NASA Technical Memorandum 81223

(NASA-TM-81223) USE OF AN ELECTRICAL RESISTANCE HYGROMETER TO MEASURE HUMAN SWEAT RATES (NASA) 30 p HC A03/MF A01 CSCL 06P
N81-17692
Unclas
G3/51 41423

Use of an Electrical Resistance Hygrometer to Measure Human Sweat Rates

Toshiyuki Suga

October 1980

National Aeronautics and
Space Administration

NASA Technical Memorandum 81223

Use of an Electrical Resistance Hygrometer to Measure Human Sweat Rates

Toshiyuki Suga, Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

SYMBOLS

C_{pm}	specific heat of moist air, kcal/kg-°C
D	diffusion coefficient, m/sec
Dw	coefficient of mass (water vapor) diffusivity of air, kcal/sec-m-°C
f	fanning friction factor (function of the viscous shear at interface)
h_C	convective heat-transfer coefficient, kcal/sec-°C
he	evaporative heat-transfer coefficient, kcal/mmHg
h_D	mass-transfer coefficient, m^3/sec
K	thermal conductivity of air, kcal/sec-m-°C
L*	generalized characteristic dimension of any geometric shape
M	mass, kg
P	partial pressure, mmHg
Rw	gas constant of water vapor, 3.47 mmHg-m^3/kg-K
T	temperature, °C
V	velocity, m/sec
W	mass fraction of water vapor, kg water/kg air
λ	latent heat of vaporization of water, kcal/kg
μ	absolute viscosity of dry air, kg/sec-m
ν	kinematic viscosity of dry air, m^2/kcal
ρ	density, kgm/m^3
ρ_{am}	partial density of moist air, kg/m^3
$\propto$	thermal diffusivity of dry air, m^2/sec

USE OF AN ELECTRICAL RESISTANCE HYGROMETER TO MEASURE HUMAN SWEAT RATES[*]

Toshiyuki Suga[†]

Ames Research Center

SUMMARY

This study was carried out at the NASA Ames Research Center and the University of Santa Clara. It was concerned with the application of the resistance hygrometer as a tool to measure the localized sweat rate from the human body in both the active and passive sweat regions. It was found that the physiological function of the skin membrane and fluid carrier transport phenomena from the outer skin have an indistinguishable effect on the observed findings from the instrument.

This paper identifies the problems associated with the resistance hygrometer technique and evaluates the usage of the instrument in the physiological experimentation from the engineering standpoint.

INTRODUCTION

To properly design a contained environment or microclimate, such as a shelter, space vehicle, or protective garment, one must consider the physiology of human thermoregulation, or body temperature control. In studies designed to amplify our understanding of thermoregulation, Dr. John Greenleaf of Ames Research Center is using a hygrometer to measure localized sweat rates.

At the Department of Mechanical Engineering, Santa Clara University (Santa Clara, Calif.) Professor Pefley and his associates have, for the past 15 years, used a human calorimeter and computer models to study human thermal response to the environment (ref. 1). These studies have related primarily to warm, humid environments. Overall sweat rates and heat-transfer rates, as well as heat- and mass-transfer coefficients averaged over the human body, have been derived. However, no local sweat rates or mass-transfer coefficients have been measured.

Under the guidance of Dr. Greenleaf and Professor Pefley, students at the University of Santa Clara (including the author) have studied for two years the possible use of a resistance hygrometer for the physiological measurement of the local sweat rates as well as engineering determination of the

---

[*] Prepared under NASA contract NAS2-9967.

[†] Present address: Mechanical Engineering Department, University of Santa Clara, Santa Clara, California 95053.

local mass-transfer coefficients. The object of this work was to establish the fundamental constructive framework of hygrometer techniques from these cumulative studies.

The elements of this report are discussions of (1) the resistance hygrometer and its related accuracy and reliability problems, (2) some physiological aspects of human sweat and sweating, (3) formal methods of convective heat-transfer theory contained in the literature for rational analysis of the environment, (4) the use of a "sweat" cylinder to study the classical heat-mass transfer analogy — the so-called Lewis relationship, and (5) the use of such theories for applications to human physiology.

THE RESISTANCE HYGROMETER: ACCURACY AND RELIABILITY

The resistance hygrometer has been used as one method of measuring human sweat since 1959. In such measurements, controlled humidity air is sent into the sweat monitoring capsule[1] where it picks up the moisture from the outer skin. The air is then analyzed at the exit by a resistance hygrosensor. The operation of the instrument relies primarily on the moisture dependence of the electrical resistivity of the hygrosensor, but it can be influenced by the dielectric constant of many insulators and the stability of the temperature control unit. An operational schematic of the resistance hygrometer is shown in figure 1. The instrument, tested at the University of Santa Clara, was very sensitive to the ambient temperature. As a result, it presented many problems that had to be solved before it could be used effectively.

Problems Associated with the Resistance Hygrometer

It was proposed that the resistance hygrometer would be useful in an environment in which the temperature and humidity were not controlled. However, a number of technical problems were encountered when attempts were made to use the resistance hygrometer in uncontrolled atmospheres. Some of the major problems were as follows:

1. The calibration baseline was found to shift continuously, hence the instrument was first modified so that air was brought to the baseline at a more consistent temperature and humidity by adding water vapor saturation impingers and a cooling system.

2. During calibration the water inside the calibration tube provided an unsteady evaporation rate due to the variation of shape of the air-water boundary inside the tube. Even with careful adjustment, it gave variations in the results. Here a more consistent and easier calibration system should be installed.

---

[1] Capsule is a small plastic cavity which is sealed against the skin.

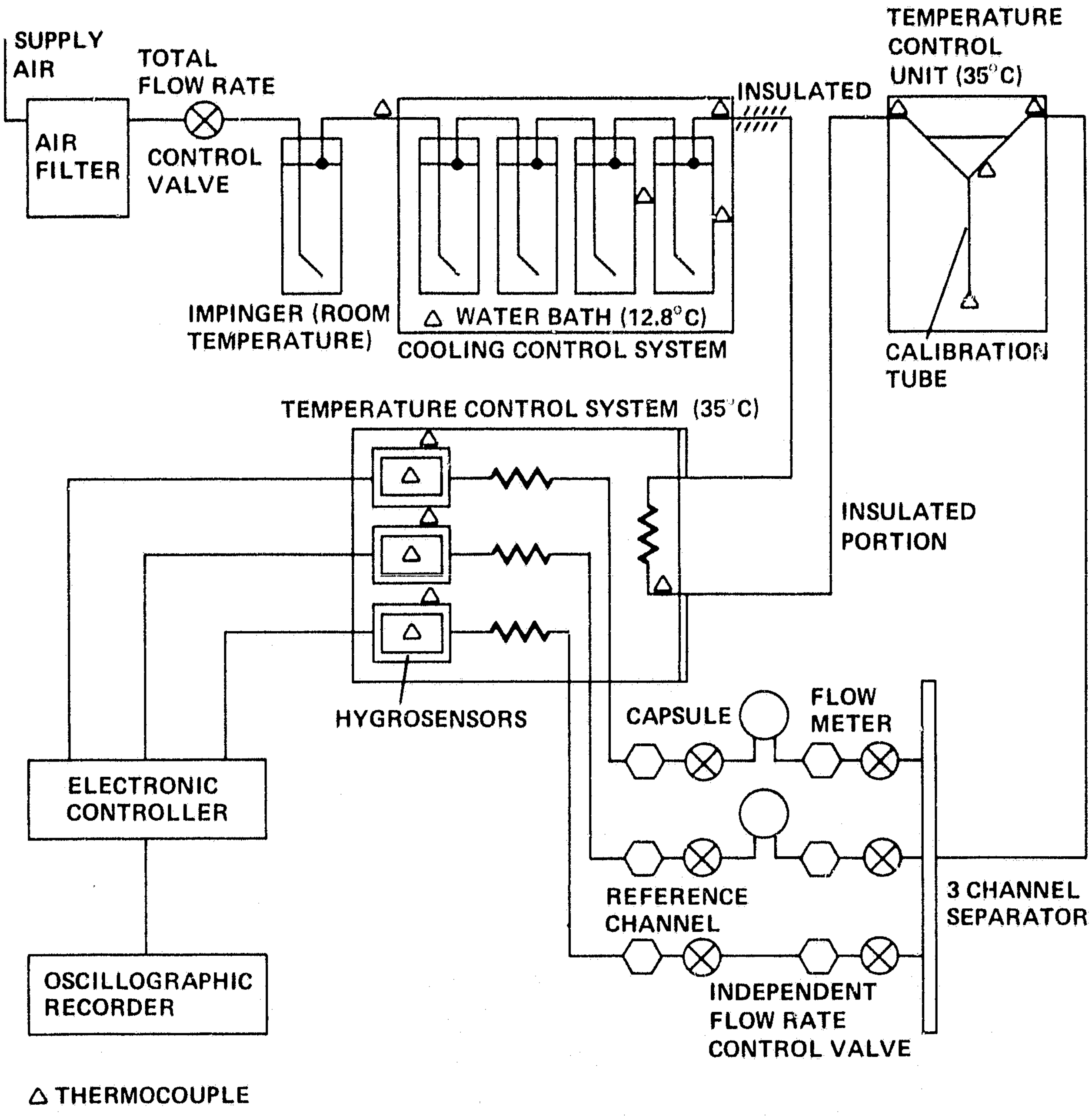

Figure 1.- Hygrometer schematic.

