that completely absorbs all radiation. According to Kirchoff's law, emissivity equals absorptivity, at a given wave length. Except for polished or highly reflective surfaces, the emissivity of most surfaces is 0.95 or greater in the IR or thermal wave-lengths (2.14).

The term for R_b in equation 16 is expressed as a flux: a rate of energy flow per unit area ($W \cdot m^{-2}$). Radiative heat exchange does not occur evenly on the body surface. For that reason, some biologists prefer to express heat exchange as the total rate per animal (W). Human physiologists prefer to express heat exchange terms as fluxes. For a human physiologist, it would be desirable to express the total radiation exchanged with the environment as a single term related to surface area. Mean radiant temperature (T_r) is defined as "the temperature of a uniform black enclosure in which man would exchange the same radiant heat as in his nonuniform environment" (31). Expressing the radiation term as a pseudo-temperature allows the investigator to use radiation in calculations in units of temperature rather than radiation ($W \cdot m^{-2}$). When expressed as T_r , the net radiation received is treated as if it was equally distributed on all exposed surfaces.

$$R_{net} = h_r (T_r - T_s) \quad [W \cdot m^{-2}] \quad (17)$$

Mean radiant temperature can be calculated directly from the temperature of a Vernon globe thermometer (70). That method is presented and discussed in the instrument section of this chapter. The radiant heat transfer coefficient (h_r) can be calculated as a linear relation (5.31):

$$h_r = 4 A_r \sigma [(T_r + T_a)/2]^3 \quad [W \cdot m^{-2} \cdot K^{-1}] \quad (18)$$

Gagge (1970) uses the term Effective Radiant Flux (ERF) for the net radiation exchanged between a man-shaped object with a surface temperature equal to air temperature and the environment.

$$ERF = \sigma \alpha A_r/A_D (T_r^4 - T_a^4) \quad [W \cdot m^{-2}] \quad (19)$$

where A_r is the effective radiating surface area of the body. For all practical purposes, A_r is equal to the exposed surface area of the subject or object. In the case of the cylinder model, only the cylinder base in direct contact with the surface would not be considered an emitting surface. For a standing human, this would be an area equal to the foot surface area and the areas "shaded" by other body parts; such as the inner surfaces of legs, arms and fingers.

There are several approaches to calculating the radiant heat load. T_r obscures the importance of solar exposure by expressing radiation as a uniformly distributed flux. Another approach is to calculate the total (whole animal) radiative heat exchange rate from the six separate thermal and solar radiation terms. The latter approach is desirable if the various radiation terms can be quantified because it allows the contribution of different radiation sources to be considered independently. The incoming solar load (Q_s) can be calculated by summing the three solar parameters:

$$Q_s = A_p \alpha_l D + A_1 \alpha_l d + A_2 \alpha_l r \quad [W] \quad (20)$$

A_1 and A_2 are the surface areas exposed to radiation from the sky and ground, respectively. Both areas may be estimated as equal to or less than the effective radiating surface area (A_r) (1.11). Fanger (1970) gives the ratio of A_r/A_D as 0.73 for a standing man and 0.70 for a sitting man. Berglund et al. (1987) use $0.7 \cdot A_D$ for A_1 and $A_r/2$ for A_2 for a cycling subject. The incoming thermal radiation (Q_{ti}) can be calculated by summing the incoming ground and sky thermal loads:

$$Q_{ti} = A_1 \epsilon R_{sky} + A_2 \epsilon R_{gr} \quad [W] \quad (21)$$

The net radiation balance is calculated by simply the incoming radiation and subtracting the outgoing or emitted radiation term. Emitted radiation is calculated by entering the surface temperature, emissivity and effective radiating surface area (A_r) of the subject into the Stefan-Boltzmann equation:

$$Q_e = A_r \cdot \sigma \cdot \epsilon \cdot T_s^4 \quad [W] \quad (22)$$

The net radiation absorbed (Q_{abs}) is the sum of the absorbed solar and thermal radiation:

$$Q_{abs} = Q_s + Q_{ti} \quad [W] \quad (23)$$

The ERF can be calculated from the total (whole animal) exchange rate (Q_t) by dividing by A_r .

$$Q_t = Q_{abs} - Q_e \quad [W] \quad (24)$$

$$ERF = Q_t / A_r \quad [W \cdot m^{-2}] \quad (25)$$

Insensible or evaporative heat exchange

Insensible heat exchange is the result of the evaporation or condensation of water on the body surface. Insensible, "wet" or evaporative heat exchange is normally a one-way heat flow from an individual body surface to the environment. The basic principle involved is that the phase change from liquid to water vapor requiring 2.45 J/kg, the latent heat of vaporization for water (14.54). Because the heat of vaporization is "absorbed" without changing the measured temperature of the water, the heat exchange is considered "insensible". A third term for insensible or evaporative

heat exchange is "moist" heat exchange, because unlike convective, conductive or radiative heat exchange, water is required. The physical determinant of the evaporative potential is the water concentration gradient between the body surface and the environment. The physiological limits are the sweating rate and the level of individual hydration.

The basic equation for determining evaporative heat exchange (E) is:

$$E = \omega h_m (P_{s,sk} - P_w) \quad [W \cdot m^{-2} \cdot Torr^{-1}] \quad (26)$$

The two water vapor pressures are saturated pressure at skin temperature ($P_{s,sk}$) and saturated vapor pressure at the ambient dewpoint temperature (P_w). The difference between the two water vapor pressures is used by physiologists as a convenient analog to the actual water concentration gradient. ω is the wetted skin surface area fraction (24,31,39) and h_m is the mass transfer coefficient.

A common simplification is to use the Lewis number (L_R), 2.2 K/Torr, to relate the mass heat transfer coefficient to the convective heat transfer coefficient (60). The Lewis number (L_e) defines the relationship between thermal diffusivity and the diffusion coefficient for water vapor in air (57,60). The Lewis relationship (60) relates h_m to h_c by the equation:

$$h_m = 2.2 \cdot h_c \quad [W \cdot m^{-2} \cdot Torr^{-1}] \quad (27)$$

Relatively little attention is focused on air moisture below 0° C. Intuitively we recognize that colder air has very little moisture capacity and will be quickly saturated by a very low level of absolute moisture. However, if the temperature of very cold air is raised, the moisture or water capacity of the air can be increased significantly. If

for example saturated arctic air is inhaled, the air is rapidly warmed as it travels through the nasal and oral cavities into contact with the moist lung tissue. As the cold saturated air is warmed it essentially becomes very "dry" in terms of moisture capacity. An analogous situation arises if air is warmed as it comes in contact with the body surface. As a consequence, despite the saturated or near saturated state of cold air, dehydration is a common problem during activities under arctic conditions.

Another aspect of the effect of temperature on the water carrying capacity of air is that as warm air moves out from the skin through clothing in extreme cold, it is cooled and water condenses in the clothing; reducing the insulation afforded by the clothing. Sweat can also be absorbed directly from the skin into the clothing. By adjusting the insulation to prevent heat building and sweating, and by ventilating the clothing to pass moist air directly into the outside environment instead of through the clothing, the loss of insulation due to moisture can be avoided. This will be considered in another chapter.

Heat storage

Heat storage (S) is not an "environmental stress" term in the heat balance equation. What the storage term actually represents is whether an individual is able to maintain a thermal equilibrium with the environment. It is the net result of the interaction of environmental conditions, certain physical parameters such as clothing insulation or absorptivity, and physiology, especially hydration level. If the individual is not in equilibrium, the sign of the storage term will indicate whether there is a net loss to the environment (negative) or heat gain (positive). A positive flow occurs when an individual is unable to transfer excess body heat to the environment. The basic principle that relates body temperature to heat storage parallels insensible loss of heat via the latent heat of vaporization. The accumulation or loss of sufficient heat

(the specific heat (c_p) of body tissue is about 3.5 kJ/(kg·K) (7.16.52) will result in a net change in body temperature. A net negative heat flow will result in hypothermia and a positive flow in hyperthermia.

What is important to remember about the heat storage term is that as body temperature (T_b) changes, the thermal gradient between an individual and the environment also changes and as a result, net heat exchange is altered in direct relation to the new gradient. As body temperatures change in response to storage in a stable environment, the storage term tends towards zero or equilibrium. The question is whether equilibrium will be reached before body core temperatures reach a critical tolerance level.

Other environmental factors

Altitude

The primary effects of the reduced pressure due to increasing elevation are physiological. The most important physiological parameter is the reduction in oxygen concentration with increasing altitude. In terms of the thermal environment, higher altitudes receive more solar radiation because the air mass that the incoming radiation travels through before reaching the earth's surface is reduced. Reflected radiation levels may also be increased because of the high albedo of rock and ice or snow (14.64). As air density is reduced, this results in a reduction in the rate of convective heat transfer. The convective heat transfer coefficient is a power function of the barometric pressure associated with higher elevations (28.56):

$$h_c' = h_c (P_b/760)^{0.55} \quad [W \cdot m^{-2} \cdot K^{-1}] \quad (29)$$

where, P_b is the barometric pressure in Torr (760 Torr = 1 atmosphere; 1 atm = 1.01325×10^5 Pascals, Pa). An increase in evaporative heat transfer can also be related to the change in the thermal diffusivity (D). The mass transfer coefficient, h_m , can also be adjusted for the effects of pressure (23,49):

$$h'_m = h_m (760/P_b)^{0.45} \quad [W \cdot m^{-2} \cdot Torr^{-1}] \quad (30)$$

The most interesting aspect of altitude is that the Lewis relationship between convective and evaporative heat exchange becomes uncoupled as pressure is significantly reduced (Gonzalez, unpublished).

Precipitation

Relatively little research has been done on the effects of precipitation, especially rainfall, on heat exchange. This may be due to the fact that the normal response to significant rainfall is to retreat to shelter or put on protective clothing. Rain has several effects. First, rain water is often colder than air temperature. Second, the thermal conductivity of water is greater than air. Third, the insulation provided by clothing is reduced by wetting (9). Marathon runners may actually appreciate a light rain because the increased heat loss on a cool day prevents heat storage.

Being soaked in a rain is equivalent to completely saturating one's skin surface with sweat; but while it is raining, the air is completely moisture saturated so no evaporation should occur with no forced convection if the air is close to skin temperature. If the air temperature is colder than skin, air entering the clothing can be warmed and the moisture capacity thereby increased, allowing some evaporation from the skin. As the air is re-cooled, the water capacity is again reduced and condensation will occur. If the air is rapidly removed from the clothing before it is cooled to air temperature, recondensation will not occur inside the clothing.

Air pollution

Conventional weather forecasting rather than micrometeorology is the best predictor of the concentration of air pollution. The site, concentration and toxicity of air pollutants is determined by the location of the site relative to local and regional pollution sources, the direction and speed of upper air movements, terrain features, air temperature and solar radiation, pollutant chemistry, precipitation and particle or aerosol size. The impact of a concentrated pollutant plume on an elevated terrain feature may result in very high local pollution levels under certain meteorological conditions. Different chemical pollutants mix and react in the atmosphere, dependent in part on the presence of solar radiation, air temperature and humidity. Air temperature and particle size also affect the buoyancy of some air-borne pollutants. Precipitation may scavenge or scrub out pollutants, rendering the expression "pure as the driven snow" a quaint anachorism in many places.

