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Chapter 3

THERMAL EXCHANGES AND TEMPERATURE STRESS

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Space flights for human passengers have been conducted in the blandest thermal environment man can devise. Since temperature, gas movement, and humidity of the artificial atmosphere in spacecraft can be totally controlled, thermal comfort can be engineered for astronauts within the vehicle. Certain variations from standard air-conditioning practice are necessary in artificial atmospheres if the pressure is lower than 1 atm or where the gas composition is not that of air; precise and positive control of temperature and humidity is necessary in these small atmospheric volumes, but the physiologic comfort state, where metabolic heat is dissipated at minimal physiologic cost, has been achieved. Because the volume of the artificial atmosphere in a spacecraft is small compared with the ocean of air on Earth, the men within this sealed small volume become important sources of both heat and water vapor. Along with the thermal energy generated by equipment, they constitute the primary loading of the environmental control system.

When astronauts leave the spacecraft for extravehicular activity (EVA), either during flight or on the lunar surface, their full pressure suits contain artificial atmospheres of even smaller volume. Now the astronaut is the dominant thermal load as he generates heat and water vapor that are frequently in large amounts. Neither the spacecraft nor the astronaut in a full pressure suit exchanges much heat with the space environment. Both are essentially isolated in the airless void, where energy transfer takes place primarily by electromagnetic (thermal) radiation. But because of the high thermal energy from direct sunlight and the low effective radiant temperature of space, and because the vehicle or the astronaut may move unpredictably into full sunlight or full shadow, the surfaces of spacecraft or space suits have been treated so that incoming radiant energy is largely reflected, and out-going radiant energy largely prevented from escaping.

Since men within spacecraft or wearing spacesuits during extravehicular activity are major sources of heat and water vapor, it has become increasingly important to know in detail the characteristics of metabolic heat generated under various conditions of human activity, particularly those connected with space flight. Metabolism might be expected to decrease somewhat during prolonged confinement, restricted activity, and weightlessness; during extravehicular activity, of course, it is vital to know what levels the metabolic heat production will reach, how long high levels can be sustained, and what the relationships are between heat produced in the body and heat dissipated from its surface.

Metabolic heat production can be extremely high during extravehicular activity, which made it necessary to develop a special method for transferring heat from the man's body to the heat sink in his portable life-support system. The method developed was the water-cooled garment, which proved to be far more effective for removing heat than the gas-cooling used in early pressure suits. Should a failure occur in the astronaut's portable life-support system during extravehicular activity, loss of the heat sink would soon lead to serious trouble from body heat storage [1] and rising body temperatures. This has led to renewed interest in the limits of heat storage, particularly when the source of the stored heat is internal rather than external to the man.

For many years there has been strong interest in those conditions of supersonic flight in the atmosphere when external heat loads are not negligible, but, quite the contrary, are far higher than anything in man's normal climatic experience. During reentry of the spacecraft into the Earth's atmosphere, enormous thermal energy is generated at the leading surface of the spacecraft, most of which is dissipated by ablation of the heat shield. But should some failure occur, there might be a rapid increase in cabin temperature, making important man's tolerance for what has been called slow heat pulses.[2] It was recognized that human limits for these extreme temperatures were set by surface pain rather than by heat storage, but heat storage limits are also important if the temperatures are less severe. Any supersonic flight by aircraft or spacecraft carries the possibility, however remote, that cabin cooling could fail and high cabin temperatures would lead to serious storage of body heat. A great amount of work has been done on the effects of stored body heat which is of external origin, both in laboratories of the Soviet Union and the United States.

Cold, as a thermal stress, has not been of major concern. However, in some early lunar landings the astronauts complained of being overcooled while resting within the lunar module and wearing water-cooled garments. There is a potential cold problem if returning astronauts land in cold ocean waters or in winter terrain and rescue should be delayed. (The problem of survival in cold will not be treated in this chapter.)

Discussions in this chapter will be on the major topics: human comfort, metabolic heat production, rates of heat dissipation and water loss, the water-cooling technique for extravehicular activity, tolerance for extreme heat and heat storage, and, finally, biothermal models used in the space program.[3]

THERMAL COMFORT DURING SPACE FLIGHT

Definitions of thermal comfort for humans are disappointingly imprecise, because the comfort state is subjectively defined and because there are many different combinations of clothing, activity, temperature, sunshine, humidity, barometric pressure, and wind that are judged to be comfortable. The standard definition of comfort among heating and air-conditioning engineers in the United States is "that condition of mind which expresses satisfaction with the thermal environment."

In the introductory section of this chapter it was suggested that comfort is a state of heat balance, the maintenance of which requires minimal physiologic effort—that is, all metabolic heat should be readily transferred to the immediate environment without imposing major physiologic responses such as sweating and shivering. Heat balance can be maintained with these thermoregulatory responses in climatic levels of heat and cold, but if these responses are prolonged, fatigue accumulates over a period of hours and the exposure may have to be terminated. Fanger [21] shows that there are three necessary conditions for optimum thermal comfort: that a state of heat balance exists; that the mean skin temperature stays at a level related to metabolic heat production; and that the sweat rate is no more than that appropriate for a particular metabolic activity level. Comfort conditions are shown by the curves in

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[1] The accumulation of heat in the body leading to a rise in body temperature.

[2] Conditions where wall temperatures rise at rates of 30°–60°C/min, leading to skin pain and burning when wall temperatures exceed 110°C.

[3] The valuable contribution made by E. Ya. Shepelev of the Institute of Biomedical Problems, Moscow, is gratefully acknowledged. His review of Soviet research, especially in the field of human thermal tolerance, was an important addition to the materials used in preparing this chapter.

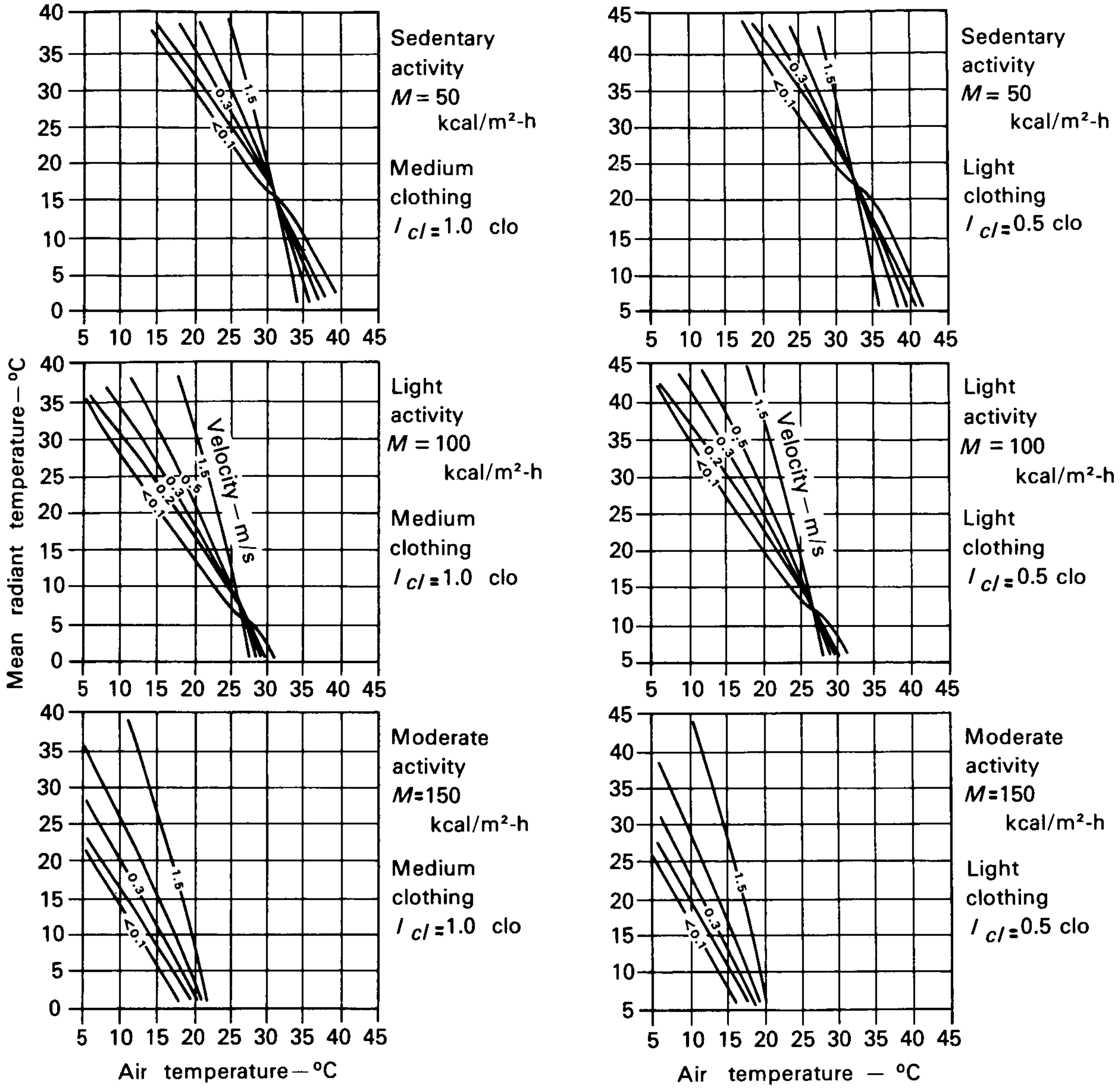

FIGURE 1.—(Left) Comfort lines for a range of air velocities, air temperatures, and mean radiant temperatures for men in light clothing and for three activity levels. RH is 50%. (Right) Men are in medium-weight clothing; charts are the same as in left column.

Figure 1 for three activity levels and two clothing weights.

To define comfort for spaceflight missions is relatively simple, because some of the major variables that must be considered on Earth are usually constant in a space vehicle. For example, metabolic activity is generally close to the resting level, at times lower than normal and at others slightly higher; the clothing assembly is known and constant; gas pressure, gas temperature, and gas velocity are essentially constant; and humidity and wall temperature are controlled. An accurate calculation of the thermal characteristics of the environment can be made in advance. Thus, the internal environment of a spacecraft is totally controlled and not subject to the kind of daily and seasonal variations to which we are accustomed on Earth.

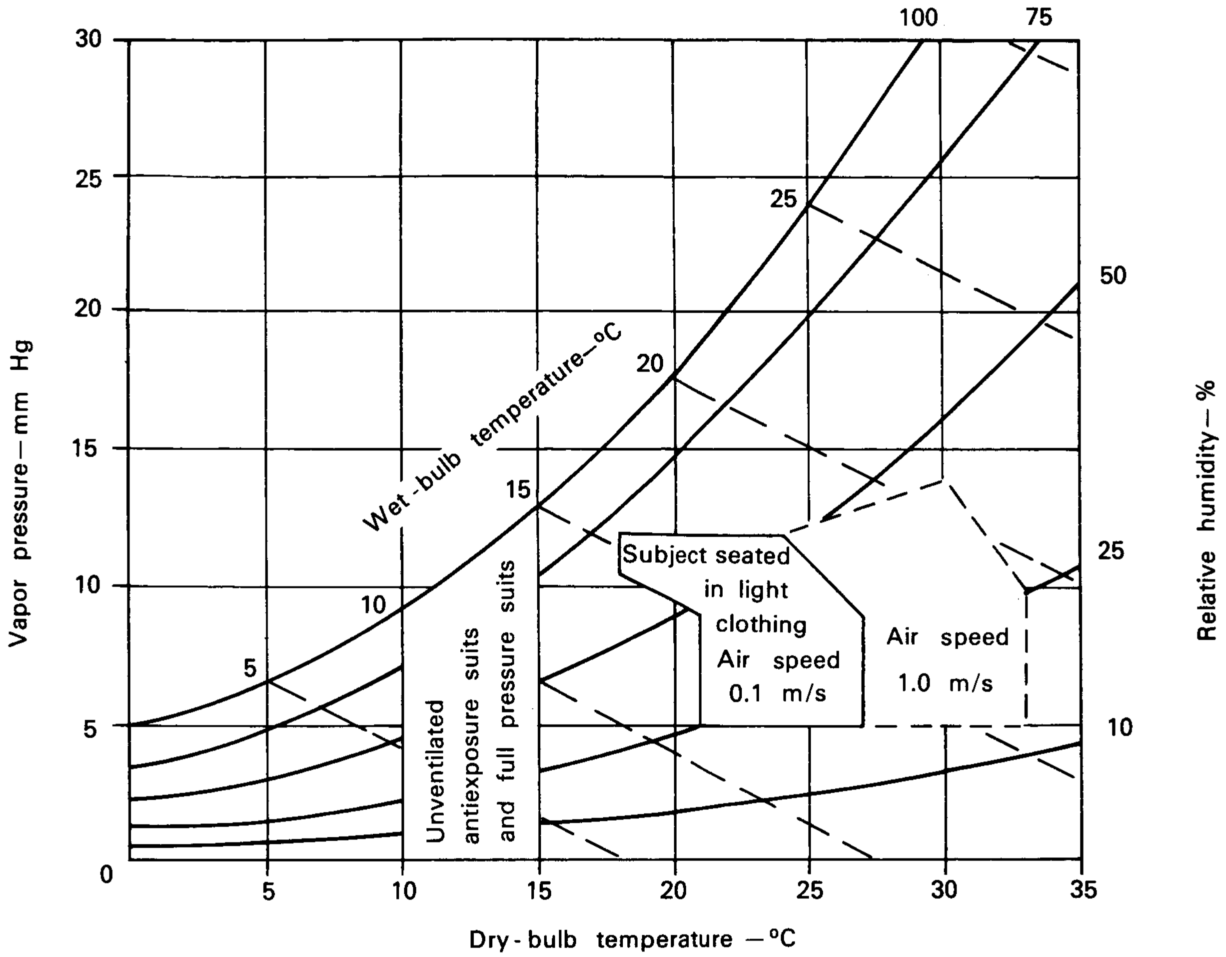

FIGURE 2.—Simple definitions of comfort for the conditions shown. Light clothing has an insulating value of 0.5 clo.

