NASA CONTRACTOR REPORT

NASA CR-804

NASA CR-804

HUMAN WATER EXCHANGE IN SPACE SUITS AND CAPSULES

by Paul Webb

Prepared by
WEBB ASSOCIATES, INC.
Yellow Springs, Ohio
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1967

NASA CR-804

HUMAN WATER EXCHANGE IN SPACE SUITS AND CAPSULES

By Paul Webb

Prepared under Contract No. NASr-115 by
WEBB ASSOCIATES, INC.
Yellow Springs, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

This paper reviews the exchanges of water in normal man and considers the control of body water content. The following subjects are presented in some detail: insensible water loss from the skin and to the expired air; non-thermal, or psychogenic sweating; thermal sweating as influenced by metabolic level, environment, and other factors.

The unexpected finding of weight loss in all manned flights, which is some 2-5% of body weight and is not affected by flight duration, may be a response to weightlessness causing a readjustment of body water.

Medical problems considered are heat storage and heat exhaustion, dehydration and skin hygiene. Operational problems discussed include water supply, mild dehydration and environmental stress indices.

Research is needed to clarify the mechanism of the weight loss of space flight and its effect on performance. A method of determining body mass should be developed. A specific thermal stress index is needed for space suit and space cabin use. We need better definitions of water requirements, and better definitions of the effects of mild dehydration.

TABLE OF CONTENTS

LIST OF FIGURES

HUMAN WATER EXCHANGE IN SPACE SUITS AND CAPSULES

SCOPE

This is an analytical report of human water production in space suits and in sealed capsules, written to aid in solving operational problems of manned space flights. A summary of the rich physiological literature on human water loss leads to an analysis of water loading in space vehicles and pressure suits.

STATEMENT OF THE PROBLEM

Water vapor is a fundamental constituent of the artificial atmosphere in space cabins and suits, which, although a relatively small portion of the gas mixture, is a critical element to be precisely controlled (Webb, 1965). Man is the source of water, and a highly variable source. Man is also threatened by high humidity in sealed environments. Failure to remove water vapor as fast as it is added in comfortably warm temperatures leads quickly to such high vapor pressures that the man is unable to lose body heat, and he is in danger of excessive heat storage.

While much is known of man as a source of water and of his processes of losing heat, the rapidity of humidity change in small sealed spaces during characteristic space activities makes it important to re-analyze what is known in the context of space flight.

To define the situation accurately, we have scanned the physiological and aerospace literature for data on human water loss, water loading on environmental control systems, water production in response to need for dissipating metabolic heat, insensible loss (diffusion through the skin and evaporation in the respiratory tract), and problems of water balance in weightlessness.

BODY WATER AND ITS REGULATION

In the adult man, water is approximately 60% of the lean body mass. Figures vary according to different authors, thus Moore et al (1956) find a range of 50% to 60%, Goldberger (1962) uses 60%, and Stevenson (1965) places the value at 70%, as does Gamble (1950). The water content of the body varies with age, that is, a lower percentage of body weight is water in children and old people; however, some of this may be from the varying fat content rather than a ratio of water to lean body mass. Obese people, of course, have a much smaller percentage of water to total body weight, but approximately the same water content as other adults if measured against lean body mass.

Body water is found in the cells of the body, around the cells, and in the blood vessels and lymphatic vessels. Each of these sites or compartments contains a given proportion of the total body water, with a division as follows: 2/3 of the total body water is in the cells (approximately 40% of lean body mass); 1/3 of the total body water is extracellular (approximately 20% of lean body mass), of which 1/4 is in blood plasma and lymph (5% of lean body mass) and 3/4 in tissue fluid lying between the cells but outside of blood and lymphatic vessels (15% of lean body mass).

Water moves freely between the three compartments--blood and lymph, interstitial (tissue) fluid, and intracellular fluid. This movement is controlled by the osmotic pressure found on each side of the separating membrane of the cell wall or the capillary wall. Water moves in response to a change in concentration of the osmotically active material in each compartment.

The "chemical anatomy" of the various fluid compartments, and also the chemical anatomy of sea water, are shown in Figure 1, a classical chart from Gamble (1950). The chart shows relative values for the various cations and anions in chemically equivalent terms, that is in milliequivalents per litre.

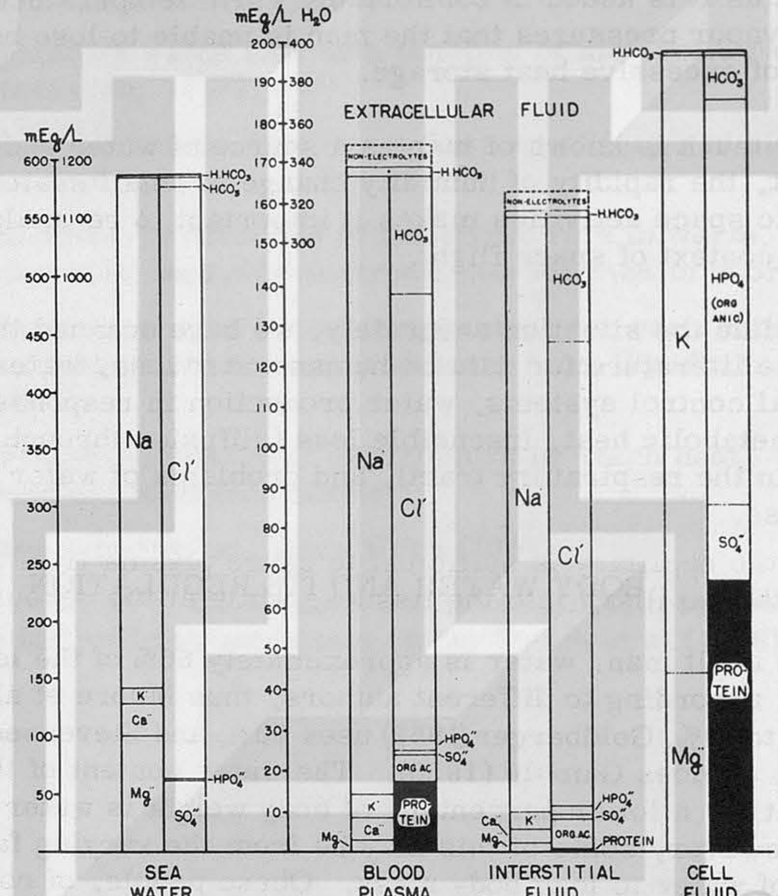

Figure 1. Chemical anatomy of body fluids, and of sea water, from Gamble (1950).

In terms of osmolarity, the values for the three body fluid compartments are approximately equal, while that of sea water is greater. (The similarity between the constituents of sea water and those of body fluids is intriguing, and many people speculate that body fluids are essentially sea water of the concentration that prevailed at the time land animals evolved from the sea.)

Osmotic pressure in the intracellular fluids can be seen to come mainly from the cation potassium (K^+) and the anions of phosphate (HPO_4^-) and protein (Pro^-). The osmotic pressure in extracellular fluid is mainly from the cation sodium (Na^+) and the anions of chloride (Cl^-) and bicarbonate (HCO_3^-). When water comes into the extracellular fluid from the blood, as occurs for example when water is absorbed from the intestine into the blood stream, ions in the blood are diluted, making an osmotic imbalance between the blood and the extracellular fluid; water moves from blood to extracellular fluid, making an osmotic imbalance with intracellular fluid. Water then moves into the cell to balance the osmotic relationship between extracellular sodium and intracellular potassium. Conversely, decreased water in extracellular fluid, as might occur in dehydration from sweating or diuresis, causes a concentration of sodium in the extracellular fluid and water moves out of the cells to balance.

Fluid movement from the capillaries of the blood vessels to the extracellular fluid is under the control of the effective osmotic pressure across the capillary membrane, which is additive to intracapillary fluid pressure and tissue distortion pressure. Here, however, the important solute is the plasma protein which does not move across the capillary membrane under normal circumstances. The concentration of proteins in the blood is greater (7 grams per 100 grams of plasma) than the protein content of interstitial fluid (1 gram per 100 grams of interstitial fluid). The other electrolytes are fairly well balanced so that there is a higher concentration of water in the interstitial fluid than in the plasma, and thus osmotic pressure tends to move water from the interstitial fluid into the capillary. In the capillary, however, the arterial end has a fairly high hydrostatic pressure from the pumping action of the heart, while the venous end of the capillary has a very small hydrostatic pressure. The combined hydrostatic and osmotic pressure at the arterial end of the capillary is sufficient to cause plasma fluid without protein to move out of the capillary into the tissues, while at the venous end tissue fluid without protein moves into the blood plasma. This fluid movement in and out of the capillary aids in conveying food and other materials into the tissue and also in removing metabolites and waste materials from the tissues back into the circulating blood stream. The solutes move principally by diffusion along concentration gradients across cell membranes, but bulk transport helps.

The internal water balances between the three body compartments are very much influenced by the continual and necessary exchange of water between the man and his environment. There are continuous and obligatory losses of water from the body in the urine and feces, and from the skin and respiratory tract. These losses are necessary for carrying away waste products and also for temperature regulation. These losses must be made up by water taken in as liquid or as water in food or as the water produced chemically in the metabolism of food. Imbalance over a long enough period of time will produce dehydration, which has serious clinical consequences, or a water excess (overhydration) leading to edema.

Water exchange in the intestinal tract is also sizable. In addition to the water ingested with food or as liquid taken in, a great deal of water is secreted along with digestive enzymes into the mouth, stomach, and intestines; water is re-absorbed later in the large intestine, with a small residue coming out in the feces.

Figure 2 is a diagrammatic summary of the water exchanges between man and his environment. Notice that the diagram shows the alimentary tract as being "outside" the body, and that large quantities of fluid move in and out of the alimentary tract during the course of a normal day. The diagram also makes it clear that vomiting or diarrhea would result in large losses of fluid as well as electrolytes. If either of these conditions persist, water balance is seriously upset.

Water is absorbed through the walls of the stomach and small intestine at rates usually estimated at 10-20 ml/min. This absorbed water is taken into the portal veins which drain the gut, and thence to the liver. Recently it has been shown that the liver may have an important role in preventing immediate diuresis from a flooding of the general circulation with hypotonic venous blood; it may act as a capacity tank which releases absorbed water more slowly than it is taken up by the portal circulation. This concept of the role of the liver in osmoregulation is advanced by Haberich (Haberich et al, 1965), a view he supports with nice experimental evidence. He postulates that the osmoreceptor mechanism in the portal circulation (including the liver) may represent a first line of defense against gross disturbance of water balance (prevention of diuresis) during water absorption from the gut, a mechanism which responds before the osmoreceptors of the brain (Verney, 1947-1948) become involved. Haberich suspects the liver releases a humoral agent which controls water output by the kidney.

For the purpose of this report, the main concern is with water balance between the normally functioning man and his environment. That is to say, we can assume that water absorption and other exchanges in the intestinal tract are proceeding normally in space flight, and the movement of water from plasma to interstitial fluid to intracellular fluid is undisturbed. Exceptions would be medical conditions including vomiting, diarrhea, increased capillary permeability, and thermal stress sufficient to reduce the splanchnic circulation.

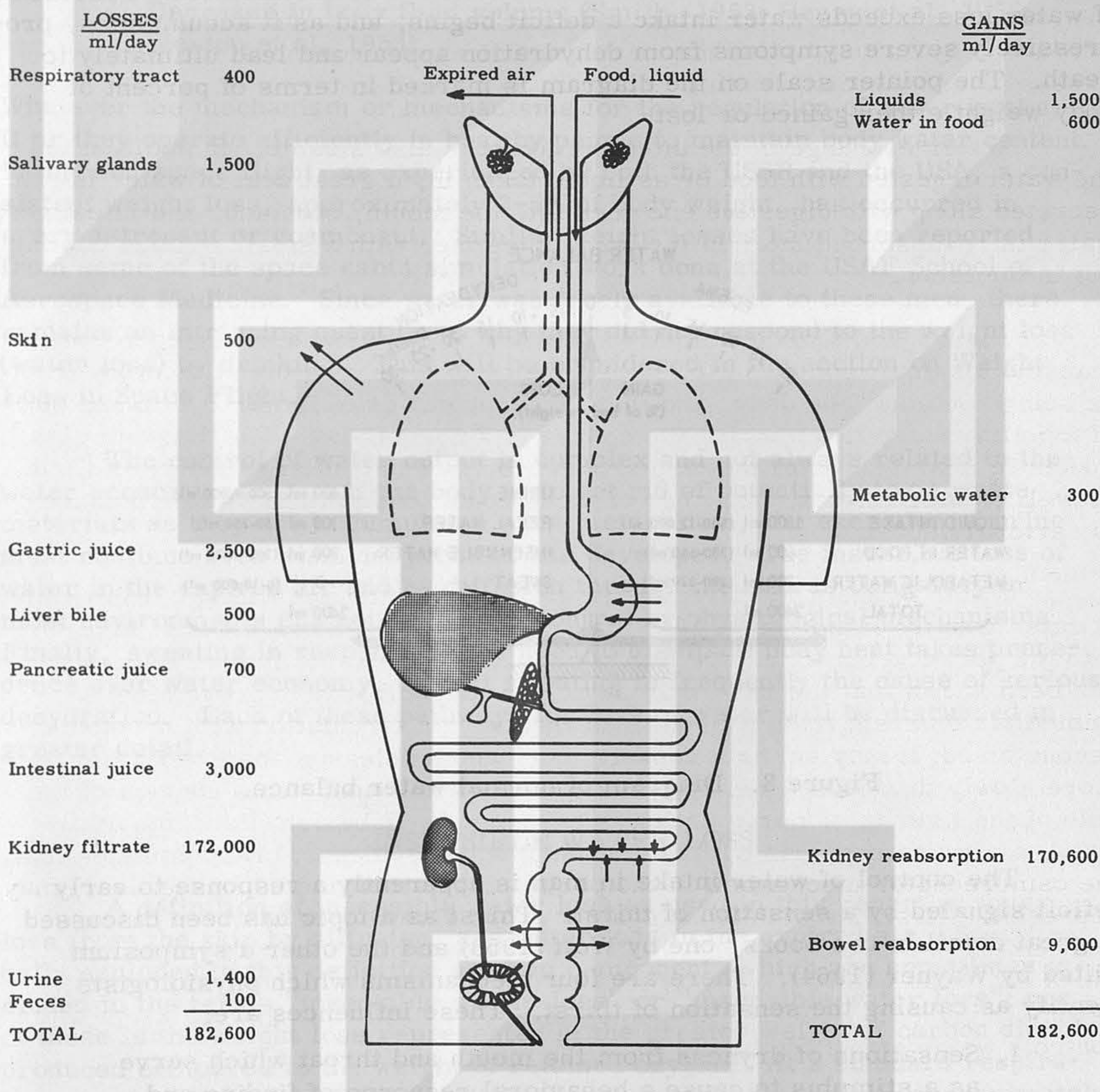

Figure 2. Diagram of water exchanges between man and environment.

The exchange of water with the environment can be depicted as a balance as shown diagrammatically in Figure 3. In this diagram a standard value for daily water intake and water output is shown in large numerals and beside each value is shown a range of high and low values which may occur under certain conditions. As the diagram suggests, if intake exceeds output water accumulates and it may cause accumulation of excess water in the tissue spaces, which is edema. Death can result from water intoxication. Conversely, if water loss exceeds water intake a deficit begins, and as it accumulates, progressively severe symptoms from dehydration appear and lead ultimately to death. The pointer scale on the diagram is marked in terms of percent of body weight either gained or lost.

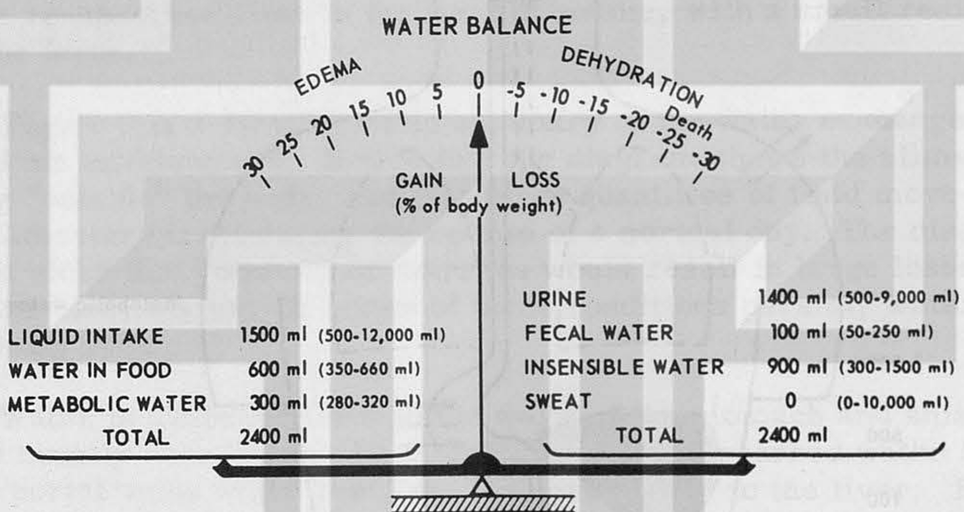

Figure 3. Diagram of normal water balance.

The control of water intake in man is apparently a response to early deficit signaled by a sensation of thirst. Thirst as a topic has been discussed in great detail in two books, one by Wolf (1958) and the other a symposium edited by Wayner (1964). There are four mechanisms which physiologists identify as causing the sensation of thirst. These influences are:

1. Sensations of dryness from the mouth and throat which serve as a stimulus to cause a behavioral response of finding and drinking water.
2. Deficit of water in deeper tissues, and possibly all cells of the body, evoking the sensation of thirst. In this category are the "osmotic factors" of Wolf (1958).

3. Receptors in the central nervous system which are specifically responsible for the sensation of thirst and produce the drinking response. The site of these sensors is thought from animal experiments to be in the lateral hypothalamus (Stevenson, 1964; Stevenson, 1965). Other parts of the central nervous system have also been implicated.

4. Decrease in body fluid volume (Smith, 1957; Henry et al, 1956; Weston et al, 1953).

Whatever the mechanism or mechanisms for the regulation of water intake, it or they operate efficiently in healthy people to maintain body water content. In manned space flight, as experienced by both the USSR and the USA, a consistent weight loss, approximately 2-5% of body weight, has occurred in every astronaut or cosmonaut. Similar weight losses have been reported from some of the space cabin simulation work done at the USAF School of Aerospace Medicine. Since water was freely available to these men, there remains an intriguing question of why they did not respond to the weight loss (water loss) by drinking. This will be considered in the section on Weight Loss in Space Flight.

The control of water output is complex and not always related to the water economy per se. If the body is to get rid of potentially toxic waste materials as they are accumulated from metabolism, the excretion of urine must continue even when dehydration has developed. The insensible loss of water in the expired air and by diffusion through the skin is obligatory in most environments and not subject to control by physiological mechanisms. Finally, sweating in response to the need to dissipate body heat takes precedence over water economy, so that sweating is frequently the cause of serious dehydration. Each of these pathways for loss of water will be discussed in greater detail.

INSENSIBLE WATER LOSS

A definition of insensible water loss as used in this report is water loss from the skin by diffusion, and water loss in the expired air. Specifically excluded in this definition are two components which are sometimes included in the terms "insensible weight loss" or "insensible water loss"; one of these is the weight loss represented in the greater weight of carbon dioxide produced compared to the weight of retained oxygen. At a standard respiratory quotient (R.Q.) of 0.82 this difference in weight amounts to approximately 50 grams per day. The other loss which is excluded in our definition is water produced by the sweat glands which evaporates from the surface and is not visible or "sensible." All sweat losses we include in the sections on non-thermal sweating and thermoregulatory sweating. The practice of including this unnoticed sweat has its origin in work by Sanctorius (1720) who made careful weighings of his bodily change over 24-hour periods; he coined the term insensible perspiration. Other authors (Lavoisier, 1790; Lombard, 1906; Benedict and Root, 1926) continued to use the term insensible perspiration to include all body weight changes exclusive of those from elimination or from frank sweating. In this report the more rigorous definition of insensible water loss is used; again, it includes only cutaneous diffusion and respiratory loss. These two avenues of insensible water loss are discussed separately.

Diffusion Through the Skin

Water diffuses through the skin into the adjacent atmosphere at a rate which is determined by the difference in vapor pressure under the skin and in the ambient air, and limited by the diffusion resistance of the epidermis as a barrier. Knowledge of the rate of diffusion comes from several experimental approaches. These include measurement of diffusion from samples of excised human and animal skin placed over beakers of water, measurements of water transfer into capsules fixed over living skin, and measurements of total weight change in living subjects in whom sweating is either prevented or is excluded from the weighting.

The chief influence on the rate of diffusion across the skin is the vapor pressure gradient. The low end of the gradient is determined by the vapor pressure of the surrounding atmosphere, while the high end of the gradient is determined by the vapor pressure of the water in tissue under the skin at the prevailing skin temperature. In other words, as atmospheric vapor pressure increases the diffusion rate becomes less and less until it stops. Buettner (1959) has shown that no net diffusional transfer occurs when the ambient vapor pressure equals 90% of the saturation vapor pressure at skin temperature, which is one way of defining the diffusion resistance of the skin.

If the data of Buettner are combined with those of Brebner et al (1956) and Webb et al (1957), the relation between rate of water loss as a function of vapor pressure gradient can be shown in a single figure--Figure 4. Buettner's experiments were done on small areas of skin covered by capsules in which humidity was controlled. Brebner et al used intact human subjects in cool temperatures so that the skin was not sweating; they took the added precaution of covering the face, hands, feet, groin, and axillae with impermeable film to eliminate the possibility of non-thermal sweating altering the results. The experiments of Webb et al were done in subjects who were given massive doses of atropine to prevent sweating despite environmental conditions which caused the skin temperature to vary from low to high.