Underwater diving environment

Divers encounter a relatively simplified thermal environment. The two primary environmental parameters are water temperature and pressure. Water temperature is frequently stratified, but relatively stable compared to the fluctuations in air temperature. Unless a current is present, most heat exchange is by free convection. Because of the higher thermal conductivity of water, a relatively small difference in temperature between the body surface and the surrounding water will result in very rapid heat exchange. An ambient temperature that would not be life threatening in air can rapidly result in hypothermia and death in water. Pressure is directly related to water depth so an accurate depth gauge should suffice to predict pressure. As in the case of altitude, the primary consequences of higher pressure are physiological rather than thermal once corrections for increased fluid density are made. The physiology of diving in greater detail in a later chapter in this volume.

ENVIRONMENTAL DETERMINANTS OF HEAT EXCHANGE POTENTIAL AND INSTRUMENTS FOR MEASUREMENT

The pathways for heat exchange are evaporation, convection, conductance, and radiation, but the primary meteorological parameters that we measure to calculate or estimate the potential effects of the environment are temperature, wind speed, radiation, and humidity. At any given time, we occupy only a single point in our total potential environment. The term "nannoclimate" (67) is used to indicate the meteorological conditions that immediately impact on an organism in a given time and place; basically an instantaneous climate. The "microclimate" of a species is the aggregate of nannoclimates occupied by a species in a given environment. Among human physiologists the term "microclimate" refers to conditions between the skin surface and the clothing of a subject. Consequently, it would be more appropriate to refer to the site "micrometeorology" rather than the microclimate when referring to human physiology.

The roadblock to characterizing the environment is generally insufficient knowledge regarding which instruments to use. In an academic research setting, consultation with meteorology faculty is recommended. Bakken (1987) offers a list of sources for portable, remote instrumentation.

Temperature

Technically temperature is the "mean kinetic energy of the molecules of a substance," or an equivalent definition. The "zeroth law" of thermodynamics, however, focuses on the functional consequence of temperature differences (63). The zeroth law states that "if two objects are brought into contact through a diathermal wall, and the objects are the same temperature, no net heat flow will occur." Temperature is, therefore, a measurement of the potential for heat exchange between two objects or

substances. Measurement of air and ground temperature are, therefore, important environmental parameters which determine the potential for heat exchange via convection and conduction between an individual and their environment.

Location of measurements

In common with several other meteorological parameters, temperature demonstrates a vertical profile or gradient in many environments. During the later daylight hours of the summer, the ground is heated by solar radiation and warmer than the air above. The presence of snow or ice would reduce the effects of solar radiation on air temperatures near the ground. In the desert regions, the difference between ground and air temperatures can be considerable, with observed air temperatures at 2 m of 43° C and ground temperatures of 68° C (v. Palm Springs, CA [59]). A standing individual may experience a considerable temperature profile in the desert standing on a hot surface and experiencing a vertical air temperature profile from his feet to his head. For example, in deep desert canyons in southern Utah, the difference in temperature between boulders in and out of direct sunlight may be used to provide natural cooling for hikers that overheated in the late morning as they hiked along the canyon bottom in full sunlight. By lying down on rock still cold from the previous night, heat is conducted from their bodies into the rock surface, effectively dumping their excess heat. A certain amount of caution is necessary when this method of cooling is employed because rattlesnakes and other animals also utilize the cooler microenvironment of the shaded rocks. The position where temperature is measured is determined according to the basic criteria given by Platt and Griffith (1966), the site most representative of the conditions experienced by the subject. Typically, if a single temperature is taken it is at approximately head level for a standing man, between 1.7 and 2 m. The Wet Bulb Globe Temperature measurements are taken at 4 ft (1.2 m). Ideally, of course,

multiple temperatures, including ground and a uniform series of air temperatures should be measured. Santee (1985) utilized a series of measurements including 10 cm below surface, ground, 0.5, 1.0, 1.5, 2.0 and 3.0 m. The first value is not of interest to most investigators and the 3 m value is primarily used in calculating a temperature profile.

[INSERT FIGURE 3 HERE]

"Thermometers"

A thermometer is essentially any "instrument" that is used to measure temperature. A thermometer works by relating a change in an intrinsic property of the sensor element to the mean kinetic energy of the substance being measured. For practical measurements within the human tolerance range there are directly read liquid and metal thermometers and electronic analog thermometers which are frequently automatically recorded.

There are three basic types of electronic "thermometers": thermocouples, thermistors and thermopiles (5.57). When incorporated with the appropriate electronics they are generally faster and more accurate than directly read thermometers. Electronic thermometers are incorporated into the majority of automated temperature collection systems. Their cost and the bulk/weight of the necessary electronics are the negative aspects of these instruments.

Wind

Measurement sites

In natural environments, air movement like temperature, frequently varies along a vertical profile (30). Air movement is classified as laminar or turbulent. Laminar flow

is linear in parallel currents whereas turbulent flow has eddies or other cross currents which are difficult to measure and enhance convective heat transfer by disrupting the boundary layer and thermal gradient characteristic of laminar flow and increasing the surface area. Near the ground, friction or drag at the ground-air interface slows the wind speed and creates turbulence. Uneven surface features or vegetation can enhance the turbulence at ground level. Because of the vertical distribution of wind speeds it is extremely desirable to use multiple measurement points along a vertical profile. With two known points, wind speeds along a vertical profile can be calculated with reasonable accuracy (14,57), but as in the case with temperature a direct measurement is more desirable than a calculated value. A second consideration regards fetch, the unobstructed distance the wind travels before reaching the subject or measurement point. Building, vegetation and other obstacles create complex air movements which make the analysis of air flow much more difficult. The general rule for a wind speed measurement sites is that the fetch, should be ten times the height of the nearest obstruction (57). For example, if a shrub is 2 m high, the anemometer should be 20 m from the shrub. Anemometers are often not ideally sited according to that criteria, but investigators should be especially concerned about buildings, walls and vegetation that create abrupt microscale variations in wind speed.

[INSERT FIGURE 4 HERE]

Hand-held instruments

The simplest method for approximating the wind speed is the "Beaufort scale", based on the observable effects of wind in the outdoor environment. Such observations are clearly not too precise, but careful observation may be no worse than a single measurement made with a hand-held instrument at a poorly selected or

uncharacteristic site. The presence of the observer operating a hand-held anemometer or wind gauge creates an obstruction that is undesirable and generally hand-held observation are frequently assigned a status just slightly more desirable than a guess. Hand held instruments may be mechanical or electronic. An example of a simple hand held wind gauge is based on the same principle as chimneys, the Bernoulli effect. As wind blows across the mouth of a narrow tube, pressure within the tube is reduced and light-weight objects are drawn upward by a combination of higher pressure below and lower pressure above. In this simple gauge, a small ball inside the tube is drawn up the tube and its position relative to a scale on the side of the tube indicates the wind speed. Proper orientation of the tube and the observer is necessary. The device is very inexpensive and adequate for gross wind measurements. The U.S. Forest Service includes this type of wind gauge in its "fire kit", a simple belt mounted packet of meteorological instruments used to measure meteorological parameters at a fire site.

Mechanical anemometers

More complex mechanical anemometers consist of a propeller or set of cup that are rotated by the force of the wind. The two disadvantages of these devices are the inertia due to the mass of the cups or propeller and frictional resistance of the bearings which limits the measurement of low wind speeds and the fact that all measurements are for air movement in a single plane. The threshold of an accurate cup anemometer is 0.2 to $0.3 \text{ m}\cdot\text{s}^{-1}$ due to the inertia of the cups that must be overcome before the instrument will rotate, creating a reading.

Electrical anemometers

Mechanical anemometers usually operate with some type of electronic pulse counter that "counts" the number of rotations. In the context of this chapter, an

"electronic anemometer" is an instrument that operates directly on the principle of convective heat exchange. In principle, such devices are quite simple. In a "hot wire anemometer", a thin wire is heated and maintained through electronic circuitry at a high, constant temperature through use of a wheatstone bridge. The power required to maintain the constant temperature of the wire is directly proportional to the convective heat exchange between the wire and the surrounding air and the "cooling power" of the air flow can be calculated from the power required and the air temperature. An electronic anemometer, therefore, actually measures convection rather than linear wind speed, which is actually the rationale for measuring wind speed, to calculate the potential for convective heat exchange.

In addition to hot wire anemometers, spherical or globe heated anemometers which operate on the same principle also exist. The advantage of the latter is that orientation relative to the air stream is not as important whereas a hot wire anemometer must be carefully positioned relative to the air flow. In general, heated electronic anemometers are indoor laboratory instruments that are accurate, expensive and rather delicate. The potential to measure low wind speeds, turbulent as well as laminar air flow and accuracy are very attractive features of heated electronic anemometers but sensitive electronic anemometers for outdoor use are normally custom-built by knowledgeable individuals and require careful calibration.

In actual field use, the less complex, more rugged and less expensive cup anemometers are more practical than electronic anemometers. The inertia factor can be compensated by adding a small constant "correction value", usually close to the threshold value, to the instrument reading and ignoring the free convective heat exchange.

Radiation

For many physiological studies, the investigator may be satisfied by deriving a value for the mean radiant temperature (T_r) from a black globe thermometer (discussed in the section on combination instruments) as a descriptor of the radiation conditions during the study. For outdoor studies during daylight hours, unless conditions are uniformly clear or heavily overcast, more precise measurement of solar radiation is desirable. During indoor studies where radiation is unevenly distributed, such as an office with a heat radiator or a large window, direct measurement of radiation is also important (47).

UV radiation

In term of heat exchange, the most important wave lengths for radiation are in the visible (400 to 750 nm) and the "thermal" or near infra-red (800 to 8.0×10^4 nm) wave lengths. Short wave radiation is biologically disruptive because of the higher energy levels (Planck's law), but due to the screening effect of atmospheric ozone, the actual radiation levels (2% of total) attributed to UV radiation on the earth's surface has been considered negligible. As a consequence, the fact that the pyranometers and radiometers commonly used to measure radiation do not measure UV wave lengths was not considered a significant deficiency. Concern about the possible increase in ultra-violet (UV) radiation resurfaced when studies of the ozone levels over Antarctica revealed the appearance of a "hole" (15,43). Because of the biological importance of UV radiation and the possible increase in UV radiation reaching the earth's surface, investigators may soon have to consider the consequences of not monitoring UV radiation.

Direct, diffuse sky and reflected solar radiation

The optimum instrumentation for measuring the direct, diffuse and reflected components of solar radiation would be to use three instruments to measure each parameter individually. A more efficient use of instrumentation is to measure global and diffuse radiation. Global radiation is the combined value for diffuse and direct solar radiation impacting a horizontal surface.