If it is clear that thermal comfort can be obtained with many combinations of environmental temperature, humidity, pressure, air motion, clothing, and activity, we can examine the major environmental conditions that affect comfort. In Figure 2, a comfort zone is defined in terms of the temperature and the absolute humidity of air for men at rest wearing lightweight clothing (insulation 0.5 clo) and where the air pressure is 1 atm absolute (ata), as it is at sea level. Certain variations in temperature and humidity are permissible if the air velocity changes, shown in Figure 2 by the extension of the comfort zone (indicated by a dashed line). Below the primary comfort zone is a different area which shows what is comfortable for a man not wearing standard clothing, but wearing insulated and impermeable clothing typical of flight clothing worn in high-performance aircraft. Above the comfort zone, within a limited range of temperatures and humidities, it is possible for men to maintain heat balance for up to 12 hours, but at a considerable physiologic cost characterized by raised cardiac output and heavy sweating.

A different way of defining human comfort under Earth conditions has been used in the United States for many years by the heating and air-conditioning engineers. The comfort chart of the American Society of Heating, Refrigeration, and Air Conditioning Engineers is reproduced as Figure 3; it is based on the familiar scale of Effective Temperature, which relates the thermal effects of temperature, humidity, and air motion into combinations that produce

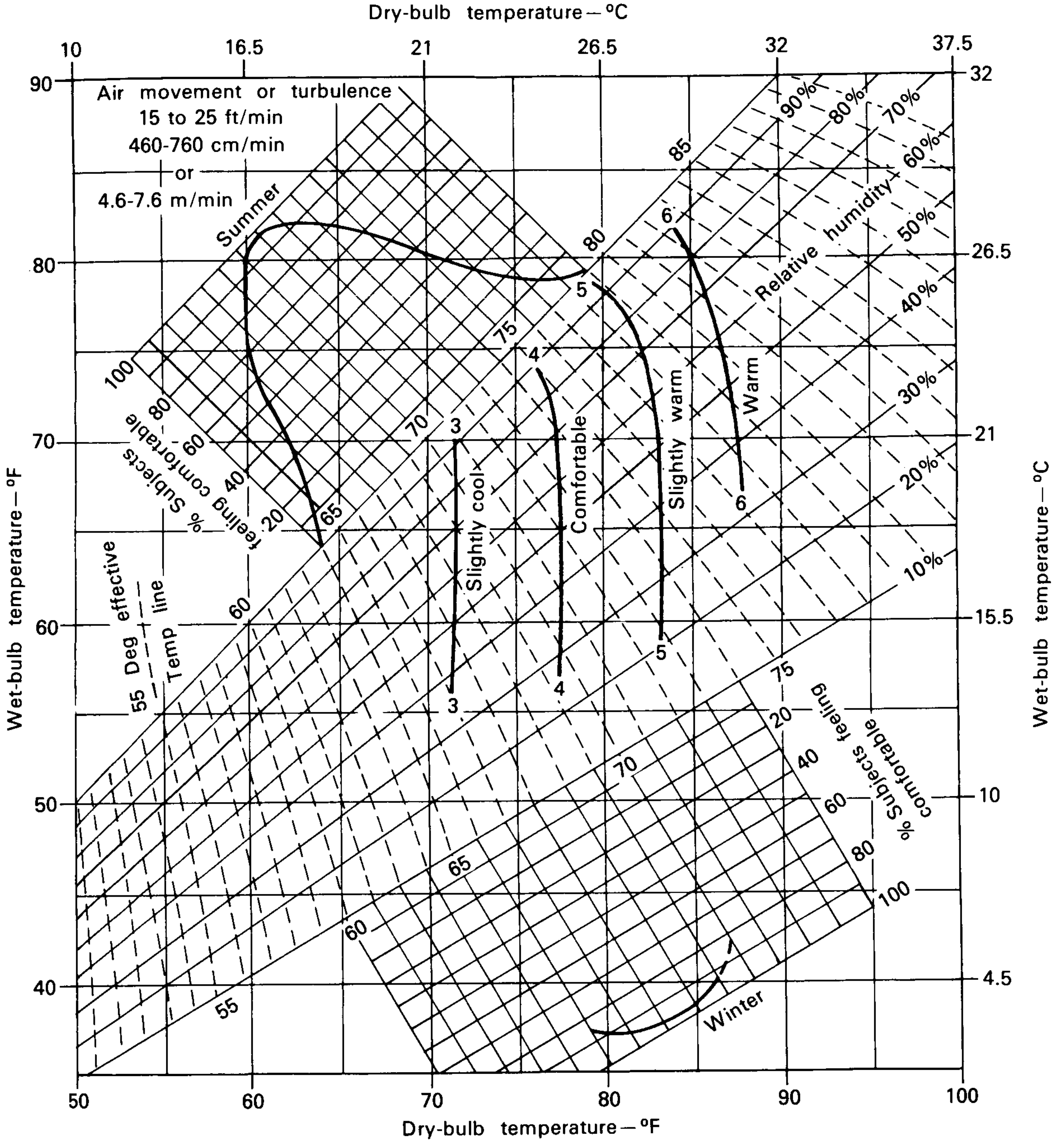

FIGURE 3.—Comfort and near-comfort conditions of air temperature and humidity (wet bulb temperature or relative humidity), indicated by the nearly vertical lines labeled "slightly cool," "comfortable," "slightly warm," and "warm." A secondary scale of Effective Temperature is given as a band of dashed lines. Note that this Effective Temperature scale is only for air motion of 15–25 fpmin (4.6–7.6 m/min). (From ASHRAE *Handbook of Fundamentals*, p. 122, by permission)

the same feeling of warmth. Comfort was defined by numerous people who cast votes upon whether they felt a given environment to be comfortable, slightly warm, warm, or slightly cool, which is shown in the central, more or less vertical lines, on the diagram. These lines are related to Effective Temperature, which is shown on a scale using wet and dry bulb temperatures at a given low-air movement. In addition to the nearly vertical comfort lines, distribution curves show the percentage of subjects who felt comfortable at various temperatures, both in summer and winter. Preferences in summer are for slightly higher Effective Temperatures than those preferred in winter.

Since the data in Figures 1–3 are based upon Earth conditions at 1 ata, and with resting subjects normally clothed, it is evident that one cannot apply these data directly to the spacecraft environment. The composition of the artificial atmosphere may be similar to that of air, or it may contain very different gases—for example, pure oxygen in many American spacecraft. In addition, the natural movement of gases in Earth gravity is very different from their movement in subgravity states of orbital flight, or on the lunar surface. Next, we consider estimates of the effect these changes have on the comfort conditions in the environment.

Berenson [4], using equations for heat transfer between the man and the environment, calculates comfort temperatures for a mildly active nude man in a cabin where the total pressure is 310 mm Hg and in which all gas motion is by forced convection. This curve is shown in Figure 4, with one derived from Fanger's comfort charts [21] when the air pressure is 760 mm Hg. In both cases, comfort is defined similarly in terms of heat balance, skin temperature, and sweat level.

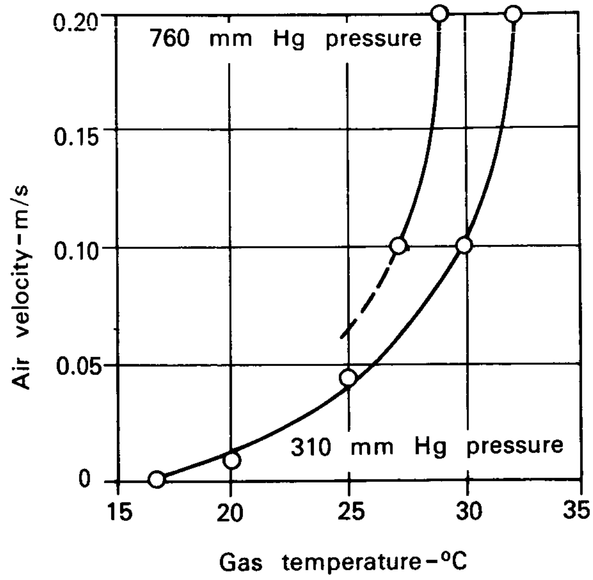

FIGURE 4.—Comfort temperatures at two different barometric pressures as a function of forced gas velocity. (Based on Fanger [21] and Berenson [4])

The conventional heat balance equation is

$$M=E\pm R\pm C\pm K\pm W\pm S \text{ kcal/m}^2\text{-h} \qquad (1)$$

where M is metabolic heat production; E is evaporative heat loss; R is heat loss or gain by radiation; C is heat loss by convection; K is heat loss or gain by conduction; W is mechanical work; and S is heat storage. In the comfort state, storage is zero; for rest and most activities, W is zero, and M is taken at some standard value—e.g. 70 kcal/m²-h in the examples shown in Figure 4. Heat transfer by conduction is usually negligibly small. The remaining heat exchange terms (E, R, and C) can be estimated for given environments by the following equations, adapted from Berenson [4].

$$E=0.126WT_a\mathrm{A_b}K_e\left(\frac{v}{P}\right)^{0.5}(P_{ws}-P_{wa}) \qquad (2)$$

where W is the ratio of the body surface that is wet to the whole body surface area (not greater than 0.25 for comfort or mild activity); T_a is air temperature in °C; $\mathrm{A_b}$ is body surface area in m²; K_e is a fluid property that depends on diffusivity of water vapor in the gas mixture and on transport properties of the gas mixture (for air, $K_e=1$); v is velocity of the gas in m/s; P is barometric pressure in mm Hg; P_{ws} is the saturation vapor pressure in mm Hg for water at skin temperature; and P_{wa} is the vapor pressure of air. Note the enhancement of evaporative heat loss by low barometric pressure, a factor which will be noted in later discussion.

$$R=\sigma \mathrm{A_r}(\bar{T}_s^4-\bar{T}_r^4) \qquad (3)$$

where σ is the Stefan-Boltzmann constant; A_r is the radiation area of the body in m^2; $\bar{T}_s$ is mean skin temperature in °K; and $\bar{T}_r$ is the mean radiant temperature in °K.

$$C=0.21k_cPvA_b(\bar{T}_s-T_a) \qquad (4)$$

where k_c is a factor that varies with the transfer properties of the gas mixture (and for oxygen-nitrogen mixtures $k_c=1$).

It is possible to make calculations of thermal comfort and heat exchange in gas compositions different from those of air and for various total pressures. A complete analysis by Bottomley and Roth [10] gives equations for the effects of various inert gases on convective transfer and evaporative heat loss. Table 1 summarizes empirical tests on unusual gas mixtures at several barometric pressures.

It has been common practice to test any special artificial atmosphere with prolonged exposure in ground-based simulators, a practice which will probably continue until sufficient empirical data are at hand to write comfort equations for such special conditions.

TABLE 1.—*Temperatures Selected by Subjects in Space Cabin Simulators* [10, 29]

Gaseous environment, mm Hg		Selected temperature, °C
Helium	509	24.5–27.5 (awake)
Oxygen	171	26–29 (asleep)
Other gases	80	
	760	
Helium	220	
Oxygen	160	24–25
	380	
Helium	93	
Oxygen	160	24–25
	253	
Helium	230	
Oxygen	150	24
	380	
Helium	74	
Oxygen	175	24
	249	
Nitrogen	206	
Oxygen	165	23
	371	
Oxygen	258	22
Oxygen	191	21

Studies on the physiologic effects and convective heat loss in helium-oxygen atmospheres over a range of barometric pressures were reviewed by Hiatt and Weiss [29]. They summarized animal experiments which at first had suggested a metabolic stimulating effect of 20°C helium-oxygen environments, but then showed that the effect was thermal, since oxygen consumption was the same in helium-oxygen as in air when the temperature was raised to 27°–30°C. Human experiments at normal pressure and at $^1/_2$ atm showed little effect on oxygen consumption, but a modest increase in skin cooling. The convective heat transfer at 1 atm pressure in helium-oxygen was about twice that for air, while at $^1/_2$ atm the helium-oxygen mixtures used to simulate space-cabin environments were equal to air or perhaps a little less effective as cooling media. But both Soviet and American studies in space cabin simulators (at pressures from $^1/_3$–1 atm) showed that the comfort temperatures for men during prolonged habitation were higher than for air, with a narrower temperature range (see Table 1). There was evidence that at least some of the effect was due to a decreased insulating value for the clothing when it was soaked in helium-oxygen instead of air. The authors concluded that there was little advantage in substituting helium for nitrogen in space cabin or space suit atmospheres.