ORIGINAL PAGE IS
OF POOR QUALITY

3. It was found that the humidity sensing range of the hygrosensor (with a yellow sensing element[2]) operating at 35°C is between 26% and 35% relative humidity. This is an extremely narrow range and it is very temperature sensitive. Reduced temperature sensitivity and a wider humidity range would be preferable.

4. Daily shifts of the calibration curve were encountered. This may be due to aging problems of the resistance hygrosensor or other effects. However, stability for more than a day was never achieved, and a more stable hygrosensor would be preferable.

5. The poorly designed temperature control unit has only one light bulb, located at the center as a heat source for temperature control. It is controlled by a relay and a thermister circuit. This on-off heat source gave varying temperature-induced disturbances. Although adding insulation helped, this unit should be redesigned to give better temperature stability and control.

The instrument was modified in additional ways to solve some other minor difficulties. The sum of all modifications, given careful operation, was an instrument that was usable in a narrow humidity range.

Humidity Detection Techniques

The dew-point hygrometer (ref. 2) is one of several other means of measuring humidity. In the dew-point hygrometer, the temperature of a polished metal container is reduced until there is visible condensation of water vapor; the temperature at condensation is called the "dew-point temperature." This hygrometer is independent of room temperature, the detector assembly can be readily opened for cleaning and inspection, and dynamic response and accuracy seem to be adequate. However, the dew-point hygrometer has the disadvantages of mechanical complexity and optical element fragility.

An infrared gas analyzer (ref. 3) has been used successfully as a hygrometer. The analyzer operates on the principle that water vapor absorbs infrared radiation. The radiation source is usually a heated nichrome coil and the detector a thermopile arranged so that the signal is the potential difference between the sets of junctions. The sensitivity of the instrument is practically linear over a wide range of humidity and independent of the environmental temperature. However, the sensing response of the gas analyzer is rather slow, and simultaneous multichannel sensing is not practical.

---

[2] Humidity Sensor, American Instrument Company, 8030 Georgia Avenue, Silver Spring, Maryland 20910.

New Types of Resistance Hygrosensors

The crucial element of the hygrometer is the hygrosensing device. Although the resistance hygrosensor has the disadvantages previously mentioned, careful design of the resistance hygrosensor yields the advantages of lightweight, compactness, quick response, mechanical rigidity, and multichannel sensing capability.

A new type of resistance hygrosensor has been recently developed. Ackerman (in ref. 4) described an unusually effective lithium chloride humidity sensor that was developed to have a shorter response time. His construction details are presented in reference 4. The device is easy to make and quite temperature insensitive. Figure 2 shows typical data for the sensor, which exhibits a resistance of about 25 Ω at 12% and 2 MΩ at 90% relative humidity. Ackerman used a current of 0.5 μA to measure the humidity-induced resistance change. The humidity sensor shown in figure 2 consists of a film of 0.2 vol % $LiCl \cdot H_2O$ and 0.8 vol % $AlCl_3$ applied to a zig-zag electrode configuration.

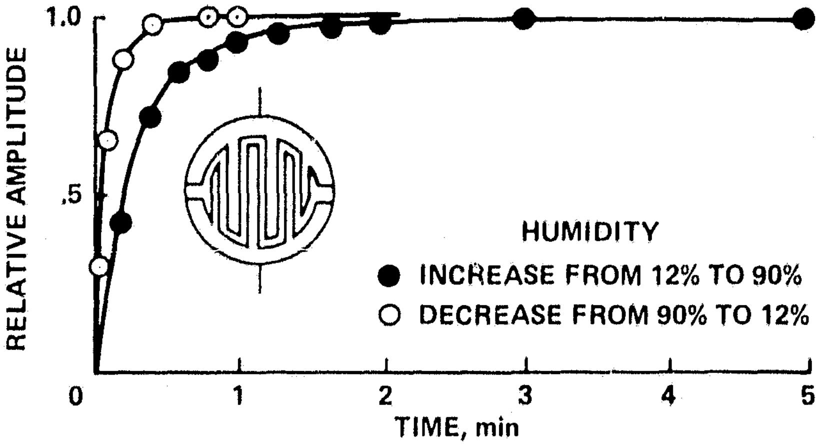

Figure 2.- Response to a step change in relative humidity of a lithium chloride humidity sensor. (Reproduced with permission of L. E. Baker. Courtesy of John Wiley & Sons, Inc.)

A new type of hygrometer has been designed by the McDonnell Douglas Corporation. The humidity sensing element is aluminum oxide, which is sensitive throughout the entire relative humidity range of 0 to 100%. Response curves of this instrument are shown in figure 3. It is expected that its superior sensitivity and self-contained microcomputer will allow more extensive study of human physiology and thermoregulation of the body.

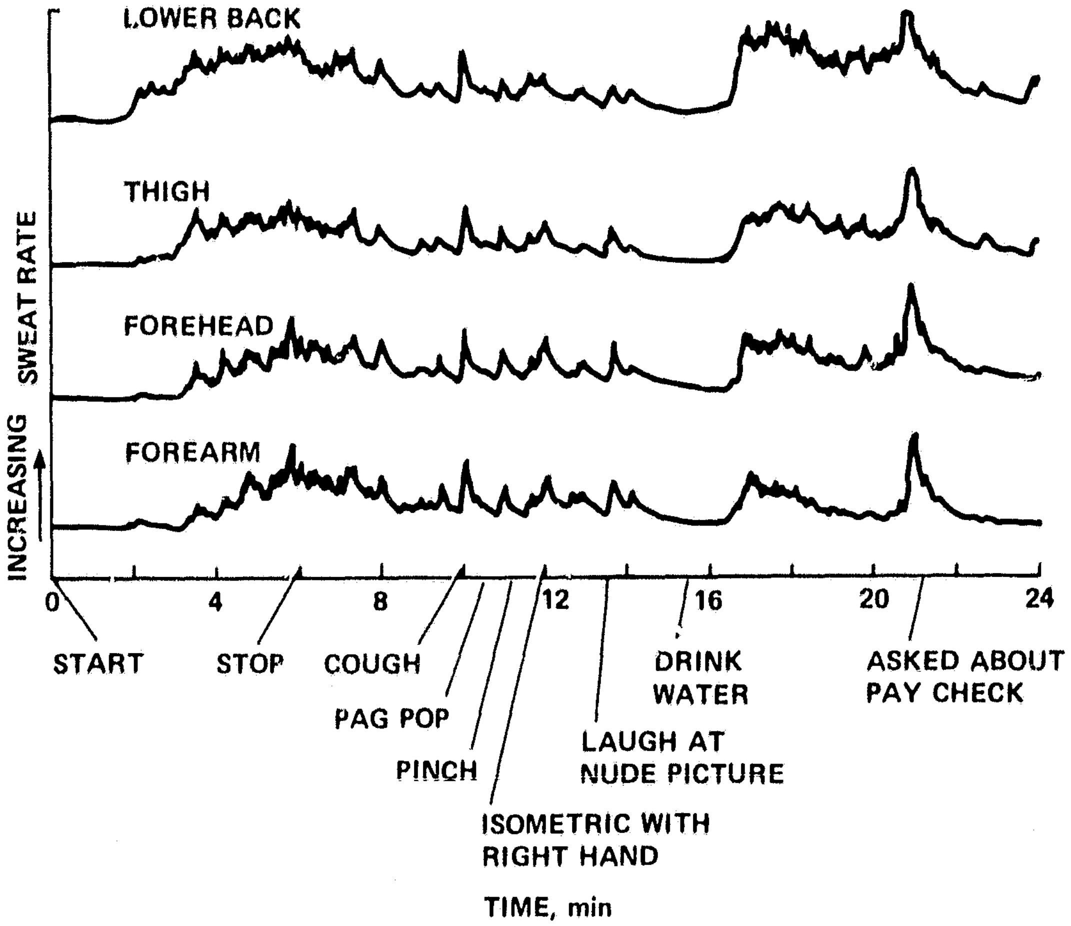

Figure 3.- Response curves of the hygrometer. (Reproduced with permission of McDonnell Douglas Astronautics Company.)

HUMAN PHYSIOLOGY

The evaluation of experimental results obtained with the hygrometer requires that the physiological functions of skin membranes and thermoregulation in humans, including sweating, be understood. The following discussion is based on the works of Stoll (ref. 5) and Kuno (ref. 6).

The Surface Skin as the Boundary Layer

The human thermoregulatory system is a very complex and sophisticated control network capable of responding to a wide variety of conditions when the body is subjected to thermal conditions within the limits of tolerability. To maintain the deep-core temperature of the body, the human body must constantly reject the metabolized heat into the surrounding environment (ref 1.).