[INSERT FIGURE 5 HERE]

Diffuse radiation can be measured through use of a shade ring or shadowband. The shadowband consists of a platform to hold a pyranometer and an adjustable band of metal that is adjusted to block direct solar radiation from striking the pyranometer. The shaded pyranometer, with a small correction due to the width of the shadowband, directly measures diffuse solar radiation. When the diffuse radiation value is subtracted from the global radiation value, the remainder is the direct solar component impacting a horizontal surface. By dividing that value by the cosine of the zenith angle (Lambert's law), the full intensity of direct solar radiation can be calculated. Reflected solar radiation can be estimated by multiplying the global radiation value by the albedo (reflectivity) of the ground surface which can be found in most meteorology texts for common surface types. Reflected solar radiation can also be measured directly with an inverted pyranometer (4.57).

Radiometers

Radiometers are instruments that measure radiation. The most common instruments in current use are net radiometers based on electric thermopiles protected by a transparent dome of plastic or glass. Glass domes screen out long-wave radiation

($>3 \times 10^3$ nm). Net radiometers use clear plastic screens which allow the penetration of light from 300 to 6.0×10^4 nm. Net radiometers measure both incoming ground and sky radiation and electronically "subtract" the difference to determine the net value (4,23,48). In calculating the radiation balance of an object, the sky and ground radiation values, not the net product, are the desired values. The usual solution to this problem is to use a pair of net radiometers. One is modified, with either a special dome or cup, painted white on the outside and black on the inside and fitted with a thermocouple temperature sensor (40,41). The modification is a simple project consisting of locating a properly sized metal can or cup, painting the radiation guard, attaching a thermocouple to the inside and taping around the bottom hemisphere. The radiometer is furnished with a dome that may be modified and directly installed in place of the regular dome. Conversion cups are also commercially available.

The radiometer fitted with the radiation guard measures the total incoming sky radiation: direct and diffuse solar radiation plus sky thermal. The radiation term recorded from the modified net radiometer is the product of the incoming sky radiation minus the radiation received from the black inside surface of the radiation shield. By entering the temperature of the shield and assuming an emissivity of 0.95 for the inside surface, the Stefan-Boltzmann equation can be used to calculate the radiation received as total incoming ground radiation. By adding that calculated value to the radiometer reading, a term for the total sky radiation can be obtained. By subtracting the global radiation which is the combined incoming solar term, the actual incoming thermal sky radiation can be determined. By subtracting the net radiation term from the unmodified radiometer from the uncorrected total sky radiation term, a total ground radiation term can be calculated. The thermal ground radiation can be determined by subtracting the reflected solar radiation term from the total ground radiation term.

Pyranometers

Pyranometers are radiometers that measure short-wave or visible radiation (4.48,57). As noted above, the glass globes or domes filter out thermal and UV radiation. Colored filters may be ordered which measure only a narrow band of the visible spectrum. If fitted with a quartz dome, pyranometers can measure UV radiation. The better quality pyranometers use a thermopile as the radiation sensor, but less expensive silicon cell detectors should be adequate for most field studies.

Direct solar radiation can be measured with a pyrliometer which tracks the sun's movement across the sky, measuring solar radiation normal to the sun's rays. The expense of a pyrliometer would not usually be justified for normal field work. The use of a shadowband to measure diffuse radiation and indirectly direct solar radiation should provide adequate data.

Pyranometers are mounted on level stands above the ground. For measuring global and diffuse radiation, the only requirement is that the instruments not be shaded by the surrounding vegetation or other surface features. If an inverted pyranometer is used to measure reflected solar radiation, the instrument is usually mounted on a ring mounted at the end of an extension arm. The height of this pyranometer should be 1-1.5 m above a level surface representative of the study site if possible.

Because of the cost and relative complexity of measuring incoming solar radiation a considerable effort has been made to calculate direct and diffuse solar radiation values (12,14,21,34,40,70). On clear days, in simple terrain, calculated direct and diffuse solar radiation values are acceptable for general physiological studies. The cost of operating a single, silicon cell pyranometer is not excessive and is particularly useful on heavily overcast days when virtually all solar radiation is diffuse. For partial cloud cover, and especially transitory sky cover, the relationship between I_D and I_d is difficult to define. Commercially manufactured shadowbands are equivalent in cost to a top

quality pyranometer. Design and construction of a shadowband is sufficiently complex that it cannot be recommended as a routine laboratory or instrument shop project. In theory it is possible to temporarily block direct solar radiation to obtain a quick estimate of diffuse radiation from a pyranometer, but the practice cannot be recommended at this time. The best solution for utilizing a single pyranometer to obtain values for both I_D and I_d is to relate diffuse radiation to calculated direct solar radiation and observations of cloud or sky cover. However, at this time no simple, reliable relationship has been determined (4.13.29).

Air moisture or humidity

Absolute, relative humidity, vapor pressure and dew-point temperature:

Many individuals have difficulty with the concept of air moisture. Part of this is perception. We can appreciate the effects of wind and radiation by sensing the difference between shade and full sunlight or the cooling effects of a breeze, but humidity is so pervasive that we cannot readily escape it without totally leaving the environment.

Humidity is an attribute of the physical environment generally recognized by its role affecting climate, weather and thermal comfort. In addition, besides its effect on the natural environment, humidity is important in simulated environments and life support systems (19.28.38).

As with the other physical variables - air temperature, barometric pressure and wind velocity - humidity has long been documented and transcribed as a regular factor in history which spans weather prediction. For example, the meteorologist gives attention to boundary layer properties on the earth's atmosphere that include humidity turbulence. Increasing interest is prevalent nowadays in quantification of the water vapor gradients important to the humidity effects on weather patterns, air quality and

overall energy transfer. In the artificial simulation of the environment, such as in spacecraft or submersible life support systems, humidity is a vital part of safety and comfort (19,28).

Such interest and needs have provided the impetus for more accurate humidity measuring devices. The following is a brief review of the essential elements of humidity and its analysis. In its simplest concept, humidity is the amount of water, in the vapor phase, present in a gaseous atmosphere. Typically, the quantity of water vapor in a gas can be expressed in multiple ways: wet bulb temperature, mixing ratio (i.e., pounds per cubic foot), dew point temperature, parts per million and partial pressure.

One of the properties often overlooked is the concept of Dalton's Law in considering humidity effects. Dalton was the first to recognize that total pressure (P_m), exerted by a mixture of ideal gases or vapors, is the sum of the pressures of each gas if it were to occupy the same volume solely (28,29). The pressure which each gas component of such a constituent gas mixture (i.e., "air") exerts is its partial pressure. Thus, air must be considered a mixture of the gases oxygen, nitrogen, water vapor and inert gases. All measurements of humidity can be, therefore, reduced to the effects of water vapor pressure, as we shall see constantly in this volume, and all definitions encountered vaguely as "humidity effects" can be (and should be) expressed in terms of its apparent vapor pressure. Thus, relative humidity is the ratio of the actual vapor pressure in the mixture to the saturation vapor pressure with respect to water at the prevailing dry bulb (ambient) temperature (28).

Added to this is the concept of dew point. Dew point temperature is the saturation temperature to which air (or any gas) must be cooled at constant pressure so that it will be saturated with respect to water. Frost point is the definitive saturation temperature to which the air (or any gas) has to be cooled so that it will be saturated with respect to ice (18,29).

Since the definition applicable to relative humidity includes saturation vapor pressure with respect to "dew" or water, generally super-cooled dew point tables are used below 0° C (32° F) instead of frost point tables. Little, if any, reliable experimental data exist for super-cooled water below 0° C, so typical dew point tables are extrapolated from 0° C (32° F) to -51° C (-60° F). Thus, relative humidity is a meaningless concept when discussing equivalent dew points below -51° C (-60° F).

The concept of %rh is usually defined with respect to water for the following reasons: a) many humidity sensors, which are responsive to relative humidity, indicate %rh with respect to water; b) clouds, usually at temperatures below 0° C (32° F), consist of super-cooled water; c) the atmosphere describing "air quality" is often super-saturated with respect to ice at temperatures below 0° C and this fact prevents relative humidity from exceeding 100% so it has become a convenient empirical index.

One index of ambient humidity, which is also widely used to gauge air quality, is the parts per million (PPM) index. PPM by volume is the ratio of the amount of water vapor to the amount of dry gas on a volume basis. For example, PPMv for an air system at total pressure (P_b) of 760 Torr and -57.2° C frost point ($P_w = 1.26 \times 10^{-2}$ Torr) would be:

$$\begin{aligned} \text{PPM}_v &= [P_w / (P_b - P_w)] \times 10^6 \quad [\text{ppm by volume}] \\ &= [(1.26 \times 10^{-2}) / (760 - 1.26 \times 10^{-2})] \times 10^6 \\ &= 16.6 \text{ ppm by volume} \end{aligned} \tag{31}$$

PPM by weight, on the other hand, is defined as the ratio of the amount of water vapor to the amount of dry carrier gas on a gravimetric basis. It is determined by the product of the molecular weight ratio of water vapor: carrier gas and the PPM is obtained by volume. For the example above, if the carrier gas is hydrogen and the total system is at 760 Torr, PPMw would be:

$$\begin{aligned}
 \text{PPMw} &= \text{PPMv} \cdot \frac{\text{Mol. weight of H}_2\text{O}}{\text{mol. weight of hydrogen (H}_2\text{)}} \\
 &= 16.6 \cdot 18/2 = 153 \text{ [PPM by weight]}
 \end{aligned}
 \tag{32}$$

One property which should be recognized is that as the total pressure of a gas sample changes, all the partial pressures included in the total pressure also alter in the same ratio. This is especially important in considering any analysis of dew point properties in hyperbaric or hypobaric pressures. For our example, the frost point of -57.2°C at a total pressure of 760 Torr would alter dramatically at a total pressure of 4380 Torr (5.76 atmospheres, ATA) as follows:

$$\begin{aligned}
 \text{vapor pressure at} &= P_w \mid 4380/760 \text{ [Torr]} \\
 \text{new dew point} & \\
 &= 1.26 \times 10^{-2} \text{ Torr} \times 5.76 \\
 &= 7.26 \times 10^{-2} \text{ Torr}
 \end{aligned}
 \tag{33}$$

This would bring the frost point to roughly -42.5°C .

From a physiological perspective, the importance of air moisture is related to the capacity of the surrounding air to absorb water from the body surface. Measurements of absolute and specific humidity measure the actual quantity of water present in the atmosphere, expressing the values as mass of water per volume or air mass, respectively. Relative humidity, dewpoint temperature and water vapor pressure are more directly related to the evaporative potential of the environment, a function of the combination of absolute water and temperature. The key to determining what the ambient potential for evaporation is to determine the difference between the actual air moisture content and the saturation value.

Psychrometrics

One of the easiest ways to visualize the concept of humidity is by the use of a psychrometric chart.