What are the problems that arise if comfort conditions are not maintained? In a review on thermal comfort and health, Hardy [27] shows that the greater the departure from comfort conditions and the longer the duration of such exposure, the more serious the effects. Within the comfort zone, small variations in temperature are consistent with sensations of comfort and pleasure, and in this zone, body temperature is regulated by vasomotor activity in the skin. With a moderate departure from the comfort zone there is increased sensation of thermal effect and increasing sensations of discomfort, accompanied by measurable physiologic strains on the cardiovascular, respiratory, and other systems involved in thermoregulation. With large departures from comfort and with long exposure, the thermal sensations become intense and often painful, there may be failure of thermoregulation and acute discomfort, excitability, restlessness, depression, and fatigue. Severe cold exposure, of course, leads to tissue injuries such as frostbite, while prolonged and severe heat exposure may lead to heat prostration or heat stroke and death.

Finally, comfort conditions in space flight involve not only the low metabolic levels prevalent within the cabin but also the high levels produced by extravehicular activity. It is possible to keep a man comfortable under these conditions, which has been shown in the laboratory by Webb and Annis [58]. They demonstrated that for activities up to six times the resting level, enough cooling can be supplied so that sweating is not needed to dissipate metabolic heat. Cooling was supplied in two forms: by cold air moving at a velocity great enough so that metabolic heat was removed from the body surface at low sweat levels; and by a water-cooling garment worn under an insulated and impermeable suit. As might be expected, the harder the work, the lower the skin temperature had to be in order that a sufficient temperature gradient existed to remove the large quantities of metabolic heat produced. Such data are shown in Figure 5, where the final mean skin temperature after an hour or more of the indicated physical activity had reached a near-equilibrium level. Final heart rates and final rectal temperature data are shown on the same figure. A curve has been added from a formula by Fanger [21] for the desirable or comfortable skin temperature recommended as a function of metabolic activity. Notice that the slope and location of the Fanger curve nearly coincide with that from the Webb and Annis data when air cooling was used. The slope for the skin temperature with water cooling is shallower. This probably reflects the effectiveness of the coupling between the water-cooling tubes and the skin. The steady-state levels of heart rate and rectal temperature, reached near the end of each experiment, are those for exercise without thermal strain. There was no evidence of continuing heat storage, and the physiologic cost was evidently minimal in terms of heat dissipation. Incidentally, the criterion for minimal sweating was that the total weight loss be no greater than 100 g/h under any of the conditions of exercise.

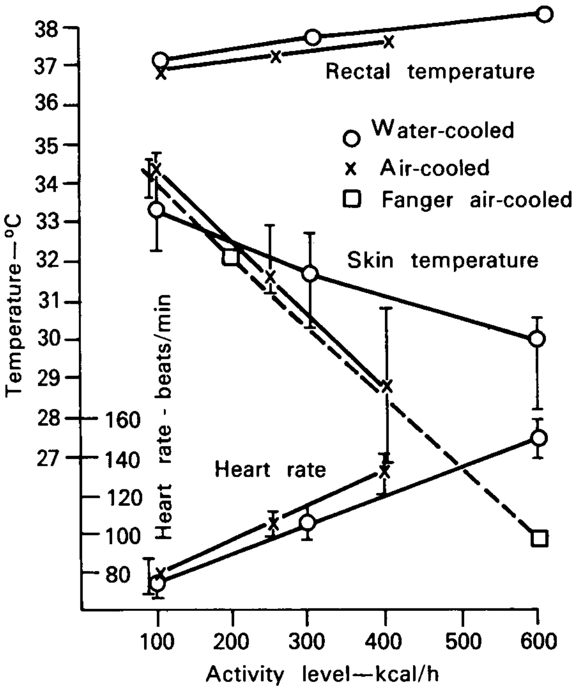

FIGURE 5.—Final steady-state values for heart rate, skin temperature, and rectal temperature for a range of metabolic activities when subjects worked in cooling environments which kept sweating below 100 g/h. (From Webb and Annis [58]; added dashed line for skin temperature from an equation from Fanger [21])

Thus, the principles of designing for thermal comfort in the artificial atmosphere of spacecraft are understood, and thermal comfort has been achieved in the first decade of Earth orbital and lunar flights.

HEAT PRODUCTION OF MAN DURING SPACE FLIGHT

Heat production from metabolism and muscular activity is a matter of special concern during space flight. The machinery that controls thermal conditions of the artificial atmosphere must be capable of responding quickly and accurately in order to maintain the heat balance of the astronauts. Unlike the situation on Earth where the ocean of air dissipates metabolic heat easily, the small and confined volume of artificial atmosphere could, if not properly controlled, permit rapid increase of heat and humidity, quickly leading to uncomfortable conditions—possibly to the tolerance limit of stored body heat.

The heat balance equation was given in the preceding section as Equation (1); in this section the emphasis is on the heat-production term, M. Since there is seldom a sizable heat load or heat drain during space flight, the man's own heat production is of dominant concern in calculating the conditions necessary for heat balance. The general level of M during flight, whether the men are awake, asleep, or active within the vehicle, and especially the level of M during activity outside the vehicle, defines the load placed upon the environmental control system.

The heat generated by astronauts during flight inside the vehicle has been estimated from oxygen consumption and CO_2 production using the classical values for the caloric equivalent of oxygen as influenced by the respiratory quotient (RQ). In Table 2, the first set of data is that reported by Voronin et al [51] for four Soviet astronauts in the Vostok spacecraft. The second set of data is that given by Berry and Catterson [6] for American flights lasting 4–14 days; these estimates are based on the amount of CO_2 absorbed in the chemical purifying beds of the spacecraft. The third set of data is from Voronin et al [51], who studied astronauts in sealed cabin simulators on the ground for various periods of time; note that the ground-based estimates are slightly higher than those from actual flights. The fourth set of data is that reported by Jackson et al [30], based on a study of four men in a sealed cabin simulator during a 90-day period. These values are still higher. They come from the first American experiment with a mixed gas in a sealed space, where total pressure was 517 mm Hg, and nitrogen was the major constituent of the atmosphere. Of course, no ground simulator can produce the effect of weightlessness on metabolic processes, which ought to be to decrease metabolism.

Estimates from ground-based simulators, as well as estimates made from the classical physiologic literature, seem conservative—that is, they cause more-than-adequate supplies of oxygen to be carried and more-than-adequate heat removal capacity. This has caused no serious weight penalty in space vehicles designed to operate for 2 or 3 weeks. However, more precise data on heat generation, hence oxygen supply and CO_2 removal, will be needed for flights of longer duration. More extensive flight data on metabolic activity will be very useful in planning for longer flights. This topic is discussed further in Volume III, Part 2, Chapter 1.

Heat production is not constant within a 24-hour day, even when the subject is at rest and

TABLE 2.—*Metabolic Heat During Flight Inside the Spacecraft, or in Ground Simulators*

Vehicle	Average O_2 consumption l/min	Average CO_2 production l/min	Respiratory Quotient	Average heat production	
				W	kcal/min
Vostok spacecraft [51]					
A. G. Nokolayev	0.293	0.250	0.85	99	1.42
P. R. Popovich	0.333	0.283	0.85	113	1.62
V. V. Tereshkova	0.288	0.235	0.82	97	1.39
V. F. Bykovskiy	0.292	0.242	0.83	98	1.41
Gemini spacecraft [6]					
Gemini 4					1.67
Gemini 5					1.40
Gemini 7					1.54
Simulators of Vostok and Voshkod spacecraft 12–13 d exposures [51]	0.333–0.368	0.271–0.299	0.81	112–123	1.60–1.77
NASA/McDonnell-Douglas space station simulator, 4 men for 90 d [30]	0.443	0.333	0.75	146	2.10

in a constant environment. Aschoff and Pohl [1] discuss the rhythmic variations in energy metabolism in animal forms, including man. Their preliminary data on oxygen consumption of a woman subject during 24-hour periods suggested a definite circadian pattern related to the established diurnal curve of body temperature. More recently, Webb [57] reported definite circadian cycles in oxygen consumption, heat dissipation, and body temperature in two subjects who were studied for 24-hour periods by direct and indirect calorimetry. Since these experiments were conducted in Earth laboratories under carefully controlled conditions, there can only be speculation about the effects of space flight on the circadian pattern of metabolism. But the cycles appear to be independent of diurnal patterns of physical activity.

So far we have discussed the low heat production levels of men during space flight, including the possibility that these estimates are generally too high for very prolonged weightless flight. But there is a very different picture of heat production when astronauts wearing space suits are active outside their vehicles. This was first suggested during the first walk in space by the Soviet astronaut Leonov, who showed surprisingly high heart rates and considerable fatigue following 20 min in the vacuum, 10 of which were spent outside the vehicle. During the first four American space walks, made on Geminis IV, IX–A, X, and XI, not only were heart rates sustained at a high level for much of the ½–hour to 2–hour periods, but also the work planned for these periods of extravehicular activity had to be modified or terminated [16, 35]. In Gemini IX–A, the activity of the astronaut was so high that he became hot, sweated profusely, and fogged the faceplate of his helmet. In Gemini XI, high heart rate was coupled with high respiratory rate, which may have been due to excessive buildup of carbon dioxide, and the astronaut became tired and had to reenter the vehicle before completing his assigned tasks. In the final outside excursion of the Gemini series (Gemini XII), a 2–hour extravehicular activity was completed successfully by using better restraints to help the astronaut to do his work and by changing the workload so that the man could handle it readily. Only once did his heart rate rise above 140 beats/min. Although no direct measurements of heat, oxygen consumption, or CO_2 production were made, it was clear that the high metabolic heat production of most of the space walks was more than could be removed by the cooled, recirculated gas in the suits. It appeared that gas-cooling of space suits could not handle the high heat production to be expected during nonlimited extravehicular activity.

When lunar landings were made, the astronauts left the vehicle in space suits that were directly and positively cooled with water-cooling undergarments. It was possible to estimate metabolic heat from heart rate, from the decay of the pressure in the oxygen supply cylinder, and, even more convincingly, from the heat extraction by the liquid-cooled garment. Data of this sort have been reported by Berry [5] for the first lunar landing, the flight of Apollo 11. In 2.5 hours of lunar exploration on foot, one astronaut generated 565 kcal of heat and the other, 763 kcal, as shown in Figures 6 and 7. This means that heat production averaged 281 W (watts) and 354 W for the two men, respec-

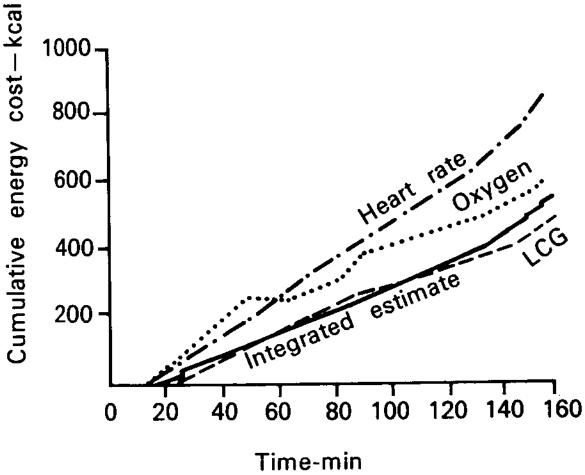

FIGURE 6.—Cumulative energy cost during lunar extravehicular activity for the Apollo 11 commander based on three different methods of estimation, plus a fourth (solid) line representing the best integrated estimate from these and other data. "LCG" is data from the Apollo liquid-cooled garment. (From Berry [5])

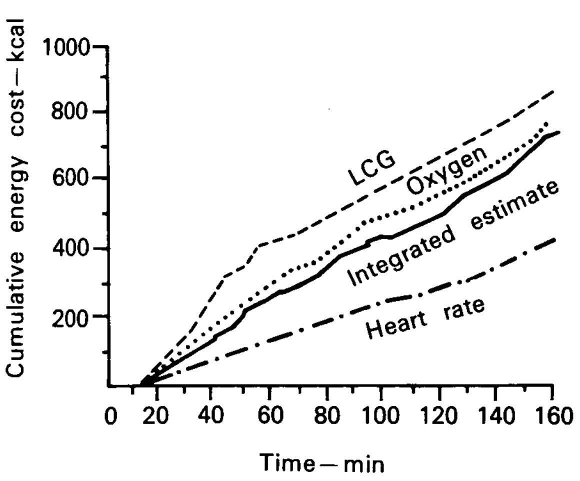

FIGURE 7.—Cumulative energy cost during lunar extravehicular activity for the Apollo 11 lunar module pilot. (From Berry [5])

tively, or roughly three times the resting level of heat production. The men could have worked at a higher level, but they were not permitted by the ground controllers to work at their maximum rates. Longer periods of lunar exploration have since been accomplished, but the data on heat production have not yet been published.

Men who are in good physical condition can sustain work levels at 80% of their maximum capacity for an hour or longer without resting, and some champion athletes can sustain even higher levels for 3 to 4 hours at a time. A man weighing 70 kg with a maximum oxygen consumption of 60 ml/kg, or 4.2 l/min could then be expected to sustain 80% of this level for an hour, which is 3.36 l/min or 16.8 kcal/min, or 1171 W. (Experimental data of this kind will be found in Åstrand and Rodahl's *Textbook of Work Physiology* [2].) This great increase in heat production is generated in the active skeletal muscles. A rise in muscle temperature occurs exponentially over a 10-min period, as was reported by Saltin et al [43]. In addition, as soon as work begins there is an exponential rise in oxygen consumption and heart rate, the rise being essentially complete in about 3 min. However, the excess heat being produced does not appear on the body surface immediately. The sequence of events is shown in Figure 8, where subjects were working in water-cooled suits controlled to prevent significant sweating. The curve labeled *Q* is heat extraction, which rises exponentially but much more slowly than the curve labeled *MR*, which is metabolic rate from oxygen consumption. Notice that during the early part of work the rectal temperature rises, suggesting that there is an obligatory heat storage despite the presence of adequate cooling.