Each individual balances this physiological requirement, through conduction, convection, evaporation, and radiation, in energy exchange with his surroundings.

From the previous statement, it is evident that the skin surface is the boundary layer of the body in a heat transfer sense. Less often it is thought of in terms of a thermal system although it is itself a heat generator, observer, transmitter, radiator, conductor, vaporizer, and detector (ref. 5).

To appreciate some of the irregular and heterogeneous aspects of the skin, consider figure 4 which shows the nature of the epidermis and dermis. The epidermis is subdivided into four layers — the stratum corneum, stratum lucidum, stratum granulosum, and stratum germinativum. The dermis is subdivided into two layers; subepithelia or papillary layer, and the recticular layer, both of which are composed of connective tissue. All layers except the stratum corneum are living, growing tissue and therefore produce metabolic heat (ref. 5).

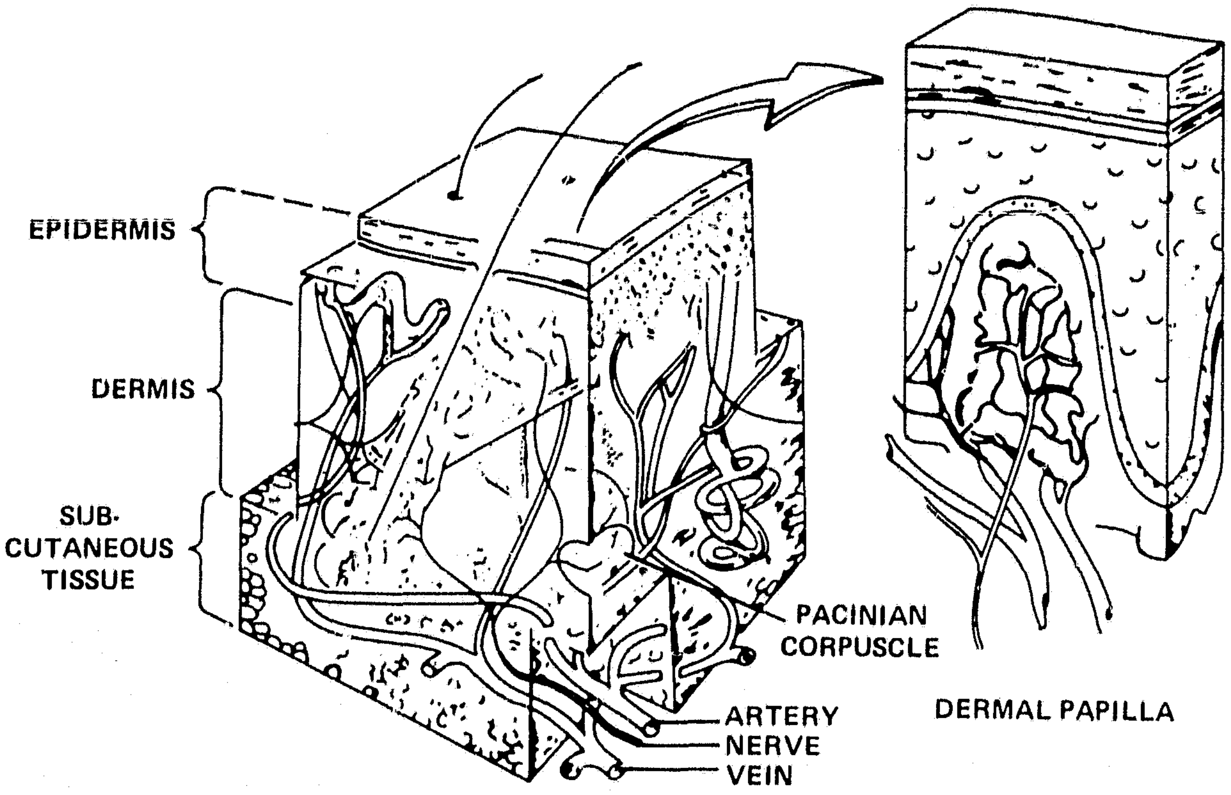

Figure 4.- Structure of human skin.

The thickness of the whole skin varies widely over the surface of the body. It may be more than 5 mm on the back and 0.5 mm on the eyelids. The usual thickness is about 1 to 2 mm. The approximate physical dimensions and the material properties are shown in table 1. From these figures, it is readily recognized that, by weight as well as surface area, the skin is one of the largest organs of the body. It comprises about 6% of the total body weight and exceeds the weight of the liver, brain, heart, and kidneys put together (ref. 5).

TABLE 1.- THE PHYSICAL DIMENSION AND MATERIAL PROPERTY OF THE SKIN
(Reproduced with permission of The American Society of Mechanical Engineers and A. M. Stoll.)

Approximate values of the physical dimensions of whole skin for the "average man" (weight 70 kg (154 lb); height 170 cm (67 in.))	
Dimension	Value
Weight	4 kg (8.8 lb)
Surface area	1.8 m^2 (20 ft^2)
Volume	3.6 ℓ (3.7 qt)
Water content	70 to 75%
Specific gravity	1.1
Thickness	0.5 to 5 mm (0.02 to 0.2 in.)
Approximate values for thermal and optical properties of skin	
Property	Value
Heat production	240 kcal/day
Conductance	9 to 30 kcal/m^2hr°C
Thermal conductivity, k	$(1.5 \pm 0.3)\times10^{-3}$ cal/cm sec°C at 23 to 25°C ambient
Mass diffusivity, k/pc	7×10^{-4} cm^2/sec (surface layer 0.26 mm thick)
Thermal inertia, kpc	90 to 400×10^{-5} $cal^2/cm^4 sec°C^2$
Heat capacity, c	0.8 cal/g°C
Emissivity, infrared	0.999
Reflectance, wavelength-dependent	Maxima 0.6 to 1.1 Minima 0.3 and 1.2
Transmittance, wavelength-dependent	Maxima 1.2, 1.7, 2.2, 6, 11 Minima 0.5, 1.4, 1.9, 3, 7, 12

Human Sweating

Sweating from the skin can be divided into two physiologically distinct and mechanically different water elimination processes: insensible and sensible water loss. Insensible water loss is subdivided into (1) cutaneous and (2) respiratory loss. Sensible water loss is subdivided into (1) thermal sweating and (2) mentally induced sweating. Figure 5 shows a simplified schematic of the human sweating system.

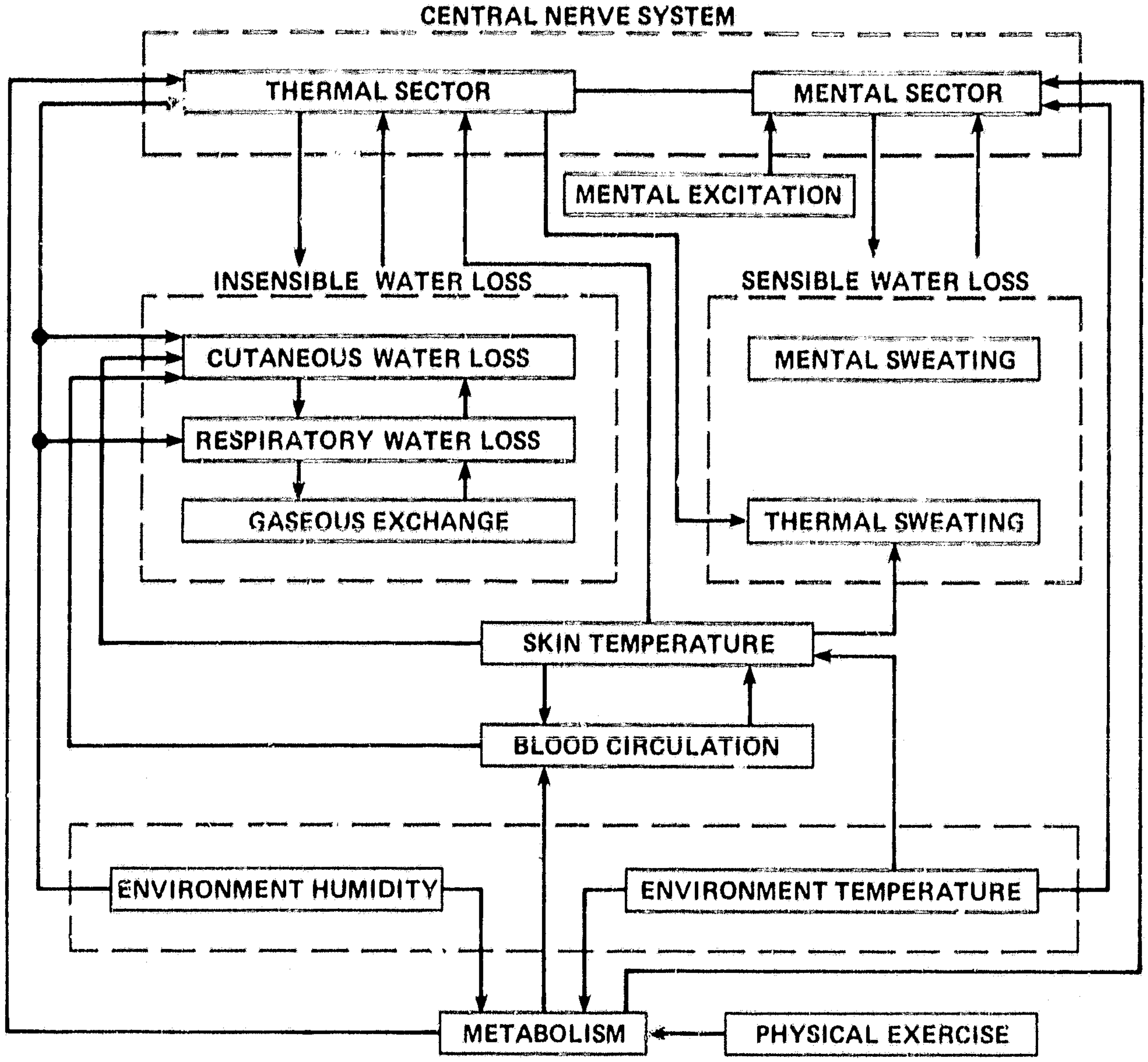

Figure 5.- Simplified schematic of sweating control.