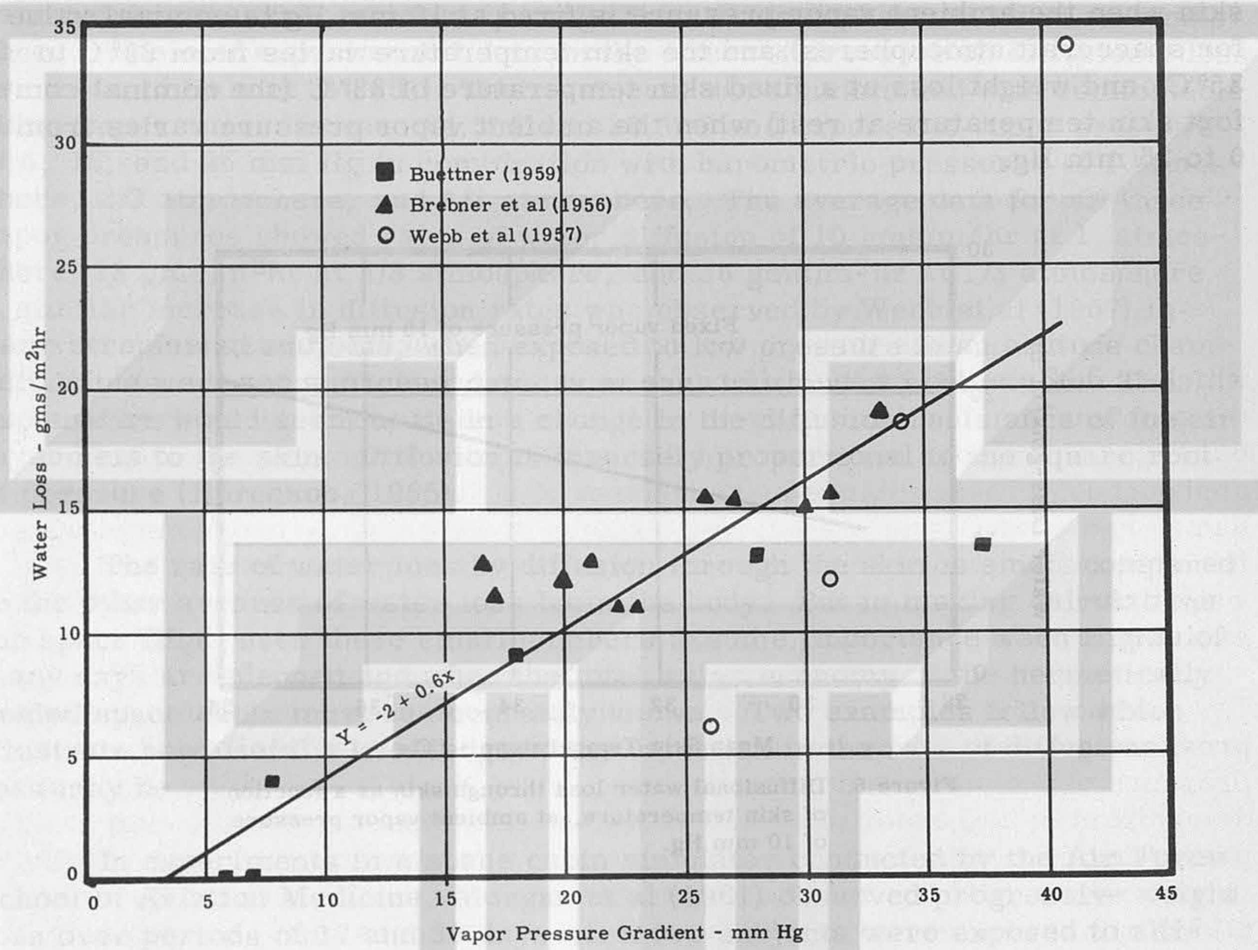

Figure 4. Diffusional water loss through the skin as a function of vapor pressure gradient.

The data plotted in Figure 4, and the derived equation for the curve relating cutaneous diffusion to vapor pressure gradient are very nearly matched by the findings of three other authors--Hale et al (1958); Ohara and Ono (1963); and Zollner et al (1955). In these three studies, however, no attempt was made to exclude the possible contribution of sweat glands from the observed rates of water loss. Ohara and Ono showed, on a single subject, that rates of "insensible perspiration" vary widely over the body surface. Their data show that most skin areas produced water at rates from 10-17 gms/m^2hr. Higher rates, from 27-57 gms/m^2hr, were measured from the palms, soles, neck, and face. These are the very areas where non-thermal sweating is expected, and the authors themselves point out that sweat gland activity is probably included.

The data may be presented in a different way, perhaps more usefully. Figures 5 and 6 show, respectively, the weight loss by diffusion through the skin when the ambient vapor pressure is fixed at 10 mm Hg (a nominal value for spacecraft atmospheres) and the skin temperature varies from 29° C to 35° C; and weight loss at a fixed skin temperature of 33° C (the nominal comfort skin temperature at rest) when the ambient vapor pressure varies from 0 to 25 mm Hg.

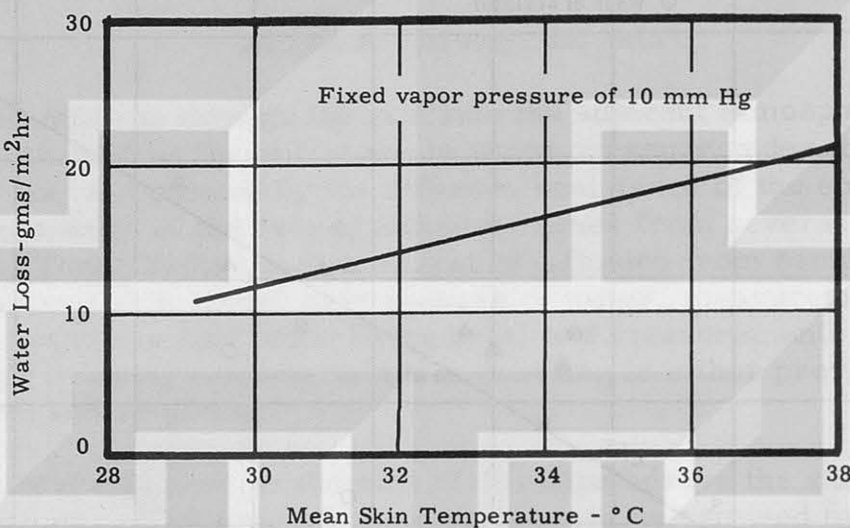

Figure 5. Diffusional water loss through skin as a function of skin temperature, at ambient vapor pressure of 10 mm Hg.

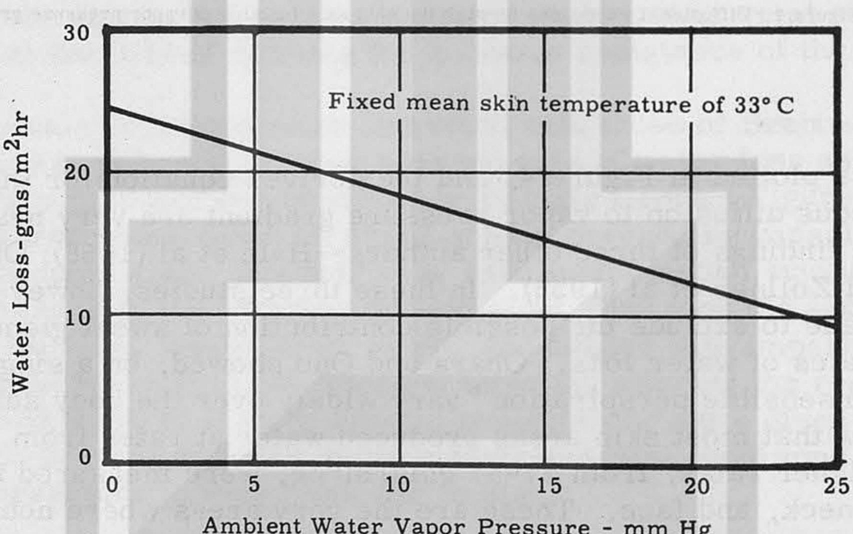

Figure 6. Diffusional water loss through skin as a function of ambient vapor pressure at a fixed mean skin temperature of 33° C.

There is an additional factor in spacecraft environments which influences the rate of diffusion of water through the skin. This is the variation in barometric pressure, which may range from 1 atmosphere to 1/3 of an atmosphere. The best experimental data on the effect of pressure on diffusional loss are those of Hale et al (1958). Their subjects were maintained with comfortable skin temperatures between 34.5° C and 35.5° C and exposed to vapor pressure of 6, 16, and 26 mm Hg in combination with barometric pressures of 1 atmosphere, 2/3 atmosphere, and 1/3 atmosphere. The average data for all three vapor pressures showed rates of water diffusion of 10 gms/m^{2}hr at 1 atmosphere, 13 gms/m^{2}hr at 2/3 atmosphere, and 16 gms/m^{2}hr at 1/3 atmosphere. A similar increase in diffusion rates was observed by Webb et al (1957) in their atropinized subjects, when exposed to low pressure in an altitude chamber; there were not sufficient data, however, to warrant publication. The explanation would seem to lie in a change in the diffusion resistance of the air layer next to the skin. Diffusion is inversely proportional to the square root of pressure (Berenson, 1965).

The rate of water loss by diffusion through the skin is small compared to the other avenues of water loss from the body. But in making calculations for space flight even these small numbers assume importance when flights of many days are planned and when the total water economy of the hermetically sealed space cabin must be accurately known. Two examples follow which illustrate how useful a knowledge of the variation in the rate of diffusional loss may be.

In experiments in a space cabin simulator conducted by the Air Force School of Aviation Medicine, Morgan et al (1961) observed progressive weight loss over periods of 17 and 30 days when two subjects were exposed to altitudes of 18,000 and 33,500 feet. The weight losses were between 95 gms/day and 121 gms/day. At the same time there was a decrease in the estimated body water and plasma volume. There was no evidence of diuresis or any change in renal function. One possible explanation which did not occur to these authors was that the diffusional component of cutaneous water loss increased as a result of the reduced barometric pressure, and that this increased loss was not sensed and compensated for by drinking. A change in insensible water loss of only 5 gms/hr would amount to 120 grams of water loss per day, enough to equal the observed change in body weight during the experiments. This may be the route by which water was lost, but it does not explain why the subjects failed to make up for this small daily weight loss by drinking extra water. Water was freely available at all times. Speculatively, the water loss may have been more related to an adjustment in body water content as a result of the relative confinement and inactivity. Such changes have been reported for studies of bed rest, water immersion, and weightlessness, as will be discussed in the section on Weight Loss in Space Flight.

The question of increased water loss at reduced barometric pressure was raised by Miller (1962) when he observed that a subject wearing a new type of full pressure suit (the Litton Industries hard-shell suit) produced water at the rate of 270 to 530 gms/hr in an environment of dry oxygen at approximately 1/3 atmosphere pressure. The increase in cutaneous diffusion would account for 20 to 30 gms/hr. It seems likely that the metabolic cost of operating in the suit was high enough to require some thermal sweating to maintain thermal balance, even though this might not be detected by the subject as sweating. The conditions for evaporation were certainly good--dry oxygen at 5 psia circulated through the suit at a rate of 15 cfm. The increased weight loss could be explained too on the basis of sizable non-thermal sweating, which also seems likely. It was unnecessary for the author to invoke some new factor to explain his observations.

Respiratory Water Loss

The loss of water from the respiratory tract is, like diffusion through the skin, a small part of the total water economy. It amounts to approximately 20 grams of water per hour under normal resting conditions. The source of greatest variation in this figure is the quantity of gas exchanged in the respiratory tract per minute, the respiratory minute volume. Also modifying the water loss is the water vapor content in inspired gas and the small but significant variation in water vapor in the expired gas.

Water is lost to the expired air when dry inspired air is warmed and moistened by passing over the linings of the upper respiratory tract. This process is essentially complete in the first ten centimeters of travel in the nose, mouth, and nasopharynx (Seeley, 1940, and Webb, 1951). There is little doubt that warming to body temperature and saturation of inspired air are complete as the air moves into the bronchial tree and finally the alveoli. It is not correct, however, to assume that the expired air exits from the respiratory tract at body temperature and saturated. As the expired air moves from deep to shallow portions of the respiratory tract a certain amount of cooling takes place, and with cooling the saturated air must lost water if it is not to become super-saturated. No one has yet been able to demonstrate consistent super-saturation in the upper tract.

The magnitude of the cooling of expired air is not great in comfortable temperatures. It is greatest when the inspired air is very cold and dry. Even when air is warmer than body temperature and dry, expired air at the portal of the respiratory tract is lower than body temperature (McCutchan and Taylor, 1951). Good experimental data are available in the literature for air temperatures down to -40° C (Webb, 1951, and Webb, 1955) and for temperatures up to 88° C (McCutchan and Taylor, 1951), and one can distinguish between respiratory water loss and sensible heating or cooling. For present purposes we will look particularly at data for men in the temperatures, humidities, and barometric pressures, and for the activities which are expected in the space cabin or space suit environment.

A simple expression for the water lost in expired air is:

$$Q_w = \dot{V}_E (q_{we} - q_{wi})$$

where Q_w is water lost in gms/min, $\dot{V}_E$ is respiratory minute volume in liters/min, q_{we} is water content of expired air in gms/liter, and q_{wi} is water content of inspired air in gms/liter.

The major cause of variation in respiratory water loss is change in respiratory minute volume, which varies with activity level or metabolic rate. Values for respiratory tract heat loss in men working at various tasks in the field under subarctic conditions were shown to be directly predictable from data taken from resting men, when the respiratory minute volume--$\dot{V}_E$-- was measured (Brebbia et al, 1957). In other words, if the expired air temperature is either measured, or calculated from the data from Webb (1955), the respiratory tract water loss can be estimated accurately for any given ventilation rate. In Figure 7, the data of Brebbia et al (1957) are summarized showing respiratory water loss in gms/hr as a function of respiratory ventilation rate for cold dry air (vapor pressure less than 3 mm Hg, air temperatures -20 to -30° C).

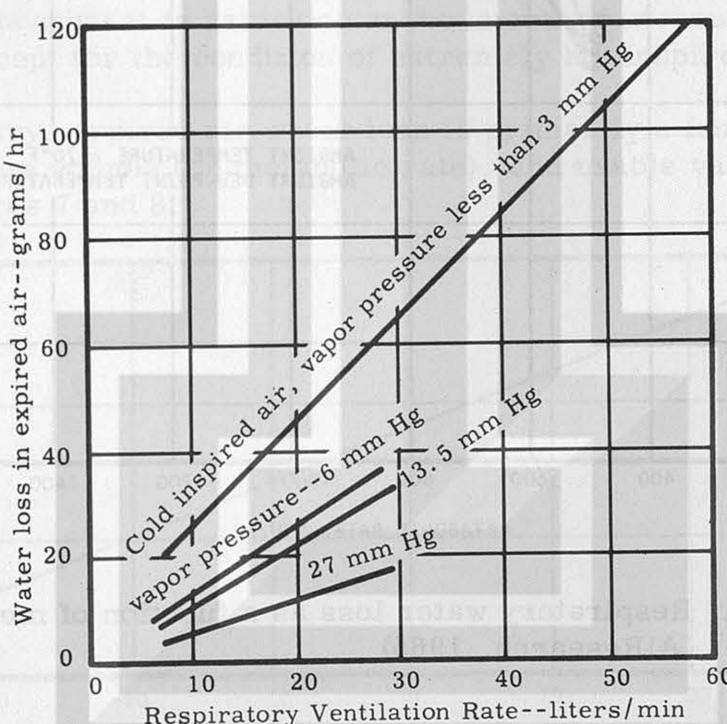

Figure 7. Respiratory water loss as a function of respiratory ventilation rate.

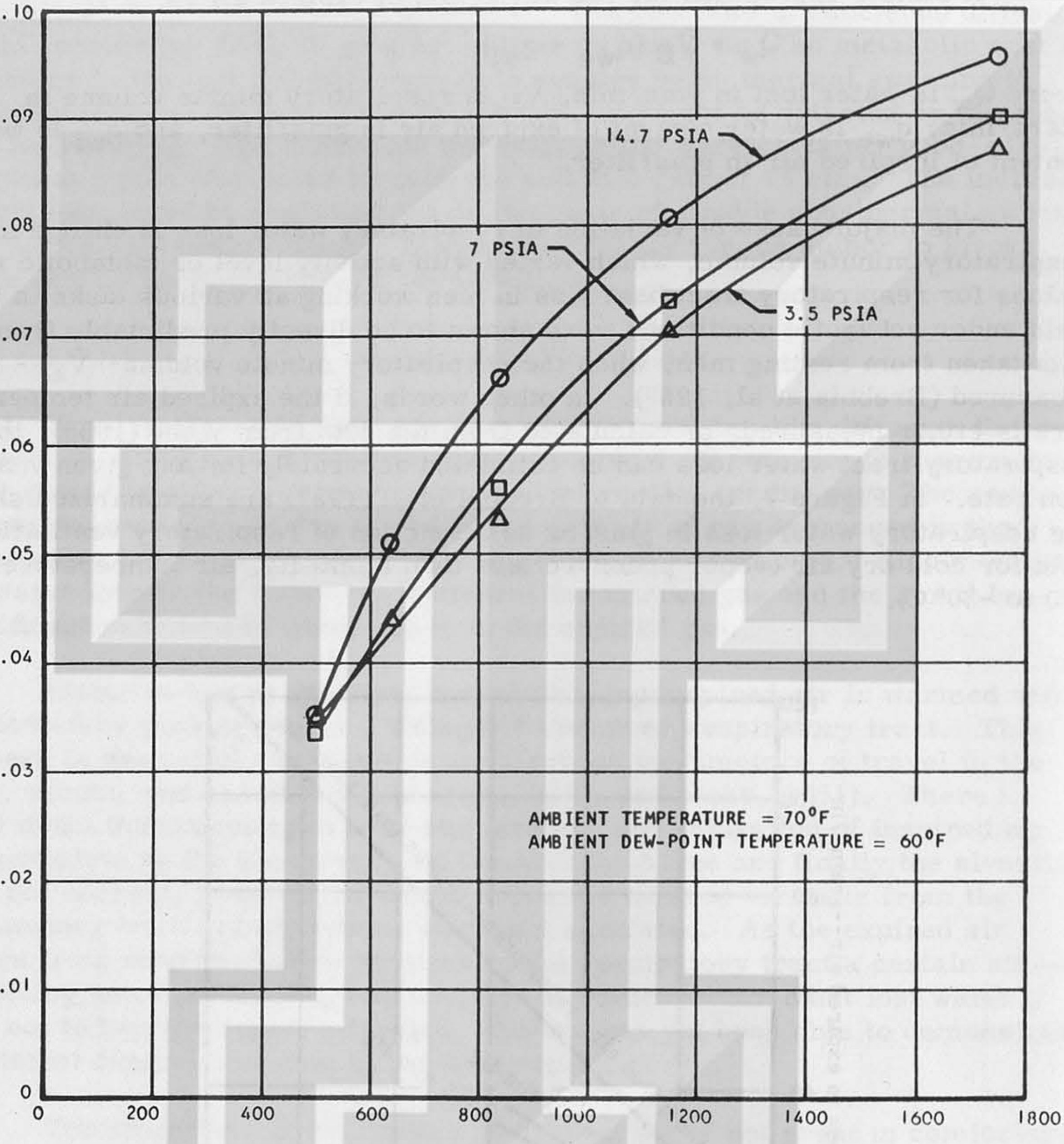

Figure 8. Respiratory water loss as a function of metabolic rate. (AiResearch, 1965)

Figure 7 also shows data for respiratory water loss as a function of respiratory minute volume for a group of subjects breathing warmer air (4.4°, 24°, and 35° C) at a series of vapor pressures ranging from 6-27 mm Hg. In this study by Wortz et al (1964) subjects were connected by an instrumented mouthpiece to a supply of conditioned oxygen and exposed to sea level pressure and pressures of 7.0 and 3.5 psia. The subjects were either standing at rest or marching on a treadmill at 2 mph or 4 mph with zero grade. The same data have been expressed also as respiratory water loss as a function of metabolic rate. This is shown in Figure 8 (AiResearch, 1965).

The study of Wortz et al (1964) verifies that changes in barometric pressures per se do not cause changes in expired water vapor. They did notice a diminution of expired air water loss due to a decreased mass of air respired per minute at altitude. They also noticed a relatively small effect of the temperature of inspired air on the respiratory water loss. This is consistent with the cooling effect of inspired air on the temperature of expired air as demonstrated previously by Seeley (1940) and Webb (1955)

The effect of cold inspired gas on the expired air temperature is more clearly seen when the inspired gas temperature is very low. The relationship is expressed in Figure 9 from Webb (1955). Again the importance of the information in the figure is that expired air does not exit at body temperature, and the lower the expired air temperature the lower the water content. There continues to be argument about whether expired air is saturated, but it appears safe to say that it is saturated at the known or measured expired air temperature, except for the condition of extremely hot inspired air.

In summary, expired air water loss is primarily a function of the respiratory minute volume (or metabolic rate), and usable values can be found from Figures 7 and 8.