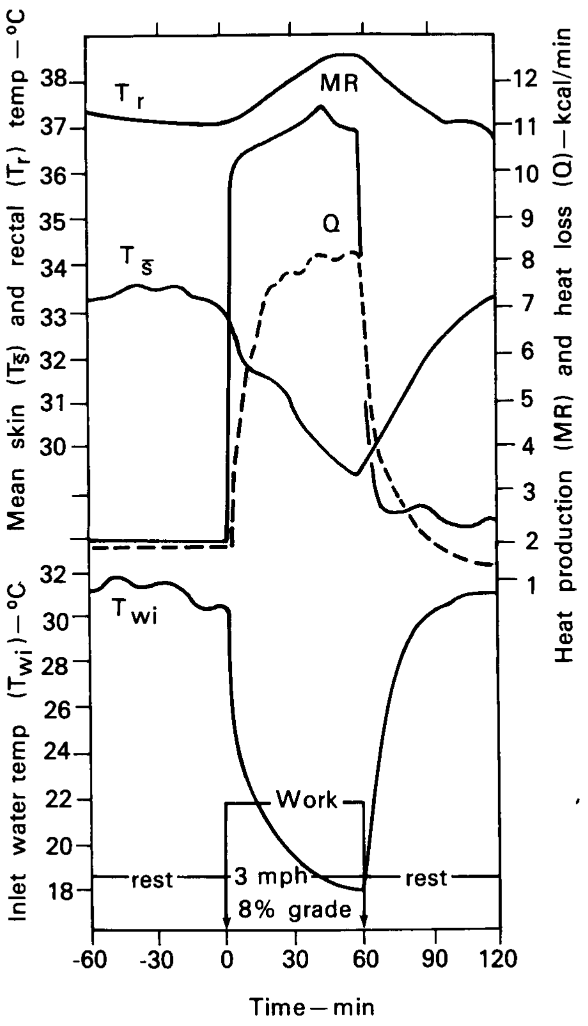

FIGURE 8.—Averaged rectal temperature (T_r), metabolic rate (*MR*), and heat removal (*Q*) from six experiments where subjects were cooled by controlling the water inlet temperature (T_{wi}) to a water-cooled suit while subjects rested, then worked at 10–11 kcal/min for 1 h. (From Webb and Annis [58])

Metabolic heat is generally produced at a low resting level during space flight, but can rise to very high levels during the vigorous activity of men who leave the space vehicle wearing space suits. The quantity of heat involved and the time course of its dissipation from the body surface following the start of work are both of great interest in the design of cooling control, which is discussed in a later section. Further data on the low levels of heat produced during long, quiet flight are to be hoped for in future missions.

WATER LOSS AS A MEANS OF DISSIPATING HEAT

The body loses heat steadily by water evaporation from the skin and from the moist linings of the respiratory tract. Each gram of water lost in this way carries with it 0.58 kcal as latent heat of evaporation, and under normal comfort conditions this steady loss of water, the so-called insensible perspiration, represents approximately one-fourth of the resting metabolic heat production. In the small sealed artificial atmosphere of a space cabin or space suit, the water produced by the man must be removed constantly to avoid causing high vapor pressure and loss of the thermal comfort state. Therefore, the environmental control system for the artificial atmosphere must be designed to remove water vapor at the rate generated by the astronaut. Just as the direct heat loss of the body surface must be removed as fast as it is generated in the small sealed atmosphere, so must water vapor if intolerable thermal conditions are to be prevented. It is appropriate to consider man as a source of water vapor and also the effect of high vapor pressures on comfort and thermal tolerance.

A small continuous obligatory loss of water has long been called insensible perspiration; it consists of water lost by diffusion through the skin and in the exhaled air. Both losses are affected by the vapor pressure of the air around the man—the higher the vapor pressure, the smaller the loss. Under most conditions with which we are familiar on Earth, the vapor pressure of air around us does not vary over a wide range; hence, we are accustomed to thinking of insensible water loss as relatively constant at about 30 to 50 g/h.

The rate of water diffusing through the skin is determined by the difference in the vapor pressure under the skin and that of ambient air, and is limited by the diffusion resistance of the skin as a barrier. The rate is also influenced by the total pressure of the environment, since diffusion is inversely proportional to the square root of pressure. The major factor is the vapor pressure gradient between tissue fluid under the skin and the ambient vapor pressure. It is usually assumed that the vapor pressure under the skin is that of water at skin temperature; thus a skin temperature of 33°C would give a vapor pressure of 38 mm Hg. Ambient vapor pressures are nominally around 10 mm Hg in spacecraft; thus the gradient would be 28 mm Hg. It has been shown by Buettner [14] that diffusional transfer stops when the ambient vapor pressure equals 90% of the saturation vapor pressure at skin temperature, thus defining the diffusion resistance of the

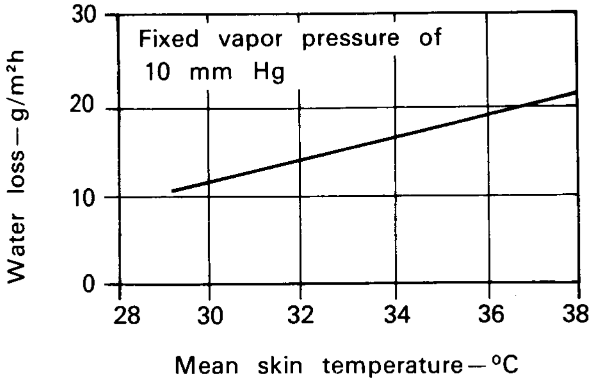

FIGURE 9.—Diffusional water loss through skin as a function of skin temperature, at ambient vapor pressure of 10 mm Hg.

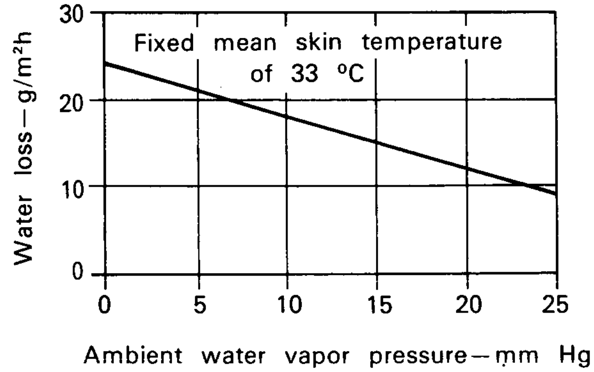

FIGURE 10.—Diffusional water loss through skin as a function of ambient vapor pressure at a fixed mean skin temperature of 33°C.

skin. In a review of this topic and other water exchanges in space suits and capsules, Webb [55] summarized water loss by diffusion through the skin, as shown in Figures 9 and 10. These two figures show the effect of a change in skin temperature when the vapor pressure of the ambient air is fixed, or, if the skin temperature is fixed, the effect of a change in the ambient vapor pressure.

Water loss through the skin is higher at low ambient pressures, as shown by Hale et al [25]. They reported that diffusional water loss from the arm increased from a rate of 10 g/m^2-h when the barometric pressure was 760 mm Hg to approximately 17 g/m^2-h when the barometric pressure was 253 mm Hg. Unpublished observations by the author showed an even greater effect on weight change of nude men in an altitude chamber where sweating was prevented by administration of atropine; in this case the rate was 15 g/m^2-h at 760 mm Hg, and 38 g/m^2-h at 253 mm Hg.

The rate of water lost from the respiratory tract is primarily determined by the respiratory ventilation rate. Ambient vapor pressure and total pressure also have an influence. Data of this sort are summarized in Figure 11, from the review of Webb [55]; in this figure one may determine the respiratory water loss in g/h as a function of respiratory ventilation rate, and at a number of ambient vapor pressures from low (3 mm Hg) to high (27 mm Hg). Since respiratory minute volume increases with the activity of the subject, so respiratory water loss increases as a function of metabolic level.

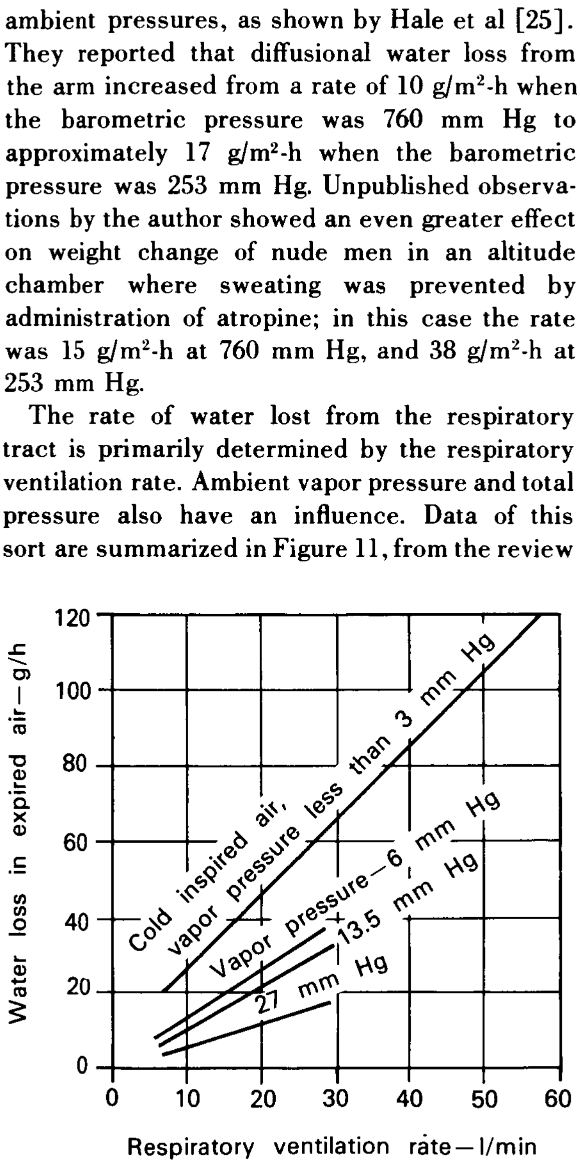

FIGURE 11. – Water losses in expired air as a function of respiratory ventilation rate, for several vapor pressures of the inspired (ambient) air. (From Webb [55])

For most purposes it is sufficient to take a standard value for insensible water loss, since it represents only a relatively small part of the metabolic heat dissipation and a relatively small water load on a well-designed environmental control system. Such a standard value is usually given as 900 g/d, or 37.5 g/h. This represents 14 kcal/h, or 16 W. If the artificial atmosphere is at considerably less than 1 atm pressure, then this value might increase by 50% or 100%, but it still represents only a small part of the total metabolic heat dissipation.

Water is actively secreted by the sweat glands for the purpose of cooling the skin. There is also a nonthermal or psychogenic activity of the sweat glands, but quantitative data on the amount of nonthermal sweating is scarce. Perhaps the clearest set of experimental data on the rate of nonthermal sweating is that of Brebner et al [11]. They observed that subjects in a cool room who required no sweating for thermal balance were losing water at higher than diffusional rates from the face, hands, soles of feet, axillae, and groin. These rates were two to four times higher than the rate of insensible water loss measured over the rest of the skin surface. Such rates would not necessarily prevail throughout 24 hours, but would be most likely during the waking hours, especially when the subjects were alert, anxious, or excited. This sort of sweating could be expected in astronauts during the busier periods of space flight.

Thermal sweating is a major physiologic response to the need for heat dissipation. It occurs when ambient conditions are not cool enough for dissipation of metabolic heat. The rates of sustained thermal sweating can be very high, as much as 2000 g/h and higher. There is a great amount of literature on the rate of sweating as a function of environmental conditions and activity. One summary of such data is shown in Figure 12. The studies, from which this figure was drawn, were made of men lightly dressed in shorts and shoes, rather than in the space-related conditions of low barometric pressure and wearing space suits. However, the principle remains the same: sweating increases as ambient conditions are warmer and as the metabolic heat generated is higher. Sweat rates can be high when activity is undertaken in space suits of limited mobility, illustrated by the report of Harrington et al [28], also by the early days of extravehicular activity in the Gemini program, reported by Burns et al [16].