Insensible Water Loss

Insensible water loss is a condition of discharge of water vapor from the respiratory passage (the respiratory water loss), and through the skin tissue (the cutaneous water loss), by diffusional process. Incidentally, the insensible water loss is not unique in animals. It is known as a "transpirational cooling system" in engineering and it has important cooling consequences in physical structures such as turbine blades and rocket nozzles where effective heat transfer is required.

With regard to the mechanism of insensible water loss, the respiratory and cutaneous losses differ a great deal from one another. The mucous membranes of the respiratory passageways are always very wet. The inspired air becomes saturated with the water vapor as it passes over those moist mucosal surfaces, and during expiration this vapor leaves the body. The loss of water by respiration may be theoretically calculated from the volume of respiratory air and the change in amount of vapor contained in the inspired and expired air. During severe muscular exercise the respiratory volume increases significantly.

Cutaneous water loss is passage of water vapor through the epidermis by diffusion, that does not involve sweating. The deepest layers of the epidermis are very wet, and the outer layers are dry. The whole system of the epidermis may be considered as a three-dimensional fibrous net, the bottom of which is immersed in the tissue fluid which soaks into the mesh. The mesh becomes smaller near the surface, and the water content of the epidermis becomes progressively less. Although the diffusivity of vapor through the skin varies for every part of the body, corresponding to the thickness of epidermis, the major barrier to diffusion is considered to be almost exclusively in the stratum corneum (refs. 6-8).

The respiratory water loss may be changed with varying humidity of the inspired air, and, according to Kuno (ref. 6), the greatest respiratory water losses occur with the breathing of dry air. The skin temperature and the blood circulation beneath the skin are known to affect the cutaneous water losses significantly. For example, local cooling can cause a shutdown of blood flow to the skin to a minimum estimated at about 0.015 $cm^3/min/cm^2$ (ref. 5). Local heating brings about local vasodilation, flooding the heated skin with blood at over 100 times the minimum rate, resulting in measured thermal conductivity as much as 4 times the value determined at the normal temperature (ref. 5).

Sensible Water Loss

Sensible water loss is the evaporation of sweat from the skin surface from thermal sweating or mental sweating, which are considerably different from each other.

Thermal sweating does not start immediately on exposure to a hot environment, but after a latent period (ref. 6). The latent period varies considerably with surroundings and intrinsic conditions. The skin temperature is one of the most important factors influencing thermal sweating. Prolonged local heating brings on sweating, not only of the heated area, but also of nonheated areas of the skin, indicating that remote as well as local effects may be produced by signals relayed from the skin detectors to the central nervous system (see fig. 5) (ref. 5). More intensive heating may stimulate pain receptors, resulting in reflex withdrawal of the limb or perhaps the entire body. Increase in metabolism due to physical exercise also increases thermal sweating considerably. The active secretion of sweat requires energy as well, so that thermal sweating is accompanied by increased heart rate and supplementary heat loss from the entire body. The excitability of thermal sweating is very low under normal conditions, but becomes high under thermal stress (ref. 6).

The features of mental sweating differ considerably from those of thermal sweating. Mental sweating has a spontaneous reaction at its onset; it immediately attains a certain rate of secretion which corresponds to the intensity of stimulation, remains so as long as the stimulation lasts, and subsides at once after it ends. Some factors of mental sweating are quite contrary to the body temperature regulation. Unlike thermal sweating, this mentally induced center of sweating is always ready to actively respond to any stimulation (ref. 6). This observation can be seen clearly from the response curve of the hygrometer (see "asked about pay check," fig. 3).

Physiological Application of the Hygrometer

As we have seen, human sweating is a highly complex servomechanism of the thermoregulation of the body. From reference 5:

> Within less than 5 mm of thickness of the boundary, the skin manifests an alarm system to detect and transmit signals indicating dangerous extremes of temperature; a living organ generating, dissipating, and modulating the flow of heat between the entire organism and its environment; an indispensable, valuable yet highly regenerative and adaptable thermal integument having remarkable ability to alter its properties, thus inhibiting heat loss in cold and augmenting heat loss in the heat.

The significance of sweating is reflected most obviously in the relative narrowness of the thermal comfort zone. It is the skin rather than the body as a whole, which by virtue of its wealth of sensory receptors, dictates the physical features of a comfort environment (ref. 5). However, under extreme heat, when the heat lost by evaporation of sweat is not large enough to cover the heat gained by the body from the surroundings or by metabolic output, heat will be accumulated in the body and heat stroke may develop. The sweating seems to decrease or disappear in some stages of heat accumulation, for the dry hot skin indicating the suppression of sweating is known as one of the characteristics of heat stroke (ref. 6).

Measurement of the local skin conditions certainly gives us clues to any changes in the thermosensory mechanisms of the entire body as well as disturbances of thermal function of the entire body. The individual margin of safety will be considerably improved if the early warning of impending danger is sensed by a hygrometer and corrective action results. An example of such a warning is the appearance of "cold sweat," accompanied by the occurrence of motion sickness when the subject is experiencing accelerative forces and the increase or decrease of insensible water loss and unusual sweating during space flight. Measuring any of these sweat disturbances would provide vital information to monitors of long-duration space flights in which the loss of thermal sensation by a crew member might signal a dangerous health problem. Performance of complicated tasks requiring judgment and precision on the part of an operator can be continued over long periods of time only when crew members are healthy. In any event, monitoring the state of this sensory system during voyages to outer space will undoubtedly be important.

HEAT AND MASS TRANSFER

The main environmental factors that determine the evaporative heat loss from a human are temperature, humidity, and movement of the surrounding air. One of the central challenges associated with the resistance hygrometer-evaporative capsule technique is the ability to separate the physical state of an organism's environment from its physical response to that environment.

Much has been learned empirically about the effects of the environment that separately influence the evaporative heat loss from the localized skin (refs. 9, 10). Changing the humidity inside a capsule covering a small area of sweating skin has a marked effect on the local evaporative heat loss (ref. 11). Goodman and Wolf (ref. 12) also indicate that insensible water loss is a function of the vapor concentration inside the sweat monitor capsule (see table 2), although it is not linearly distributed.

TABLE 2.- INSENSIBLE WATER LOSS AS A FUNCTION OF THE VAPOR CONCENTRATION INSIDE THE SWEAT-MONITOR CAPSULE: PAIRED EXPERIMENT[a]
(Reproduced with permission. Courtesy of J. Appl. Physiol.)

Subject	Capsule vapor pressure, mmHg		Increment of loss rate,[b] μg/cm^2/min	% decrease[c]
	0.0	7.0 ± 0.5		
9	8.6	5.9	2.7	31
	10.6	7.5	3.1	29
10	12.8	7.9	4.9	38
11	12.6	8.5	4.1	32
12	11.9	8.1	3.8	32
14	12.5	8.5	4.0	32
	14.1	9.8	4.3	30
15	14.6	10.6	4.0	27
	16.0	11.1	4.9	31
	15.6	8.9	6.7	43
16	21.6	15.5	6.1	28
Mean[d]	13.9	9.4	4.5	

[a] Air velocity = 17.7 cm/min; room temperature = 25.0 ± 1.0°C.

[b] Loss rate at 0.0 mmHg minus loss rate at 7.0 mmHg.

[c] Increment of loss rate divided by loss rate at 0.0 mmHg.

[d] Mean computed with average value for each subject.