[INSERT FIGURE 6 HERE]

Typical psychrometric charts show ambient or dry bulb temperatures along the bottom horizontal axis. Saturation temperatures (dew point and wet bulb) are expressed by a curved line on the left side. Along the vertical line on the right, ambient water vapor pressure (Torr or kPa) is depicted and parallel to the vertical axis absolute moisture content (as $\text{gH}_2\text{O/g dry air}$ or grains of $\text{H}_2\text{O/pound of dry air}$) is often drawn. Moisture content is linear but the ambient water vapor scale is not. Lower percentages of relative humidity, less than 100% saturation, are represented as diverging curved lines below the saturation curve. Dew point temperatures will always be indicated on such a chart by the intersection of the horizontal (dry bulb) lines with the 100% rh curve. Wet bulb temperatures will be indicated by the intersection of a 45 degree sloping line with the 100% rh curve. Psychrometric charts, such as the one described, are useful in describing dependent variables (vapor pressure, dew point temperatures) as a function of a temperature index such as operative temperature or effective temperature (27.28) and thereby allow graphical displays of the heat balance equation (27.31) or other heat stress indices in a psychrometric format. One problem occurs in that description of enthalpic lines (depicting true heat content, J.g^{-1} dry air) and wet bulb temperature lines are confounded and wet bulb lines are often used to represent both properties. A "enthalpic deviation" line is used to correct for enthalpy from the wet bulb line; often these values are not clear-cut. Another approach first developed by Mollier (50) and more recently used by Gagge et al. (27) unifying heat

strain lines of a new effective temperature. In a Mollier chart, by depicting dry bulb temperature on a vertical left axis and ambient water vapor pressure on a bottom horizontal axis and humidity ratio on a top horizontal axis, enthalpic lines can be drawn more exactly without application of a correction factor added to wet bulb temperature lines.

Wood (74) circumvented many of the problems inherent in conventional psychrometric charts by construction of a psychrometric chart with dew point temperature (y-axis) and dry bulb temperature (x-axis) coordinates. He also showed that the original Antoine equation was an accurate approximation of saturated vapor pressure of water from 0° C to 60° C. This equation is used quite frequently in physiological and clothing research, and throughout the chapters of this book, for obtaining saturated vapor pressures (P.t) where:

$$P.t = \exp (16.6536 - 4030.183/(t+235)) \quad [\text{kPa}] \quad (35)$$

$$= \exp (18.6686 - 4030.183/(t+235)) \quad [\text{Torr}] \quad (36)$$

where t represents the given temperature (°C) which must be used to obtain P.t.

The classical psychrometric chart as described holds for variables defined at constant barometric pressure (sea level). Construction of psychrometric charts for various other total pressures (altitudes) is, however, possible (18.34.44). Characteristically, effect of lowered barometric pressure increases %rh, ambient water vapor pressure, and humidity ratio for a given dry bulb temperature (18.45). Enthalpy lines are not appreciably affected and the slope of the wet bulb lines are not changed although the saturation curve and each given %rh lines are displaced to the left with lowered Pb. The converse effect on %rh lines occurs with hyperbaric environments.

Humidity measuring devices

There exist a multitude of humidity measuring instruments which have been categorized extensively according to accuracy and sensitivity (72). A hierarchy of those frequently used in the laboratory is presented in Appendix B.

Pressure and/or altitude

Barometric pressure is often monitored even in controlled laboratory studies to adjust physiological measurements for variations from STP conditions. As noted in the discussion of altitude effects, both convective and evaporative heat exchange rates are altered by changes in pressure. However, pressure is usually systematically monitored as an environmental parameter only when the study occurs at sufficient elevation to affect oxygen levels (2500 m).

The simplest method for obtaining a gross estimate of the effects of altitude on pressure is to obtain a topographic map which will allow a reasonably accurate determination of the altitude of the study site. In the United States, state indexes to topographic maps may be obtained from the U.S. Geological Survey (USGS), Washington, D.C. 20242. The state indexes may list local map sources in addition to the regional USGS offices. In addition, map collections may be located at universities or colleges, either in the general library collection or in the geology or geography department. Standard tables can be used to adjust STP values according to the change in altitude.

If a more precise measurement of barometric pressure is desired, a hand-held barometer, either mechanical or electronically operated can be purchased. Barometers measure changes in atmospheric pressure due to both altitude and high and low pressure weather systems. Barometers are classified as mercury or aneroid barometers depending on whether the pressure sensitive element is mercury or a diaphragm, spring

or other non-liquid sensor. An altimeter interprets pressure differences as elevation rather than force.

Generally the hand-held barometers will suffice if only a few reference readings are collected. If a continuous record is desired an electronic, automatically recorded analog barometer is the best solution.

Combination instruments

Direct measurement of a single environmental parameter is generally the preferred method; however, precise environmental monitoring is expensive and time consuming. Industrial and military safety personnel often are less interested in the fundamental theory of heat exchange since they require easy, quick and accurate assessment of the potential risks at a minimal investment in time and money. A minimum number of simple, inexpensive, easy to operate and maintain instruments also serve as an attractive solution to environmental monitoring when the researcher faces a reduced budget. A few such instruments are described here.

The best example of a simple combination instrument in widespread use is the Vernon or black globe thermometer. A sphere always presents the same cross-sectional area (A_p) normal to the direct solar radiation regardless of the sun's position. Consequently, the impact of direct solar radiation on a sphere is dependent on only I_D . A sphere also presents a constant, uniform surface area to diffuse and reflected solar and incoming thermal radiation. As indicated in the section on radiation instrumentation, the mean radiant temperature can be calculated from the black globe temperature (T_g , °C), air temperature (°C) and the wind speed (48.75):

$$T_r = T_g^4 + 0.247 \cdot 10^{-8} \cdot (\sqrt{v}) \cdot (T_g - T_a)) \quad [^\circ \text{C}] \quad (38)$$

The equation for T_r also indicates the primary disadvantage of the globe thermometer. The observed measurement is the combined effect of radiation and wind speed. An error in the measurement of wind speed will result in an error in the calculation of T_r .

Another instrument that simultaneously measures the effects of several environmental parameters is the "naturally aspirated" wet bulb thermometer. A hand-held psychrometer is spun to obtain maximum or at least uniform air flow, but a natural wet bulb simply has a saturated wick over the bulb. As a consequence, wind speed, air temperature and evaporation are all variables which contribute to the observed value. Again there is a problem of separating the effects of wind from humidity. Both the globe thermometer and the natural wet bulb are used in the calculation of the Wet Bulb Globe Temperature (WBGT) index (78).

Environmental data loggers

The best way to obtain an accurate, continuous record of environmental conditions is collect the data from meteorological instruments on a data logger or data acquisition system (4). For physiological studies it may be desirable to record physiological responses and environmental parameters in the same data file. All of the microenvironmental parameters can be measured by meteorological instruments which generate similar voltage output signals.

The simplest data collection devices are field portable data loggers which are completely battery-powered. These basic data loggers may have built-in thermocouple reference thermometers but are limited in the number of total input channels. The addition of multiplexers to increase the number of input channels and a tape printer will enhance the performance of the logger, but at the cost of increased weight, bulk and expense.

Some instruments, for example a hot wire anemometer, require an initial excitation or signal conditioner to operate the sensor. A D-cell battery-powered data logger has limited capabilities for generating an excitation signal. Other data loggers have lead-acid batteries or can be converted to operate off AC power sources. Batteries discharge rapidly when air temperatures drop below 0° C. An alkaline battery-powered data logger was successfully operated through an Indiana winter in an unheated shed by placing a 100 W light bulb about 8 cm above the battery pack to warm the batteries (Santee, unpublished). Larger portable data loggers may operate off a lead-acid battery pack or AC current and the number of input channels can be increased significantly. Other data logging systems are available for fixed sites.

Climatic data

An important source of basic information regarding a site's environment is the compiled climatic data. However, excessive reliance on local climatic summaries, even during the planning stages, can present problems. The most serious shortcoming of climatic tables is the presentation of unsupported mean temperatures. In the fall, under the clear skies associated with high pressure systems, it is not uncommon to see a daily minimum-maximum temperature range of 10 to 26° C in central Texas even though the mean daily temperature is a pleasantly cool 16° C.

An important question regarding local climatic data is how representative the data collection site is of the local climate. In one case, the National Weather Service (NWS) forced the relocation of the local meteorological station. The town in which the station was located was an important tourist area by the shores of a desert reservoir. Data were collected on the well-watered lawn of the local fire station. When NWS personnel requested that the meteorological instruments be located in more representative desert conditions, local interests objected, fearing that high temperatures

would be reported regionally and nationally as the daily extreme, thereby discouraging potential visitors. International Falls, Minnesota and by association the entire state of Minnesota, has acquired a reputation for extremely cold winters by frequently having the coldest officially reported temperature in the contiguous United States, even though much lower temperatures occur at other locations. In Utah, a local television weatherman established a remote weather station in a small, high elevation depression where cold air accumulated and began to report phenomenally low temperatures. The relevance of extreme high and low temperatures is reduced when the size of the local population is taken into consideration.

More than one study has attempted to utilize data collected at a fixed meteorological station located several kilometers from the actual study site. In many locations, this may result in serious errors (4). As noted in the preceding paragraphs, both temperature and wind speed vary considerably in the vertical profile. Both parameters are strongly influenced by local topography, terrain features and vegetation. Moisture is strongly influenced by vegetation, air movement, bodies of water, etc. Reflected solar and thermal ground radiation are strongly dependent on the nature of the surface. Direct and scattered solar radiation measurement may be useful on clear or overcast days provided sky cover is equivalent at the study and instrument sites. Scattered cloudiness or rapidly changing cloud cover reduce the value of remote radiation measurements.

METHODS FOR QUANTIFYING THE THERMAL ENVIRONMENT

Below an elevation of 2500 m, only those physical parameters which affect heat exchange, the parameters which define the thermal environment, have a significant impact on human physiology. Heat exchange between a subject and the environment can follow four basic pathways. Dry or sensible heat exchange can occur by

convection, conductance or radiation. Evaporation, the fourth pathway, is termed wet or insensible heat exchange.

Heat exchange may occur simultaneously along all four pathways. From the heat balance equation, it is clear that the actual heat exchange is the sum of the individual terms. It would be desirable for the purpose of the statistical analysis of data to express the net result of the interaction of the different heat exchange pathways as a net potential for heat exchange.

In response to the desire for a single temperature or index that will sum up the thermal environmental conditions (the weather report for a layman), several different indices have been developed. The simplest to understand is the "wind-chill" index (49,63,70). We all recognize intuitively that the presence or absence of wind affects how warm or cold we feel. The wind-chill index is a method for quantitatively expressing the combined effects of wind and air temperature as an "equivalent" temperature. For example, a combination of an air temperature of -34.4°C and $2.2\text{ m}\cdot\text{s}^{-1}$ wind speed represents the same potential for heat loss from exposed skin as still air at -38°C . The practice of media "weather" reporters to cite only wind-chill to describe outdoor climatic conditions is a disservice to the public. Although wind-chill is a useful method for emphasizing the importance and potential danger of convective heat loss to laymen, the insulation provided by clothing and any form of wind protection; either wind-proof clothing or physical barriers; quickly reduces the utility of wind-chill. There is a considerable difference between a wind-chill of -40°C produced by an air temperature of -17.8°C (0°F) and a wind speed of $10.0\text{ m}\cdot\text{s}^{-1}$ (22.5 mph) and an actual air temperature of -40°C (or $^{\circ}\text{F}$) in still air when you go to start your car in the morning.