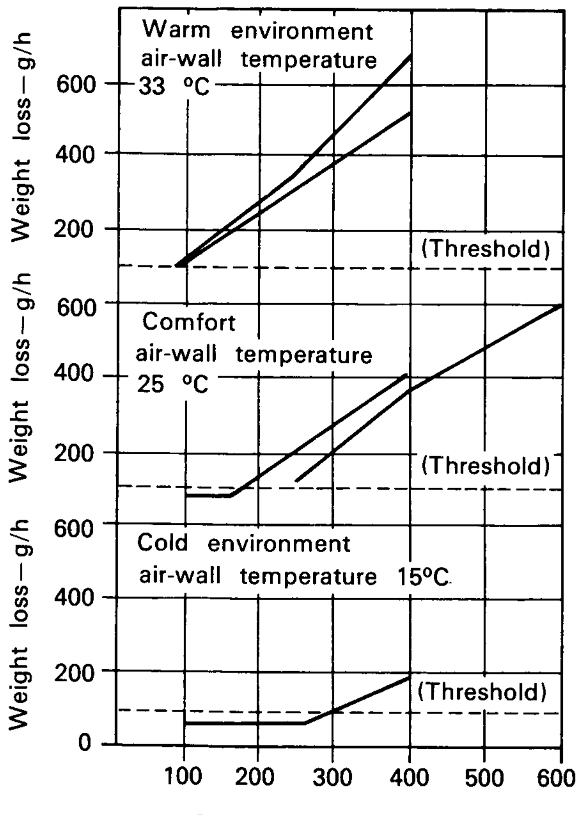

FIGURE 12.—Sweat production (from weight loss) as a function of metabolic rate for men wearing only shorts and shoes in three different environments. Threshold level for thermal sweating is indicated by a dashed line at 100 g/h. The curves were derived from three separate studies; there were two sources of data at 33°C, and two sources at 25°C, hence two similar curves in these two parts of the figure. (From Webb [55])

To illustrate the critical nature of high rates of sweating if the gas-conditioning system in a space suit cannot keep up with the amount of water evaporated, consider the following example. Suppose that the free volume of the artificial atmosphere in the suit is 300 l and has an initial vapor pressure of 10 mm Hg (10 mg/l water). Suppose further that the man is working hard enough to produce 10 g/min sweat, all of which evaporates, and that the portable life-support system removes 8 g/min from the recirculated gas. The net addition of 2 g/min water vapor over a 5-min period will add 10 g water to the atmosphere for a total of 13 g in the 300 l. This is equivalent to air saturated at a temperature of 37°C or a vapor pressure of 47 mm Hg. In such an atmosphere, no sweat would evaporate and all cooling by this route would have ceased. Under such conditions there would be rapid storage of body heat.

The preferred value for the water vapor pressure in an artificial atmosphere is 10 mm Hg. As little as 5 mm Hg is acceptable, but lower than that may cause uncomfortable drying of the mucous membranes of the respiratory tract. Probably an upper limit is 15 mm Hg, for beyond this level the evaporation of sweat is reduced and thermal discomfort begins.

Heavy sweating in space suits and overloading of the environmental control system during the earlier days of extravehicular activity led to the development of a more direct means of cooling whenever high metabolic activity was expected. It became important to prevent the high sweat rates during high metabolic activity. This new means of cooling, the liquid-cooling garment, will be discussed next.

WATER-COOLED GARMENTS

Perhaps the most significant development in thermal control to come from the space program is the water-cooled garment, which has been used during extravehicular activity in the Apollo lunar landing program. This method of removing heat directly from the body surface, using water as a heat transfer fluid, is a powerful method of maintaining thermal balance during high metabolic activity; the method can be readily controlled either by the astronaut or automatically. It has also proved a reliable means of measuring heat loss calorimetrically, both in the laboratory and during lunar excursions.

Despite the successful use of air-ventilated suits for men in industry, when in sealed clothing and seated in aircraft under hot conditions, gas cooling proved totally inadequate for men working in pressurized full-pressure suits [23, 32, 36, 41, 53]. This became evident both in laboratory studies [28], and in the extravehicular activities of the Gemini program [16, 35]. The problem was essentially that of an engineering limitation due to the power needed to circulate a very high volume of the relatively thin gas, oxygen, at 0.25 ata, to carry heat and water vapor from the skin to the life-support system. Estimates were that 1000 to 2000 l/min of this thin gas would be needed to remove the metabolic heat from a man exercising at five times his resting level in a space suit, where there was little external heat load. An electric motor to drive a blower to move this much gas would require several hundred watts, which would mean an excessively large and heavy battery pack.

The water-cooling garment was first proposed by Billingham [7], in a theoretical paper on thermal problems of men on the Moon. In 1962, the first water-conditioned suit was made at the Royal Aircraft Establishment in Farnborough, England, as reported by Burton and Collier [17]. Their intent was to provide thermal comfort for pilots who were confined to a closed cockpit while the aircraft waited on the runway and heat from sunshine accumulated. Experimental evidence showed that comfort conditions could be maintained despite high external heat loads. It was also evident that the power required to pump the water through the suit was far less than the power required to circulate sufficient cool air to do the same job. Soon after, the water-cooled suit was adopted in the United States by the National Aeronautics and Space Administration as the means of removing heat in the Apollo space suit. This development was described by Jennings [31], and physiologic evaluations of the suit have been reported [18, 49, 52, 58]. The major Soviet study is that of Barer et al [3].

It was demonstrated by Crocker et al [18] and Webb and Annis [58] that as much heat could be extracted by the suit as was being generated by men working hard in insulated sealed clothing. Waligora and Michel [52] demonstrated the quantity of cooling required for men working in space suits in the laboratory; and Veghte [49] showed that under conditions of high external heat load, water cooling was far more effective than gas cooling in full pressure suits.

A water-cooled suit consists of a network of small plastic tubes whose total length is about 100 m. The network lies against the skin or is held in tunnels of thin cloth sewn to a suit of underwear. Water is circulated through the tubing network at a flow rate of 1–2 l/min, and the flow is usually constant. Increased cooling is achieved by lowering the temperature of the water entering the suit. An excellent review of the development of water-cooled suits and the various designs which have emerged is that of Nunneley [39]. She points out that applications have been found in industry as well as in aircraft and space-flight situations. Shvartz [45] has also reviewed the subject recently, comparing the effectiveness of cooling applied to different parts of the body.

The distribution of cooling tubes over the skin has been designed in several different ways. One approach has been to proportion the number of tubes according to either the mass of a given body segment or to its area. In both cases, the torso received the greatest amount of cooling, the legs next, and the arms least. Head, hands, and feet are omitted in these suits. This design seems to make sense when the heat load is largely external, such as when a pilot is seated in a hot cockpit. This function of the cooling garment is essentially to block heat leakage from outside the clothing rather than to remove metabolically produced heat.

A second design approach, which seems to work better when the heat load is principally internal (metabolic), is to distribute the cooling in relation to where most of metabolic heat appears. The head is one such site, and the legs an even more important one if the subject is using his leg muscles during work. The hands and feet should be included if possible, since these are major sites used by the body when thermoregulation demands a variation in heat dissipation. As an example of this design approach, Webb et al [59] proportioned their cooling tubes as: legs and feet, 50%; arms and hands, 23%; torso, 19%; and head and neck, 8%. But flow through these tubes was proportioned as: legs and feet, 40%; arms and hands, 26%; head, 22%; and torso, 12%.

A vital part of the design of these garments is the means to assure good fit and continuous contact of the cooling tubes with the skin. One approach was to use an open-mesh garment made with elastic fibers to which the cooling tubes are attached, and another, a diamond pattern of tubing which stretches open as the garment is put on. Both designs appear to work satisfactorily, since experiments with both types have shown that skin temperature can be lowered at will, even during exercise, with water flow rates of 1–2 l/min and inlet temperatures between 5° and 30°C.

The flow rate of water has been most often reported as 1.5 l/min [56–60] or 1.82 l/min [5, 52]. This amount of flow permits satisfactory heat removal during rest or hard work, and at reasonable water temperatures.

The application of water-cooled garments was successfully demonstrated in the Apollo lunar landing program [5]. In all lunar landing missions in the Apollo program, the water-cooled garment has proved capable of removing metabolic heat as it is generated while the astronaut works. In fact, as predicted from laboratory findings, there was more than enough cooling since the astronauts, who had a manual control valve with three positions, felt overcooled if they used the maximum cooling available. As the lunar exploration program developed, longer and longer extravehicular activities were possible, partly because of the success of water cooling. There was no evidence of metabolic heat storage despite that, on the lunar surface, there was little or no heat loss to the airless lunar environment. Fairly high work rates were occasionally undertaken by the astronauts in their enthusiasm over lunar exploration, as evidenced by high heart rates, but there was no report of heavy sweating, heat storage, or similar signs of inadequate heat removal.

Physiologically speaking, it is important that a powerful means of cooling has been developed which permits a man to work at nearly any level without need for sweating. A new means was found for insuring thermal comfort even during work. When work levels are high, and heat dissipation to the environment is severely limited, as it is in space suits worn in the vacuum of space, the water-cooled suit can be controlled so that skin temperatures are reduced and heat dissipation is made easy. There is very little physiologic cost to heat dissipation under these conditions.

With such a powerful means of heat removal at hand, a new problem arose: how to control the cooling in relation to the need for heat dissipation. After a number of experiments of the type illustrated by Figure 8, Webb et al [60] found that immediately following the onset of work, physiologic responses changed exponentially, each response with a characteristic time course. Oxygen consumption and heart rate rose rapidly, while heat dissipation rose with a much slower time course, during which time the rectal temperature rose and reached a plateau level. The time constants for each of these variables given by the authors are shown in Table 3. They proceeded to develop automatic controllers for regulating the temperature of the water entering the water-cooled suit. Their first automatic controller relied upon the exponential character of the response of oxygen consumption and its direct relation to the metabolic heat being produced in the active muscle. The relatively rapid response of oxygen consumption was sufficiently ahead of the release of heat on the skin surface that a controller could be made to match, in time and magnitude, the need for

TABLE 3.— *Values for Metabolic Time Constants* [60]

Metabolic variable	Time constant, min
Heart rate	0.4
Oxygen consumption	0.5
Mean skin temperature (estimated)	1
Heat dissipation	10
Rectal temperature	10

heat removal. The controller equation was

$$\tau\dot{T}_{wi} = -T_{wi} + B(M_0 - M) \qquad (5)$$

where τ is the time constant for heat dissipation; T_{wi} the rate of change of temperature for water entering the suit; T_{wi} the instantaneous temperature of water entering the suit; B the gain of the system; M_0 a reference (maximal) metabolic rate; and M the instantaneous metabolic rate.

A second type of automatic controller was based on the observation that heat dissipation, which could be continuously measured by watching the change in water temperature traversing the suit, was in fact a physiologic signal from the man. As the amount of heat appearing in the suit increased, so water temperature could be lowered and more heat extracted. If too much cooling occurred, cutaneous vasoconstriction would reduce the amount of heat appearing in the suit and the cooling would accordingly be reduced. However, this alone as a control system was unsatisfactory because of oscillations in the control loop. By adding a skin temperature signal to the input of this controller, smooth and effective control of heat removal was achieved. The controller equation was

$$T_{wi} = T_{wi_0} - \frac{\alpha}{\dot{m}c}(H - H_0) - \beta(T_{cs} - T_{cs_0}) \qquad (6)$$

where the subscript zero indicates initial condition at rest; α and β are proportionality constants; $\dot{m}$ is the mass flow rate of water, and c is its specific heat; H is rate of heat removal by the suit; and T_{cs} the mean skin temperature used for control purposes.

Some authors suggest that cooling capacity with a water-cooled suit is limited so that work should be kept below levels of about 700 W (10 kcal/min). For example, Waligora and Michel [52] reported such limitations, but the Apollo suit used in their studies did not provide for cooling in the head, hands, or feet. The head is particularly important for heat extraction. Blood circulation in the head is high and the blood vessels apparently do not constrict when strong cooling is applied. Studies by Nunneley et al [40] and by Shvartz [45] emphasize the value of head cooling as a major component of total body cooling.

The effectiveness of the water-cooled garment as a means of thermal control in space suits worn by active men has an added significant advantage: it has proved to be an extremely effective measuring tool. Berry [5] reported that the measurement of heat extraction in the water-cooled suit during lunar excursions was subsequently relied upon during the Apollo program. There were three methods for monitoring the work rate of the astronauts: individual heart rates as a function of activity level determined for each astronaut; the decay of pressure in the oxygen supply bottle in the astronaut's portable life-support system; and heat removal measured by the temperature change of water traversing the water-cooled suit. The heart rate data, unfortunately, showed not only the metabolic activity level but also the state of excitement or anxiety of the man. The pressure change in the oxygen bottle was a relatively insensitive measure, which might be greatly in error should there be leakage of gas from the space suit. However, the temperature change of water traversing the suit was continuously available for monitoring and indicated in real time the quantity of heat removed. This method of measuring heat extraction in the water-cooled suit and comparing it against measured heat production has been extensively studied in the laboratory [57–60].

The water-cooled garment makes an excellent direct calorimeter [59]. Complete metabolic heat balances for 24-hour periods have proved quite accurate, and interesting data on circadian rhythms in metabolism, heat storage, and similar topics [57] are coming from such studies. This method of estimating metabolism during prolonged space flight may prove useful, since our direct measurements of metabolic level during space flight are only approximate. It should be possible to carry out not only indirect (respiratory) calorimetry by measuring oxygen consumption, but also the direct heat dissipation from men by using the water-cooled garment.