A similar contrast exists for air movement. Increasing the wind velocity to which a human is exposed results in reduced cutaneous water loss (see discussion in ref. 9) presumably because a decrease in evaporative demand is the result of an increase of convective heat loss (ref. 9). On the other hand, increasing the ventilation rate through an evaporative capsule increased the rate of evaporation (ref. 9). Similar observations were recorded using the resistance hygrometer we tested. Figure 6 shows the influence of the air flow through the capsule versus the insensible water loss, when the skin temperature was held constant. There is a noticeable drying of the skin due to higher air flow through the capsule and, simultaneously, the evaporative water loss increases. The marked effect of skin temperature on the rate of sweating is indicated by many authors; figure 7 shows one of these observations (ref. 13). Each curve in figure 7 represents one experiment. The thermal status of the subject is indicated at the upper left-hand corner. (T_{ty} = tympanic temperature, T_{re} = rectal temperature, T_{mws} = mean weighted skin temperature, $\bar{T}_b$ = calculated mean body temperature.) The figures at the top of each column are ambient temperatures.

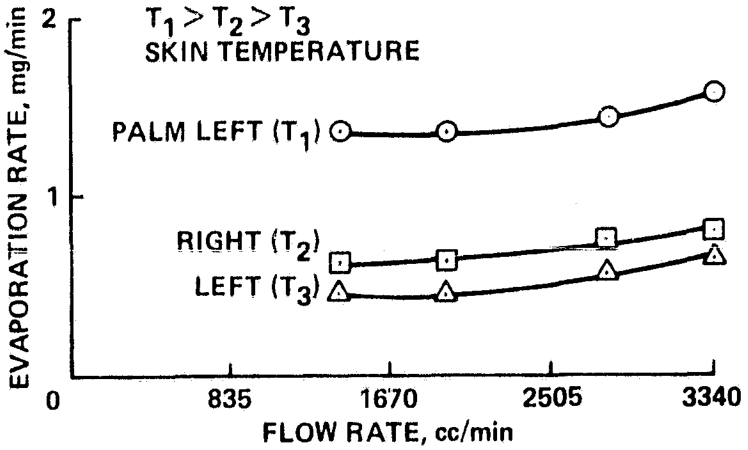

Figure 6.- Influence of air flow through the evaporative capsule holding the skin temperature constant.

A serious question arises from all of these observations as how the physiological adjustments of human perspiration are so effective in controlling evaporative heat loss when locally it is so easily influenced by environmental factors. Evaporation from the skin, which is the conversion of the liquid to the gaseous phase, is probably caused by a particular set of external conditions, and by the ability of the appropriate control centers of the organism to sense this condition and ultimately to stimulate the sweating centers from the outer skin.

In the search for the rational specification of environment, the following discussion of convective heat and mass transfer equations is developed to express the evaporative phenomena of the outer skin as explicit functions of the temperature, humidity, and movements of the surrounding air.

T_a°C	34	35	37	39
T_{t_y}	37.14	37.23	37.20	37.96
T_{re}	37.20	37.80	37.30	38.23
T_{mws}	35.00	36.50	35.50	37.20
$\bar{T}_b$	36.54	37.20	36.76	37.90

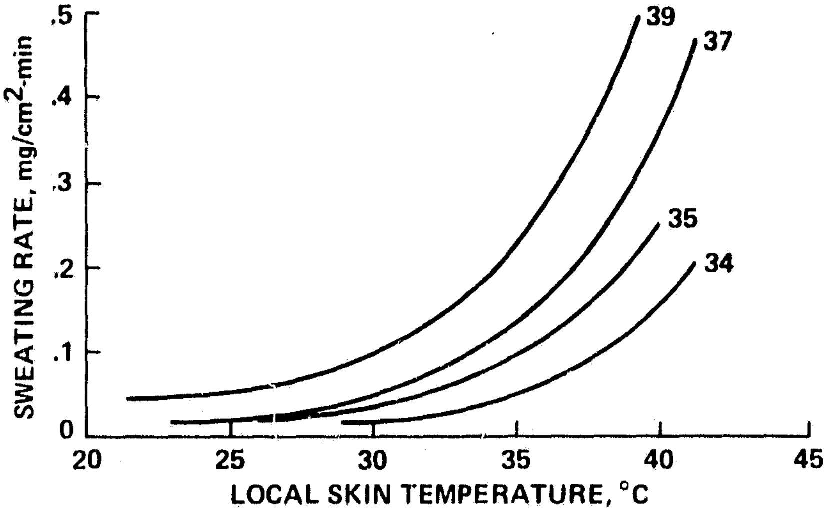

Figure 7.- Marked effect of skin temperature on the rate of sweating (ref. 14).

Stefan's Law

The symbology and derivation discussed here are taken directly from Stefan, as expressed in reference 14, where he shows a combination of diffusive and convective mass transfer from a liquid surface, for isothermal, one-dimensional, stagnated air flow. Stefan's law is applied to the diffusion of water vapor from the wet skin placed inside the sweat monitor capsule (fig. 8).

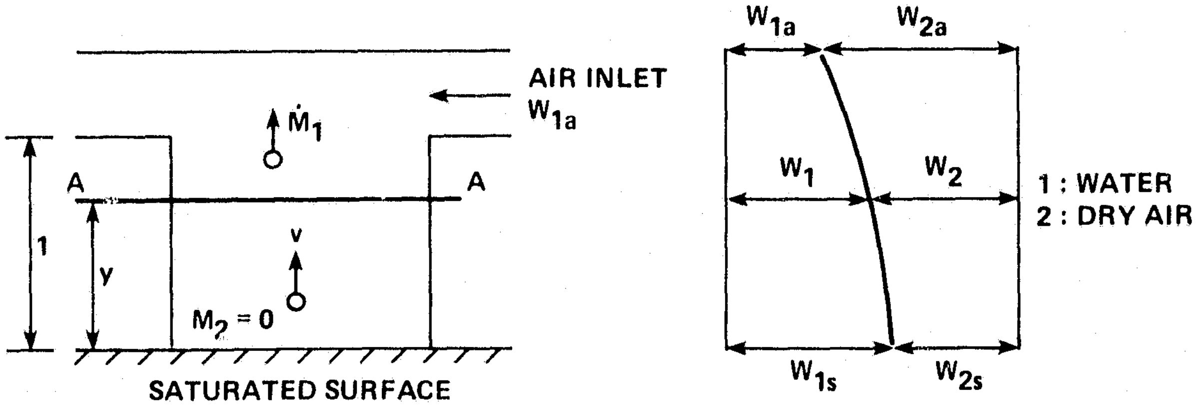

Figure 8.- Diffusion of water vapor from wet skin placed inside sweat monitor capsule.

Air is blown with a certain mass fraction W_{1a} of water vapor across the top of the capsule, and air velocity is assumed very small so that stagnation conditions at the base of the sweat monitor capsule are maintained. The total pressure inside the capsule is constant and approximately equal to the outside pressure. Also the temperature is assumed as constant throughout the sweat monitor capsule. The mass fraction W_{1a} of the water vapor outside the capsule is generally different from that at the saturated surface. The partial pressure of the water vapor over the water surface equals the saturation pressure at the surface temperature. In this way the mass fraction W_{1s} is prescribed. Gradients of the mass fraction W_1 and a diffusive flow of water vapor exist in the capsule. Since the mass fraction of the water vapor W_1 and the mass fraction of the air W_2 add up to 1, a gradient of the vapor mass fraction corresponds to a gradient of the mass fraction of the air. Because a diffusion law must also be valid for air, a mass flow of air must arise that is in a direction opposite that of the vapor flow. No air can leave the tube at the bottom, however, for it is closed there. Therefore, a convective flow in an upward direction must be present within the capsule, which compensates for the diffusive air flow. The velocity of this convective flow is v. The amount of water vapor that is transported by this convective flow through the cross section AA per unit area and time is $\rho_1 v$. Therefore, the whole mass velocity of the water vapor at the cross section AA is

$$\dot{M}_1 = -\rho D \frac{dW_1}{dy} + \rho_1 v \tag{1}$$

where D = the diffusion coefficient. The same relation must be valid for the resulting air flow. Since this flow is zero, the resulting equation is

$$\dot{M}_2 = -\rho D \frac{dW_2}{dy} + \rho_2 v = 0 \tag{2}$$

This equation gives the velocity:

$$v = \frac{D}{W_2} \frac{dW_2}{dy} \tag{3}$$

The mass fraction of the air can be expressed by

$$W_2 = 1 - W_1 \tag{4}$$

$$\frac{dW_2}{dy} = -\frac{dW_1}{dy} \tag{5}$$

This gives

$$v = -\frac{D}{1 - W_1} \frac{dW_1}{dy} \tag{6}$$

The mass flow of water vapor through the tube is, according to equation (1)

$$M_1 = -\rho D \frac{dW_1}{dy} - \frac{\rho_1}{1 - W_1} D \frac{dW_1}{dy} = -\frac{\rho^2}{\rho_2} D \frac{dW_1}{dy} \tag{7}$$