To a large degree the perception of the environment is determined by culture and personal environment. A great number of scientists that deal in human factors

research are employed at urban centers where the normal extremes of environmental stress are experienced only during transitory movements from one sheltered environment to another. The majority of scientists, as well as the general population of urban centers, are engaged in sedentary indoor activities. Exposure to extreme environments tend to occur in the context of brief exposures during recreation activities such as skiing, mountain climbing or driving across the desert. Consequently, for most of us, our anthropomorphic perception of severe environments is that of a tourist. For more primitive cultures, outdoor workers and the military, environmental exposure is not as selective or elective. An Inuit seal hunter may be forced to squat motionless for hours on an icefield waiting for his prey. Military personnel may be facing an enemy force in a dense jungle or a high mountain pass, unable to retreat or advance. The thermal environment experienced by these individuals cannot be adequately described by a standard environment appropriate for office workers or joggers. Media meteorologists offer the public a forecast that will allow them to plan activities to avoid extreme outdoor exposure or to adjust their clothing. The indoor work or home environment may be quite different. For a physiologist attempting to anticipate or even replicate environmental stress, there is a need for a more sophisticated "forecast".

Ecologists frequently have to describe microenvironments that are quite different from normal human environments. Porter and Gates (1969) introduced the idea of a climate space (Fig. 7) which uses radiation, wind speed and air temperature as three axes to plot the limits of a species' thermal environment. The radiation limits are set by the maximum (solar and thermal) and minimum (night-time, clear sky) possible radiation. The upper and lower temperature limits are the upper and lower critical temperatures of the species. Within the boundary limits each point represents a unique combination of radiation and air temperature. The effects of wind speed are demonstrated in a two-dimensional diagram by drawing sloped lines that indicate

equivalent temperatures at a specified wind speed. The climate space diagram especially defines different combinations of temperature, radiation and wind as points within the overall potential environment; the parameters that define the potential for dry heat exchange. The introduction of the climate space concept was followed by a series of attempts by physiological ecologists to develop equations for an "equivalent black-body temperature (T_e)": a single "temperature" that was equivalent to the simultaneous effects of wind, radiation and temperature on the subject species (51).

[INSERT FIGURE 7 HERE]

During the vigorous debate over the best formulation for expressing T_e (3), ecologists found that the idea of expressing the net potential for heat exchange as an equivalent temperature was not the exclusive providence of field biologists. One of the earliest and most successful "equivalent temperatures" (6) was operative temperature (T_o) which was introduced by Gagge (1940) as a method of expressing all the parameters of dry heat as a single variable for human subjects. Operative temperature was defined as "the temperature of an imaginary isothermal 'black' enclosure in which a man would exchange the same heat by radiation, convection and conduction from his skin surface at temperature (T_s) as he would in his actual non-uniform environment" (31.73).

$$M - E = (h_c + h_r) \cdot (T_s - T_o) \quad [W \cdot m^{-2}] \quad (39)$$

In addition to metabolism and evaporation the other variable is surface temperature (T_s). Operative temperature can be calculated from either of the following equivalent equations:

$$T_o = (h_c T_a + h_r T_r) / (h_c + h_r) \quad [^{\circ}\text{C}] \quad (40)$$

$$T_o = T_a + H_r / (h_c + h_r) \quad [^{\circ}\text{C}] \quad (41)$$

$$H_r = h_r (T_r - T_a) \quad [^{\circ}\text{C}] \quad (42)$$

H_r is the effective radiant field. Bakken *et al.* (1985) presents alternate equations based on whole body net radiation which avoid calculation of T_r .

[INSERT FIGURE 8 HERE]

Operative temperature does not account for evaporative heat exchange, but as noted earlier in saturated air or when protective clothing eliminates evaporative exchange, dry heat exchange represents all of the variability in the potential environmental stress. One shortcoming of operative temperature is that while it is a good predictor of dry heat exchange potential, it is not a wholly adequate index or reference for comparison between environments because a change in the wind speed alters the convective heat transfer coefficient (h_c). Standard operative temperature (T_{so}) eliminates that problem by adjusting the operative temperature to a standard convective condition (usually zero wind speed [25]).

Building from a base of operative temperature, a series of other equivalent temperatures were formulated, including humid operative temperature (T_{oh}) and standard humid operative temperature (T_{soh}). Humid operative temperature is essentially a term for expressing how the combined parameters for dry and evaporative heat exchange "operate" on a human subject. Standard humid operative temperature is analogous to T_{os} with the assumption of a standard condition for humidity (saturated).

Operative temperature and humid operative temperature are referred to as "rational" temperatures because the equations are derived from actual heat transfer

theory and therefore have a sounder biophysical basis (6.31). Other indices of thermal stress, such as the WBGT index (78), are derived empirically from observations of meteorological measurements and human performance. WBGT is an accessible, easily understood and easily measured index. For a scientist, a major shortcoming of this index is that it cannot be used to quantify or identify the contributions of different environmental parameters to the overall heat stress. WBGT and similar empirical indices can only relate an observed value to an anticipated level of environmental stress for a given set of conditions. If significantly different clothing is worn, which alters the potential for heat exchange, the empirical relationships that are the basis for the WBGT index, are altered.

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Appendix A...Calculation of the Zenith Angle.

The zenith angle (θ_z) can be calculated from the following parameters; site latitude (L) and longitude (l). time (civil or clock time, t_{cl}) and solar declination angle (δ).

The hour angle converts clock time (t_{cl}) into a solar angle (h).

$$ch = \Delta l \cdot (1440/360) \quad [\text{min}] \quad (43)$$

$$t_{\text{sun}} = (t_{cl} \cdot 60) - ch \quad [\text{min}] \quad (44)$$

The sun is directly over the standard meridian (l_s) at 12:00 noon plus or minus a correction factor (the equation of time). Hour angle correction (ch) means that at a site of longitude $87^\circ 13.5'W$, the sun is directly overhead on the average day (mean solar time) at 12:50 EST because the site is west of the standard time meridian ($75^\circ W$). The investigator should also make an allowance for the sampling interval when selecting t_{cl} .

$$l_s = 75^\circ W$$

$$l = 87.25$$

$$\Delta l = -12.25$$

$$ch = ((-12.25) \cdot 4)$$

$$= -50^\circ$$

If data are collected in 15 minute blocks, data recorded at 12:00 spans the period from 11:45 to 12:00. 11:52:30, the mid-point of the sampling period ($12:00 - (15/2)$), may be a more appropriate clock time.

$$h = ((t_{\text{sun}} - 720)/1440) \cdot 2 \cdot \pi + \Delta E \quad [\text{radians}] \quad (45)$$

ΔE , the correction factor from the equation of time, is an adjustment that relates apparent solar time to mean solar time. This correction is essentially an adjustment due to the fact that the earth's orbit and rotation are not uniform. The equation of time correction can be found in the ASHRAE Fundamentals Handbook (1985). The Ephemeris or the Air Almanac. It may also be calculated (2.65).

The following equation is presented for either the $\cos \theta_z$ or $\sin \theta_s$, the complimentary solar elevation angle (2.14).

$$\cos \theta_z = \sin L \cdot \sin \delta + \cos L \cdot \cos \delta \cdot \cos h \text{ [N.D.]} \quad (46)$$

The declination angle (D) is also published in The Ephemeris or equivalent reference. It also may be approximated with the appropriate equation (2.14).

Appendix B....Humidity measuring devices.

The multitude of humidity measuring instruments have been categorized according to accuracy and sensitivity (36.37) in the following way with highest precision being the NBS standard (72):

Hierarchy of Humidity Instruments

TYPE 1: NBS Standard

TYPE 2: a. Optical b. Double
 chilled mirror pressure generator
 dew point

TYPE 3: a. Wet Bulb b. Saturated c. Pneumatic
 psychrometer salt solutions bridge

TYPE 4: a. Saturated b1. Piezoelectric c1. Mechanical
 heated lithium chloride
 b2. Electrolytic c2. Spectroscopic
 b3. Dunmore Elements

Type 1 is the most precise gravimetric hygrometer developed by the National Bureau of Standards (NBS, Washington, D.C.) (70). In this instrument, a test sample flows from a humidity generator through a drying tube and a precise volume measuring

column in a temperature controlled bath. Thus, the required measurements of temperature, weight, pressure and volume are known. One disadvantage is in its operation time which may be up to 30 h at low humidity ranges. NBS generally uses a two pressure humidity generator as a definitive source reference hygrometric (type 2). In this device the gas sample is saturated at constant temperature, followed by an expansion to a lower pressure which may be at the same or a higher or lower temperature. By Dalton's law (ratio of partial pressures vary directly with total pressure) %rh is determined very accurately by the ratio of the test chamber pressure (P_c) to the saturation pressure (P_{st}):

$$\% \text{ rh at } P_{st} = P_c / P_{st} \times 100 \quad [\%] \quad (37)$$

As is apparent the relative humidity is not dependent arbitrarily on the measurement of water content of a testing sample but on measurement of pressures only in an isothermal condition. This system although accurate is not wholly practical for continuous monitoring. For this reason the chilled mirror optical dew point calibration techniques have been developed. At saturation temperature, or the dew point, an air-water mixture is saturated with respect to water or the ice point. Theoretically if the mirror is completely clear, the rate of water molecules condensing on the mirror surface is equal to the rate of those being evaporated from the surface and entering the atmosphere. Thus at equilibrium, the water vapor partial pressure of the condensate equals the water vapor partial pressure of the gas atmosphere (ambient water vapor pressure, P_w). The necessary requirements are that the mirror surface must be cooled at the precise saturation temperature. Cooling of the mirror surface is usually done by continually flowing refrigerant liquids, acetone, liquid CO_2 or other cooling fluids.

Recently, precise and miniaturized dew point sensors (32) have been developed using the thermoelectrical heating pump technique, first developed by Peltier (46). These are becoming useful in clothing water vapor analysis and in methods which ascertain the sweating rate of small areas of the skin mentioned in many of the chapters in this book. In this method the dew point is measured by a thermocouple or thermal module operable by a servo-loop or microprocessor device which detects and signals changes in the temperature of a sensing plate. The latter is alternately cooled and heated to cause moisture in the ambient gas, close to a surface, to condense between a pair of electrodes supported on either side of the sensing plate. The sensing plate is composed of a high thermally conductive material. As condensate forms on the plate the change in resistance (analogous to change in reflectance of a chilled mirror) is detected. This type of hygrometer is extremely valuable because of its small size, accuracy and almost continuous direct absolute humidity reading property.

The thermodynamic wet bulb temperature most frequently used in laboratory or field experiments is an example of Type 3 hierarchy humidity devices. The wet bulb temperature is either obtained by covering a glass thermometer, thermocouple or thermistor with a moistened wick aspirating the system at a constant flow ($>3 \text{ m}\cdot\text{s}^{-1}$) and then noting the lowest cooling depression. In theory, the wet bulb temperature of moist air at constant pressure, temperature and humidity is the temperature at which water evaporates into the air to saturate it without gain or loss of heat (i.e., adiabatically). The method is fairly accurate; however, errors in measurement exist due to placement of the sensing device such as a thermocouple into the interface of the wick, purity of water, how clean the wick is, air flow, radiation effects, density, viscosity and thermal conductivity of the gas. Many of these properties are associated with the barometric pressure, temperature and type of gas so wet bulb psychrometry is not wholly accurate for use in either hyperbaric or hypobaric environments.