TOLERANCE FOR EXTREME HEAT AND BODY HEAT STORAGE

Because of the special nature of thermal balance in a spaceship, the major problems in man's energy exchange are related more to removing excess heat, than to cold exposure and serious body cooling. Investigators in both the Soviet Union and the United States have been interested in high thermal loads and developing means of protection against them. The foundations were laid during the past 40 years while investigators were concerned with the problems of heat exposure in industry; much of this work has been summarized in the US and Soviet literature [12, 22, 24, 37, 38]. Additional interest in heat exposure was generated in the period just prior to the space era, when aerodynamic heating in high-performance aircraft led to the ever-present possibility of exposure to high temperature in the aircraft cabin. Spacecraft that pass at high speed through the atmosphere of Earth, or possibly that of other planets, have a similar potential problem; the temperature stress could be even higher, if briefer, should the mechanisms for heat dissipation and cabin cooling fail.

Human response above the zone of thermal comfort falls into three recognizable zones.

> The first zone is where the heat exposure is compensable; that is, vasodilation and sweating permit thermal balance to be achieved, usually at a higher than normal body temperature, and a steady state can exist for some hours. These exposures are fatiguing and time-limited, depending on how much physiologic activity is called for to maintain thermal balance.
>
> In the second zone, the heat exposure is not compensable, and no thermal balance exists. Heat is stored, both metabolic heat and that which may be arriving from the environment, and the limit is set by how much heat storage the body can tolerate.
>
> A third zone exists at even higher temperatures where the thermal influx is so high that surface heating causes severe pain, followed by skin burns if the exposure continues. Experimental determination has been made of the conditions that produce intolerable pain, just as conditions have been defined for limits of body heat storage and for lower but compensable heat exposures.

The zone of compensable heat exposure will not be discussed here, which is presented fully in standard works on physiology. In the age of space flight, more attention has been paid to higher levels of heating, and the two zones of heat storage and surface pain will be considered in greater detail.

Overheating Limited by Body Heat Storage

When the temperature of the air and surrounding walls exceeds 60°C (140°F), the body cannot maintain a heat balance, even through profuse sweating, and it begins to store heat. This is the zone of noncompensable heat exposure and hyperthermia. The higher the temperature, the shorter the time a man can tolerate such exposures, since the quantity of heat stored and the rate of storage increases. However, the more clothing he wears and the greater its insulating value, the longer it takes to reach tolerance. Also, at altitudes where the barometric pressure is low, it takes longer to reach tolerance than under the same high temperature conditions at sea level. The end point of such exposures, the tolerance limit, is reached when physiologic mechanisms begin to break down, but even before this performance has deteriorated. Most investigators relate the tolerance condition to the quantity of heat stored. The same physiological end point is reached whether the added heat is from an external load or from the condition where body heat loss is prevented and metabolic heat is stored.

The temperature range that has been studied is from 60° to 120°C, with the majority of research done at 70° to 80°C; beyond this temperature the instruments in aircraft and spacecraft would begin to fail before the man reached tolerance. Experimental subjects have been exposed unclothed, with light flight coveralls, and wearing heavier clothing up to and including Arctic flight gear and insulated antiexposure suits. Nearly all reports concern subjects in the resting condition.

The tolerance time for exposure to these high temperatures is shown in its simplest form in

Figure 13, which is based on data from major Soviet studies reported by Dorodonitsin et al [19], and that of the major American study summarized by Blockley [8]. In both cases the experiments were conducted at ground level with air and wall temperatures approximately equal and with resting subjects clad only in light clothing. Figure 14 shows similar data from men resting at a low barometric pressure equivalent to 8000 m altitude wearing both light flight clothing (1.2 clo) and medium flight clothing (1.9 clo), based on the study of Dorodonitsin et al [19].

It is possible to combine the many factors necessary to calculate the tolerance time for these high temperatures. The factors include air and wall temperatures, radiant load from the sun and other high temperature surfaces, air density, air velocity, clothing, and activity level. After carrying out many experiments, Blockley et al [9] derived mathematical expressions for each major factor and presented them in graphic form for easy solution when specific conditions are known. The general form of these calculations is that the rate of accumulation of heat in the body, or heat storage, is equal to the sum of metabolic heat production and heat transfer to the body by convection, conduction, radiation, and evaporation. It was important to establish empirically the rate of heat storage and total quantity of heat stored that was tolerable, both physiologically and in the performance sense. Figure 15 shows a prediction chart based on the work of Blockley et al [9], where the body storage rate can be determined for a number of conditions over a range of "operative temperatures," the solution being to find the tolerance limit in terms of the heat storage rate in the body. The example on the graph is for a man lightly clothed in underwear at sea level in an operative temperature of 100°C, whose physiologic tolerance limit is predicted to be 27 min.

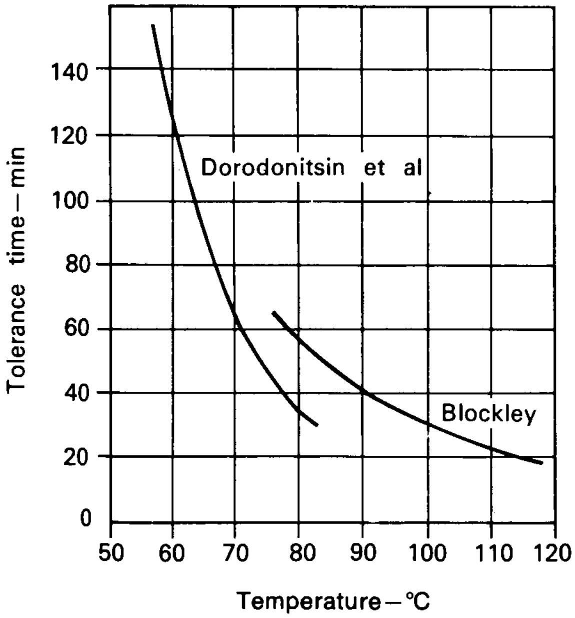

FIGURE 13.—Tolerance times for lightly clothed resting men during noncompensable heat exposures at 1 ata where the limit is determined by body heat storage. (After Blockley [8] and Dorodonitsin et al [19])

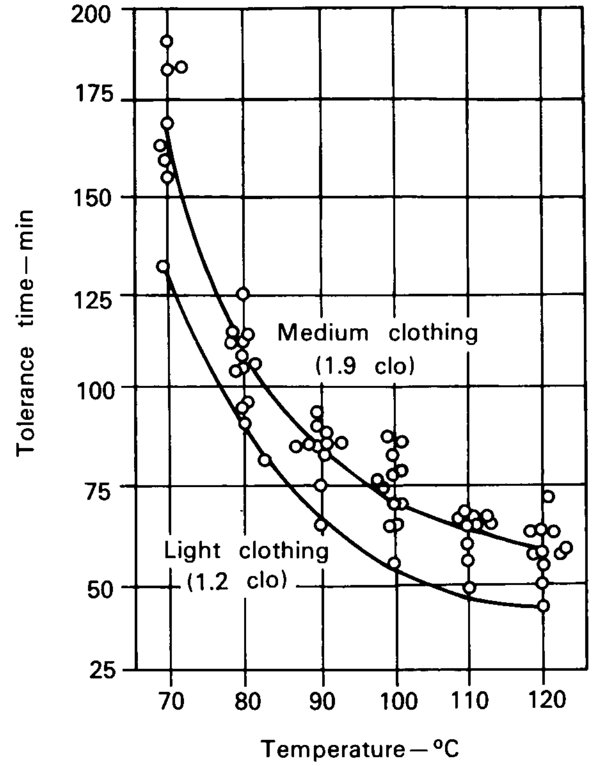

FIGURE 14.—Tolerance times for resting men at an altitude of 8000 m (26 240 ft), or 0.35 ata, during noncompensable heat exposures while wearing light and medium weight clothing. (After Dorodonitsin et al [19])

Body Heat Storage and Thermal Tolerance

The condition of the subject who is approaching the physiologic tolerance limit during a

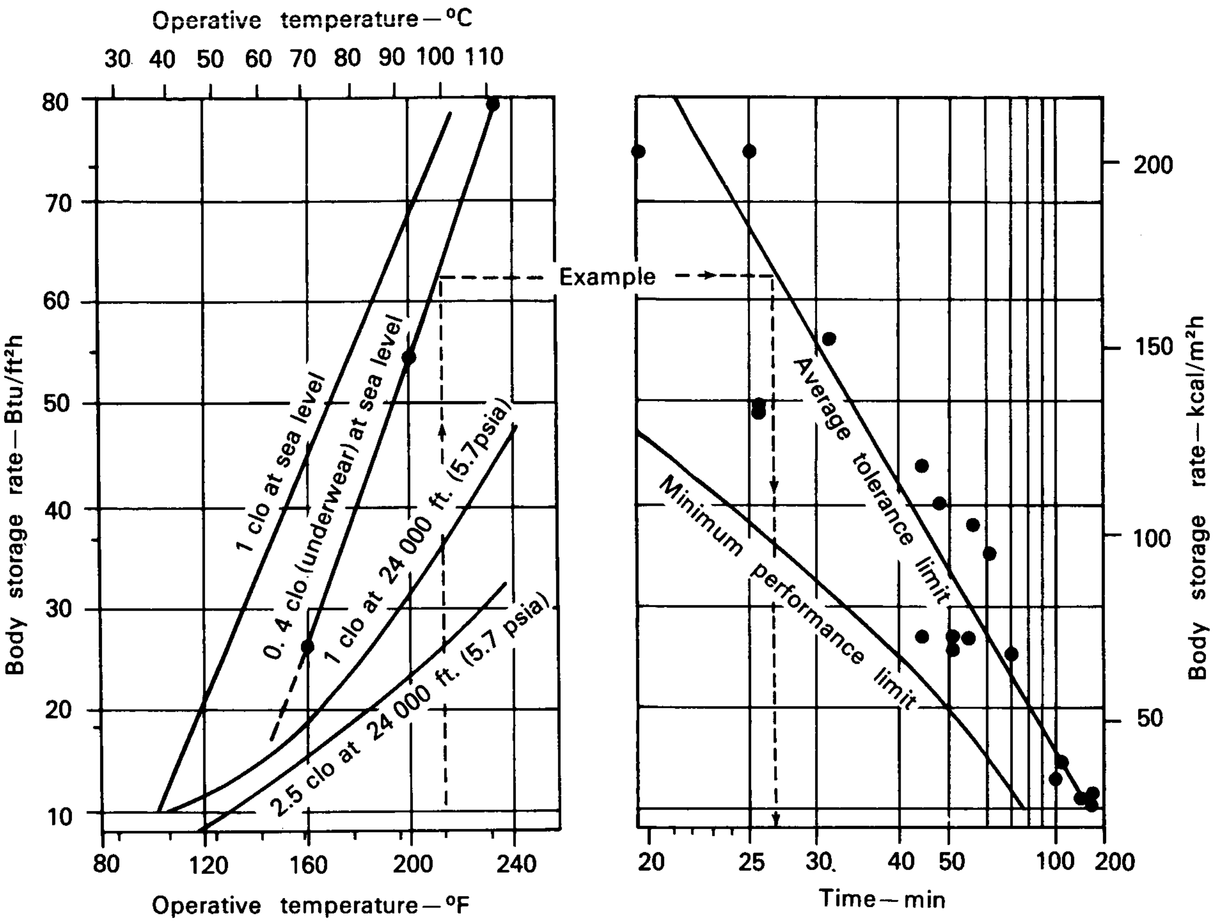

FIGURE 15.—Chart shows rate of storage of body heat for several conditions of clothing and altitude, where seated and untrained men are exposed to noncompensable heat. Entry is by means of the reference operative temperature, defined as the temperatures of air and walls which, in combination with a vapor pressure of 20 mm Hg, has equivalent effects to some other combination of humidity and temperatures. Operative temperature is the weighted mean of air and wall temperatures, where the weighting coefficients are the respective heat transfer coefficients for convection and radiation. (From Blockley et al [9])

noncompensable heat exposure is quite clear to the trained observer. The subject has been subjectively hot and sweating heavily, but quite able to perform tasks, read, and otherwise be occupied. As the tolerance point is reached, the subject becomes anxious, restless, and is unable to keep his attention fixed for very long. His performance has begun to deteriorate and he becomes more difficult to handle. The subject's heart rate has become quite high, usually in the range of 140 to 180 beat/min, depending somewhat on his physical condition. The pulse is full and strong and blood pressure shows a wide distance between systolic, which may be somewhat elevated, and diastolic, which is usually very low; the man's cardiac output is two or three times the resting level. His body temperature is high, rising rapidly, and his skin is hot and somewhat dry; his sweating is reduced. Some observers note a pallor developing around the eyes, which is quite striking since the rest of the face is flushed and red. This condition has been described by Blockley et al [9], Kaufman [33], and Webb [53]; it is also summarized in Soviet literature based on the work of Shepelev [44], Dorodonitsin et al [19, 20], as shown in

TABLE 4.—*Certain Functional Changes Related to the Degree of Overheating of the Body* [1]

Functional change	Degree of Overheating			
	1	2	3	4
Nature of sweating	moderate	profuse	significant decrease	cessation
Temperature increase, °C	to 0.3–0.5	to 1.5–2	to 2.5–3	2.5–3
Heat accumulation, kcal/m^2	to 10–15	to 45–55	to 70–90	70–90
Heat production, kcal/m^2·min	below 0.2–0.3	above 0.4–0.5	above 0.8	increase stopped; possible decrease
Pulse increase, beats/min	to 15–20	to 55–60	double or more	drop to original and below
Change in maximum arterial pressure, mm Hg	intermediate or no change	increase to 20–30	increase to 40–50	rapid drop to original or below
Change in minimum arterial pressure, mm Hg	″	decrease to 30–40	decrease to 50–60	decrease stopped; possibly increased

[1] From A. N. Azhayev, *Third All Union Conference on Aviation and Space Medicine*, Moscow, 1969.