For an integration of this equation, it is advantageous to change to partial pressure. With the relations

$$W_1 = \frac{P_1 R}{R_1 P} \tag{8}$$

$$(R = W_1(R_1 - R_2) + R_2)$$

there is obtained

$$\frac{dW_1}{dy} = \frac{R^2}{R_1 R_2} \frac{1}{P} \frac{dP_1}{dy} \tag{9}$$

$$\dot{M}_1 = \frac{\rho R}{\rho_2 R_2} \frac{D}{R_1 T} \frac{dP_1}{dy} \tag{10}$$

$$\dot{M}_1 = -\frac{D}{R_1 T} \frac{P}{P - P_1} \frac{dP_1}{dy} \tag{11}$$

This equation is called Stefan's law. By separating the variables, there results

$$\frac{dP_1}{P - P_1} = -\frac{M_1}{D} \frac{R_1 T}{P} dy \tag{12}$$

By integration between $y = 0$ and $y = 1$

$$\ln \frac{P - P_{1a}}{P - P_{1s}} = \dot{M}_1 \frac{1}{D} \frac{R_1 T}{P} \tag{13}$$

$$\dot{M}_1 = \frac{D}{1} \frac{P}{R_1 T} \ln \frac{P - P_{1a}}{P - P_{1s}} \tag{14}$$

where

P_{1a} = partial pressure of water vapor at the top

P_{1s} = partial pressure of water vapor at the skin

As long as the partial pressure of the diffusing gas at the surface and the stream are small compared with the total pressure, equation (14) can be simplified to

$$\dot{M}_1 = \frac{D}{l}\frac{1}{RwT}(P_{1w} - P_{1s}) \quad (15)$$

Rw is the gas constant for water vapor (47 N-m/kg-K) for pressure in units of kg/m^2, or 3.47 mmHg/kg-K for pressure in units of mmHg. As we can see, Stefan's law can transform into Fick's law of diffusion. It can be expressed in mass-transfer coefficient h_D (kg/hr per kg/m^3 or m^3/hr)

$$\dot{M}_1 = h_D \frac{1}{RwT}(P_{1w} - P_{1s}) \quad (16)$$

By substituting the latent heat of vaporization (λ), the equation can be expressed in the equation of evaporative heat transfer

$$\dot{E}s = he(\Delta P)$$

$$he = \frac{h_D\lambda}{RwT} \quad (17)$$

Theoretically, however, the use of equation (17) can be argued a little further. All the evaporation from a saturated skin fulfills the condition of a semipermeable surface. However, the dry air does not reach zero velocity, for it is always dissolving in the liquid. An examination of the temperature distribution along a normal to the surface interface would reveal the profile illustrated in figure 9. The temperature varies continuously, having its lowest point at the water-air interface. It is therefore evident that heat is transferred toward the interface from both sides. A vapor pressure gradient will occur at the surface as soon as mass flow from the surface occurs, but the difference is very small and usually can be neglected (ref. 15).

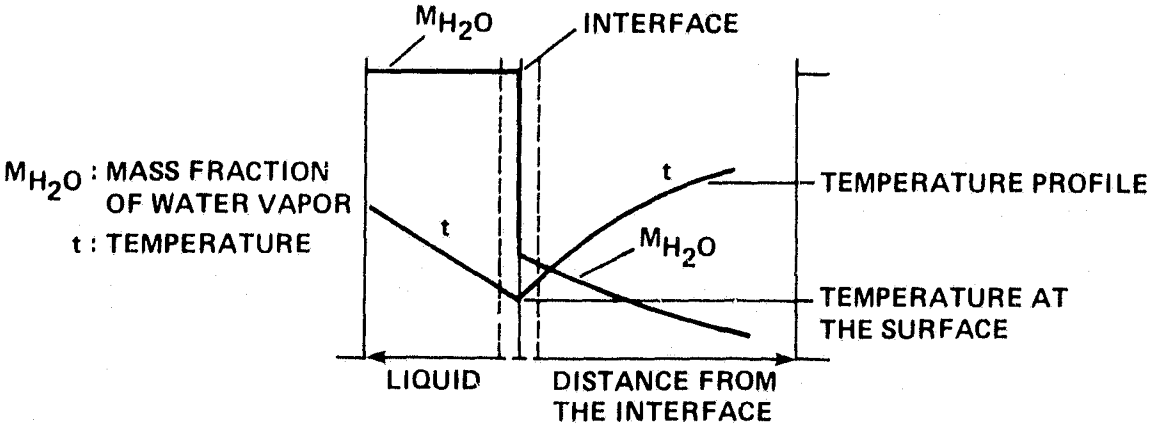

Figure 9.- Temperature profile along water-air interface.

From all these considerations, we recognize some of the limitations of equation (17), which is widely used in the physiological literature as a basic heat- and mass-transfer equation. Equation (17) can only apply to the one-dimensional, isothermal, stagnated air flow, with an impermeable saturated surface. More complex and dynamic forced or free mass movements of the fluid are frequently described, using the concept of dimensionless numbers and experimentations to account for the various groupings of thermophysical properties of the particular carrier fluid in different combinations with other aspects of transport process.

Lewis Number

There are known correlations in heat and mass transfer that have analogies. In the laminar boundary layer overlaying a water-air interface, the dimensionless profile of temperature (heat), partial pressure (mass), and velocity (momentum) are similar in both laminar and turbulent flow. Mathematically, this can be expressed by equating the similar dimensionless groups

$$\frac{h_D L^*}{Dw} = \frac{h_C L^*}{K} = \frac{f}{2}\,\frac{VL^*}{\nu} \qquad (18)$$

In these equalities

$\frac{h_D L}{Dw}$ is the Sherwood number

$\frac{h_C L^*}{K}$ is the Nusselt number

$\frac{VL^*}{\nu}$ is the Reynolds number

f is the function factor

Equation (18) applies only to gases (e.g., moist air) for which the Prandtl number ($Pr = C_{pm}\mu/K = \nu/\alpha$) and Schmidt number ($Sc = \mu/\rho_{am}Dw = \nu/Dw$) are equal and approximately unity, that is, where the mass, thermal, and momentum diffusivity are essentially the same ($Dw = \alpha = \nu$). Also it is restricted to conditions where the partial pressure difference is small, which is the case with most physiological conditions (ref. 15).

Equation (18) transforms into one of the most widely used mass- and heat-transfer equations in the engineering literature. The Prandtl number divided by the Schmidt number gives

$$\frac{Pr}{Sc} = \frac{C_{pm}\mu/K}{\mu/\rho_{am}Dw}$$

$$= \frac{\rho_{am}DwC_{pm}}{K}$$

$$\frac{Pr}{Sc} \cdot \frac{1}{\rho_{am}C_{pm}} = \frac{Dw}{K}$$

Substituting into the right-hand side of equation (18)

$$\frac{h_D L^*}{Dw} = \frac{h_C L^*}{K}$$

$$h_D = h_C \frac{Dw}{K}$$

$$h_D = \frac{h_c}{\rho_{am}C_{pm}} \cdot \frac{Pr}{Sc}$$

Under the postulated equality $Pr/Sc \approx 1$, this reduces to

$$h_D \approx \frac{h_C}{\rho_{am}C_{pm}}$$

$$\frac{h_C}{h_D\rho_{am}C_{pm}} \approx 1 \text{ (the Lewis number)}$$

The Lewis number[3] is a basic relationship that relates the wet-bulb temperature and dry-bulb temperature to the air humidity; it is frequently used in the engineering design of the evaporative systems. This same modeling logic has been used in heat- and mass-transfer predictions from the saturated skin surface of human. Both physiologists and engineers have historically set the Lewis number equal to 1 in such uses. However, the Schmidt number for the diffusion of water in air at 1 atm is constant at $Sc = 0.60 \pm 4\%$ over the air temperature range of 0 to 50°C. Therefore, the Lewis relationship is not strictly correct, because the ratio $Pr/Sc = 0.72/0.60 = 1.2$ rather than unity (ref. 15).

The inaccuracy of the Lewis number, being set equal to 1, has also been improved to include the effects of the Prandtl number to a more precise degree, by another analogy known as the Chilton-Colbun analogy (ref. 16),

---

[3] The coefficient of mass transfer is equal to the mean convection coefficient divided by the volumetric specific heat of the main stream moist air.

$$h_D = \frac{h_C}{\rho_{am} C_{pm}} (Pr/Sc)^{2/3}$$

$$\frac{h_C}{h_D \rho_{am} C_{pm}} = (Pr/Sc)^{2/3} = 1.129$$

This correction to the heat-mass transfer analogy was deduced from extensive correlation of experimental data on heat and mass transfer from planes, surfaces, cylinders, and spheres by Ede (ref. 17). However, in turbulent flow, where the laminar sublayer is very thin, Eckert (ref. 14) has shown that the Lewis number is 1, regardless of whether or not the Prandtl and Schmidt numbers are equal.

As a result, it becomes important for us to verify experimentally the validity and accuracy of the Lewis number. Consequently, an inanimate evaporative object was designed and installed inside a calorimeter to test the Lewis number correlation.