Another example of a type 3 humidity device includes the pneumatic bridge hygrometer (33). In this system, two sets of optimum flow nozzles are connected in series in an arrangement analogous to the Wheatstone bridge. Mass flow rate of a gas through the downstream nozzle is arranged to be proportional to the gas upstream pressure. Any change in mass flow introduced by a desiccant placed between the two nozzle arrangements is introduced as a variable which affects the pressure in a test branch. A differential manometer is used to compare the test branch and a reference branch. Although a bit cumbersome, the change in water vapor concentration produced by the desiccator in the test branch of the pneumatic bridge, in comparison to the absolute value of pressure in the reference, produces a very accurate reading.

Less accurate but easily determined type-3 systems include use of saturated and unsaturated aqueous salt solutions (77). Experimentally a given salt: H_2O solution determines by its ambient temperature the equilibrium water vapor pressure. Thus, water vapor pressure versus temperature curves of many salt solutions such as lithium chloride, ammonium chloride, calcium chloride, etc. may be used. In these solutions the dissolving salt along with water depresses the solution. In supersaturated solutions where a solid phase of salt and water vapor coexist in isothermal expansion, the vapor pressure depression reaches a limit. Therefore, the temperature at which equilibrium (by mass balance) is reached will signify the vapor pressure of the saturated solution very accurately. This is somewhat analogous to the chilled mirror dew point hygrometric concept already discussed.

Type-4 humidity devices are widely used because of their simple operation but have shortfalls compared to the devices previously discussed. The family of heated lithium chloride sensors, although widely used in air quality or meteorological measurements,

are affected by direct water exposure. These sensors have wide drift and often exhibit errors in calibration properties as a result of changing solution concentration and contamination. Also response time of such sensors is slow: for example, a lithium chloride sensor may need almost five minutes to record 67% step change.

A whole series of resistive and electrolytic hygrometer and spectroscopic (infrared/ultraviolet) are being introduced. The spectroscopic hygrometers measure the humidity of a gas sample by detection of the energy absorption in the water vapor bands. A typical system requires as an energy source a thermal radiation energy detector and an optical system to discriminate the wavelengths and a measuring device to quantitate the decreases in radiation caused by water vapor present in the optical path. The response time is very fast, typically 90% of the final reading occurs within five seconds. These instruments, however, are still relegated to use of separate calibration by use of the higher order methods already described.

FIGURE LEGENDS

Figure 1. The impact of direct, diffuse and reflected solar radiation are dependent on the orientation of the individual relative to the radiation source.

Figure 2. The position of the sun relative to an object determines the cross-sectional area which receives the full intensity of direct solar radiation.

Figure 3. Hourly mean air temperature ($^{\circ}\text{C}$) and standard deviations observed at 2 m during June, 1982 in west-central Indiana (Santee, 1985).

Figure 4. Mean wind speed ($\text{m}\cdot\text{s}^{-1}$) and standard deviation observed at 3 m during June, 1982 in west-central Indiana (Santee, unpublished).

Figure 5. Hourly mean global radiation ($\text{W}\cdot\text{m}^{-2}$) and standard deviations observed during June, 1982 in west-central Indiana (Santee, 1985).

Figure 6. Psychometric table (redrawn with permission, Chambers, 1970).

Figure 7. Simplified climate space diagram (redrawn with permission, Porter and Gates, 1969).

Figure 8. Air (T_s) and operative (T_o) temperature ($^{\circ}\text{C}$) for June 12, 1982 in west-central Indiana.