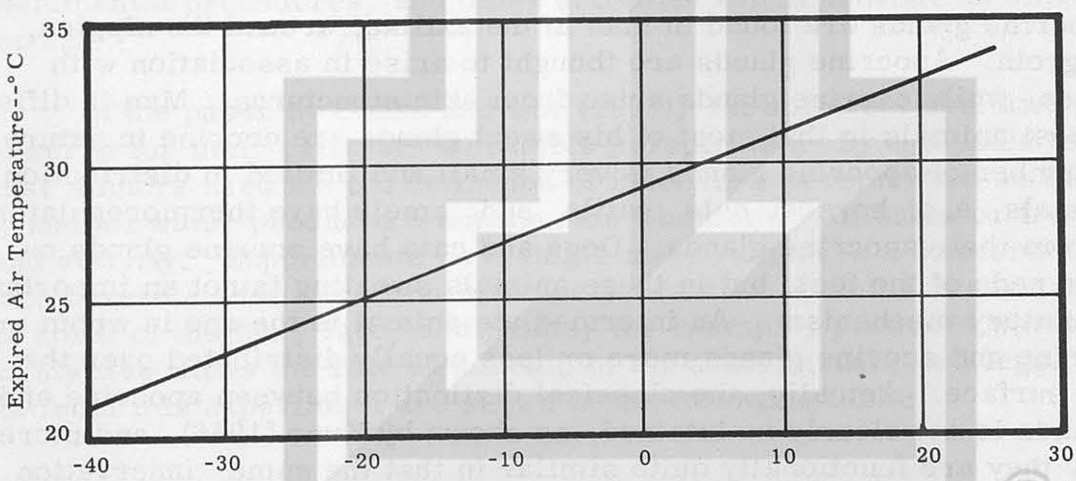

Figure 9. Expired air temperature as a function of inspired air temperature.

NON-THERMAL (PSYCHOGENIC)SWEATING

Activity of the sweat glands is usually thought of as thermoregulatory. However, it is common experience that the palms of the hands and the soles of the feet are moist when one is comfortable or cool. Students are familiar with sweating in response to an imminent examination; the "cold sweat" of fear is a perfectly real phenomenon. Kuno (1956) reviewed the subject and showed that the palms, soles, and axillae were the principal sites for non-thermal sweating. He mentions increased CO_2 and low blood sugar as conditions other than psychological which produce non-thermal sweating, and both of these can occur in space flight.

Quantitative data on non-thermal, or psychogenic, sweating are difficult to come by. What data exist will be summarized in this section. The topic is relevant to manned space flight in that astronauts are certainly expected to be keyed up, excited, possibly anxious at times, and certainly alert and striving during critical moments of the flight. These are all situations in which psychogenic sweating would be expected to increase. For our purposes, the important question is to what extent this kind of sweating will represent a load on the spacecraft cooling system or on the cooling system carried by an astronaut performing extravehicular activities.

To begin with, there are two distinct varieties of sweat gland, the eccrine sweat gland normally responsible for the production of water on the skin for cooling purposes and also primarily involved in non-thermal sweating, and the apocrine glands, which are histologically different and of limited distribution.

Apocrine and Eccrine Glands

Apocrine glands are found in man in the axillae, around the nipples, and in the groin. Apocrine glands are thought to arise in association with hair follicles, while eccrine glands arise from skin structures. Man is different from most animals in that most of his sweat glands are eccrine in nature while the number of apocrine glands is very small and limited in distribution. Most mammals, e. g. horses, cats, cattle, and camels have thermoregulatory sweating from their apocrine glands. Dogs and cats have eccrine glands on the hairless pads of the feet, but in these animals sweating is not an important thermoregulatory mechanism. An intermediate animal is the ape in whom are found apocrine and eccrine glands more or less equally distributed over the whole body surface. Actually, the classical distinction between apocrine and eccrine glands is not clearly maintained, as shown by Kuno (1956), and more importantly they are functionally quite similar in that the same innervation and the same physiological response can be expected from both varieties. The histological distinction, which is not entirely true in man, rests primarily on the fact that the apocrine glands secrete a fluid which is high in colloid content while the eccrine glands secrete a thin watery solution which contains electrolytes and only a few colloids. Apocrine glands are found elsewhere than in the skin; mammary glands are basically apocrine in character. The distinction is that the apocrine is said to produce a fluid which contains some part of the cytoplasmic content of the cell (Bloom and Fawcett, 1962). The secretion of the apocrine glands in the skin is odoriferous and, according to Kuno (1956), this secretion may be in some way related to sexual function.

Since apocrine and eccrine glands are similar in function and since apocrine glands are rather small in number in the human, the remaining discussion will not distinguish between the two.

Rates of Non-Thermal Sweating

The clearest experimental estimation of the quantity of non-thermal sweating is in the report of Brebner et al (1956). These authors were interested in measuring the rate of water diffusion through the skin in cool environments where thermal sweating was absent. They found it necessary to eliminate a number of skin areas while they followed the small changes in the weight of nude men. This they did by covering with a plastic sheet the face, hands, soles of the feet, axillae, and the groin. Air temperature ranged from 24° C to 29° C and skin temperature between 31.6° C and 34.5° C. By comparing the rates of weight loss both covered and uncovered in these temperature ranges, they found that their resting subjects produced between 80 and 220 gms/hr from the covered areas as compared to 20 to 40 gms/hr by diffusion from the rest of the skin surface.

Most experimenters measuring weight loss continuously observe sudden changes in weight loss associated with noise, conversation, stressful experimental procedures, and other activities which provoke an emotional response.

In the paper by Ohara and Ono (1963), 108 different skin areas were measured for their rates of "insensible perspiration" by a capsule technique. These authors used the old definition of insensible perspiration as including any and all water produced from the skin whether by diffusion or from sweat gland activity. Experiments on a single male subject in a comfortably cool room showed a wide variation in water production from the areas sampled. The soles of the feet, face, and palms, for example, produced water at roughly five times the rate of the skin of the arms, trunk, and legs. Their data from this experiment are shown in the following table:

Location	Numbers of Sampled Points	Rate of "Insensible" Perspiration gms/m^2hr
Sole	5	57
Face	6	55
Palm	6	46
Neck	4	27
Back of hand	2	17
Gluteal region	5	16
Instep	2	15
Lower Leg	10	13
Back (scapular region)	7	13
Forearm (flexor side)	6	13
Brachium (extensor side)	4	13
Thigh (frontal)	10	12
Forearm (extensor side)	4	12
Shoulder	4	12
Back (lumbar region)	5	12
Epigastrium	6	11
Brachium (flexor side)	4	11
Chest	6	11
Thigh (back side)	6	10
Abdominal region	6	10

Source: Ohara and Ono (1963)

The standard values for "insensible perspiration," or weight loss from the entire body on a daily basis, are derived from measurements of bodily weight changes with sensitive blanaces. It is interesting to examine these values to see how much of a component psychogenic sweating may have been.

Since most of these studies were done with men seated or lying at rest, we can take as the water loss by diffusion through the skin the value 15 gms/m^2hr (see Figures 4, 5, and 6) and respiratory water loss as 12 gms/hr (see Figures 7 and 8). Assuming a surface for the man of 1.8 m^2, the total loss of water is 39 gms/hr or 936 gms/day (2.06 lbs/day). Comparing this figure with the data for total body weight loss measured over fairly long periods of time, the following table lists the usual rates for "insensible perspiration" and the difference between these values and 936 gms/day.

Investigator	Rate gms/day	Probable non-thermal sweating (difference from 936 gms/day) gms/day
Sanctorius - 1614	1400	464
Lavoisier - 1790	1333	397
Lombard - 1906	953	17
Benedict & Root - 1926	470-1060	none to 124
Kuno - 1956	994	58

The estimates of insensible weight loss shown in this table are not seriously disturbed by what is probably non-thermal sweating. However, in estimates of men who are active and under the real stresses of space flight it seems certain that non-thermal sweating will be present in good measure.

Mechanism of Action

A full discussion of the innervation and mechanisms of action of the sweat glands may be found in Kuno (1956) and in Robinson (1949). Sweat glands have cholinergic sympathetic innervation. It has been established that acetylcholine is the transmitter substance to activate sweat glands. Sweat gland activity is stimulated by injections of epinephrine (Sonnenschein et al, 1951), of mecholyl (Randall, 1946), of pilocarpine (Ogata, 1936), and by acetylcholine. Sweating is blocked by atropine, as shown for example in the study of Webb et al (1957). Atropine painted on the skin surface also blocks sweating locally (Buettner and Holmes, 1959). There remains the possibility that sweat glands are supplied not only with sympathetic nerves but also with parasympathetic nerves or nerves from the posterior spinal roots.

This rich nervous supply to the sweat glands is part of the background of sweating which is not related to the need for dissipation of body heat. Such non-thermal sweating has been something of a "bother factor" in many experiments where the mechanism of thermal sweating was being studied--see for example Allen and Lyman (1962). The "state of arousal" and the activity level in the reticular formation is known to affect many autonomic functions, and sweating would seem to be no exception. Chalmers and Keele (1952) blame emotional sweating on overactivity of sweating control centers.

One additional piece of evidence comes from the work of Van Beaumont and Bullard (1963). These authors have reported that in a warm environment sweating can be observed to begin within two or three seconds after the onset of muscular work, which is far too soon to be explained by the need for dissipation of increased metabolic heat. This suggests the presence of a neuromuscular reflex.

THERMOREGULATORY SWEATING

Secretion of sweat for the purpose of providing cooling to the skin by evaporation has a high priority in the body economy. Sweating continues during dehydration as the body attempts to maintain normal temperature in working men in the desert (Adolph, 1947). Sweating is a powerful mechanism for the dissipation of metabolic heat and for the dissipation of heat gained from the environment when air temperature is higher than skin temperature, or when air temperature plus radiant heat load combine to produce heat gain. The maintenance of homeothermy has a priority second only to maintenance of gas exchange in the blood and tissues.

The rate of sweating when called for to maintain body temperature varies from 0 to 1500 gms/hr (Robinson and Gerking, 1947), or in unusual cases 2000 or 3000 gms/hr (Robinson, 1949). On a daily basis, sweat losses as high as 20 lbs/day, or 9 liters/ day, have been observed by Adolph (1947) in working men in the desert. This activity of the sweat glands is independent of the water lost by respiratory exchange, by diffusion through the skin and from non-thermal activities of the sweat glands.

Temperature regulation in man, mammals, and warm blooded animals is a topic far too large for this report. Reviews and comprehensive summaries of the many thousand reports in the literature may be found in the following: Adolph (1947) Physiology of man in the desert; Burton and Edholm (1955) Man in a cold environment; Hardy (1961) "Physiology of Temperature Regulation"; Hardy, ed., (1964) Temperature: its measurement and control in science and industry; Laddell (1964) "Terrestrial animals in humid heat:man"; Lee (1964) "Terrestrial animals in dry heat: man in the desert"; Leithead and Lind (1964) Heat stress and heat disorders; Macpherson (1960) Physiological responses to hot environments; Newburgh (1949) Physiology of heat regulation and the science of clothing.

Sweating as a thermoregulatory phenomenon is also a large topic. The first comprehensive treatise is the classic monograph of Kuno (1934), which he revised in 1956. Robinson and Robinson (1954) reviewed the chemical composition of sweat. The books and reviews listed in the previous paragraph contain summaries of much of the extensive literature on thermoregulatory sweating.

In order to confine the discussion to manageable proportions, I have chosen a small number of recent articles to illustrate the range of sweating as a thermoregulatory response, and, particularly, I have chosen articles which deal with sweat production in working men, since this is the subject of greatest concern in designing for astronauts in pressure suits during extravehicular duty.

Initiation and Control

A brief review of the innervation of sweat glands was given in the last section, in connection with the mechanism of action of non-thermal sweating. Thermal sweating appears in response to thermal stress, whether the heat has come from the environment, or the thermal stress comes from a restricted ability to dissipate metabolic heat. Sweating is control action taken when heat must leave the body more rapidly in order to maintain a nearly constant body temperature.

Among physiologists there is a running argument over the importance of peripheral versus central thermal receptors to trigger the sweating response. The basic arguments were summarized by Bazett and by Robinson in Newburgh's book (Newburgh, 1949). Peripheral receptors sense increasing temperatures or changing gradients from surface to deeper layers, and initiate sweating. The hypothalamic centers for control of heat dissipation act to increase or decrease sweating in accordance with the information from peripheral receptors. In other words, the hypothalamus acts as a sensitizer for the peripheral information. This is one major school of thought.

More recently two additional important hypotheses have been advanced. Kerslake (1955) suggests on theoretical grounds that the control of sweating is by the temperature of "deep skin receptors" located at about the level of the superficial vascular plexus of the dermis. Much experimental work can be explained in terms of the hypothesis and so far no direct evidence against it has been found. The study of Blockley (1965) tends to bolster this view of where the critical temperature lies, and the study of Robinson et al (1965) showed that the variable best related to onset of sweating, its rate of increase in hard work and its decline in recovery is the temperature of the blood in the femoral vein. The other recent hypothesis is that of Benzinger (1959), who attributed the initiation and quantification of sweating solely to the temperature of the blood reaching the hypothalamus. After exploring a number of cranial locations with temperature probes, in the paranasal sinuses and elsewhere, he settled on measurement of the temperature of the eardrum as being closely related to the temperature of blood reaching the hypothalamus. Benzinger's work stirred up a good deal of discussion among environmental physiologists, and many people added tympanic temperature measurement to measurements in the more conventional sites in order to test the idea. It is fair to say at this point that a good deal of experimental data both recent and classic cannot be explained solely on the basis of a hypothalamic sensor (Benzinger's "Thermal Eye"). The importance of the hypothalamic center is not to be denied; however, it does not act entirely alone.

Once sweating is initiated for thermoregulatory reasons, the amount of sweat required is graded in accordance to the need for dissipation of heat. The pattern of recruitment of sweat glands has been studied most extensively by Hertzman et al (1952), Hertzman (1957), and by Randall et al (1958). While the particular pattern of recruitment of sweat glands is quite individual, recruitment is by dermatomal segments, with the first areas being the limbs, and, as the need for cooling increases, more and more glands are added until both the limbs and the trunk are fully active. This pattern of increasing activity of sweat glands is interesting in relation to the design of cooling systems in space suits.

What conditions are associated with the onset of sweating? The answer to this question is complex. In the physiology laboratory the answer is usually given in terms of a measured mean skin temperature. For resting man this is given by most workers as 34.5° C (95° F) (Robinson, 1949). This skin temperature as the threshold condition for sweating holds true only for inactive men who are essentially comfortable and who do not carry the residue of a previous thermal stress. If the body heat content is high, the threshold for sweating for resting men is lower. If one considers men who are active, the greater the activity the lower the threshold skin temperature for the initiation of sweating (Robinson, 1949; Benzinger, 1959; Blockley, 1965; Macpherson, 1960; and Robinson et al, 1965). This relationship is clearly seen in Figure 10.

The onset of sweating has been related to a measured internal body temperature, particularly by Benzinger (1959). A major difficulty with this approach is that the internal temperature at equilibrium (in which a man is judged to be in thermal balance by constancy of surface and deep temperatures) is known to vary with the metabolic rate. The higher the metabolic rate, the higher the equilibrium internal temperature (Nielsen, 1938, and Webb, 1964, page 110).

To be able to specify when significant sweating will appear in a given practical situation, one would have to know the activity level of the man, the characteristics of the immediate environment, and any pre-existing thermal condition which might have produced a heat storage or a heat deficit. It is often true that for a given design situation a set of physiological experiments must be done in order to be able to specify when sweating begins and how great in quantity for each of the specific activities anticipated. Such a study was made by Blockley (1965) in relation to expected activity levels of astronauts, in environmental conditions which might obtain in space suits. Data from that report plus pertinent and closely related data from Robinson et al (1965) and Macpherson (1960) will form the basis of the following discussion of quantity of sweat produced in response to activity and environment.

Sweat Responses to Work and Environment

In a NASA sponsored study of the physiological "cost" of sweating in men working at activity levels expected for astronauts, Blockley (1965) reported the results of exposing six healthy men aged 25-37 and weighing 150-189 pounds to environments varying from cool to oppressively warm while engaged in three levels of activity--seated at rest (100 kcal/hr), mild work on a treadmill (250 kcal/hr), and moderate work (400 kcal/hr). Five different environments were selected at each level of activity to have an environmental stress index on the P4SR scale* of 0, 0.5, 1, 2, and 3. With an environmental humidity kept below 15 mm Hg, where the skin temperature is essentially independent of the level of humidity, combined air and wall temepratures covered the range from 13° C (55° F) to 53.5° C (128.5° F). In this study the mean skin temperature at the threshold of frank sweating, defined as total weight loss less than 100 gm/hr, was inversely proportional to metabolic rate. At rest, the threshold mean skin temperature lay between 33.5 and 34.9° C; with mild exercise (250 kcal/hr), the mean skin temperature at threshold lay between 31.2 and 33° C; at the moderate exercise level (400 kcal/hr) the threshold mean skin temperature for sweating was found to lie between 26.5 and 30.8° C for five of the subjects, while the sixth man had a threshold mean skin temperature at about 21° C. This sixth man had a much greater amount of subcutaneous fat as measured by skinfold thickness and this seemed to influence his physiological responses. In terms of environmental temperature, sweat thresholds in this study of men in shorts were associated with an air temperature of 10° C (50° F) for the moderate activity level (400 kcal/hr), 20.5° C (69° F) for the mild activity level (250 kcal/hr), and 29.5° C (85° F) for the seated resting activity (100 kcal/hr). Above the threshold level for sweating, sweat rate was a linear function of skin temperature at each level of activity. When the activity level was low, a small change in skin temperature was associated with a large change in sweat rate; in high activity, a large increase in skin temperature was associated with similar increments in sweat rates. Data from this study have been reworked to match data of the other two studies, and all three are represented graphically in Figure 10.

Figure 10 shows sweat rate from threshold level, 100 gm/hr or less, to levels of 500-600 gm/hr as a function of metabolic rate in three different environments. A warm environment was defined as one in which the combined air and wall temperature is 33° C, comfort temperature with an air-wall temperature of 25° C, and cold with air-wall temperature of 15° C. The humidity in the Blockley study and in the Robinson study was low, while the humidity in the Macpherson study was high. Adjustments were made with the P4SR scale to make the Blockley and Macpherson data equivalent.

* See page 55 for definition.

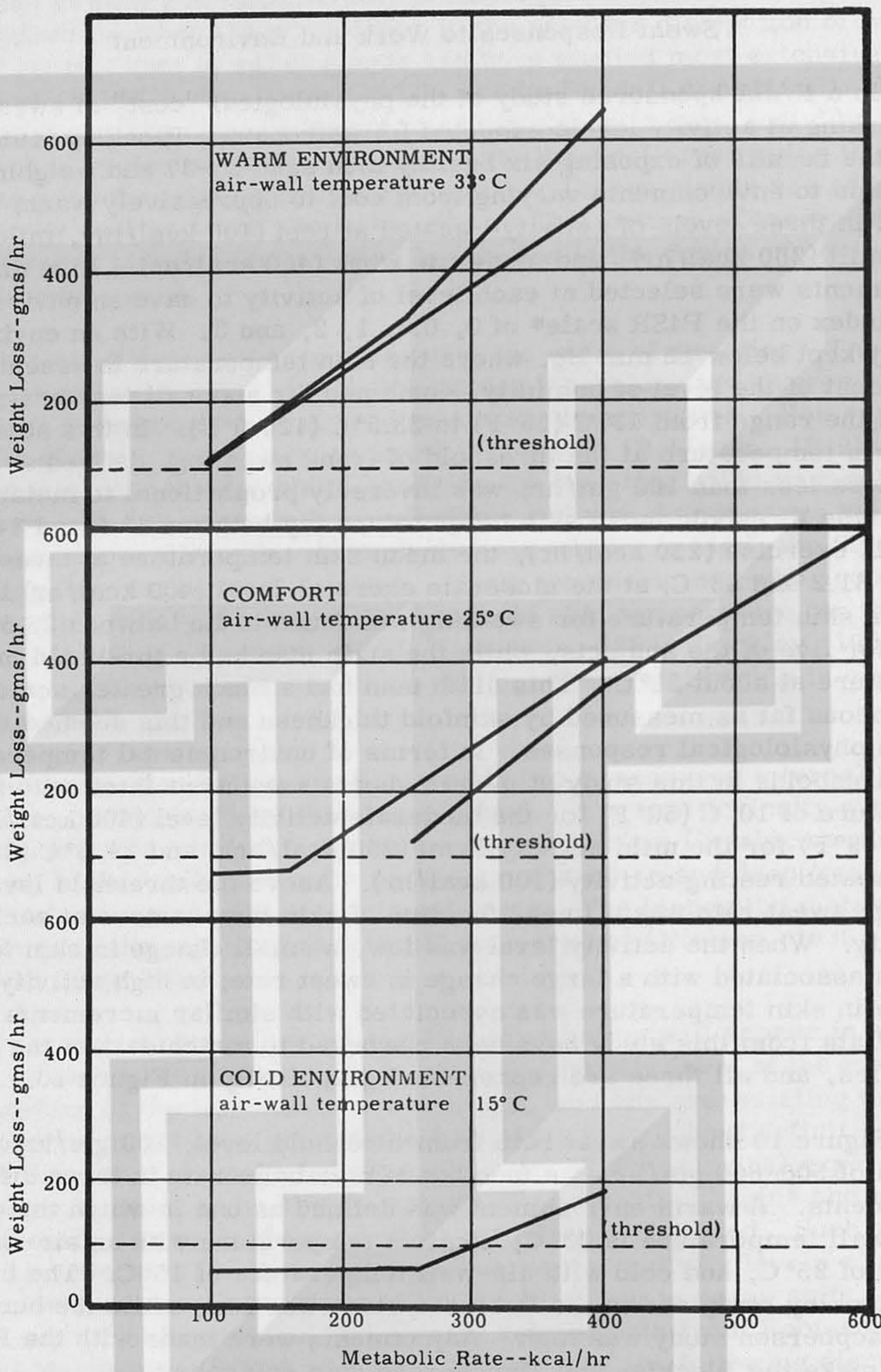

Figure 10. Sweat rates as functions of metabolic rate in warm, comfortable, and cold environments for men in shorts. The threshold for sweating is taken to be a rate of weight loss of 100 gm/hr.