The Sweat Cylinder Experiment

A 0.2-μm-porous sweat cylinder was installed inside the calorimeter to investigate the validity and accuracy of the Lewis number. The experimental setup (fig. 10) was designed to simulate the evaporation from completely saturated body segments, such as the thigh. Since the surface tension lifts water from the beaker into the cylinder, water level between the beaker and cylinder is critical in this experiment. The optimum height was determined so that water saturated the entire surface, and the water consumption from the beaker was essentially equal to that of evaporation from the cylinder. Thermocouples were attached to the side face of the cylinder to monitor its skin temperature. The skin temperature was recorded every 20 min and the constant skin temperature was observed after adiabatic saturation was achieved. Dry-bulb and wet-bulb temperatures of the inlet and outlet air were plotted on the psychrometric chart to determine the enthalpy changes, which would be used to determine the coefficient of mass transfer and the mean convection coefficient. The net enthalpy change, however, would be essentially negligible if the adiabatic saturation condition was achieved.

The Experimental Result

The Lewis number for an inanimate evaporative cylinder was determined, and the experimental results are shown in table 3. The Lewis number was found to be slightly larger than the unity. Note that the air flow rate was sufficiently small that a laminar boundary layer was probably formed around the cylinder. However, since the Monoman calorimeter was designed to measure human metabolism, precise measurements of evaporative heat loss from the cylinder was difficult. A number of tests were abandoned because the mass and humidity balances of the calorimeter were not within acceptable levels. The indicated result was from the best test.

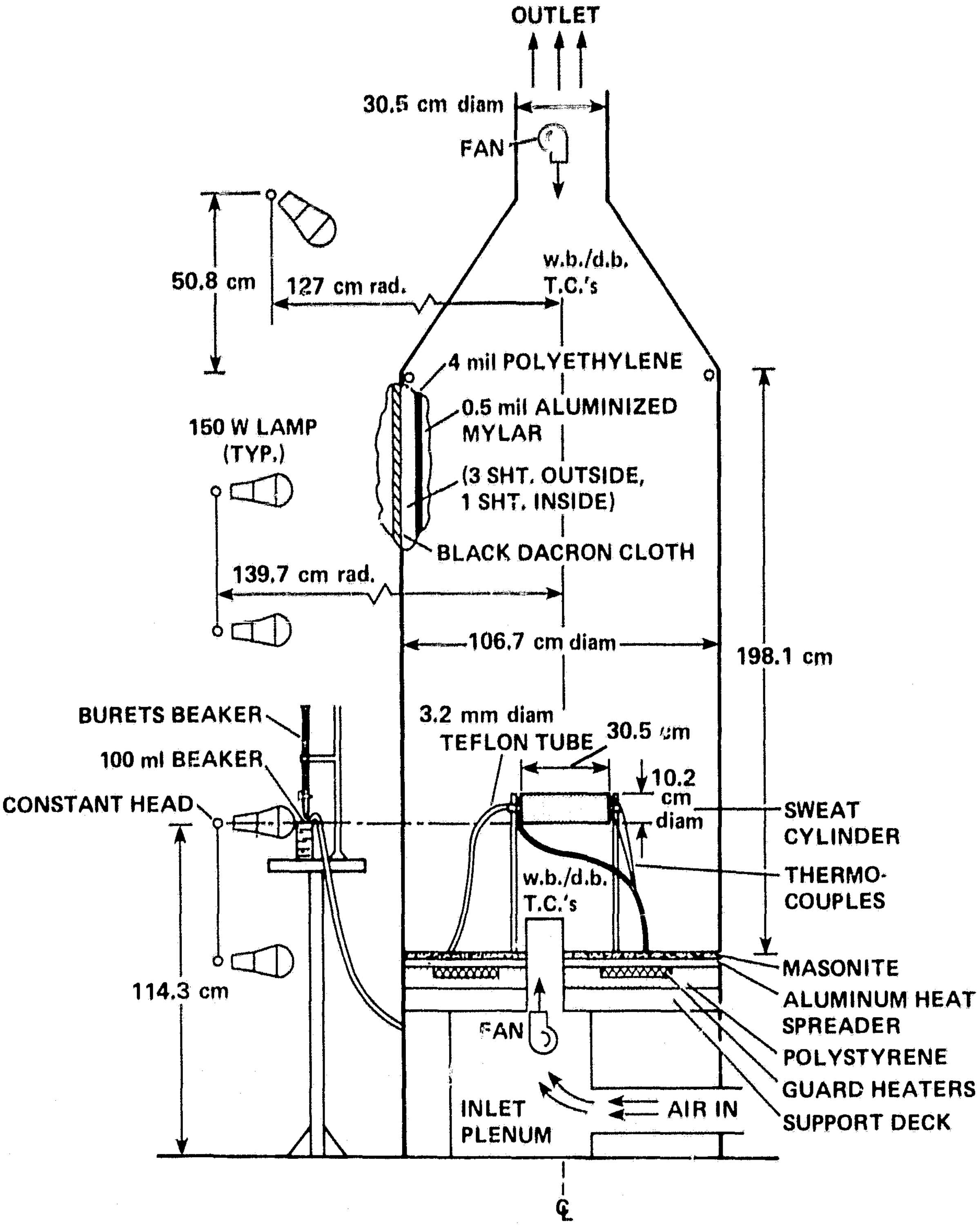

Figure 10.- Experimental setup of the sweat cylinder.

TABLE 3.- COEFFICIENT OF MASS TRANSFER AND EVAPORATIVE HEAT LOSS FROM SWEAT CYLINDER

Airflow velocity, ft/min	4.20
Experimental condition[a]	
T_a, °C.	34.1
T_s, °C.	27.4
P_A, mmHg.	14.30
P_{skin}, mmHg	27.60
Re.	131.1
Mean convection coefficient, cal/sec-°C.	0.172
Mass transfer coefficient, m^3/sec.	4.9×10^{-4}
Volumetric specific heat of air ($P_{am}C_{pm}$), kcal/m^3-°C	0.28
Lewis number	1.24

[a] T_a = inlet temperature; T_s = cylinder surface temperature, P_A = inlet partial pressure of water vapor; Re = Reynolds number = Vd/ν, calculated on sweat cylinder diameter; number of tests = 5.

CONCLUSIONS

1. It is desirable to apply formal methods of convective heat- and mass-transfer theory in the evaluation and support of experimental findings derived from hygrometer measurements. This application to physiology of heat- and mass-transfer theory, employing nondimensional parameters, permits verification, classification, and useful generalization of experimental procedures. The concept of dimensionless numbers and the related modeling logic can be applied in the case in which a laminar boundary layer overlies a continuous water-air interface. Extending this analysis to the condition where only a portion of the skin area is saturated (which is frequently the physiological condition), is a more questionable undertaking. Concepts that apply a skin wetness fraction factor (X) as a multiplier on the surface area (A) to give an effective area (XA) (ref. 1) may cause trouble in applying classical correlations.

Kerslake (as noted in ref. 15) determined experimentally the ratio of the coefficient of evaporative heat loss to the mean convection coefficient ($he/h\bar{c}$ = 2.26 sec°C/mmHg) on nude subjects under conditions where their skin was completely saturated with water. However, if complete wetting of skin is observed under thermal heat stress, does not the secretion of sweat exceed the evaporation from the skin?

Heat- and mass-transfer projections derived from an inanimate evaporative object are unlikely to apply to the human skin. As a result, the use of the same Lewis number in heat- and mass-transfer predictions for the human as for an inanimate object is probably not justified.

2. In the original design of the hygrometer, dry inlet air was used; indeed, many hygrometers use dry air or dry N_2. Since the evaporative phenomena from the outer skin are dominated by thermophysical properties of the particular carrier fluid as previously mentioned, the observed findings from these hygrometers would be seriously different from the actual diffusion process for the actual environment. It is desirable to set the microclimate created inside the evaporative capsule as close as possible to the actual environment.

3. Some newly designed hygrometers (ref. 18) are equipped to control the temperature of the skin beneath the evaporative capsule. The purpose of this unit is to match the skin temperature in the capsule with that of the adjacent skin areas. However, is it physiologically possible to maintain the constant localized skin temperature without disturbing thermosensory mechanisms of the skin? Or are there any constant localized skin temperatures for the human body?

An acceptable method, from the author's viewpoint, for measuring the physiological change on sweating rate or transpirational water loss is to operate the evaporative capsule without any temperature control of the skin.

4. The central problem of the evaporative capsule technique is essentially the ability to obtain the physiological response of human perspiration without any disturbance of the physical state of the environment. Neither does the present design of the evaporative capsule separate nor distinguish insensible water loss from the presence of sweating. The evaporative capsule design (fig. 11) detects not only the evaporative water loss, but also any noticeable change in the skin temperature as well as changes in the localized metabolism. The adiabatic evaporative capsule, which can be considered as the partial calorimeter, might be able to distinguish sensible and insensible water loss by measuring the local metabolism accompanied by the secretion of sweat; however, its design would be very challenging.

5. The evidence of this study leads to the conclusion that more extensive research, using the evaporative capsule-resistance hygrometer technique, is necessary before the significance of human sweating will be understood. Again, unless the components of the thermal environment can be specified in a physiologically meaningful way, the nature of the physiological response cannot be recognized and understood. Some of the crucial investigations relative to the resistance hygrometer can be listed as follows:

- To design various shapes for the evaporative capsule and to find out how convective flow created inside the evaporative capsule will change the local sweating rate.