Table 4. When the subject has reached this state, heat exposure must be terminated or he will lose consciousness. Should heat exposure continue, the subject's life would be threatened, either from circulatory failure or heat stroke.

This physiologic tolerance limit is reached in resting subjects when a certain quantity of heat has been stored. Heat storage is not measureable directly, but most investigators measure internal body temperature, either rectally or orally, and skin temperature. There is a tradition that storage can be found from a change in average body temperature, which can be determined by combining the change in skin and rectal temperatures with weighting coefficients.

$$\Delta\bar{T}_b=\alpha(\Delta T_{re})+(1-\alpha)(\Delta\bar{T}_s) \qquad (7)$$

where $\bar{T}_b$ is mean body temperature, α is a constant, and T_{re} is rectal temperature. This change in average body temperature is multiplied by the subject's body weight and by the specific body heat, which is 0.83. The original weighting coefficients, dating from the studies of A. R. Burton in the 1930s, were approximately $^2/_3$ times the rectal temperature plus $^1/_3$ times the mean skin temperature. However, it can be argued that in severe heat exposure, the weighting coefficient for the skin should be less, since supposedly it accounts for the usually cool shell temperature compared to the more-or-less constant core temperature. In heat exposure the skin and subcutaneous tissue approach and sometimes exceed the rectal temperature. The tendency, in Soviet literature, is to calculate heat storage on the basis of internal temperature alone, or the internal temperature with a weight of 0.9 and the skin temperature with a weight of 0.1. The difficulty is that heat storage cannot be measured directly, only temperature change; it is extremely difficult to sample enough parts of the body mass to be sure of determining a mean body temperature.

Another difficulty is that accumulation of heat in the body does not produce a linear rise in rectal temperature. For the first 5 to 10 min at least, there is either no rise or a fall in rectal temperature. This observation indicated to Blockley et al [9] a body storage index—the rate of rise of rectal temperature after the initial period. They pointed out that the rate of rise was essentially linear after the first 10 minutes. The only way to be sure of the actual quantity of heat accumulated in storage-limited heat exposures is to do a direct calorimetric study capable of adding heat to the body while at the same time measuring metabolic heat production from oxygen consumption. These experiments have not yet been done.

Although different authors calculate heat storage from core and surface temperatures in different ways, the values given by most investigators for the tolerable amount of heat stored do not vary markedly. When a resting subject has accumulated 120–150 kcal, he reaches the tolerance limit. Or (as it is usually expressed), the rate of storage of heat plotted against the tolerance time gives the type of curve shown in Figures

16 and 17. Dorodonitsin et al [19, 20] point out that when the heat exposure is severe and tolerance time short, a greater quantity of heat can be stored than when the heat exposure is less and the tolerance time longer. This idea, illustrated in Figure 18, shows the total heat stored at tolerance as a function of the heat storage rate.

The origin of the accumulated heat stored in the body is clearly a combination of metabolic heat production and external heatload. Shepelev [44] shows that evaporative heat loss is greater than the external heatload at temperatures up to 70°C, so that the accumulation of heat to that temperature can be thought of as increasing amounts of the metabolic heat production being retained. Evaporative loss equals external load at 70°C at ground level, in a resting man lightly clothed. Beyond 70°C, accumulation from both metabolic heat and the external heatload is not met by evaporative heat loss. Figure 19 shows this analysis graphically. Figure 20 shows that at 8000 m altitude, the evaporative heat loss accounts for the external heatload up to a temperature of 90°C, when the subject is wearing light clothing. In Figure 21, again at 8000 m but with clothing of greater insulation, evaporative heat loss balances the external load up to a temperature of 110°C. This sort of analysis illustrates the improved thermal tolerance for given ambient temperatures when the barometric pressure is lowered, which improves evaporative heat loss, also when the insulating quality of the clothing increases. But it is clear that at any temperature above 60°C, a significant rate of heat storage, i.e. 0.5 kcal/m^2 — min, or 30 kcal/m^2 — h, leads to tolerance after exposures lasting about 2 hours.

Tolerance levels for stored metabolic heat alone have been described in the experimental work of Roth and Blockley [42]. They measured the rate of heat storage and the tolerance limit of men totally insulated — that is, when no heat exchange occurs with the environment by any pathway, and at the same time the men are working at rates comparable to those during extravehicular activity. Interestingly, the tolerable amounts of heat storage were greater in those exercising men who could lose no metabolic heat, than for resting subjects in 70°–110°C heat exposures, but who could lose heat through the evaporative pathway. The total accumulation of this heat of only metabolic origin ranged between 200–250 kcal, compared to an average of 146 kcal shown in earlier work of Blockley et al [9] whose subjects were resting and there was high external heatload.

The intent of these experiments with working men who were "totally insulated" was to simulate the condition of an astronaut during extravehicular activity in case of complete failure in the cooling system of his space suit. In the laboratory simulation, the subjects wore impermeable garments in an environmental chamber where the chamber temperature was kept equal to the rectal temperature, while at the same time the men were breathing saturated air at the same temperature. Thus there was no evaporative water loss either from the respiratory tract or from the skin, and the exchange between the man and the environment was essentially zero. As the men worked on a

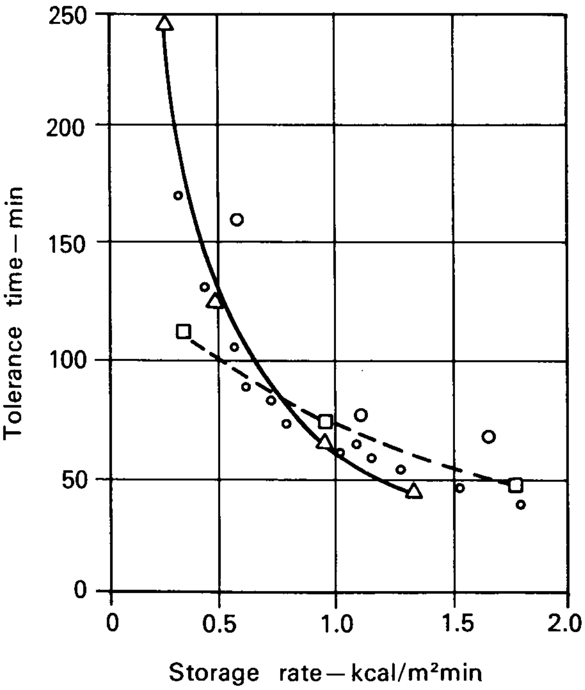

FIGURE 16. — Tolerance times as function of heat storage rates for different types of noncompensable heat exposures. Diamond symbols for resting men in light flying clothing (1.2 clo) at ground level and temperatures 50°–75°C; small circles for men at rest dressed in either 1.2 clo or 1.9 clo uniforms at 8000 m alt and temperatures 70°–120°C; large circles for men working in 1.9 clo uniforms; and three squares for men resting in a heat-insulating suit at 35°C. (Based on Dorodonitsin et al [19])

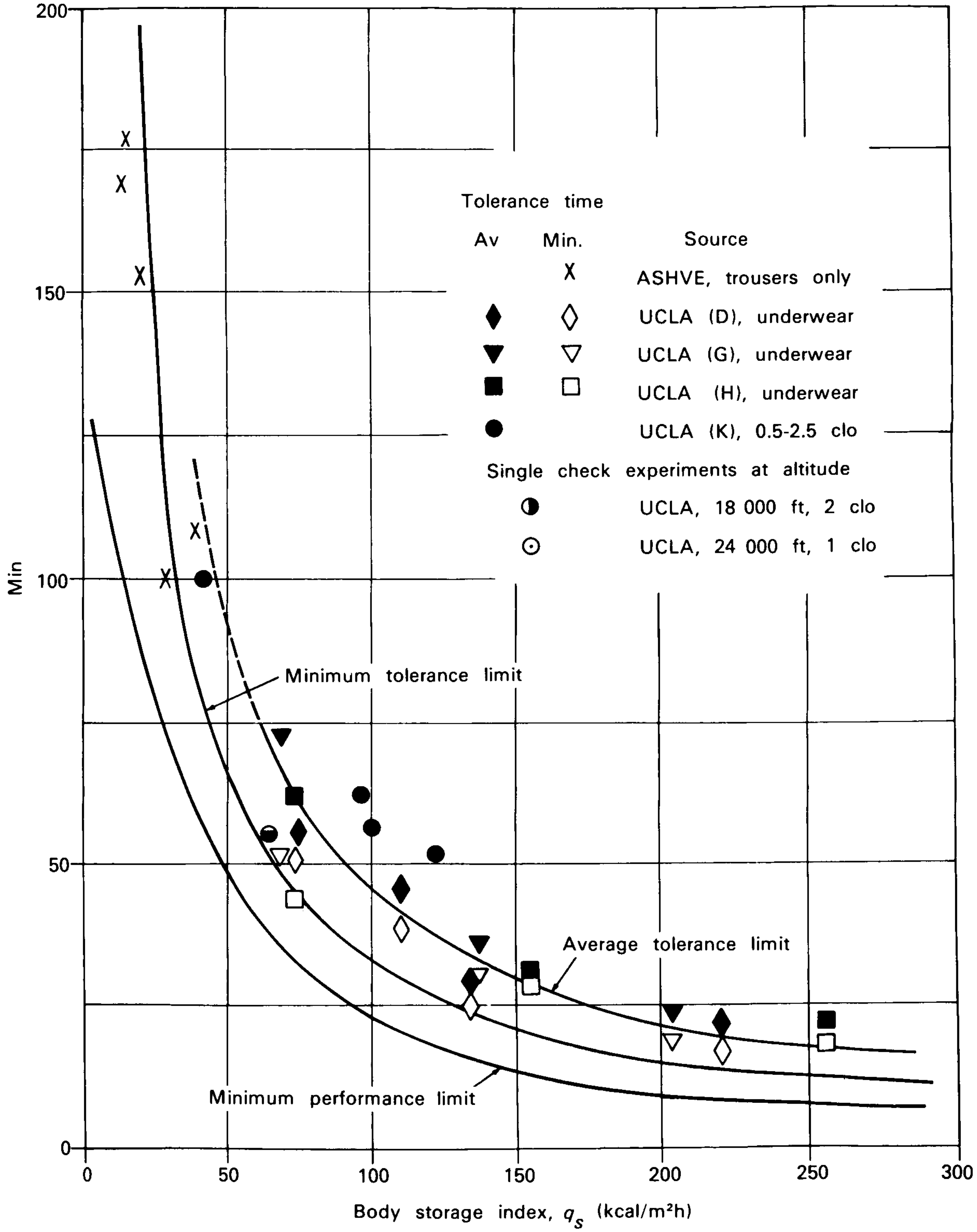

FIGURE 17.—Tolerance times for performance limits and two physiologic limits as a function of body storage index (see text) for resting men in light to heavy clothing at ground level, or at 5472 m (18 000 ft), or 7296 m (24 000 ft). (From Blockley [8])

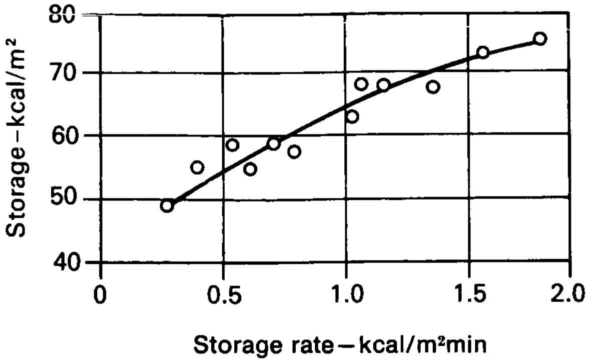

FIGURE 18.—Total heat stored to the physiologic tolerance limit as a function of rate of heat storage. (After Dorodonitsin et al [19, 20])

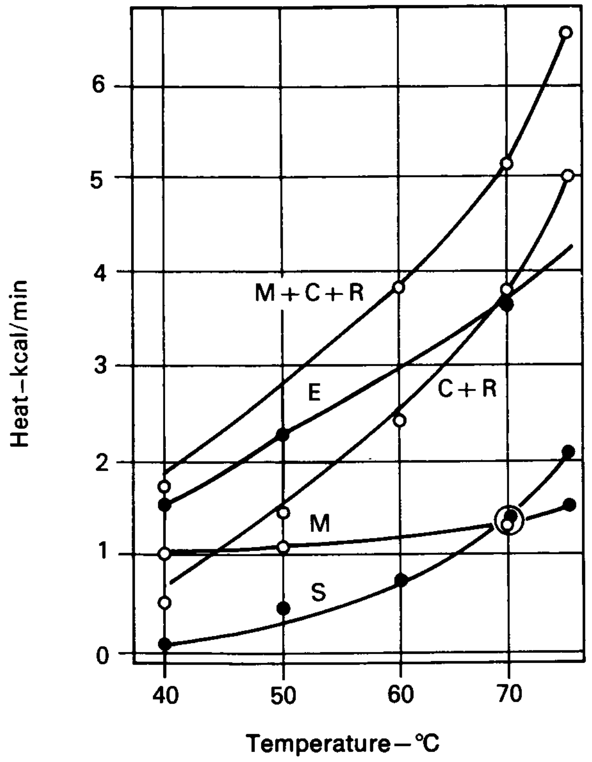

FIGURE 19.—Analysis of heat fluxes during noncompensable heat exposures between 40° and 70°C—for resting men, lightly clothed, at ground level. *S* is heat storage, *M* is metabolic heat production, *C*+*R* is heat transfer by convection and radiation combined, *E* is evaporative heat loss, and *M*+*C*+*R* is the sum of convective and radiative heat gain with metabolism. (After Shepelev [44])