In the study of Robinson et al (1965) three men in their middle twenties and one man of 59, ranging in weight from 145-198 pounds, worked at moderate to severe levels (360 kcal/hr to over 1000 kcal/hr) primarily in a comfortable environment of 25° C with a vapor pressure of 6 mm Hg. The subjects were heroically instrumented for the measurement of surface temperature, rectal and tympanic membrane temperature, temperature of the venous blood in the leg, and intramuscular temperature. In Figure 10 are plotted sweat rates versus metabolic rate for two of the more thoroughly studied of the subjects in a comfortable environment. Data at an extremely high metabolic rate for one subject over the same kind of temperature range from cold to comfortably warm are consistent with the data in Figure 10, but have not been plotted since the number of observations is small.

In the study reported in Macpherson (1960), which was work done by Ferres, Fox, and Lind, four Army men aged 19-23 and wieghing 135-156 pounds were exposed to a temperature of 32.2° C and a vapor pressure of 23.5 mm Hg. (In order to make the exposures comparable to those in the other two studies, the environments were adjusted by means of the P4SR index scale. An environment of 33° C with a low vapor pressure was equivalent in thermal stress to 32° C and 23.5 mm Hg.) The men marched on a treadmill at one of six speeds between 2 and 4 mph. Resting metabolism was found to be approximately 90 kcal/hr while the working level ranged from 160-360 kcal/hr. The data from this study are shown in the top section of Figure 10 in the block labeled "Warm Environment."

In summary, Figure 10 represents sweat rates for fit men of normal size as a function of metabolic rate, in three different environments, warm, comfortable, and cold.

Sweating in Space Suits and Capsules

It is common experience in laboratories where space suits and full pressure suits are tested that test subjects become hot and perspire even when seated or only mildly active, despite the usual supply of ventilating air. When external heat loads are added or when simulated flight conditions are produced in test chambers, sweat production in the range of 300-600 gm/hr is common. Reports with data of this kind are to be found in Libber et al (1957), Miller (1962), and Webb and Klemm (1959). Higher rates of sweating may be expected if external heat loads are greater, if the men are active (especially when the suit is pressurized), or if the ventilating gas fails to evaporate sweat as rapidly as produced.

Men working in pressurized pressure suits have high metabolic rates. Harrington et al (1965) report that a given task in a pressurized suit in Earth gravity causes double the metabolic rate of the same task unpressurized. Roth (1966) proposed 500-600 kcal/hr as a reasonable level of expenditure for a man on the lunar surface. Gemini flight reports of high pulse rates and sweating indicate high work rates during extravehicular activity.

In a recent study it has been estimated that 82-87% of the heat produced at an activity level of 300 kcal/hr (walking 2 mph on a level treadmill with an unpressurized Apollo prototype suit) is carried away in the form of latent heat by the ventilating gas. This AiResearch study was reviewed by Roth (1966), who went on to point out that at this activity level, when the suit was used in an altitude chamber with a total pressure of 1/2 or 1/4 atmosphere, only about 3/4 of the heat produced was being removed by the ventilating gas, which included both sensible and latent heat transfer. The subjects were sweating at a rate of 350-450 gm/hr. This was considered stressful in itself, but in view of the failure of the ventilating gas to remove all the heat produced there was an accumulating storage of heat in the body. Heat storage became more and more of a factor when activity levels above 250 kcal/hr were tested.

Because of the universal experience that wearing full pressure suits cooled by ventilating gas causes sweating, especially if the men are working, and even more especially if the suit is pressurized, a new method of suit cooling has been developed. At the Royal Aircraft Establishment in England, Burton and Collier (1964) described a cooling system of water circulated through small plastic tubes lying against the skin. Wortz et al (1964) described a different version of liquid cooling combined with air ventilation. These authors and also the report of Crocker et al (1964) show that skin temperatures can be controlled to low enough levels that sweating is minimized.

While definite quantitative data from space flight projects is not available, it was observed that the astronauts in the orbital flights of project Mercury were recovered in their space suits which had become wet with sweat (National Aeronautics and Space Administration 1962 a, 1962 b, 1962 c, and 1963). The sweating was thought to have occurred primarily during the recovery operation when the astronaut was confined to his capsule on the water. Some sweating may have occurred during the final orbit and reentry procedure. All of the Mercury astronauts lost weight, amounting to 3-6 pounds, and similar weight losses have been reported by Soviet cosmonauts and the astronauts in the Gemini project; however, this weight loss is not from thermal sweating. As will be discussed more fully in the next section, the consistent finding of weight loss may be due to excess urine production, or from excess urine production plus sweating.

Sweating in flight clothing, much of which contains layers of impermeable cloth, can be a serious problem for the wearer. Often sweating builds up to high levels because the clothing reduces the evaporation, hence the cooling power of sweat. Or if the sweat produced and evaporated causes the cabin (or suit) atmosphere to become humid, again the cooling power of sweat is reduced as evaporation is lessened in the humid environment. These are real problems, and occasionally nearly disastrous ones. (See section on Medical Considerations--Heat Storage and Heat Exhaustion.) In a recent paper (Webb, 1965), I related sweat rates and inadequate water sinks to some troublesome experiences in flights and in laboratory work. I concluded that the control of water vapor in small sealed spaces was critical, and that a vapor pressure of 10 mm Hg (or less) was a good design figure for space suits and cabins.

Acclimatization and Sweating

Acclimatization to heat is a real phenomenon which alters the sweating response on exposure to heat. The word is qualitative and loosely used, but heat-acclimatized man shows several usefully altered responses. He sweats sooner and more copiously in response to a given heat stress. An acclimatized man can produce physical work with a smaller increase in rectal temperature and at a smaller cardiac cost. The sweating response with acclimatization is more sensitive to heat exposure; according to some it is also more accurate (new men in the tropics are often observed to overproduce sweat), and the sweat produced is more dilute, that is, it carries away a smaller quantity of electrolytes. Acclimatization can be induced simply by exposure to heat and by exposure to heat and exercise; the heat stress can be repeated day after day and by about the ninth day a peak in the process is reached. Alternatively, excellent acclimatization can be achieved by exposing a man to heat stress day after day, the level of stress being chosen each day so that the same rise in rectal temperature and pulse rate occur. Acclimatization to heat is often combined with training to work, and the effect of the double training is to produce a man particularly fit to work in heat. In fact, some of the changes seen in training for exercise are useful in heat exposure; there is a certain amount of overlap between the two processes. The background for these statements may be found in the literature cited in the following paragraphs.

The first and most obvious change with acclimatization is that on a given heat exposure sweating begins sooner (at a lower skin temperature and a lower rectal temperature), as demonstrated by Eichna et al (1950), Robinson and Gerking (1947), Horvath and Shelley (1946), Kuno (1956), and others. The sweat secreted is also more copious as shown by Horvath and Shelley (1946) and by Macpherson (1960). Similar findings are related by Adolph (1947) and reviewed by Bass (1963). Robinson (1949) cites studies where acclimatization causes men to produce sweat at the extreme rates of 2000 and 3000 gm/hr.

On the practical side, Wyndham et al(1954) showed that acclimatization to humid heat and work allowed South African miners to maintain the same high level of work output with successively lower rectal temperatures as acclimatization progressed.

A number of investigators point out that given heat exposures, or heat exposures combined with work, produce smaller increases in rectal temperatures and smaller pulse rates as acclimatization progresses--Macpherson (1960), Bass (1963), Bass et al (1955), Robinson et al (1943). The report by Robinson et al (1943) clearly showed the effectiveness of combining hard work with heat exposure to produce rapid acclimatization. Acclimatization was defined as a decreased amount of fatigue in hard work, a decreased heart rate, and a lower skin and rectal temperature during a given exposure to work in heat.

The sweating response in acclimatization can be thought of as being more sensitive (Blockley, 1965). The sweat produced is more dilute and more appropriate to the thermal stress (Adolph, 1947; Robinson and Gerking, 1947; and Robinson et al, 1943).

Acclimatization is usually produced by repeated exposure to a given heat stress, as reported by Bass et al (1955), Bass (1963), Lind and Bass (1963), Horvath and Shelley (1946), Eichna et al (1945), Eichna et al (1950), Robinson et al (1943), and Robinson and Gerking (1947). With this procedure acclimatization rises and plateaus in about nine days. This acclimatization will persist for two weeks to one month if heat exposures are not repeated. If heat exposures are repeated occasionally, acclimatization is maintained.

Another method of acclimatization pioneered by Fox (1963) is to vary the heat exposure, that is to increase it daily, so as to produce a standard response each day as acclimatization progresses. If the heat stress is increased each day so as to drive the subject to the same level of internal temperature, acclimatization progresses in daily increments and reaches very high levels as judged by a later standardized testing procedure.

In our own laboratory (unpublished observations of Blockley and Webb, 1964), we have produced acclimatization in subjects by daily exposures to prolonged hard work in combination with high environmental temperatures, driving the rectal temperature to well above 38° C (100.4° F) each day. At the end of two weeks of such training, the subject is so sensitive to thermal stress that profuse sweating begins with very mild thermal stimuli. For example, working on the treadmill in comfortable to mildly warm environments produces sweating almost immediately. Lying in bed at night, sweating will begin when the normal blanket covering, previously acceptable for the entire night, proves to be too much insulation as metabolic rates begin to rise in the early morning hours. The subject wakes up sweating and has to remove blankets in order to go back to sleep.

In the space context the question of the value of training for heat has not been settled. Astronauts and cosmonauts in the US and USSR have been trained more or less formally in terms of physical fitness. The value of sweating as a thermoregulatory response suggests that acclimatization to heat plus work would be a valuable addition. This view has been advanced by Roth (1965) and Blockley (1965). If such training were carried out, an astronaut during an extravehicular mission would be prepared to take full advantage of a gas ventilating system. If the ventilating system failed or the cooling unit in the back pack failed, the sweating response would be appropriate. Other advantages to acclimatization to heat would include a lessening of the susceptibility to circulatory insufficiency in situations involving some degree of heat load.

"Fatigue" of Sweating

First described by Gerking and Robinson (1946) and Robinson and Gerking (1947), and since confirmed by a number of other observers, high rates of sweating over prolonged periods of time in working men gradually decline after the second, third, or fourth hour. The decline may be as great as 80% of the initial value. This reduction in sweating, or "sweat gland fatigue," is more common in hot humid environments and in conditions where high rates of sweating are called for.

A recent paper by Wyndham et al (1966) gives an analysis of data taken on ten acclimatized men in ten different environmental conditions working at rates ranging from 80 kcal/hr to 420 kcal/hr. Figure 11 is reproduced from their paper. The authors conclude from these curves that the duration of the heat exposure 1) diminishes the sensitivity of the sweat response to a rise in internal body temperature, and 2) decreases markedly the maximum capacity of the sweat response to the maximal signal of a high increase in internal temperature, i. e. 103° F. The authors conclude that these two response characteristics are definite evidence of fatigue of the sweat glands.

An opposing view is argued by Brown and Sargent (1965). In their review of the process, which they term "hidromeiosis" (literally, a decline in sweating), they emphasize that in their own observations and in those of other workers, including the early reports of Robinson and Gerking, the phenomenon is more apt to occur when the humidity is high or the skin is wet. Some of the characteristics of hidromeiosis are as follows:

1. In an environment of constant high ambient temperature, a person exhibits initially an outburst of sweating which reaches a peak in one to two hours, following which the rate progressively declines.

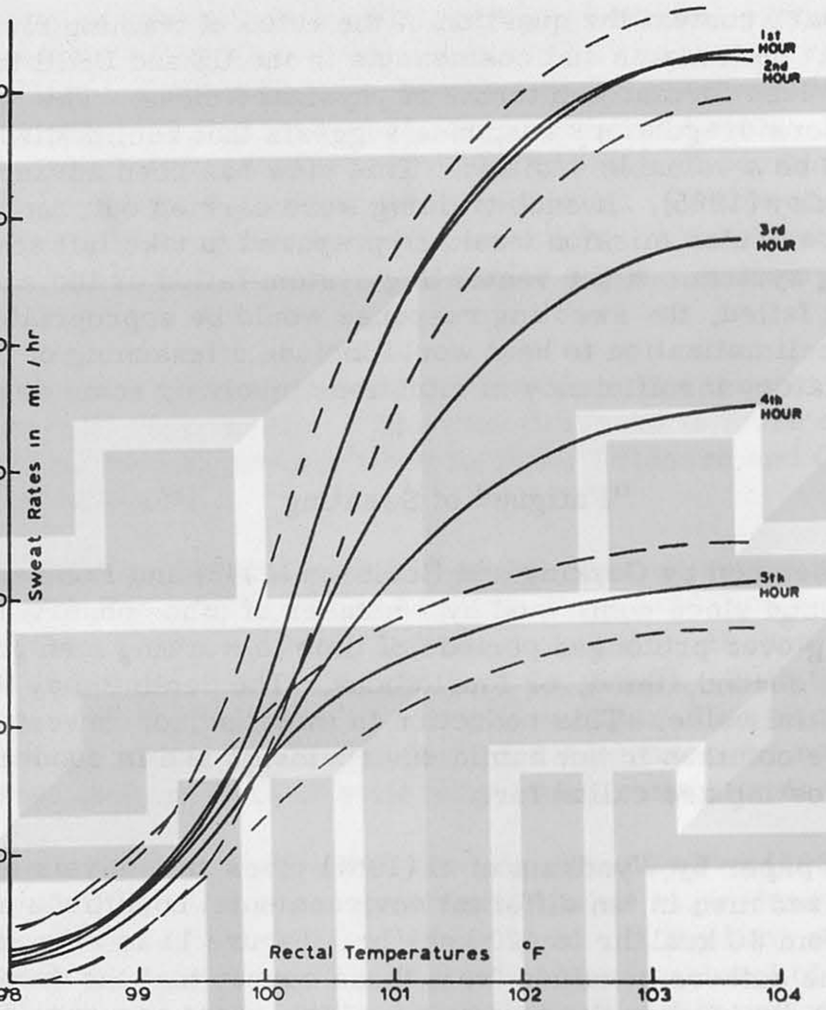

Figure 11. **Sweat rates versus rectal temperature for each hour of 5 hour exposures to work and heat (from Wyndham et al, 1966).**

2. The rate of decline is steeper in moist heat than in dry heat.
3. The degree of depression appears to be related to the magnitude of the initial maximum rate, suggesting that a threshold rate of sweating must be reached to initiate hidromeiosis.
4. Hidromeiosis does not appear to be an adaptive process since frequently the rectal temperature rises in the face of declining sweat rate.
5. Dehydration may accelerate hidromeiosis.
6. The duration of exposure to thermal stress rather than intensity of work appears to be a factor in the production of hidromeiosis.

These authors cite a number of observations in which the decline of sweating is reversed simply by drying the skin, or the decline is stopped and the normal sweat rate restored by drinking water. Randall and Peiss (1957) are particularly convincing in their demonstration that hydration of the skin supresses sweating. Brown and Sargent conclude: "The primary mechanism for hidromeiosis seems to involve the skin. One hypothesis supported by some experimental data is that of mechanical obstruction of dermal pores through hydration of keratin. Adaptation of thermal receptors and fatigue of the eccrine sweat gland are not processes related to hidromeiosis."

There is another condition frequently observed in men in the tropics, the clinical condition of prickly heat, or miliaria. This is an inflammatory process apparently arising from plugging of the opening of the sweat gland and collection of retained sweat under the stratum corneum. Sweating is reduced in the area affected. Areas commonly affected are axillae, groin, and spots where rubbing of clothing or an adjacent body part occurs. This condition is discussed later under the topic of "Skin Hygiene." In addition, the condition termed anhydrotic heat exhaustion, probably a late stage of miliaria in which chronic plugging of sweat glands leads to significant diminution of sweating, is characterized by an inability of the patient to control body temperature in heat (Leithead and Lind, 1964).

WEIGHT LOSS IN SPACE FLIGHT

Astronauts and cosmonauts lose weight during orbital flights. In all the medical data reported so far from the USSR and US Manned Space Flight programs, there has been a consistent weight loss usually amounting to 2% to 5% of body weight. This consistent observation is apparently independent of the duration of flight; that is, weight losses in this range occur in flights of three orbits (4 1/2 hours) up to missions lasting 4, 8, and 14 days. In the following table are listed the weight loss data for all the flights as they are available at the time of this writing. Sources of data are: Berry et al (1966); Gazenko and Gyurdzhian (1965); Genin et al (1963); NASA (1962 a, 1962 b, 1962 c, and 1963); Parin, ed. (1963); and Volynkin et al (1962).

Manned space flight has so far turned up very few surprises. This phenomenon of weight loss is a definite change, a readjustment of some sort. It does not seem likely that the change in weight is due to simple dehydration or to loss of body tissue. The weight is regained in 12-24 hours after return, which rules out tissue loss. Among the many possible explanations of shift in water balance (as defined in Figures 2 and 3), the following suggest themselves:

Weight loss in space flight

Name	Vehicle	Flight duration days	Weight loss kilograms	Weight loss % of body weight
Gagarin	Vostok 1	0.1	0.5	0.7
Titov	Vostok 2	1	1.8	2.9
Nikolayev	Vostok 3	4	1.8	2.6
Popovich	Vostok 4	3	2.1	2.8
Bykovskiy	Vostok 5	5	2.4	3.6
Tereshkova	Vostok 6	3	1.9	3.3
Komarov	Voskhod I	1	1.9	2.7
Feoktistov			2.9	4.0
Yegerov			3.0	3.9
Belyayev	Voskhod II	1	1.0	2.0
Leonov			0.9	2.0
Glenn	MA-6	0.2	2.4	3.1
Carpenter	MA-7	0.2	2.7	3.9
Schirra	MA-8	0.4	2.0	2.8
Cooper	MA-9	1.4	3.5	5.2
Grissom	GT-3	0.2	1.2	1.7
Young			1.6	2.1
McDivitt	GT-4	4.0	2.0	2.9
White			3.9	4.9
Cooper	GT-5	8.0	3.3	4.9
Conrad			3.9	5.5
Schirra	GT-6	1.1	1.1	1.3
Stafford			3.8	4.9
Borman	GT-7	13.8	4.5	6.2
Lovell			2.9	3.7

1. Increasing water loss due to low atmospheric pressure in space capsules, as discussed in an earlier section. However, since the magnitude of weight loss is independent of flight duration, and since Russian spacecraft have operated with a nominal pressure of 1 atmosphere, this explanation is unlikely.
2. Increased perspiration from the wearing of pressure suits and from the increased non-thermal sweating expected from men during the stresses of the mission. Arguing against this explanation are the observations that heat stress during flight was seldom a complaint, although the cooling system in early Mercury flights caused complaints from several of the pilots. It is true that Leonov and White exerted themselves strenuously during their extravehicular activities, but this is only two out of 25 exposures. Finally, since water was freely available, if the weight loss was from simple dehydration, why would not the men have restored body water by drinking? Voluntary dehydration (Adolph's term, explained in the later discussion of dehydration) is a short-term affair, usually seen at the end of an 8-hour working day.
3. Increased urine production and a change in the regulation of body water content. This explanation is bolstered by similar changes seen in studies of bed rest and water immersion, which are partial simulators of the physiological effects of weightlessness. This explanation seems the most likely and supporting evidence will be discussed in some detail below.

Urine Production in Real and Simulated Weightlessness

When healthy men are confined to bed for periods of weeks, one of the many changes induced is an increased urine production, as reported by Birkhead et al (1963), Vogt et al (1965), and in a study at Douglas Aircraft (White et al, 1966). The report of Vogt et al (1965) showed that water and sodium and potassium are excreted in increased amounts and that this is not influenced by allowing subjects to exercise isometrically while confined to bed for two weeks.

Water immersion studies have shown diuresis and increased excretion of sodium, the urine being of low specific gravity (Graveline et al, 1961, and Graveline and Jackson, 1962). Benson et al (1962) did not observe diuresis from an 18 hour submersion experiment, but Gauer et al (1965) confirmed the diuresis of water immersion as did the Douglas Aircraft study in which immersion to the neck was continued for ten days in a bath of silicone fluid (White et al, 1966). In a recent study in our laboratory (Webb and Annis, 1966), three subjects using "balanced" breathing systems and a soft helmet were submerged for 6 hours, and did not experience either diuresis or orthostatic intolerance to tilt. One of the three was then submerged for 16 hours in silicone oil, and another for 120 hours (5 days) in silicone oil. Again there was no diuresis or orthostatic intolerance to tilt, but both subjects lost weight--1.4 kg or 1.7% of body weight for the 16 hour submersion, and 1.8 kg or 2.9% of body weight for the 5 day submersion. These studies of immersion and submersion also produce a relative hemoconcentration and a decrease in circulating plasma volume.

Urine production from cosmonauts and astronauts during space flight is not always reported, or reported incompletely, making it difficult to provide a consistent set of data. In the first and fourth orbital flights of the Mercury project (vehicles MA-6 and MA-9) there was a rather low urine volume. In the second orbital flight (MA-7) there was a diuresis amounting to approximately three times the normal urine production. Federova et al (1963) reported that in the first four Russian manned orbital flights the 24-hour urine volume of all four pilots increased by 25-75% of control value. (In flight urine date is not given.) Data from the Gemini flights (GT-3 to GT-7) are not available, but the consistent weight loss will probably be reflected in increased urine volumes.