- To find comprehensive relationships among the convective flow, humidity, and temperature, and their effect on the localized perspiration rate. For example, what is the optimum inlet temperature and humidity for measuring the physiological response from the local skin?

- To build an adiabatic capsule and study whether it can detect any noticeable change in localized metabolism and skin temperature.

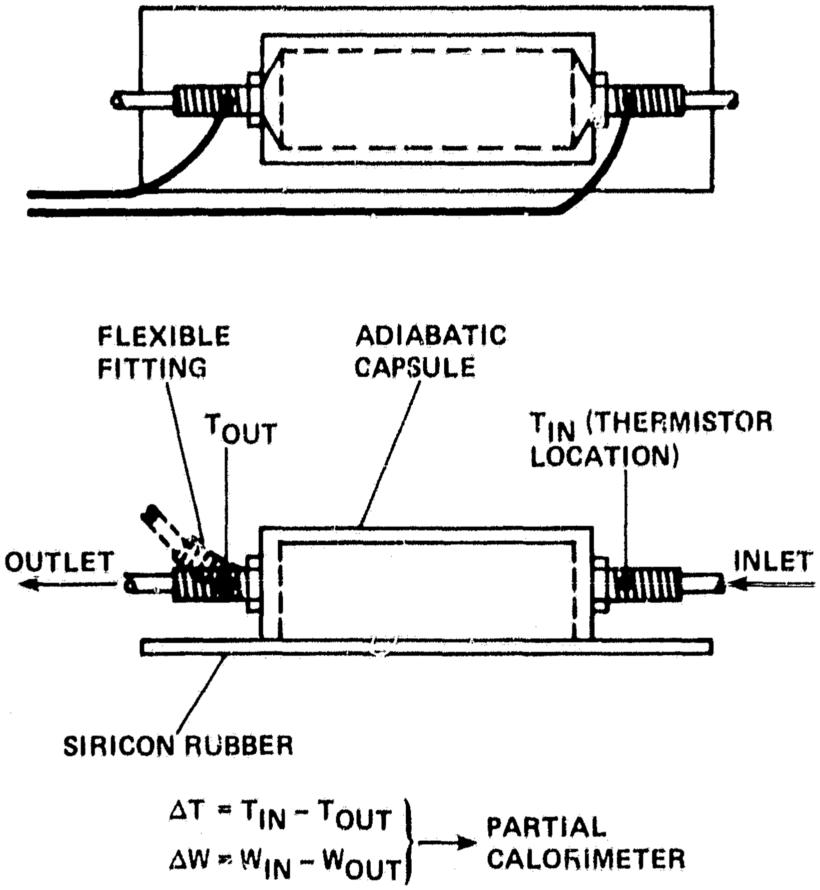

Figure 11.- Evaporative capsule design.

- To determine the heat of evaporation from the skin of human subjects. Higher heat of vaporization than the heat of evaporation of water was suggested by Snellen, and Michell and Wyndham (see discussion in ref. 9). How effective is insensible water loss for evaporative heat loss? How does sensible water loss contribute to the overall evaporative heat loss from the human body?

- The response curve of the resistance hygrometer shows that the sweat pattern from the localized skin is accompanied by periodical fluctuations and cyclic frequent changes. How is a continuously pulsatile evaporative pattern related to the physiological state of the human body?

REFERENCES

1. Pefley, R. K.; and MacDonald, J. T.: The Use of the Physiological Thermal Index (PTI) as an Alternative to Effective Temperature for Civil Defense Planning. University of Santa Clara, Santa Clara, Final Report — Part B, Defense Civil Preparedness Agency, Department of Defense, Contract No. DAHC 20-69-C-0128, Work Unit 1224D, Nov. 1977, 70 p.

2. Brengelmann, G. L.; McKeag, M.; and Rowell, L. B.: Use of Dew-Point Detection for Quantitative Measurement of Sweating Rate. J. Appl. Physiol., vol. 39, no. 3, Sept. 1975, pp. 498-500.

3. Albert, R. E.; and Palmes, E. D.: Evaporative Rate Patterns from Small Skin Areas as Measured by an Infrared Gas Analyzer. J. Appl. Physiol., vol. 4, Sept. 1951, pp. 208-214.

4. Geddes, L. A.; and Baker, L. E.: Principle of Applied Bio-Medical Instrumentation. Second ed., New York: John Wiley & Sons, 1975, 616 p.

5. Stoll, A. M.: The Role of the Skin in Heat Transfer. J. Heat Transfer, ASME Transactions, vol. 82, August 1969, pp. 239-242.

6. Kuno, Y.: Human Perspiration. C. C. Thomas, Springfield, Ill., 1956.

7. Nicoll, P. A.; and Cortese, T. A., Jr.: The Physiology of Skin. Annu. Rev. Physiol., vol. 34, 1972, pp. 177-203.

8. Tregear, R. T.: Physical Functions of Skin. New York: Academic Press, 1966.

9. McLean, J. A.: Loss of Heat by Evaporation. In: Heat Loss From Animals, J. L. Monteith and L. E. Mount, eds., London: Butterworths, 1974, pp. 19-31.

10. Pefley, R. K.; Cull, E. T., Jr.; and Skeins, K. M.: Monoman Calorimeter Project. University of Santa Clara, Santa Clara, Office of Civil Defense, Office of the Secretary of the Army, Washington, D.C. 20310, Contract No. DAHC-20-67-C-0136, Work Unit 1224B, January 1969, 66 p.

11. Buettner, K.: Diffusion of Water and Water Vapor through Human Skin. J. Appl. Physiol., vol. 6, no. 5, 1953, pp. 229-242.

12. Goodman, A. B.; and Wolf, A. V.: Insensible Water Loss from Human Skin as a Function of Ambient Vapor Concentration. J. Appl. Physiol., vol. 26, no. 2, 1969, pp. 203-207.

13. Bullard, R. W.; Benerjee, M. R.; Chen, F.; Elizondo, R.; and MacIntyre, B. A.: Skin Temperature and Thermoregulatory Sweating: A Control Systems Approach. In: Physiological and Behavioral Temperature Regulation, G. M. Rapp, J. D. Hardy, A. P. Gagge, and J. A. J. Stolwijk, eds., Springfield, Ill., C. C. Thomas, 1970, pp. 597-610.

14. Eckert, E. R. G.; Drake, Robert M., Jr.: Heat and Mass Transfer. Second ed., New York: McGraw Hill, 1959, pp. 452-454.

15. Rapp, G. M.: Convective Mass Transfer and the Coefficient of Evaporative Heat Loss from Human Skin. In: Physiological and Behavioral Temperature Regulation, J. D. Hardy, A. P. Gagge, and J. A. J. Stolwijk, eds., Springfield, Ill., C. C. Thomas, 1970, pp. 55-80.

16. Chilton, T. H.; and Colburn, A. P.: Mass Transfer (Absorption) Coefficients. Industrial and Engineering Chemistry, vol. 26, 1934, pp. 1183-1187.

17. Ede, A. J.: An Introduction to Heat Transfer Principles and Calculations. (International Series on Heating, Ventilation and Refrigeration: Vol. 2), Pergamon Press, 1966.

18. Kraning, K. K.; Schibli, E. G.; Momii, S. T.; and Merrick, E. A.: A Gas-Stream Heater to Control Local Skin Temperature Under Evaporative Sweat Capsules. J. Appl. Physiol., vol. 44, no. 6, 1978, pp. 981-985.

1. Report No.
NASA TM-81223

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
USE OF AN ELECTRICAL RESISTANCE HYGROMETER TO MEASURE HUMAN SWEAT RATES*

5. Report Date

6. Performing Organization Code

7. Author(s)
Toshiyuki Suga**

8. Performing Organization Report No.
A-8306

9. Performing Organization Name and Address
NASA-Ames Research Center
Moffett Field, Calif. 94035

10. Work Unit No.
199-20-12-12

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes
*Prepared under NASA contract NAS2-9967.
**Present address: Mechanical Engineering Department, University of Santa Clara, Santa Clara, California 95053

16. Abstract

This study was carried out at the NASA Ames Research Center and the University of Santa Clara. It was concerned with application of the resistance hygrometer as a tool to measure the localized sweat rate from the human body in both the active and passive sweat regions. It was found that the physiological function of the skin membrane and fluid carrier transport phenomena from the outer skin have an indistinguishable effect on the observed findings from the instrument.

This paper identifies the problems associated with the resistance hygrometer technique and evaluates the usage of the instrument in the physiological experimentation from the engineering standpoint.

17. Key Words (Suggested by Author(s))
Evaporation; Lewis No.
Heat flow; Sweating
Insensible water loss

18. Distribution Statement
Unlimited
STAR Category - 51

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
30

22. Price*
$6.50

*For sale by the National Technical Information Service, Springfield, Virginia 22161