FIG. 1

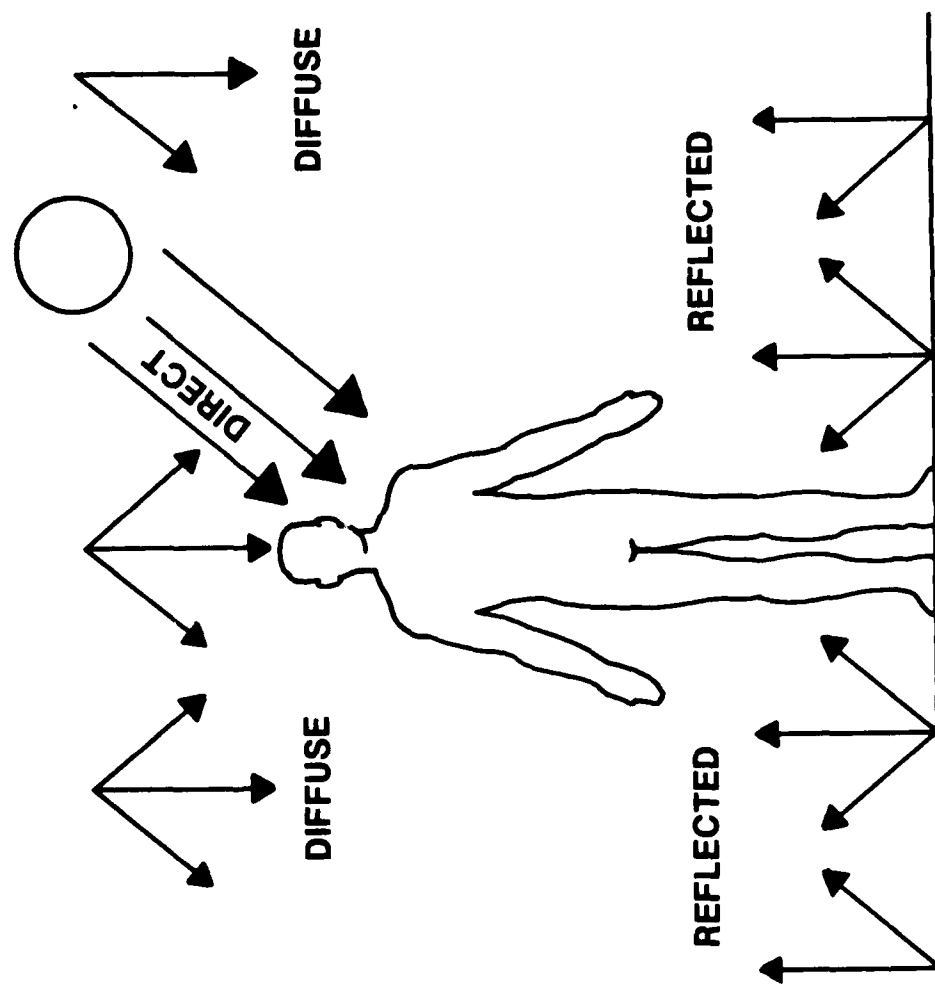


FIG. 2

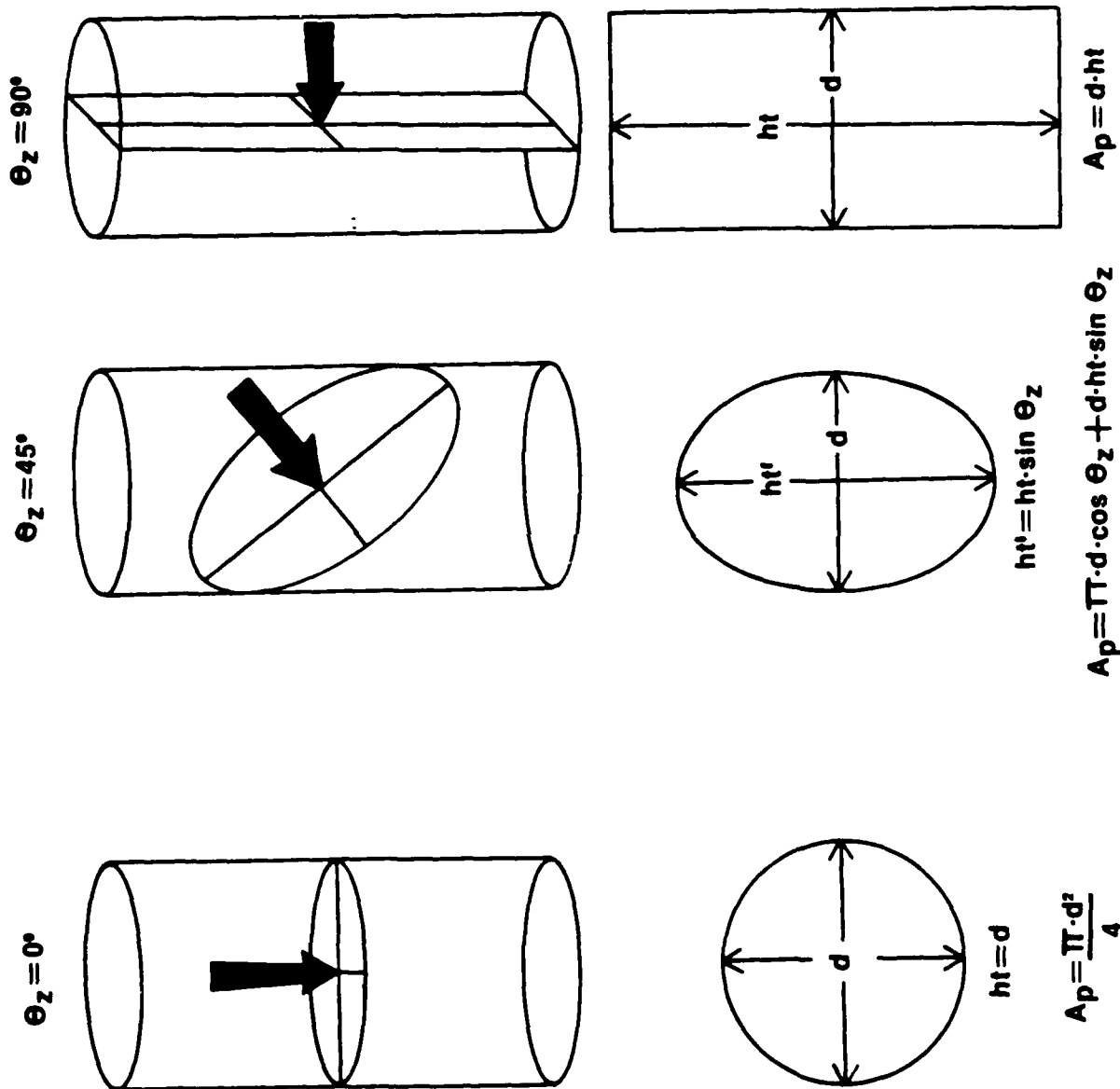


FIG. 3

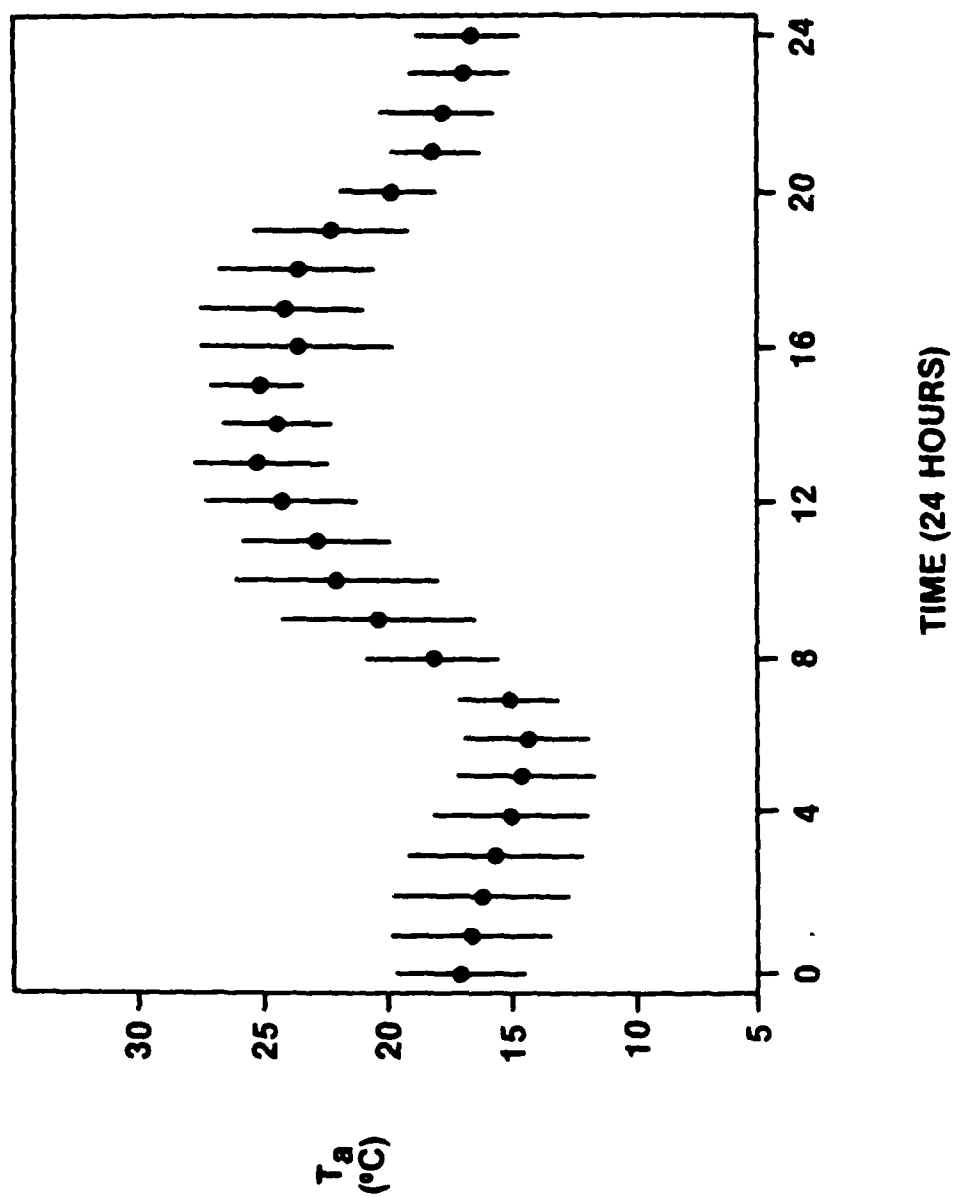


FIG. 4

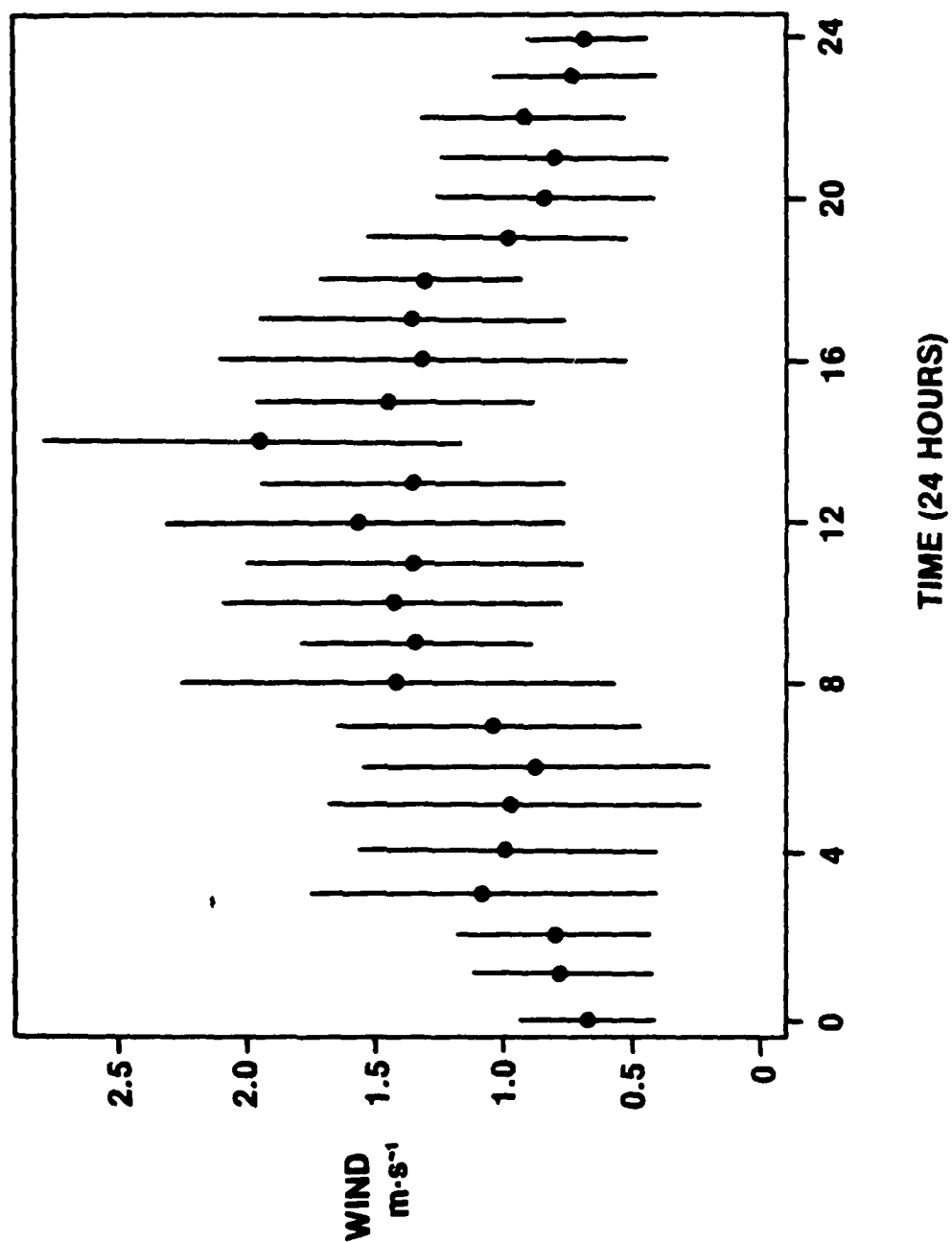


FIG. 5