Hypothesis of Readjusted Water Content

A number of investigators have advanced reasonable explanations of the diuresis of water immersion, the diuresis of recumbency (postural diuresis) and the diuresis of bed rest. Graveline and Jackson (1962) examined a number of possible explanations for the diuresis of men totally submerged in water for six hours. The diuresis, which amounted to a threefold to tenfold increase in urine volume during the exposure, was of urine with a low specific gravity (1.002 to 1.004), and sodium and potassium, while of low concentration, were also excreted in greater absolute amounts. They observed at the same time an increase in the hematocrit, suggesting a loss in circulating plasma. The picture could be explained by assuming that the antidiuretic hormone (ADH) was suppressed, just as the diuresis of recumbency is caused by a reduction in ADH.

ADH may be suppressed by water immersion as a result of the Gauer-Henry reflex, in which filling of the central veins from recumbency, immersion, negative pressure breathing, or an experimentally placed balloon in the right atrium causes diuresis (Gauer et al, 1954, and Henry et al, 1956). When a man goes from erect to supine, or is immersed in water, the initial event is a return of the blood which is normally pooled in the dependent portions of the body. This blood, amounting to 500-600 ml, fills the central veins and the right atrium. Stretch receptors detect this and signal for a reduction in the secretion of ADH, allowing water which would normally have been reabsorbed in the renal tubule to pass out in the urine along with sodium and potassium.

A similar mechanism has been suggested tentatively by Gazenko and Gyurdzhian (1965) in discussing the "impairment of the water-elimination function."

The argument that mechanical shift of blood volume in water immersion, hence in weightlessness, causes diuresis and a redistribution of fluid is most convincingly argued by Gauer et al (1965), who bolster the argument with beautifully selected experimental data. In addition to the hypothesis of a suppression of ADH to explain the diuresis and to restore circulating blood to its normal level in immersion, the authors present indirect evidence of the appearance of a "diuretic factor" in the blood plasma. Urine flow in a test rat increased by a small but significant degree when the animal was treated with small injections of serum obtained from subjects who were kept supine or immersed. Gauer et al (1965) point out that man is normally adapted to the upright posture and spends about 2/3 of his life standing or seated. Civilized man is immobilized much of the day in an erect seated or standing posture. Continuous recumbency, immersion, and weightlessness are abnormal and cause a readjustment to be made. In contrast to the usual picture of diuresis from negative pressure breathing, immersion experiments show that osmotic clearance is frequently increased in addition to the increase in free water clearance attributed to the suppression of ADH. An injection of vasopressin interrupts or prevents immersion diuresis. Plasma volume is reduced by 14% in an eight-hour immersion.

The preliminary report of the M-5 experiment from NASA's Gemini program by Dietlein and Harris (1966) is at least consistent with this picture. The two astronauts of Gemini VII which flew for 14 days lost 6.2% and 3.6% of body weight (Berry et al, 1966). Dietlein and Harris observed that the marked retention of water after the flight and the rapid restoration toward the preflight weight indicate that the weight loss was water loss. Pre- and post-flight blood and urine analysis gave data which the authors find are consistent with an in-flight diuresis and a reduction of body water from reduced ADH. The urine volumes reported by Berry et al (1966) do not show in-flight diuresis when the urine flowmeter was used. Another method of estimating urine volume, using a tritium dilution technique, is not yet reported. Even if direct diuresis in flight were not present, water could have been lost in increased amounts from insensible perspiration or sweating, the net result being a reduced body water content.

An interesting study reported by Stahl (1964) showed that when dogs are tilted to the vertical position, the urine volume falls as do the urine solutes. Despite a rise in blood pressure in the inferior vena cava there was a fall in the pressure of the renal tubules amounting to about 50%. Blood osmolarity increased and sodium excretion decreased. When the dogs were then immersed to the neck in water, an immediate large excretion of water and solute occurred. Urine osmolarity went down and sodium excretion increased. At the same time renal tubular pressure increased by 2 1/2 times. This author concluded that renal hemodynamics caused these initial changes in sodium and water excretion. Graveline and Jackson (1962) also included possible changes in renal hemodynamics in addition to the ADH mechanism.

A succinct review of the mechanisms of regulation of body fluid volume is presented by McCally (1965). Volume regulation is mediated by: (a) arterial pressure, venous volume, and capillary pressure as stimuli; (b) carotid sinus and vagus nerves as pathways from the sensors; (c) the hypothalamus, posterior diencephalon and juxtaglomerular apparatus as integrators; and (d) several hormonal pathways as effectors, including ADH, renin and angiotensin, glomerulotrophin and aldosterone. McCally (1965) goes on to discuss in some detail the specific renal responses to water immersion. The picture is one of regulation of body fluid volume, plus respiratory effects from negative pressure breathing when subjects have their heads above the water.

The literature on the role of the kidney in maintaining water balance and osmotic balance is quite extensive. The reader is referred to the classic work on the kidney by Smith (1951), to the description of ADH by Verney (1947-1948) and to two recent reviews, one by Gauer and Henry (1963) and one by Bartter (1963). The Gauer and Henry review summarizes the variety of procedures which have been used to change total blood volume, or the distribution of blood, and the consistent finding that an increase in intrathoracic blood occurs together with diuresis, while a decrease is always associated with oliguria. This change is of greater importance than the maintenance of strict osmotic pressure uniformity. Bartter's review (1963) emphasizes that the regulation of extracellular fluid volume is essentially independent of the regulation of intracellular fluid composition. He also emphasizes the mobility of the sodium and potassium ions between the intracellular and the extracellular fluid compartments when a readjustment of osmolarity is required, as in water diuresis. The action of ADH, renal hemodynamics, and aldosterone are reviewed.

Turning speculative for a moment and reflecting on the picture the authors cited above have established, the following series of steps might be involved in the weight loss observed in astronauts.

1. The loss of normal gravitational influences on the location of the circulating blood volume causes a filling of the central veins, particularly in the thorax. Blood normally pooled in the dependent parts returns to the trunk.
2. Filling of the central veins causes by neural reflex a suppression of ADH and a consequent diuresis.

3. The diuresis is reflected in a reduction in blood volume and plasma volume, with a relative increase in hematocrit. This picture would be expected to be of limited duration, in the order of days only.

4. A more permanent readjustment of body fluid (with a persistent weight loss compared to normal weight under earth gravity) should be characterized by a slightly reduced circulating blood volume with a normal hematocrit. Extracellular solute should be relatively reduced and total body water should be reduced to the extent of the persistent decreased body weight.

The hypothesis proposes that a lesser circulating blood volume is required for prolonged stay in weightlessness and that readjustments take place over a period of time (possibly 1-3 weeks), which will restore the normal composition of the blood (but not the volume) and the chemical anatomy of the extra- and intracellular fluid.

A vital question is: Does this reduced total body water affect the same functions which are disturbed by dehydration, namely tilt tolerance, exercise, and heat tolerance?

The results of the first Gemini flights have added substance to the laboratory data and the speculation. In the medical report of Gemini flights through Gemini VII, Berry et al (1966) give the following data on measurements of blood and plasma volumes, and red cell mass:

Flight	Duration	Change in Blood Volume	Change in Plasma Volume	Change in Red Cell Mass
Gemini IV	4 days	-7 to -15%	-13%	-12 to -13% (estimated from hematocrit)
Gemini V	8 days	-13%	-4 to -8%	-20%
Gemini VII	14 days	0	+4 to +15%	-7% -19%

Blood and plasma volumes were determined with a technique using radioiodinated serum albumin. Red cell mass (except for Gemini IV) was measured by using red cells tagged with the isotope chromium 51.

These investigators summarize their interpretations of the data as follows:

> "It can be concluded that the decrease in red-cell mass is not incremental with increased exposure to the space-flight environment. On the 14-day flight, the maintenance of total blood volume, by increasing plasma volume, and the weight loss noted indicated that some fluid loss occurred in the extracellular compartment but that the loss had been replaced by fluid intake after the flight. The detailed explanation of the decreased mass is unknown at the present time and several factors, including the atmosphere, may be involved."

As to cardiovascular deconditioning assessed by response to 70° tilt, Berry et al (1966) observed that the major change was an elevated heart rate, the elevation being progressively greater with flight durations--at least over the range of from 1 to 8 days. The 14 day mission showed elevated pulse responses to tilt more like that seen for the 4 day flight, although one of the two astronauts showed a vagal, presyncopal response on his first tilt, which took place 1 hour after landing. In all flights, regardless of duration, the normal tilt response returned in 50 hours of recovery, and evidence of blood pooling in the extremities occurred during a like period. Restoration of preflight weight was largely accomplished during the first 24 hours.

MEDICAL CONSIDERATIONS

A great many medical problems have a background of water imbalance. Clinical conditions which produce vomiting or diarrhea cause great losses of fluid along with electrolytes, particularly the chloride ion in vomiting because of the HCl in gastric juice, and high potassium loss in diarrhea. Figure 2 made clear how much water is exchanged in the kidney. Severe disturbances of either of these well-regulated high-volume exchangers will cause serious water imbalance. However, these would be largely from clinical illness not peculiar to space flight. The one exception is the diuresis of weightlessness, which was discussed in the preceding section.

There are several conditions related to thermal balance and water balance which are of particular interest in the space cabin or space suit context. These are heat storage and heat exhaustion, dehydration, and skin hygiene in impermeable clothing.

Heat Storage and Heat Exhaustion

In a more or less connected series of studies extending back nearly twenty years, normal subjects have been exposed to extremely high temperatures (up to 240° F), to mild heat in combination with impermeable clothing, to high combinations of heat and humidity and other conditions which were beyond the zone of compensability by the thermoregulatory mechanisms of the body. A long history of experience with heat storage to a physiological endpoint was thus acquired, and the endpoint came to be known as one of incipient heat collapse or impending heat stroke. In the first major report of this kind, Blockley et al (1954) described the state of their subjects as being characterized by faintness, nausea, restlessness, and increased breathing as they neared the end point. Steeply rising rectal temperatures and pulse rates of 140 beats/min were common, although in the most severe environments, where exposure times were short, the rectal temperature had risen only a little. Veghte and Webb (1957) and Webb (1959) described the condition a little more fully. Quoting from the latter paper:

> "At a late stage in an experiment involving a noncompensable heat exposure, we observe in the subject a high and rising rectal temperature, a strong and rapid pulse, a flushed, dry skin (where previously there had been copious sweating), some increase in the rate and depth of breathing, and a growing restlessness and inability to fix attention on any task. This man is on the verge of collapse. By experience the medical observer can tell just when to stop the experiment, knowing that another five minutes of exposure will bring unconsciousness. The subject is in a state of impending heat stroke."

Kaufman (1964) described the same symptoms again, but added that the florid face is altered by the appearance of pallor under the eyes as the end point is reached. Gold (1960) echoes these descriptions, stating that pallor is frequently noticed around the lips. The dimunition of sweating noticed by these various workers may be related to the condition of "fatigue of the sweat glands" or hidromeiosis as described earlier, but it seems more like a sign of failing thermoregulatory control. (A hot, dry skin and a strong and rapid pulse are characteristics of the clinical condition of heat stroke.) It is clear that with reduction or cessation of sweating that thermoregulation has failed. More serious is the circulatory problem in which the cardiac output has become extremely high from the extreme dilation of the cutaneous blood vessels as the body attempts to move larger volumes of blood to the surface where normally heat may be lost. In many of these exposures, of course, the effect is to increase the transfer of heat from the surface inward, since the environment is hotter than the surface and evaporation has been reduced. It is not clear if circulatory failure is the cause of unconsciousness. Certainly in this kind of exposure the internal temperature is not as high as seen in clinical heat stroke and thermal damage to enzyme systems and tissues is not likely.

A frightening example of heat storage in a flight in a balloon gondola is given in the description of the Manhigh III (Anon. 1961). The pilot wore an unventilated partial pressure suit, a garment which contains rubberized bladders. Cabin temperatures rose to a level where the wall and air temperature were equal to or slightly above skin surface temperature. At the same time the device for removing water vapor from the air had become overloaded and vapor pressure in the gondola rose to an estimated 22-25 mm Hg. As this situation developed, the metabolic heat produced by the pilot had nowhere to go and his internal temperature began to rise. By the time the decision had been made for the flight to be terminated, his rectal temperature was measured at 104° F, and by the time descent was completed several hours later, the rectal temperature was said to be over 108° F. The pilot managed to retain consciousness and sufficient control of the operation to come to a safe landing.

If we consider the situation of a man in a space suit engaged in extra-vehicular activities where metabolic heat production is 4-8 times the activity level of a man in a balloon gondola or a pilot in an aircraft, the rapidity of heat storage would be that much increased if there were a failure or an inappropriate response of the portable cooling system. The control of water vapor pressure in the hermetically sealed space cabin, or balloon gondola, or the nearly-sealed space suit is critical, as I have pointed out elsewhere (Webb, 1965), and a rather low water vapor content is strongly recommended. Figure 12 from that paper shows a variety of flight experiences and experimental situations in which heat storage sets a tolerance limit, as well as some flight conditions where thermal balance was not a problem. The analysis supports a design limit of 10 mm Hg for vapor pressure, considering the encumbrance of clothing and the severe restriction of hermetically sealed spaces.

Heat stroke (heat hyperpyrexia) is a result of the excessive storage of body heat and a progressive development of failure in the thermoregulatory system. The clinical condition is extremely serious and often fatal. The subject is discussed in some detail in Leithead and Lind (1964). In the space flight context there may occur situations where collapse comes from heat stress and circulatory insufficiency without a remarkable rise in core temperature. An unconscious or incapacitated astronaut might be unable to take some life-saving action. Or if the heat stress continues, serious or fatal heat stroke might develop.

In contrast to heat stroke or hyperpyrexia there is the condition of heat exhaustion (heat prostration, heat syncope, heat collapse) in which significant heat storage has not occurred but faintness and a shock-like condition may develop, rendering the subject ineffective. This is more apt to occur in people who are unused to heat or the stress of heat-plus-work. Water depletion may play a role in its genesis. This sort of condition would not be expected to occur in trained physically fit men, especially if they had been exposed to the range of thermal conditions expected, including emergencies and equipment failure. The condition is self-limiting, since, as in treating anyone with syncope, recovery usually follows from assuming a seated or recumbent

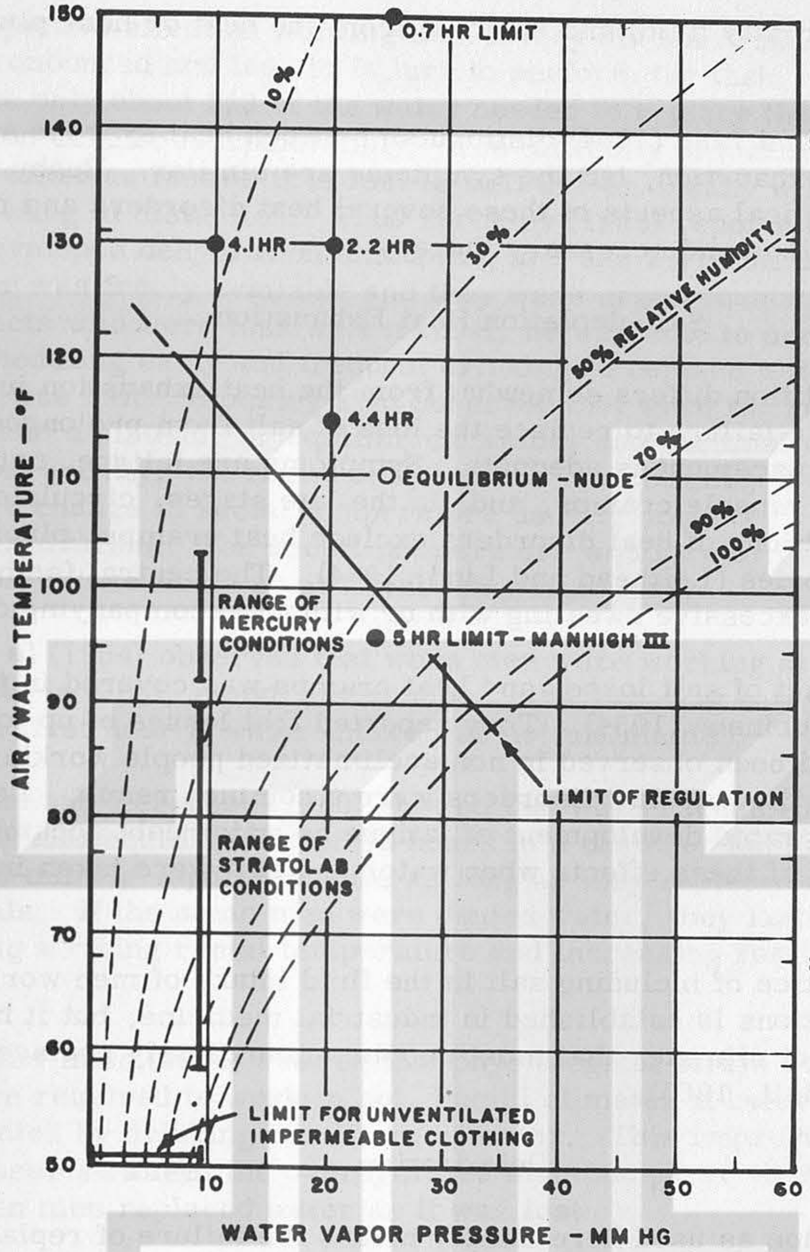

Figure 12. A variety of experimental and flight experiences in which there were problems in maintaining human thermal balance. The four solid dots above 110° F represent experimentally established time limits which are set by body heat storage, for unacclimatized, clothed, mildly active men (Kaufman, 1963). The open dot at 110° represents probably a maximum condition for nude men maintaining thermal equilibrium with a body temperature above normal, lying still. The straight sloping line represents a composite of many studies which established the upper level of heat and humidity in which lightly clothed men maintain thermoregulation. Just below the line, another solid dot locates the conditions in the Manhigh III balloon flight, in which extreme body heat storage caused the flight to terminate at 5 hours (see text). The vertical bars represent the capsule conditions for the Project Mercury manned orbital flights and the Navy Stratolab balloon flights -- conditions which are uncomfortable if the occupants were active and unable to open up their impermeable anti-exposure suits and full pressure suits when no ventilating air is introduced under the impermeable shell. The air motion in all these situations was less than 50 fpm.

position (in a gravity field) and removal from the heat or heat-plus-work condition.

Leithead and Lind (1964) distinguish between heat syncope and water-depletion heat exhaustion, but the symptoms are similar. Busby (1965) reviews the medical aspects of these several heat disorders and relates them to space operations and necessary therapy.

Salt-depletion Heat Exhaustion

This condition differs somewhat from the heat exhaustion just described. It results from a failure to replace the loss of salt from prolonged sweating, even if fluid replacement is adequate. Symptoms are fatigue, nausea, vomiting, dizziness, muscle cramps, and, in the late stages, circulatory failure. Some classifications of heat disorders exclude heat cramps, placing them in separate categories (Leithead and Lind, 1964). The central factor is the loss of salt through excessive sweating with or without accompanying dehydration.

The subject of salt losses and heat cramps was covered in the review by Robinson and Robinson (1954). They reported that losses of up to 20 grams of salt per day had been observed in non-acclimatized people working in the heat. Cramps and cardiovascular disorders were a common result. Laddell (1955) reported on the rapid development of fatigue as water debt accumulated, and on the reversal of these effects when water and salt were taken in adequate quantity.

The practice of including salt in the fluid intake of men working in hot or humid conditions is established in industrial medicine, but it has been the experience in hot climates that most people automatically replace salt at mealtime (Laddell, 1965).

Dehydration

Dehydration as used here simply means the failure of replacement of water lost through inability to find or take fluids. Serious dehydration has been the subject of a number of reports. These have been summarized in chart form as shown in Figure 13. McCance and Widdowson (1965) postulate that the terminal sequence in fatal dehydration involves decreasing volume of extracellular fluid, near-complete retention of sodium salts through the action of aldosterone, and a rising concentration of electrolytes all over the body.

Of more immediate concern here are the milder stages of dehydration which might be expected to occur in space flight, and the effect of minimal dehydration on performance and tolerance to stress. Laddell (1955) observed a marked subjective effect on working men if they did not drink. Fatigue was sudden and pronounced and led to failure to perform the task. Subjects were noticed to take only about 2/3 of the water needed to replace their weight loss and dehydration developed unknowingly. The difficulty of making men working in heat drink water as fast as it is lost is well known. Many will complain of nausea and feeling of distention. Thus Blockley (1965) reports that subjects voluntarily developed dehydration amounting to 1 and 2% of initial body weight, although water was freely available and they were urged constantly to drink. In other subjects who were less well trained, he was able to prevent this dehydration by scheduling early and frequent drinking to replace water in small amounts as it was lost. Blockley also observed that when the rectal temperature had reached a plateau, or equilibrium value, and minimal dehydration developed subsequently, the rectal temperature rose slightly to a new plateau. This step-wise change in rectal temperature usually occurred at about the level of 1% dehydration. The rectal temperature would return to an earlier plateau if water intake made up accumulated weight loss.

Ellis et al (1954) observed that when men were working at two times their basal rate in a hot, moist environment, the sweating rate began to decline after the first hour if water intake was not maintained.

Hertzman and Ferguson (1960) showed that nude recumbent subjects maintained thermal equilibrium for 32 hours in a chamber kept at 43° C (119° F) and 25 mm Hg vapor pressure as long as they replaced water at hourly intervals. If the same men were denied water, they lasted only 10 hours, showing a rising rectal temperature and increasing restlessness and distress.

Moroff and Bass (1965) showed that physiological strain was reduced when men were required to work in hot, humid climates if before working they overhydrated by drinking two liters of water. This improvement was shown by a lesser strain in the overhydrated man compared to the control data taken when men replaced water as it was lost.

Saltin (1964) reported that dehydration in the range of 1-3% of body weight caused a higher heart rate in submaximal work and a significantly decreased time to exhaustion in maximal work.

Greenleaf and Sargent (1965) made a study of voluntary dehydration in acclimated and physically fit men. They observed that their subjects became dehydrated while working at 360 kcal/hr (4 mph on a level treadmill). They failed to drink enough voluntarily to make up their weight loss and this was particularly true when the conditions were hot (120° F). They observed that recovery from dehydration was slow, particularly if the subjects were previously deficient in body water but had the usual content of body salt.

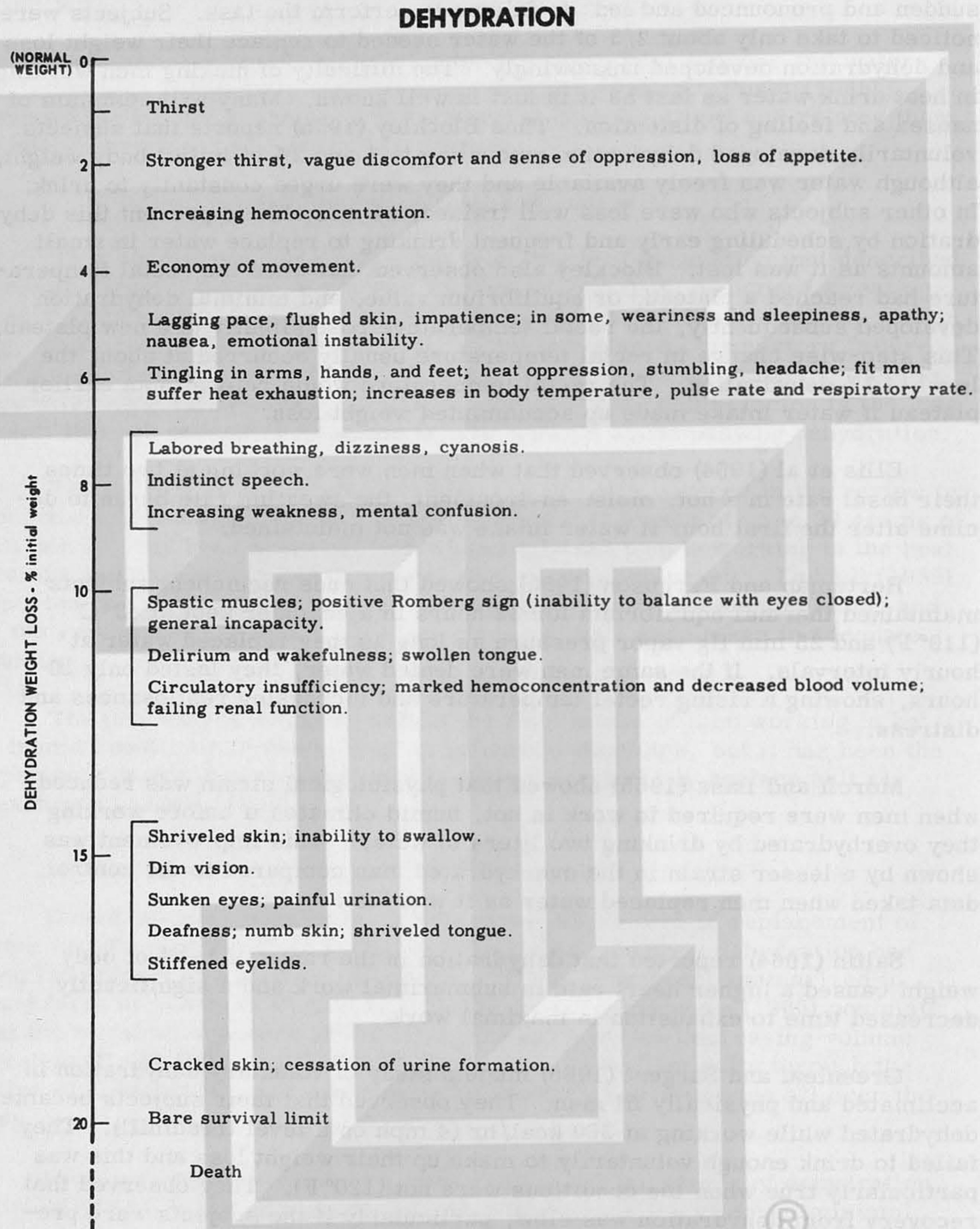

Figure 13. Severe dehydration. (Webb, 1964)

Dehydration also produces subtle effects which may turn out to be of great importance in space flight. Several authors have made a connection between orthostatic intolerance and dehydration. The dehydration need not be great in order to produce a worsening of man's response to being passively tilted from horizontal to 45° or 70° upright. Adolph (1947), in his classic and comprehensive study of dehydration, in connection with a study of man in the desert, showed that at water deficits of 1, 2, 3, and 4% of body weight, the pulse response to 45° tilt is successively higher as dehydration progresses. A similar picture was seen with a 25° tilt and also with standing in a relaxed position. Beetham and Buskirk (1958) produced dehydration to a level of 5% of initial weight in 14 subjects, then subjected them to 70° passive tilt. They observed that the normal rise in diastolic pressure on being tilted was even more marked when dehydration was present, producing an even narrower pulse pressure. Also, dehydration caused the pulse to rise more rapidly and to higher levels following tilt. They left their subjects tilted for ten minutes; in the control study, none of the men fainted. In the dehydrated condition, two of the 14 subjects became apprehensive, pale, and faint, and showed increased tachycardia. Some of the subjects were given physical training and some were given physical training and heat acclimatization, but neither of these treatments influenced the effect of dehydration on orthostatic intolerance.

After astronauts Schirra and Cooper showed a tendency toward orthostatic hypotension, Di Giovanni and Birkhead (1964) produced an exaggerated orthostatic response to 70° tilt by simultaneous dehydration and bed rest in one subject. The subject underwent four periods of bed rest for 48 hours as a control, and in the fifth, 26 hours of bed rest along with heat and dehydration to 3.2% of initial weight. In the four control periods he was able to tolerate ten minutes of 70° tilt with a normal pattern of decreased pulse pressure and increasing pulse. However, when the combination of heat, dehydration, and bed rest were tested with tilt, the subject became nauseated after the fourth minute, complained of blurring of peripheral vision in the seventh minute, and nearly fainted in the eighth minute, causing the procedure to stop. At this time his pulse pressure was 4 (blood pressure of 88/84) and the heart rate had risen to 156. A second subject showed a similar response with a dehydration of 3.2% of initial body weight, where he had previously shown normal response to bed rest. The authors make the point that the orthostatic intolerance they produced was the effect of a combination of stresses--bed rest, dehydration, and mild elevation in temperature from the heat exposure. Such multiple stresses are to be expected in actual flights.

Mild degrees of dehydration have also been shown to reduce tolerance to positive acceleration ($+G_Z$). Taliaferro et al (1965) demonstrated that tolerance to positive acceleration decreased by 15-18% when subjects were dehydrated by mild heat exposure and reduced fluid intake to 1 or 3% of initial body weight. Heat alone did not produce the effect. Greenleaf et al (1966) produced several levels of hypohydration to a maximum of 6% of body weight.

They reported that deterioration in several performance indices began at about 4% depletion. Specifically, functional deterioration began in isometric muscular strength with greater than 4% hypohydration; deterioration appeared in a modified Harvard step test at 4 to 4 1/2%; submaximal oxygen intake for a given exercise deteriorated at greater than 4%; and grayout tolerance to $+G_z$ acceleration deteriorated at greater than 4%.

Heat training leading to acclimatization for particular heat conditions of space flight and the work of EVA would be helpful in several ways. The response to heat stress would be more appropriate; the training would teach the subject when and how to drink to avoid dehydration; and he would be less likely to succumb to heat prostration during mild stress.

Skin Hygiene

The wearing of a space suit for many hours usually produces wrinkling and maceration of the skin, particularly in the hands and feet, which are usually underventilated if ventilated at all. The same skin problem comes with any sort of heavy or impermeable clothing in which the wearer is hot. Water production from the skin continues whether heat stress is present or not. With excellent thermoregulation possible with water-cooled garments, water production by insensible perspiration and by non-thermal sweating will still occur. Gas ventilation is needed to keep the skin dry as well as to keep down the CO_2 levels in the suit. The duration of exposure to wetted skin is critical. Prickly heat, bacterial infection, penetration of the epidermis, and other skin disorders are directly related to a persistent wetness of the skin; in addition, if clothing is worn for extended periods there is a trapping of bacteria and other harmful agents.

Subjects immersed in water have difficulty with skin hygiene. Benson et al (1962) in their study of 18-hour water submersion reported that all 12 subjects, who were professional divers, developed marked and painful maceration of the skin, especially on the hands, fingers, and feet. One of the men also developed an external otitis, which caused him to terminate the submersion an hour early. In the U. S. Navy Diving Manual (Navy Department, 1963), the medical problem of external ear infections and of skin infections is emphasized. SCUBA divers have difficulty with external ear infections, particularly when operating in warm climates, and the incidence increases with the frequency of diving.

Sulzberger (1965) in a brief review on the effects of heat and humidity on the human skin, groups skin disorders in the following way:

1. Intertrigos--in the groin, axilla, and external otitis.

2. Superficial fungus infections--dermatophytosis, candidiasis.

3. Superficial pyodermas and cellulitis--folliculitis, furunculosis, tropical impetigo, etc.

4. Occlusion of pores and follicles--prickly heat (miliaria), tropical acne, and anhidrotic heat exhaustion.

Taplin et al (1965) emphasize that a hydrated stratum corneum (the superficial layers of the epidermis) invites invasion and growth of bacteria and fungi. This hydration occurs particularly if sweat cannot evaporate, as would be true with the wearing of impermeable clothing. Their study concerned men transferred to the tropical jungle climate of Panama for three months. Men with pre-existing microbial skin conditions became significantly worse in the jungle environment. These authors also discuss otitis externa, reporting that it was caused by Pseudomonas aeruginosa. In the printed discussion of their paper, Sulzberger confirmed that soldiers in the tropical climate of Guam also suffered from external otitis due to Pseudomonas. This organism is particularly stubborn and resists most common antibiotics. It has been found in the external otitis of divers. It is a common secondary invader in burned tissue, and is frequently the late cause of death in patients with extensive burns.

The condition of prickly heat, or miliaria, is common in people in hot climates and particularly hot, humid climates. The condition can be annoying, or become more and more severe until the patient is disabled. The subject is reviewed in two recent publications, those of Leithead and Lind (1964) and Lobitz and Dobson (1965). The condition results from a plugging of the sweat gland duct either superficially or deep. Various qualifications of the term miliaria are used by dermatologists. These include: miliaria crystallina, where the superficial opening is plugged and a blister or vesicle of clear sweat appears under the superficial layers; miliaria rubra involves plugging with a reddening of the surrounding tissue; miliaria pustulosa describes plugging with cloudy fluid in the vesicles from infection and inflammation; miliaria profunda involves plugging of the sweat gland duct in deeper and deeper layers, this being a later stage following repeated exposure to heat and humidity. Miliaria is successfully treated by removing the person from the hot, humid conditions; numerous creams, powders and ointments have proven to be of no avail.

There is considerable experimental verification that wetting of the skin causes changes in its usual barrier function. Thus Onken and Moyer (1963) found that the water barrier in human epidermis can be virtually removed by extracting the stratum corneum chemically with acetone followed by hexane. The structure of the stratum corneum itself is not responsible for the barrier, but rather some complex of lipids or lipoproteins. Malkinson (1965), Stoughton (1965), and Suskind and Ishihara (1965) all report that hydration of the stratum corneum increases the penetration of various agents. They offer considerable data in support of the hypothesis that repeated wetting enhances percutaneous penetration and that the effect may be cumulative. Agents tested were of many types, including edible oils, alcohols, steroids, and pharmacologic agents which cause vasoconstriction or vasodilation.

In view of this large body of experimental and clinical experience concerning the detrimental effect of repeated or persistent skin wetness, space suits and constant wear garments in the capsule should be so designed as to allow the skin to remain dry as much as possible. Provision should be made for removing the impermeable garment periodically so that the skin can be restored to its normal level of hydration.

OPERATIONAL CONSIDERATIONS

In this section we shall consider those aspects of human water exchange which are of concern in the operation of a space flight and of use to engineers who must design water supplies and control the humidity of the suit or cabin atmosphere. Drawing upon the physiological explanations of the preceding sections, and omitting further considerations of medical problems dealt with in the preceding section, this section deals with the specifics of water supply, mild dehydration which may be expected, and finally, definitions of comfort and the environmental indices which include water vapor as a factor.

Water Supply

How much water does a man need per day? There are nearly as many answers to this question as there are different situations where water is critical. It is clear that the environment and the expected activity of the man are of great importance in determining the quantity. Laddell (1965) found that the official British Army allowance of 9 liters (2 gallons) of water per man per day was in fact only the amount required for drinking on the average; the total quantity which had to be supplied logistically was 22 liters (5 gallons) per man per day which included the water used in cooking, the water used for washing, for vehicles and for other purposes, as well as the 9 liters used in drinking. The effect of environmental conditions on water supply for military personnel is seen clearly in Figure 14 taken from Welch et al (1958).

For the space environment there are some specific recommendations to be found in recent literature. The Space Medicine Advisory Group (Vinograd, 1966) recommends as follows:

> "Water--2.5 liters per day (1 cc per calorie of food). Water intake should be sufficient to maintain the urine at a specific gravity of 1.015 or less or a volume of at least 1 to 1-1/2

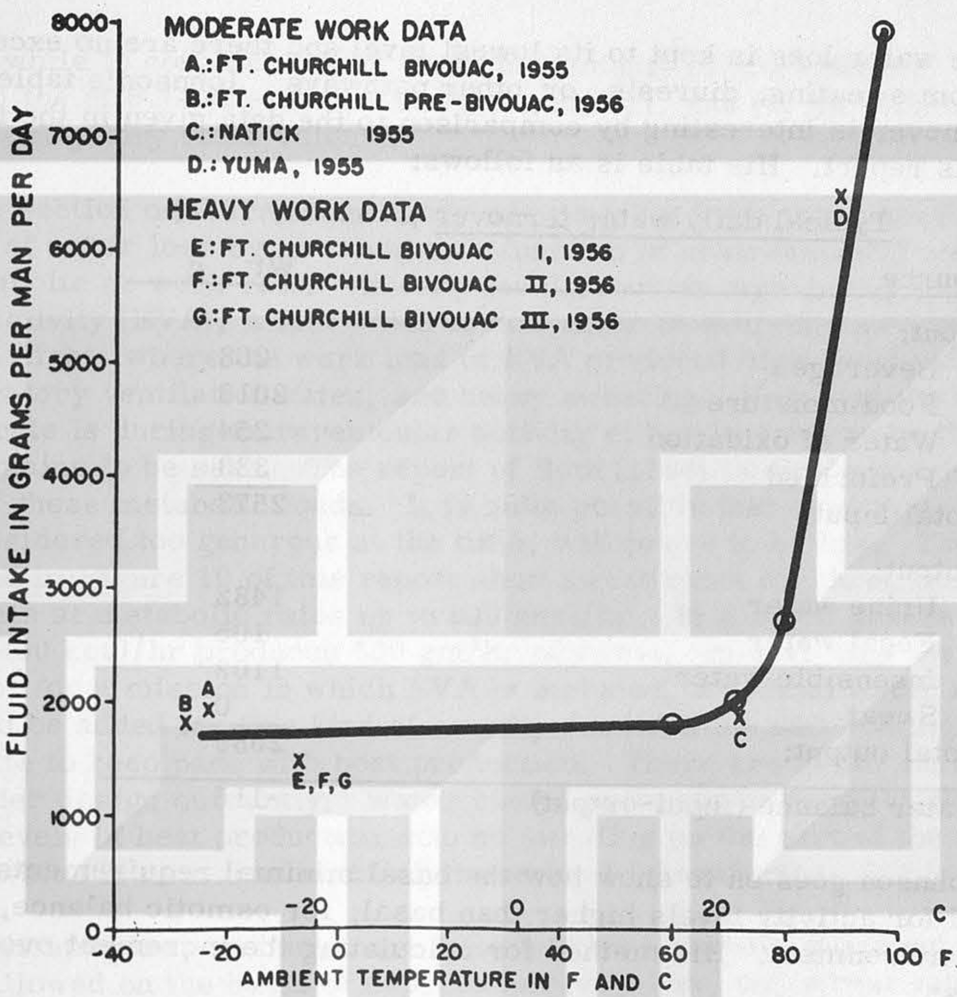

Figure 14. The relation of fluid intake and mean ambient temperature for military personnel, from Welch et al (1958).

> liters per day to avoid the development of urinary gravel. Water should be consumed in definite quantities on a programmed schedule. Daily measurements of body mass should be used to adjust water intake."

Notice, however, that this recommendation is based upon considering astronauts who are relatively confined in an orbiting laboratory where the environment is kept near comfort at all times.

In the Gemini program the water supply provided was 6 lbs (2.7 liters) per man per day (Berry et al, 1966).

In a thorough-going review of human water requirements as related to space flight, Johnson (1964) calculates the minimum basal requirement for water would be approximately 800 ml per day, of which 550 ml would be in liquid intake and 250 would be from metabolic sources. This is definitely stated to be minimal and assumes that the environment is so controlled that insensible water loss is kept to its lowest level and there are no excessive losses from sweating, diuresis, or other pathways. Johnson's table of daily water turnover is interesting by comparison to the data given in the first section of this report. His table is as follows:

Typical daily water turnover (Johnson, 1964)

Source	Wt., g
Input:	
Beverage	268
Food moisture	2018
Water of oxidation	254
Preformed	333
Total Input:	2573
Output:	
Urine water	1482
Fecal water	105
Insensible water	1102
Sweat	0
Total output:	2689
Water balance (input-output)	-116

Johnson goes on to show how the basal minimal requirements must be increased for activity levels higher than basal, for osmotic balance, and for thermal environment. His method for calculating the increment over basal is as follows:

Basal Minimum Water Requirements and Increments for Activity, Osmotic Balance, and Thermal Environment (Johnson, 1964)

Basal minimum	= Renal + Dermal + Pulmonary = 800 ml
Renal increment for osmotic adjustment	= ±(Predicted excretion, mOsm/day-400) × 2
Insensible water increment for caloric output	$= \dfrac{\text{(Estimated kcal above basal)}}{0.58 \times 4}$
Sweat increment for temperature, humidity, air motion, work, and clothing	= 6 ×(predicted 4-hr sweat rate)
Pulmonary increment for hyperventilation	= (Estimated pulmonary minute volume - 10) × (Absolute humidity of expired air - Absolute humidity of inspired air)

It is worth while to consider two of these increments in more detail. Let us examine (1) the effects of exercise and environment, and (2) the effects of diet on the obligatory urine volume.

The section on thermoregulatory sweating set forth the basis for the estimation of water loss by sweating as a function of environmental conditions and of metabolic or work rate. Activity level becomes high during extravehicular activity (EVA), a fact which is now clear to everyone as a result of the Gemini flights where the work load of EVA produced high heart rates, high respiratory ventilation rates, and heavy sweating. How high the actual metabolic rate is during extravehicular activity either in orbit or on the lunar surface remains to be seen. The report of Roth (1964) is our best present estimate of these metabolic loads. It is quite possible that even these estimates, considered too generous at the time, will prove to be low. The data summarized in Figure 10 of this report show sweat rates for three different environments at metabolic rates up to 600 kcal/hr. In a warm spacesuit environment 400 kcal/hr produces 600 gm/hr of sweat. In designing the water requirement for a mission in which EVA is included, a special water increment should be added for this kind of activity provided the suit cooling system is inadequate to keep pace with heat production. There are better suit cooling devices under design currently. Water cooled suits can be made to remove very high levels of heat production with no sweating on the part of the man, something which is now done routinely in several laboratories.

To summarize, an increment in an astronaut's daily water supply should be allowed on the basis of expected activity level and a best estimate of environmental load. The thermal index which is most nearly suited for this sort of calculation is the P4SR scale, which is defined below.

Turning now to the subject of the effect of diet on water requirement, there are two separate factors active here. The first of these is relatively small and easily defined; it is the metabolic water produced as a function of the proportioning of components in the diet. A more important effect is that of the protein content of the diet, which affects the volume of urine which must be excreted to carry away the solutes produced by metabolism.

The calculation of metabolic water is done with the following formula (Webb, 1964):

$$W = .555 \text{ carbohydrate} + 1.071 \text{ fat} + 0.413 \text{ protein}$$

The answer for W, water, comes out in grams per day when the dietary components are given in grams/day. The range of variation is not large. For example, we have computed the metabolic water produced from a 3000 kcal per day diet with four different dietary mixtures ranging from very high protein to zero protein. The figures are:

Metabolic Water from 3000 kcal Diets with varying component mixtures

	Proportions	Metabolic Water
Diet 1	50% Pro, 50% Fat, 0% CHO	314 gms/day
Diet 2	30% Pro, 30% Fat, 40% CHO	347 gms/day
Diet 3	10% Pro, 10% Fat, 80% CHO	381 gms/day
Diet 4	0% Pro, 0% Fat, 100% CHO	402 gms/day

It is clear that the change in metabolic water for 3000 kcal diets which vary from no carbohydrate to pure carbohydrate is small, only about 100 gms. If the total caloric intake is smaller than 3000 kcals, the total metabolic water is correspondingly decreased. So the water-sparing effect of a high carbohydrate diet is small in terms of metabolic water. Such is not the case, however, for the increasing requirement for water to excrete metabolic waste with increasing amounts of protein in the diet.