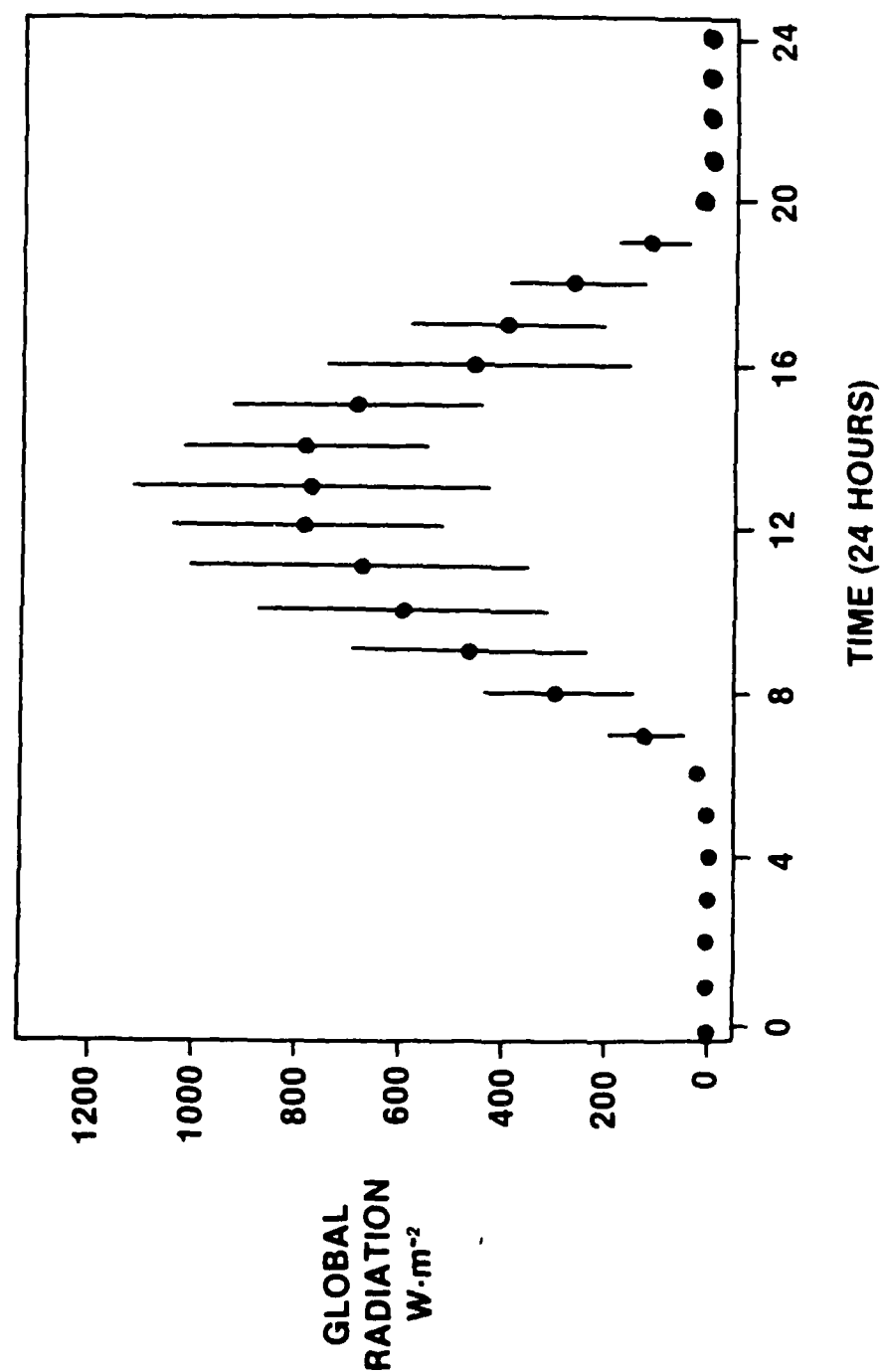


FIG. 6

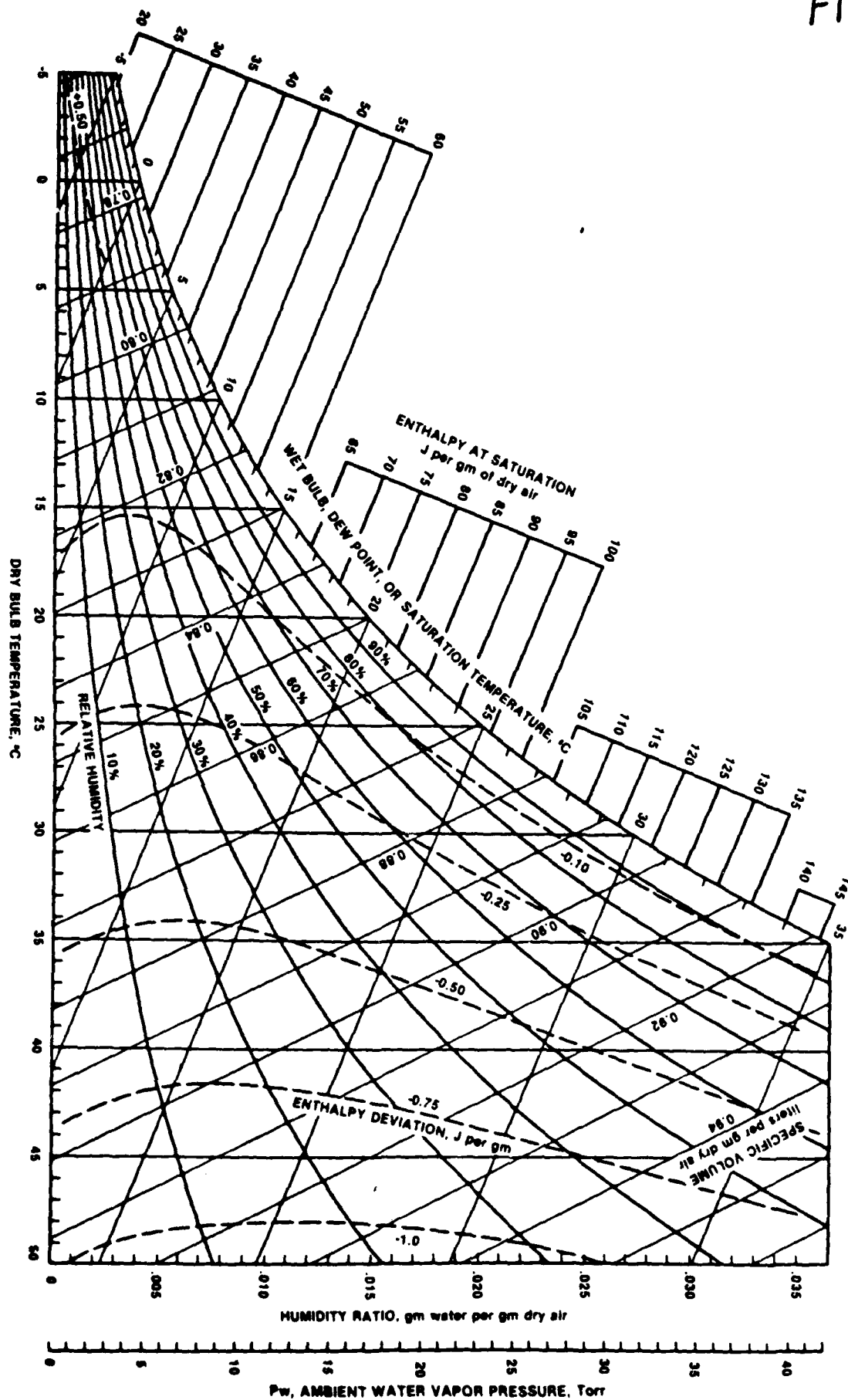


FIG. 7

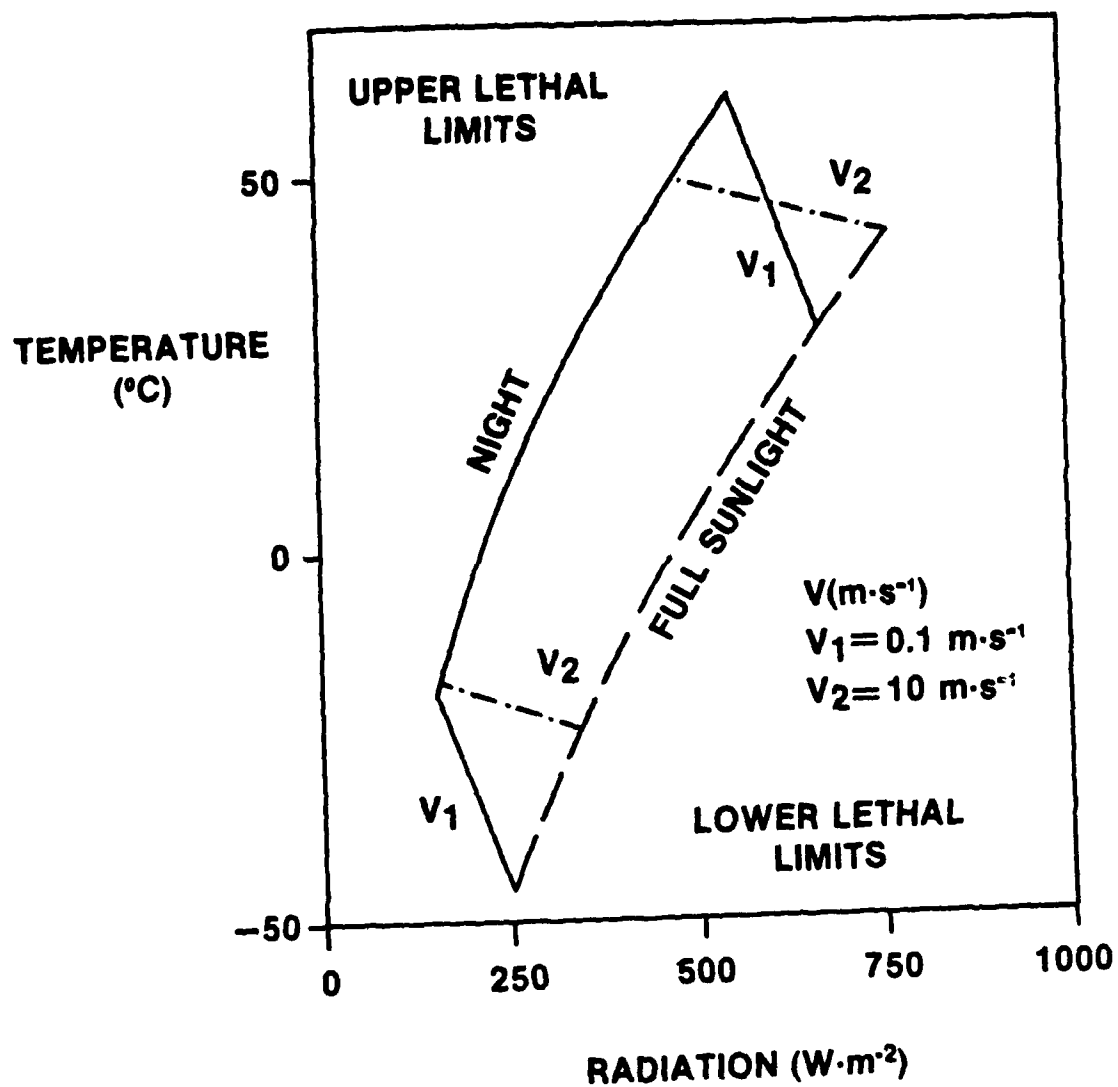
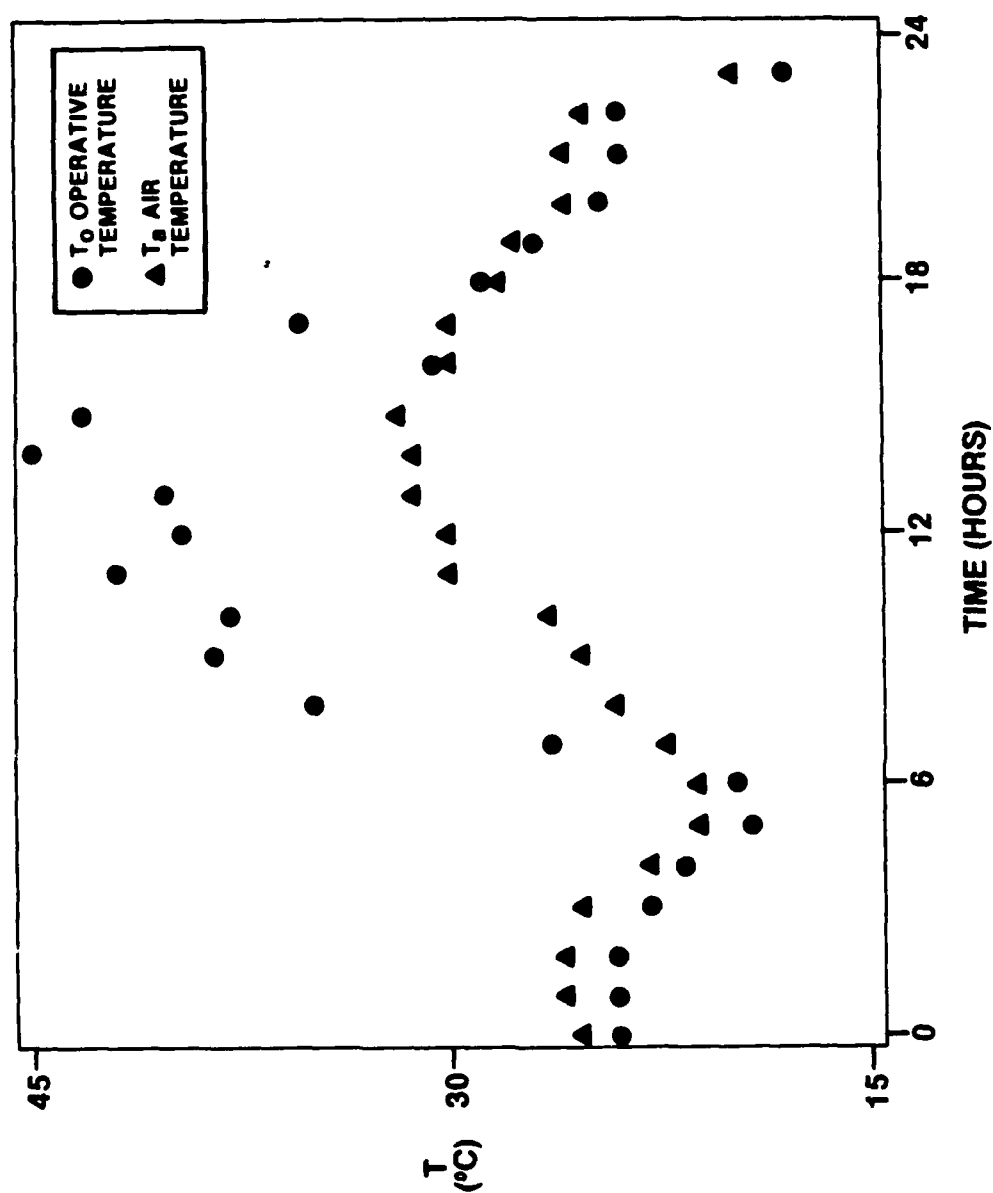


FIG. 8



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