We have seen in earlier sections of this report that water loss from the body surface and from the respiratory tract is obligatory and takes precedence over maintaining an absolute water balance if thermoregulation is threatened. We have also seen that there is a shift in body water associated with the weightless condition. The kidneys are required to do their best to maintain water balance in spite of these loads. But there is an irreducible level of urine production related to the quantity of electrolytes which must be excreted each day to maintain osmotic balance in the body. The kidney responds to a water deficit situation by secreting increasingly concentrated urine. But there is a maximum osmotic level, or urine concentration, which it can normally achieve. Gamble (1950) gives this as 1.4 osmoles/liter.

The quantity of osmotically active material which must be excreted each day is a function of the dietary composition. On a pure carbohydrate diet, or a diet consisting of only fat and carbohydrate, the osmotic load is minimal. That is, the end products of metabolism of fat and carbohydrate do not produce electrolytes to be secreted in the urine, only water and CO_2. The metabolism of protein, however, does produce osmotically active material, principally urea.

Laddell (1965) states that the minimum urine flow on a pure carbohydrate diet in the face of water deficit is 4 to 5 ml per hour (96 to 120 ml per day) whereas with a high protein diet the minimum urine flow is 20 to 25 ml per hour (480 to 600 ml per day).

Suppose that an astronaut is on a 3000 kcal per day diet with the four different compositions given in the table above. Suppose, further, that he had lost water excessively for thermal reasons and was dehydrated. In the face of a demand for minimal urine flow to conserve water, the effect of the diet on minimum urine volume for the day would be as follows:

	Total Solutes*	Minimal Urine Volume**
Diet 1 (50% Protein)	1892 milliosmols	1400 ml/day
Diet 2 (30% Protein)	1212 milliosmols	880 ml/day
Diet 3 (10% Protein)	523 milliosmols	310 ml/day
Diet 4 (0% Protein)	180 milliosmols	100 ml/day

*Assuming constant low values for potassium of 40 meq/day, chloride 65 meq/day and potassium 70 meq/day, and computing urea from the quantity of nitrogen available in the protein of the diet.

**Using the average maximal concentrating ability of the kidney at 1.4 osM/liter (Gamble, 1950).

Mild Dehydration

As an operational problem, mild dehydration is likely to be present, a dehydration over and above the shift of body water which was discussed in Section V to be a result of the weightless environment. Dehydration as a topic was considered in an earlier section. It is brought up again here because small amounts of dehydration can easily become cumulative if continued day after day, as experience with troops in hot climates has shown. The problem becomes one of recognition, and of what to do about it.

Definition of terms is in dispute. I have chosen to use the term "mild dehydration" to be the same as the "voluntary dehydration" of Adolph (1947) and Laddell (1965) and the "involuntary hypohydration" of Greenleaf (1966). The process referred to is that seen in men who, for example, are working in heat, or otherwise losing water at a high rate. These men seldom replace water as rapidly as it is lost, and during the period when body weight is reduced, that is before weight loss has been made up by water ingestion, there is a water depletion which may amount to 1-2% of body weight. Many people in hot industrial situations, and people who live in hot climates, carry such a weight deficit through the day, and make it up in the evening. Complete rehydration does not occur during the day because the men do not voluntarily increase their water intake sufficiently. Greenleaf calls this period of depletion involuntary on the part of the person. Apparently neither water loss alone nor water and salt lost together produce thirst appropriate to a depletion of body water of 2-3% of body weight (Greenleaf, 1966).

Laddell (1965) feels that there is 2 liters of "free circulating water" which is expendable without gross physiological disturbance. He feels that voluntary dehydration is simply a loss of this free circulating water in men who are habitually overhydrated.

Whether this temporary depletion of body water is significant is a moot point; it certainly would become significant if the depletion were not made up on a day to day basis and the depletion became cumulative. Also, as pointed out in an earlier section, mild dehydration has recently been shown to affect performance measures. There are the additional problems in spaceflight of weightlessness, orthostasis on return to Earth, and the high physical effort involved in extravehicular activity.

One of the difficulties in assessing this problem will be knowing when mild dehydration has progressed and accumulated over time. An accurate means of measuring body mass in weightlessness would be an important addition to medical monitoring in flight. The usual clinical intake-output records will hardly serve, since these deal only with fluid intake and urine output.

If a deficit is discovered which is greater than should be expected from the readjustment of weightlessness, there is a definite requirement for flight controllers and medical personnel to urge the astronauts to rehydrate. Ideally the rehydration should occur by taking small amounts of water frequently during the time the water loss is high. Drinking large amounts of water may produce diuresis, with a net loss of body water (Kenney, 1954). Also, drinking large amounts of water may provoke gastric distress and vomiting. It is better to make up water loss as it is occurring by continually taking small amounts of water.

Comfort and Environmental Indices

In the context of this report on human water exchange we are concerned principally with those departures from comfort which affect water loss, specifically heat stress and sweating. In the section on thermoregulatory sweating, minimal sweating was defined arbitrarily as any sweat rate occurring when weight loss was less than 100 gms/hr. Such low levels do not affect water economy.

Comfort zones of temperature and humidity and air motion have been defined for many situations; one such comfort zone may be found in the Bioastronautics Data Book page 108 (Webb, 1964). Such a comfort zone, however, like most conventional comfort definitions, does not specifically show the effects of activity, total pressure, gas composition, air motion, clothing, acclimatization, and so forth. The large number of variables which affect comfort explains why there is no universal definition of the term. A complete definition must include both physical and physiological variables.

The environmental indices which help to define comfort in conventional situations, i.e. Earth conditions at rest, include the following: the ASHRAE comfort chart which defines the zones of dry bulb and wet bulb temperature selected by large numbers of people as feeling comfortable, both for winter and for summer (ASHRAE, 1963); Effective Temperature (E. T.), which includes the variables of air movement, air temperature, and humidity (Houghton and Yaglou, 1923; Leithead and Lind, 1964; Newburgh, 1949); Operative Temperature (To), which stresses the effect of radiant heat load in addition to air motion and dry bulb temperature (Gagge, 1941, and Newburgh, 1949); Reference Operative Temperature (T_{or}), which adds the humidity effect to operative temperature (Blockley et al, 1954); Web Bulb Globe Temperature Index (WBGT), which combines the effects of humidity, air motion, radiant temperature and dry bulb together (Yaglou and Minard, 1957; Leithead and Lind, 1964); and the Predicted Four Hour Sweat Rate (P4SR), the only environmental index which combines humidity, air motion, dry bulb and radiant temperature, clothing and activity level (Macpherson, 1960).

Each of these indices has its own advantages, and each can be used to define comfort for certain conditions. The ASHRAE chart, which shows E. T. lines on a grid of wet bulb/dry bulb lines, is empirically derived from a large and varied population sample, and has had wide application in heating and cooling of homes and offices. It does not permit assessment of the effects of work or unusual clothing, and it only attempts to define comfort. The E. T. scale is also backed by long experience, and was also derived initially as a subjective assessment of how warm or comfortable various combinations of air temperature, humidity and air motion felt to seated subjects. The E. T. has been enlarged to include the effect of increased radiant loads, yielding the C. E. T., or Corrected Effective Temperature. But neither E. T. nor C. E. T. can be used successfully in defining the physiological effect of high thermal loads from the environment, or the changes brought to comfort and physiological stress by increased activity, and by special clothing. Operative Temperature (T_o) was defined without a humidity term from the physical laws governing heat exchange, and tested experimentally in a human calorimeter. Clothing was minimal, activity was limited to seated at rest, and no physiological term and no evaporative effect was included. T_{or} added a humidity term to T_o by modifying T_o in terms of the actual vapor pressure referenced to a standard vapor pressure of 20 mm Hg. (The effect of vapor pressure below 15 mm Hg on the value of T_o was small.) The WBGT index uses a globe thermometer, a standardized 6-inch black sphere with a thermometer, to combine the effects of radiation (e.g. from the sun) and air motion into a single temperature, to which is added the dry bulb and wet bulb temperature, each with its separate weighting. The WBGT index has been used successfully outdoors in helping control the level of exertion to be expected from military personnel. It is a relatively new index, and does not include any physiological variable or clothing effect.

There are other indices of environmental stress, some based entirely on the level of physiological strain produced in test subjects. These usually combine heart rate, sweat rate, and increase in body temperature in a standardized fashion. None would be too helpful in designing spacecraft or suit environments except as a means of measuring the severity of a postulated set of conditions.

The P4SR, although derived under rather different conditions than expected in space flight, offers some hope if suitably extended. It was originally based on several sets of experimental data taken on heat-acclimatized young men in Singapore and in environmental chambers. Work, clothing, temperature, air motion, and humidity were variables. The physiological term was the amount of sweat produced during a four hour exposure, hence the name. However, it is unsafe to use it as a means of predicting sweat rate unless all the conditions are similar to those originally used. Used with care, it does allow prediction of comparative thermal effect for a range of thermal conditions, as shown in the recent study by Blockley (1965). Here, too, it is seen that if the environmental humidity is below about 15 mm Hg vapor pressure, the thermal effect of humidity is small.

A definition of P4SR and how it can be used is found in Macpherson (1960); its limitations are also stated in that report. The limitations are chiefly those of a narrow range of activity (up to 250 kcal/m^2hr), limited clothing combinations, and the fact that all the subjects were heat acclimatized. The computation procedure, which includes several steps, and which is complex enough that it should be accompanied by more explanation than we have room for here, leads to definitions of environments in terms of thermal stress. I do not recommend that the P4SR be used for predicting sweat, but rather for comparing environments in terms of thermal stress, to be followed by experimental evaluation of the environments, with sweat production being taken as one dependent variable. The data of Blockley (1965) which are shown in Figure 10 are an example of such usage of the index. More such usages could lead to useful extensions of the P4SR scale to cover the environmental and physiological conditions of space flight.

It is important to define comfort and levels of thermal stress for the purpose of predicting water exchange in active astronauts. The thermal stress and high sweating observed in the extravehicular activity of the Gemini flights underscores the need for a more complete and useful definition. We do not have a good definition of comfort or a good environmental index for this purpose. The P4SR index probably comes closest, but it cannot be used easily, nor can it be used in situations much different from those under which it was derived. Here is an important area for research in support of manned space flight. It is distasteful to evade the issue like this, but it would be even worse to promise engineers and operational personnel that physiologists have indices and formulae able to cope with new situations as they occur in space flight.

RESEARCH AREAS

The following areas in water exchange call for new research:

1. Research is needed to clarify the mechanism(s) involved in the persistent weight loss of manned space flight. Also there should be an investigation of the potentially deleterious effects of lower body water content during the flight and on return to Earth.

2. An index of thermal stress should be specifically developed and validated for space suit and space capsule conditions. A likely candidate for further refinement is the P4SR scale.

3. A method should be developed for daily accurate determinations of body mass. This is important operationally for medical monitoring, it being the only way to detect dehydration. The technique would further be useful in studying the water loss of weightlessness and for assessing thermal stress. For similar reasons there should be a reliable technique for measuring urine volumes during the flight.

4. Water requirements should be defined for the many different conditions in space flight which modify the basic requirement of approximately 2500 ml/man day. Experimental evaluation of suit and cabin environments, activity levels, diets, weightless conditions, and effects of short-term and long-term dehydration should be undertaken to sharpen estimation of water requirements.

5. The physiological and performance effects of mild dehydration should be studied further, since this type of stress is to be expected in space flight.

6. Skin maceration should be studied during prolonged wearing of space suits, with various realistic activity levels and various cooling systems employed.

SUMMARY

1. As background for the rest of the report, water exchange in normal man is reviewed, and the general nature of the control of water content and osmoregulation in the body is given. Insensible loss, minimal urine flow, and sweating are obligatory or priority processes, and drinking is necessary to maintain fluid balance. Total water turnover, including the flow of digestive juices and renal filtration, amounts to more than 182 liters per day. Fluid intake and output are nominally 2.4 liters/day. Any prolonged imbalance in this external exchange causes either dehydration or edema.

2. Insensible water loss, a process not regulated by the body, amounts to 936 ml/day nominally, and consists of diffusional water loss through the skin (15 gms/m^2hr) and respiratory water loss (12 gms/hr). The rate of cutaneous diffusion is increased by low ambient vapor pressure, by high skin temperature, and by low barometric pressure. When the spacecraft environment is at 1/3 atmosphere, insensible loss should increase by 5-10 gms/hr, or 120 to 240 gms/day. Respiratory water loss is increased by high respiratory ventilation and by dry inspired air. Cold inspired air is accompanied by lower expired air temperature and lower absolute water content.

3. Non-thermal (psychogenic) sweating is water lost from sweat gland activity of the palms, soles, axillae and face as a result of tension, excitement, alertness, etc. It accounts for up to 220 gms/hr of weight loss in resting subjects in the laboratory.

4. Sweating for thermal purposes is influenced most strongly by the warmth of the environment and the metabolic level. When the air humidity is below 15 mm Hg vapor pressure, at rest, thermal sweating in the nude man begins at an air-wall temperature of 29.5° C; at a mild activity level of 250 kcal/hr it begins at 20.5° C; and for moderate work of 400 kcal/hr at 10° C. Once sweating begins, at a given activity level, its rate increases linearly with skin temperature. Or in a given environment, sweat rate increases with metabolic rate. Sweat rates of 300-600 gms/hr are commonly seen in air-ventilated pressure suits (and the wearing of a pressurized pressure suit at least doubles the metabolic cost of a given activity). Acclimatization to heat sensitizes the sweating response, and sweating is more copious on a given exposure to work and heat. Continued exposure for many hours to humid heat and work where sweating is heavy is marked by a progressive decline in sweat rate after the second hour.

5. An unexpected finding in manned space flight is a consistent reduction in body weight of 2-5%, which is independent of flight duration. Urine production is probably high, and the changes in weight, urine, and plasma volumes are similar to those seen in water immersion and prolonged bed rest. The mechanism of the suppression of ADH via the Gauer-Henry reflex is reviewed and the hypothesis is advanced that water content of the body is readjusted to fit the weightless situation in which there is no need for enough blood volume to allow gravitational pooling in dependent parts of the body. The total readjustment of all fluid compartments probably takes longer than a week; flight data from the longer Gemini missions are in general consistent with this hypothesis.

6. Medical problems related to water production in space suits and capsules include heat storage and heat exhaustion, dehydration, and skin hygiene. Heat storage, which has occurred in pressure suit work and in sealed capsules, like the near-diastrous Manhigh III balloon flight, can lead to the dangerous medical condition of heat collapse, which, if untreated, leads to heat stroke, a fatal condition. Heat exhaustion from water depletion or water and salt depletion is a syncopal condition usually seen in men unaccustomed to work in heat. Dehydration can be a major medical problem if it progresses beyond the level of 6% reduction of body weight. When dehydration of 1-4% develops, performance is impaired, temperature regulation is changed, and tolerance to passive tilting and $+G_x$ acceleration is impaired. Water accumulation on the skin or high moisture content of air within sealed clothing causes hydration and maceration of the skin, which increases problems from microbiological invasion and also reduces the normal skin barrier against penetration of potentially harmful agents.

7. The water which man constantly evolves from his skin and respiratory tract represents a specific loading on the spacecraft environmental control system (ECS) or the portable ECS of extravehicular space suits. Quantities of water produced are determined by the man's activity level and the adequacy of cooling. Thermal sweating quickly increases the water load on the ECS. The humidity of the microenvironment next to the skin should be kept at or below 10 mm Hg to avoid problems of skin hygiene and heat storage. Adequate cooling to prevent sweating and easily available, early and frequent fluid replacement are important in preventing dehydration.

8. The water supply for astronauts has a nominal value of 2500 ml/man-day plus calculable increments for increases in activity and for thermal loads causing sweating. Diets low in protein cause lower obligatory urine volume, hence lower water requirements if the water supply runs low.

9. Mild dehydration can be an operational problem of some magnitude if "involuntary hypohydration" is not corrected and becomes cumulative day after day. Rehydration is necessary, ideally in small amounts during periods of high water loss. A means of measuring body mass would be a valuable monitoring tool.

10. No adequate definition of comfort is available yet for active astronauts, although conditions which do not require sweating at even high activity levels are "comfortable" in terms of water economy. The only environmental index which approaches the need for assessing the human and environmental conditions of space flight is the P4SR; it needs further specific development for the various conditions which may occur.

REFERENCES

1. ADOLPH, E. F. and Associates. Physiology of man in the desert. Interscience, New York, 1947.

2. AIRESEARCH MANUFACTURING COMPANY. Study of the thermal processes for man-in-space. NASA CR-216. National Aeronautics and Space Administration, Washington, D. C., April 1965.

3. ALLEN, R. W. and J. LYMAN. Arm water losses under disparate arm and body thermal conditions. AMRL-TDR-62-131. Wright-Patterson Air Force Base, Ohio, November 1962.

4. ANONYMOUS. Manhigh III. USAF manned balloon flight into the stratosphere. AFMDC TR-60-16, Holloman Air Force Base, New Mexico, 1961.

5. ASHRAE. ASHRAE 1963 guide and data book. Amer. Soc. of Heating and Air Cond. Engrs., New York, 1963. (Published annually.)

6. BARTTER, FREDERIC C. Regulation of the volume and composition of extracellular and intracellular fluid. Ann. N. Y. Acad. Sci. 110: 682-703, 1963.

7. BASS, D. E. Thermoregulatory and circulatory adjustments during acclimatization to heat in man. pp. 299-305 in: Temperature, Its Measurement and Control in Science and Industry, Vol. 3, Part 3; Reinhold, N.Y., 1963.

8. BASS, D. E., C. R. KLEEMAN, and M. QUINN. Mechanism of acclimatization to heat in man. Medicine 34: 323-380, 1955.

9. BAZETT, H. C. The regulation of body temperatures. Chapter 4 in: Newburgh, L. H. (ed), Physiology of Heat Regulation and the Science of Clothing. W. B. Saunders, Philadelphia, 1949.

10. BEETHAM, W. P., Jr. and E. R. BUSKIRK. Effects of dehydration, physical conditioning and heat acclimatization on the response to passive tilting. J. Appl. Physiol. 13: 465-468, 1958.

11. BENEDICT, F. G. and H. F. ROOT. Insensible perspiration; its relation to human physiology and pathology. Arch. Int. Med. 38: 1-35, 1926.

12. BENSON, VICTOR G., EDWARD L. BECKMAN, KENNETH R. COBURN and RANDALL M. CHAMBERS. Effects of weightlessness as simulated by total body immersion upon human response to positive acceleration. Aerospace Med. 33: 198-203, 1962.

13. BENZINGER, T. H. On physical heat regulation and the sense of temperature in man. Proc. Nat. Acad. Sci. 45: 645-659, 1959.

14. BERENSON, P. J. Prediction of human thermal comfort in oxygen-nitrogen atmospheres. pp. 1-29 in: Science and Technology Series, Vol. V, Amer. Astron. Soc., 1965.

15. BERRY, CHARLES A., D.O. COONS, A.D. CATTERSON, and G. FRED KELLY. Man's response to long-duration flight in the Gemini spacecraft. Chap. 25, pp. 235-261, in: NASA SP-121, Gemini Mid-Program Conference, National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, 1966.

16. BIRKHEAD, N.C., J.J. BLIZZARD, J.W. DALY, G.J. HAUPT, B. ISSEKUTZ, Jr., R.N. MYERS, and K. RODAHL. Cardiodynamic and metabolic effects of prolonged bed rest. AMRL TDR 63-37, Aerospace Medical Division, USAF, Wright-Patterson Air Force Base, Ohio, 1963.

17. BLOCKLEY, W. VINCENT. A systematic study of the human sweat response to activity and environment in the compensable zone of thermal stress. NASA CR-65260. National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, 1965.

18. BLOCKLEY, W.V., J.W. McCUTCHAN, and CRAIG L. TAYLOR. Prediction of human tolerance for heat in aircraft: a design guide. WADC TR 53-346, Wright-Patterson Air Force Base, Ohio, 1954.

19. BLOOM, WILLIAM and DON W. FAWCETT. A textbook of histology. W.B. Saunders, Philadelphia, 1962.

20. BREBBIA, D.R., R.F. GOLDMAN, and E.R. BUSKIRK. Water vapor loss from the respiratory tract during outdoor exercise in the cold. J. Appl. Physiol. 11: 219-222, 1957.

21. BREBNER, D.F., D.McK. KERSLAKE, and J.L. WADDELL. Diffusion of water vapor through human skin. J. Physiol. 132: 225-231, 1956.

22. BROWN, WILLIAM K. and FREDERICK SARGENT II. Hidromeiosis. Arch. Envir. Health 11: 442-453, 1965.

23. BUETTNER, KONRAD J.K. Diffusion of water vapor through small areas of human skin in normal environment. J. Appl. Physiol. 14: 269-275, 1959.

24. BUETTNER, KONRAD J.K. and FREDERICK HOLMES. Diffusion of water vapor through human skin in hot environment and with application of atropine. J. Appl. Physiol. 14: 276-278, 1959.

25. BURTON, ALAN C. and OTTO G. EDHOLM. Man in a cold environment. Arnold, London, 1955.

26. BURTON, D.R. and L. COLLIER. The development of water conditioned suits. Royal Aircraft Establishment, Farnborough, England. Tech. Note ME-400. H.M. Stationery Office, London, April 1964.

27. BUSBY, D.E. Heat disorders. Chap. 5 in: Clinical problems attributable to the space environment. LF-Aero-115-5. The Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico, 1965.

28. CHALMERS, T. M. and C. A. KEELE. Nervous and chemical control of sweating. Brit. J. Dermatology 64: 43-54, 1952.

29. CROCKER, JEREMY F., PAUL WEBB and DAVID C. JENNINGS. Metabolic heat balances in working men wearing liquid-cooled sealed clothing. AIAA-NASA Third Manned Space Flight Meeting. AIAA pub. CP-10, 111-117, 1964.

30. DIETLEIN, L. F. and E. HARRIS. Experiment M-5, bioassays of body fluids. pp. 403-406 in: NASA SP-121, Gemini Mid-Program Conference, National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, 1966.

31. DI GIOVANNI, C., Jr. and N. C. BIRKHEAD. Effect of minimal dehydration on orthostatic tolerance following short-term bed rest. Aerospace Med. 35: 225-228, 1964.

32. EICHNA, L. W., W. B. BEAN, W. F. ASHE, Jr., and N. NELSON. Performance in relation to environmental temperature; reactions of normal young men to hot humid (simulated jungle) environment. Bulletin Johns Hopkins Hospital 76: 25-58, 1945.

33. EICHNA, L. W., C. R. PARK, N. NELSON, S. M. HORVATH, and E. D. PALMES. Thermal regulation during acclimatization in a hot, dry (desert type) environment. Amer. J. Physiol. 163: 585-597, 1950.

34. ELLIS, F. P., H. M. FERRES, and A. R. LIND. The effect of water intake on sweat production in hot environments. J. Physiol. 125: 61P, 1954.

35. FEDOROVA, T. A., L. T. TUTOCHKINA, M. S. USPENSKAYA, M. M. SKURIKHINA and YE. A. FEDEROV. Some metabolic indexes in the astronauts Yu. A. Gagarin, G. S. Titov, A. G. Nikolayev and P. R. Popovich. pp. 395-398 in: NASA TT-F-228, Aviation and Space Medicine (V. V. Parin, ed.; Moscow, 1963). N. A. S. A., Washington, D. C., December 1964.

36. FOX, R. H., R. GOLDSMITH, D. J. KIDD, and H. E. LEWIS. Acclimatization to heat in man by controlled elevation of body temperature. J. Physiol. 166: 530-547, 1963.

37. GAGGE, A. P. Standard operative temperature, a single measure of the combined effect of radiant temperature, of ambient air temperature and of air movement on the human body. In: Temperature, its measurement and control in science and industry. Reinhold, New York, 1941.

38. GAMBLE, JAMES L. Chemical anatomy, physiology and pathology of extracellular fluid. 5th ed. Harvard University Press, Cambridge, Mass., 1950.

39. GAUER, O. H., P. ECKERT, D. KAISER, H.-J. LINKENBACH. Fluid metabolism and circulation during and after simulated weightlessness. Preprint #11; presented at 2nd International Symposium on "Basic environmental problems of man in space," Paris, June 14-18, 1965.

40. GAUER, OTTO H. and JAMES P. HENRY. Circulatory basis of fluid volume control. Physiol. Rev. 43: 423-481, 1963.

41. GAUER, O.H., J.P. HENRY, H.O. SIEKER and W.E. WENDT. The effect of negative pressure breathing on urine flow. J. Clin. Investig. 33: 287-296, 1954.

42. GAZENKO, O.G. and A.A. GYURDZHIAN. Physiological effects of gravitation. NASA TT F-376. National Aeronautics and Space Administration, Washington, D.C., 1965.

43. GENIN, A.M., N.N. GUROVSKIY, M.D. YEMEL'YANOV, P.P. SAKSONOV and V.I. YAZDOVSKIY. Man in outer space. State Publishing House of Medical Literature, Moscow, 1963. (TT 64-41096, Joint Publ. Research Serv., U.S. Dept. of Commerce, Washington, D.C., 1964).

44. GERKING, S.D. and S. ROBINSON. Decline in the rates of sweating of men working in severe heat. Amer. J. Physiol. 147:370-378, 1946.

45. GOLD, JOSEPH. Development of heat pyrexia. J. Amer. Med. Assoc. 173: 1175-1182, 1960.

46. GOLDBERGER, EMANUEL. A primer of water, electrolyte and acid-base syndromes. Lea & Febiger, Philadelphia, 1962.

47. GRAVELINE, DUANE E., BRUNO BALKE, RICHARD McKENZIE and BRYCE HARTMAN. Psychobiologic effects of water-immersion-induced hypodynamics. Aerospace Med. 32: 387-400, 1961.

48. GRAVELINE, DUANE E. and MARGARET M. JACKSON. Diuresis associated with prolonged water immersion. J. Appl. Physiol. 17: 519-524, 1962.

49. GREENLEAF, JOHN E. Involuntary hypohydration in man and animals: a review. NASA SP-110. National Aeronautics and Space Administration, Washington, D.C., 1966.

50. GREENLEAF, J.E., M. MATTER, Jr., J. S. BOSCO, L. G. DOUGLAS and E. G. AVERKIN. Effects of hypohydration on work performance and tolerance to $+G_z$ acceleration in man. Aerospace Med. 37: 34-39, 1966.

51. GREENLEAF, JOHN E. AND FREDERICK SARGENT, II. Voluntary dehydration in man. J. Appl. Physiol. 20: 719-724, 1965.

52. HABERICH, F.J, O. AZIZ and P.E. NOWACKI. Über einen osmoreceptorisch tätigen Mechanismus in der Leber. Pflüg. Arch. 285: 73-89, 1965.

53. HALE, FRANK C., RONALD A. WESTLAND and CRAIG L. TAYLOR. Barometric and vapor pressure influences on insensible weight loss. J. Appl. Physiol. 12: 20-28, 1958.

54. HARDY, J.D. Physiology of temperature regulation. Physiol. Rev. 41: 521-606, 1961.

55. HARDY, JAMES D. (ed.). Temperature: its measurement and control in science and industry. Vol. 3, part 3, Biology and Medicine. Reinhold, New York, 1963.

56. HARRINGTON, THOMAS J., DAVID K. EDWARDS and EDWARD C. WORTZ. Metabolic rates in pressurized pressure suits. Aerospace Med. 36: 825-830, 1965.

57. HENRY, J.P., O.H. GAUER and J.L. REEVES. Evidence of the atrial location of receptors influencing urine flow. Circulation Research 4: 85-90, 1956.

58. HERTZMAN, A.B. Individual differences in regional sweating. J. Appl. Physiol. 10: 242-248, 1957.

59. HERTZMAN, A.B. and I.D. FERGUSON. Failure in temperature regulation during progressive dehydration. U.S. Armed Forces Medical Journal 11: 542-560, 1960.

60. HERTZMAN, A.B., W.C. RANDALL, C.N. PEISS and R. SECKENDORF. Regional rates of evaporation from skin at various environmental temperatures. J. Appl. Physiol. 5: 153-161, 1952.

61. HORVATH, S.M. and W.B. SHELLEY. Acclimatization to extreme heat and its effect on ability to work in less severe environments. Amer. J. Physiol. 146: 336-343, 1946.

62. HOUGHTEN, F.C. and C.P. YAGLOU. Determination of the comfort zone. J. Amer. Soc. Heat. and Vent. Engrs. 29: 515-536, 1923.

63. JOHNSON, ROBERT E. Human nutritional requirements for water in long space flights. In: Conference on Nutrition in Space and Related Waste Problems. NASA SP-70. National Aeronautics and Space Administration, Washington, D.C., 1964.

64. KAUFMAN, W.C. Human tolerance limits for some thermal environments of aerospace. Aerospace Med. 34: 889-896, 1963.

65. KENNEY, R.A. The effect of the drinking pattern on water economy in hot humid environments. Brit. J. Industr. Med. 11: 38-39, 1954.

66. KERSLAKE, D. McK. Factors concerned in the regulation of sweat production in man. J. Physiol. 127: 280-296, 1955.

67. KUNO, YAS. The physiology of human perspiration. London, Churchill, 1934.

68. KUNO, YAS. Human perspiration. Charles C. Thomas, Springfield, Illinois, 1956.

69. LADELL, W.S.S. The effects of water and salt intake upon the performance of men working in hot and humid environments. J. Physiol. 127: 11, 1955.

70. LADELL, WILLIAM S.S. Terrestrial animals in humid heat: man. Chapter 39 in: D. B. Dill, E. F. Adolph, and C. G. Wilber, eds., Adaptation to the Environment. (Sec. 4 of Handbook of Physiology) American Physiological Society, Washington, D. C., 1964.

71. LADELL, WILLIAM S.S. Water and salt (sodium chloride) intakes. Chapter 9 in: Edholm, O. G. and A. L. Bacharach, eds., The physiology of human survival. Academic Press, New York, 1965.

72. LAVOISIER. Oevres de Lavoisier, Tome II. Memoires de chimie et de physique. Imprimierie Imperiale, Paris, 1862. (original 1790)

73. LEE, DOUGLAS H. K. Terrestrial animals in dry heat: man in the desert. Chapter 35 in: D. B. Dill, E. F. Adolph and C. G. Wilber, eds, Adaptation to the Environment. (Sec. 4 of Handbook of Physiology) American Physiological Society, Washington, D. C., 1964.

74. LEITHEAD, C.S. and A.R. LIND. Heat stress and heat disorders. F. A. Davis, Philadelphia, 1964.

75. LIBBER, L.M., H.R. GREIDER and L.J. SANTAMARIA. Effects of moderate heat stress, altitude and time on the dehydration rate of subjects wearing the ventilated full pressure suit. NAMC-ACEL-342, Naval Air Material Center, Philadelphia, June 1957.

76. LIND, A.R. and D.E. BASS. Optimal exposure time for development of acclimatization to heat. Fed. Proc. 22 (3-Part I): 704-708, 1963.

77. LOBITZ, WALTER C. and RICHARD L. DOBSON. Miliaria. Arch. Envir. Health 11: 460-464, 1965.

78. LOMBARD, W.P. A method of recording changes in body weight which occur within short intervals of time. J. Amer. Med. Assoc. 47: 1790-1793, 1906.

79. MacPHERSON, R.K. Physiological responses to hot environments. MRC Special Report No. 298. H.M. Stationery Office, London, 1960.

80. MALKINSON, FREDERICK D. Industrial problems relating to the stratum corneum. Arch. Envir. Health 11: 538-545, 1965.

81. McCALLY, MICHAEL. Body fluid volumes and the renal response of human subjects to water immersion. AMRL-TR-65-115. Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, 1965.

82. McCANCE, ROBERT A. and ELSIE M. WIDDOWSON. Nutritional changes. Chapter 8 in: Edholm, O. G. and A. L. Bacharach, eds., The physiology of human survival. Academic Press, New York, 1965.

83. McCUTCHAN, JOSEPH W. and CRAIG L. TAYLOR. Respiratory heat exchange with varying temperature and humidity of inspired air. J. Appl. Physiol. 4: 121-135, 1951.

84. MILLER, SHERWIN U. Increased human body water loss at reduced ambient pressure. Aerospace Med. 33: 689-691, 1962.

85. MOORE, F. D., J. D. McMURREY, H. V. PARKER and I. C. MAGNUS. Symposium on body composition. Total body water and electrolytes: intravascular and extravascular phase volumes. Metabolism 5: 447-467, 1956.

86. MORGAN, THOMAS E., FRODE ULVEDAL and B. E. WELCH. Observations in the SAM two-man space cabin simulator. II. Biomedical Aspects. Aerospace Med. 32: 591-602, 1961.

87. MOROFF, SAUL V. and DAVID E. BASS. Effects of overhydration on man's physiological responses to work in heat. J. Appl. Physiol. 20: 267-270, 1965.

88. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. Results of the first United States manned orbital space flight. Manned Spacecraft Center, N. A. S. A., Houston, Texas, 1962 (2).

89. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. Results of the second United States manned orbital space flight. NASA SP-6, Manned Spacecraft Center, N. A. S. A., Houston, Texas, 1962 (b).

90. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. Results of the third manned orbital space flight. NASA SP-12, Manned Spacecraft Center, N. A. S. A., Houston, Texas, 1962 (c).

91. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. Mercury Project Summary, including results of the fourth manned orbital flight. NASA SP-45, Manned Spacecraft Center, N. A. S. A., Houston, Texas, 1963.

92. NAVY DEPARTMENT. U. S. Navy Diving Manual. NAVSHIPS, 250-538, Superintendent of Documents, Washington, D. C., 1963.

93. NIELSEN, M. Die regulation der Korpertemperature bei muskelarbeit. Skand. Arch. Physiol. 79: 193-230, 1938.

94. NEWBURGH, L. H. (ed.) Physiology of heat regulation and the science of clothing. W. B. Saunders, Philadelphia, 1949.

95. OGATA, K. and T. ICHIHASHI. Sweat reflexes due to changes in the posture of the human body. J. Orient. Med. 25: 98-99, 1936.

96. OHARA, KOKICHI and TAKEO ONO. Regional relationship of water vapor pressure of human body surface. J. Appl. Physiol. 18: 1019-1022, 1963.

97. ONKEN, HENRY D. and CARL A. MOYER. The water barrier in human epidermis. Arch. Dermatol. 87: 584-590, 1963.

98. PARIN, V. V. (ed.) Aviation and Space Medicine. Moscow, 1963. (NASA TT F-228, National Aeronautics and Space Administration, Washington, D. C., 1964.)

99. RANDALL, W. C. Sweat gland activity and changing patterns of sweat secretion on the skin surface. Amer. J. Physiol. 147: 391-398, 1946.

100. RANDALL, W. C. and C. N. PEISS. The relationship between skin hydration and the suppression of sweating. J. Invest. Dermatol. 28: 435-441, 1957.

101. RANDALL, W. C., C. N. PEISS and R. O. RAWSON. Simultaneous recruitment of sweating and perception of warmth in man. J. Appl. Physiol 12: 385-389, 1958.

102. ROBINSON, S. Physiological adjustments to heat. Chapter 5 in: L. H. Newburgh (ed.), Physiology of heat regulation and the science of clothing. W. B. Saunders, Philadelphia, 1949.

103. ROBINSON, S. and S. D. GERKING. Thermal balance of men working in severe heat. Amer. J. Physiol. 149: 476-488, 1947.

104. ROBINSON, S., F. R. MEYER, J. L. NEWTON, C. H. TS'AO and L. O. HOLGERSEN. Relations between sweating, cutaneous blood flow, and body temperature in work. J. Appl. Physiol. 20: 575-582, 1965.

105. ROBINSON, S. and A. H. ROBINSON. Chemical composition of sweat. Physiol Rev. 34: 202-220, 1954.

106. ROBINSON, S., E. S. TURRELL, H. S. BELDING and S. M. HORVATH. Rapid acclimatization to work in hot climates. Amer. J. Physiol. 140: 168-176, 1943.

107. ROTH, EMANUEL M. Bioenergetics of space suits for lunar exploration. NASA SP-84, National Aeronautics and Space Administration, Washington, D. C., 1966.

108. SALTIN, BENGT. Aerobic and anaerobic work capacity after dehydration. J. Appl. Physiol. 19: 1114-1118, 1964.

109. SANCTORIUS (Santorio). Medicina Statica: Being the Aphorisms of Sanctorius. London, 1720.

110. SEELEY, LAUREN E. Study of changes in the temperature and water vapor content of respired air in the nasal cavity. Heating, Piping, and Air Conditioning 12: 377-388, 1940.

111. SMITH, H. W. The kidney: structure and function in health and disease. Oxford University Press, New York, 1951.

112. SMITH, HOMER W. Salt and water volume receptors. An exercise in physiologic apologetics. Amer. J. Med. 23: 623-652, 1957.

113. SONNENSCHEIN, R. R., H. KOBRIN, H. D. JANOWITZ, and M. I. GROSSMAN. Stimulation and inhibition of human sweat glands by intradermal sympathomimetic agents. J. Appl. Physiol. 3: 573-581. 1951.

114. STAHL, WILLIAM M. Renal hemodynamics: effect of gravity on sodium and water excretion. Surg. Forum 15: 13-14, 1964.

115. STEVENSON, JAMES A. F. The hypothalamus in the regulation of energy and water balance. The Physiologist 7: 305-318, 1964.

116. STEVENSON, JAMES A. F. Control of water exchange: Regulation of content and concentration of water in the body. Chapter 12 in: William S. Yamamoto and John R. Brobeck (eds.), Physiological Controls and Regulations. W. B. Saunders, Philadelphia, 1965.

117. STOUGHTON, RICHARD B. Percutaneous absorption. Arch. Envir. Health 11: 551-554, 1965.

118. SULZBERGER, MARION B. The effects of heat and humidity on the human skin. Arch. Envir. Health 11: 400-406, 1965.

119. SUSKIND, R. R. and M. ISHIHARA. The effects of wetting on cutaneous vulnerability. Arch. Envir. Health 11: 529-537, 1965.

120. TALIAFERRO, ELLEN H., R. R. WEMPEN and W. J. WHITE. The effects of minimal dehydration upon human tolerance to positive acceleration. Aerospace Med. 36: 922-926, 1965.

121. TAPLIN, DAVID, NARDO ZAIAS and GERBERT REBELL. Environmental influences on the microbiology of the skin. Arch. Envir. Health 11: 546-550, 1965.

122. VAN BEAUMONT, W. and ROBERT W. BULLARD. Sweating: its rapid response to muscular work. Science 141: 643-646, 1963.

123. VEGHTE, JAMES H. and PAUL WEBB. Clothing and tolerance to heat. WADC TR-57-759. Wright-Patterson Air Force Base, Ohio, 1957.

124. VERNEY, E. B. Antidiuretic hormone and the factors which determine its release. Proc. Royal Society (London) B 135: 25-106, 1947-1948.

125. VINOGRAD, S. P. Medical aspects of an orbiting research laboratory. Space Medicine Advisory Group Study. NASA SP-86. National Aeronautics and Space Administration, Washington, D. C., 1966.

126. VOGT, F. B., W. A. SPENCER, D. CARDUS and C. VALLBONA. The effect of bedrest on various parameters of physiological function; Part XI, The effect of bedrest on blood volume, urinary volume, and urinary electrolyte excretion. NASA CR-181. National Aeronautics and Space Administration, Washington, D. C., 1965.

127. VOLYNKIN, YU. M., V. I. YAZDOVSKIY, and others. The first manned space flights. Acad. of Sci., USSR, Moscow, 1962. (FTD TT 62-1619/ 1 & 2, 1962).

128. WAYNER, MATTHEW J. (ed.) Thirst. MacMillan, New York, 1964.

129. WEBB, PAUL. Air temperatures in respiratory tracts of resting subjects in cold. J. Appl. Physiol. 4: 378-382, 1951.

130. WEBB, PAUL. Heat loss from the respiratory tract in cold. Project No. 7-7951, report No. 3, Arctic Aeromedical Laboratory, Ladd Air Force Base, Alaska, 1955.

131. WEBB, PAUL. Human thermal tolerance and protective clothing. Ann. N. Y. Acad. Sci. 82: 714-723, 1959.

132. WEBB, PAUL (ed.) Bioastronautics Data Book. NASA SP-3006. National Aeronautics and Space Administration, Washington, D. C., 1964.

133. WEBB, PAUL. Water vapor as a critical component in sealed cabins and pressure suits. Chapter 10 in: E. J. Amdur (ed), Humidity and Moisture--Measurement and Control in Science and Industry; Vol. II, Applications. Reinhold, New York, 1965.

134. WEBB, PAUL and JAMES F. ANNIS. Silicone submersion--a feasibility study. NADC-MR-6620. Naval Air Development Center, Johnsville, Pa., 1966.

135. WEBB, PAUL, LAURENS N. GARLINGTON and MARVIN J. SCHWARZ. Insensible weight loss at high skin temperatures. J. Appl. Physiol. 11: 41-44, 1957.

136. WEBB, PAUL and F. K. KLEMM. Design of ventilated clothing. WADC TR 58-608. Wright-Patterson Air Force Base, Ohio, March 1959.

137. WELCH, B. E., E. R. BUSKIRK and P. F. IAMPIETRO. Relation of climate and temperature to food and water intake in man. Metabolism 7: 141-148, 1958.

138. WESTON, R. E., I. B. HANENSON, J. GROSSMAN, G. A. BERDASCO and M. WOLFMAN. Natriuresis and chloruresis following pitressin-induced water retention in non-edematous patients: Evidence of a homeostatic mechanism regulating body fluid volume. J. Clin. Invest. 32: 611, 1953.

139. WHITE, P. D., J. W. NYBERG, L. M. FINNEY and W. J. WHITE. A comparative study of the physiological effects of immersion and bed rest. NASA CR-65414. Manned Spacecraft Center, N. A. S. A., Houston, Texas, 1966.

140. WOLF, A. V. Thirst; Physiology of the urge to drink and problems of water lack. Charles C. Thomas, Springfield, Ill., 1958.

141. WORTZ, EDWARD C., ROBERT A. DIAZ, FREDERICK H. GREEN, WARREN G. SANBORN, DAVID K. EDWARDS III., EDMUND J. PRESCOTT, and GILBERT R. SCHERER. Reduced barometric pressure and respiratory water loss. SAM TR 66-4. USAF School of Aerospace Medicine, Brooks Air Force Base, Texas, February 1966.

142. WORTZ, EDWARD C., DAVID K. EDWARDS and THOMAS J. HARRINGTON. New techniques in pressure suit cooling. Aerospace Med. 35: 978-984, 1964.

143. WYNDHAM, C.H., N.B. STRYDOM, J.F. MORRISON, F.D. DUTOIT, and J.G. KRAAN. A new method of acclimatization to heat. Arbeitsphysiol. 15: 373-382, 1954.

144. WYNDHAM, C.H., N.B. STRYDOM, J.F. MORRISON, C.G. WILLIAMS, G.A.G. BREDELL, and J. PETER. Fatigue of the sweat gland response. J. Appl. Physiol. 21: 107-110, 1966.

145. YAGLOU, C.P. and D. MINARD. Control of heat casualties at military training centers. Arch. Industr. Health 16: 302, 1957.

146. ZÖLLNER, G., R. THAUER, and W. KAUFMANN. Der insensible Gewichtsverlust als Funktion der Umweltbedingungen. Pflüg. Arch. ges Physiol. 260: 261-273, 1955.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546