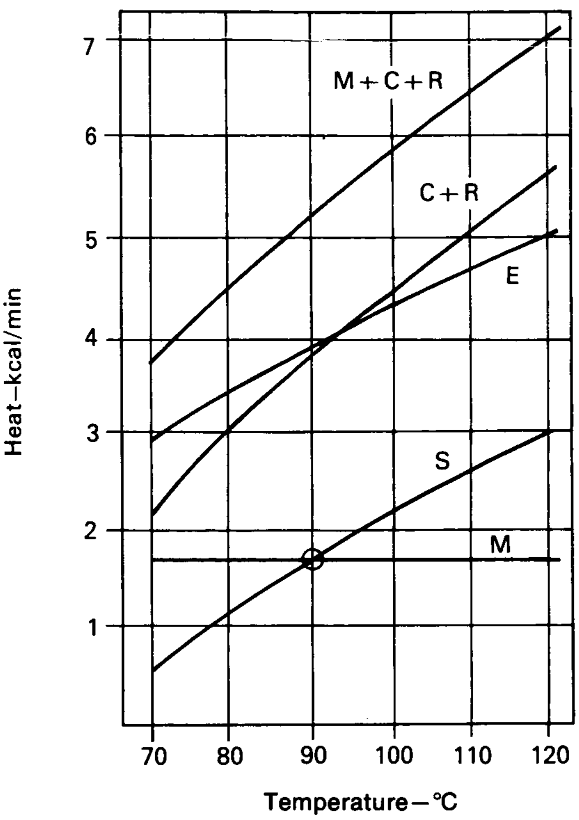

FIGURE 20.—Subjects at 8000 m alt wearing light clothing (1.2 clo); indices are the same as in Figure 19. (After Shepelev [44])

treadmill, metabolic heat accumulated as it was generated. They reached a terminal condition characterized by air hunger and respiratory distress, restlessness, dizziness, and extreme fatigue. The internal temperature measured in the auditory canal rose as high as 39.7°C, and the heart rate was between 160 and 180 beat/min at termination. Roth and Blockley [42] noted that the temperatures in the auditory canal and rectum did not rise rapidly during the first 10 min but the rise thereafter was linear. The ear canal temperature rose faster and higher than the rectal temperature. There were interesting differences in the 10 subjects studied, some being able to tolerate greater quantities of heat storage than others. The endurance times at each metabolic level were:

> 4.2 kcal/min (293 W)—47 min; 6.3 kcal/min (439 W)—38 min; 8.3 kcal/min (579 W)—30 min; 10.4 kcal/min (725 W)—24.5 min.

These authors calculated the quantity of heat stored as the change in internal temperature measured from the linear portion of the rate of

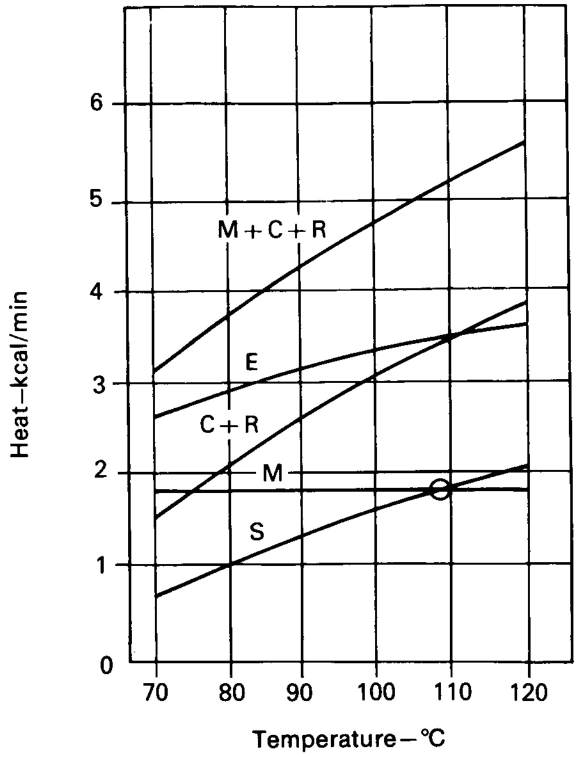

FIGURE 21.—Subjects are at 8000 m wearing heavier clothing (1.9 clo); indices are the same as in Figure 19. (After Shepelev [44])

rise of the temperature in the ear canal multiplied by $^2/_3$ and the change in skin temperature multiplied by $^1/_3$. They noted that the predictability of tolerance as a function of the quantity of heat stored was not as good as the predictability of tolerance time from the rate of rise of the temperature in the auditory canal. However, they felt that their calculation of heat storage based on these temperature data was reasonably accurate since it was nearly equal to the total metabolic heat generated (and retained) in the same period.

Heat Exposures Limited by Pain

When heat exposure is severe enough, as it is when the air and wall temperatures are greater than 120°C, the blood circulating under the skin cannot carry heat away as fast as it arrives, and skin temperature rises quickly. When the skin temperature in a local area reaches 42° to 44°C, subjects report pain. When the skin temperature reaches 45°C, the pain becomes intolerable. If the heat exposure continues and skin temperatures rise above this point, burns result. The experimental work in this zone of heat tolerance has been done using high-intensity radiating sources aimed at small areas of skin [13, 26, 46]; other experiments have been done with exposure of large areas of the body or the entire body [34, 54]. Figure 22 summarizes data from all these studies, showing tolerance time as a function of the irradiance, or the heat energy arriving per unit area of body surface. Exposures at any given irradiance longer than those shown on the figure will cause surface burns.

Because the pain threshold is variable between individuals and because it varies from day to day in a single individual, most recent studies have used as an end point unbearable or intolerable pain. The use of this end point reduces the variability between subjects. This end point has been studied by Webb [54] in exposures of two varieties. In the first type of experiment, the exposure to intense heat was abrupt. A preheated chamber about the size of an aircraft cabin was rolled on tracks to the subject, surrounding him. The heat exposure lasted until the subject requested termination, or pushed the chamber away. When subjects were unprotected by any sort of clothing, the tolerance time for whole body heating ranged from 15 min at 110°C to about 15 s at 260°C. Figure 23 shows data of this kind in a study involving five subjects who reached the end point of intolerable pain at the various temperatures shown. At 110°C for 15 min, the subjects stored a great deal of heat and responded with heavy sweating, high heart rate, and rising rectal temperature. The experiment was terminated because of surface pain.

Lightly clothed subjects showed storage tolerance limits at temperatures of 115°C at about 20 min in studies of Blockley et al [9]. There is, then, a transitional zone between 110° and 120°C and with times to tolerance between 15 and 20 min, when the exposure may be terminated either from pain or from excessive heat storage. This is depicted in Figure 24, which shows the same data as that in Figure 23, plus the data of Blockley et al.

The presence of clothing, of course, makes a great difference in the ability of a man to tolerate

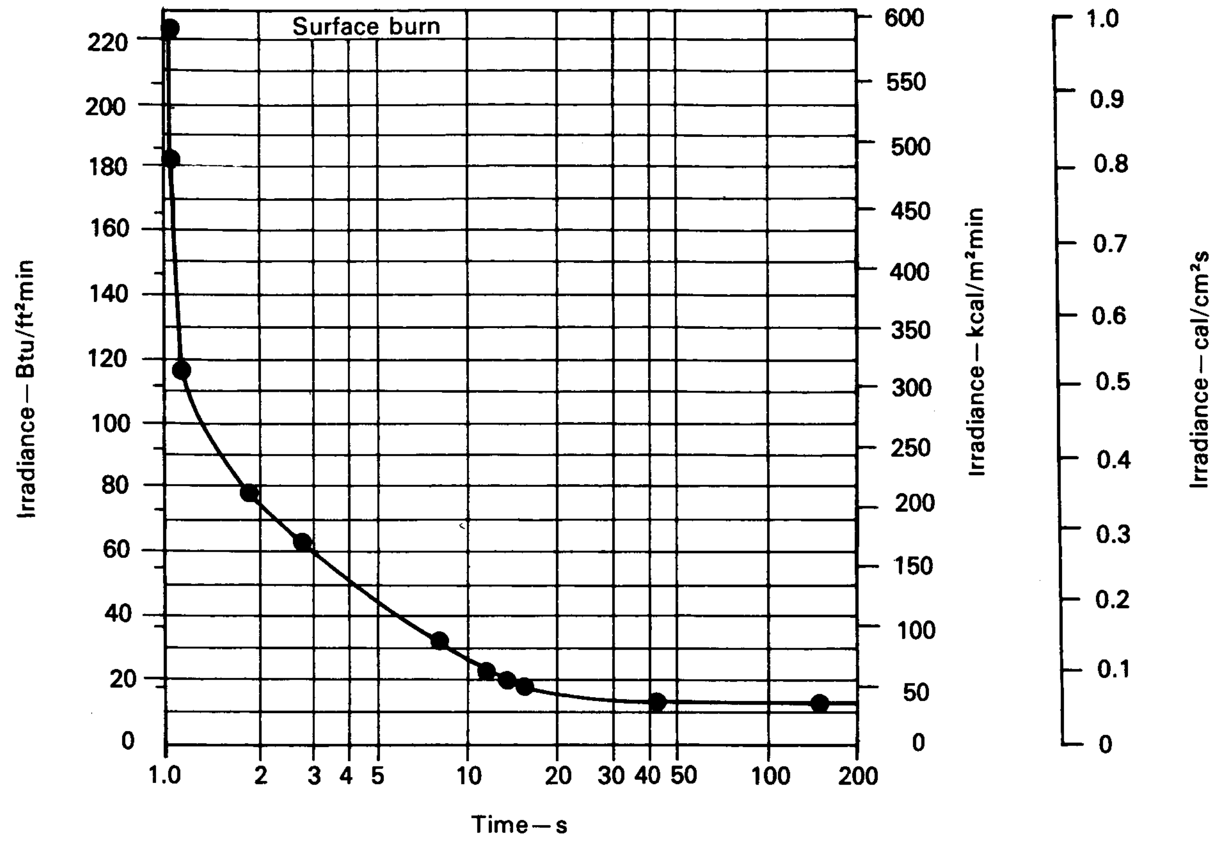

FIGURE 22.—Curve denotes combinations of heating (irradiance) and duration of exposure which produce intolerable skin pain. The highest levels of heating are similar to those from a thermonuclear flash, the lower ones from slow heat pulses related to supersonic flight and reentry of a space vehicle into the atmosphere. (Based on Buettner [13], Hardy [26], Kaufman et al [34], Stoll and Greene [46], and Webb [54])

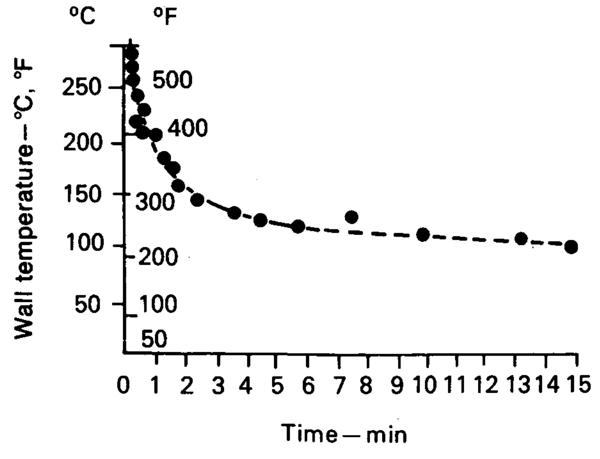

FIGURE 23.—Tolerance times set by intolerable pain for nude subjects abruptly exposed to high wall temperatures. (From Webb [54])

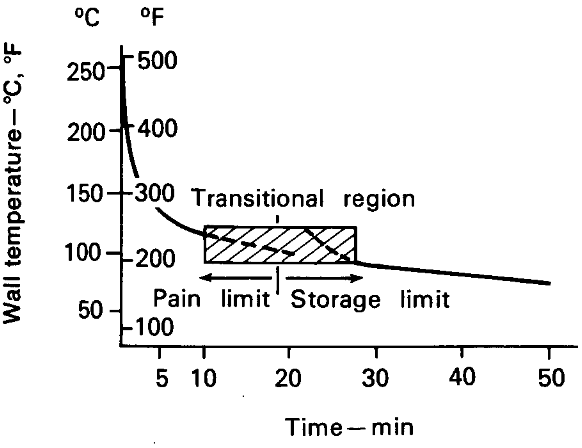

FIGURE 24.—Approximate definition of transitional region between pain-limited abrupt heat exposures of nude subjects (as in Fig. 23), and storage-limited heat exposures reported by Blockley et al [9]. (From Webb [54])

these extreme heat exposures. In another form of heat exposure, which has been called a slow heat pulse, subjects were exposed (first nude and then clothed more and more heavily) to rising temperatures that rapidly reached levels similar to those that caused unbearable pain during abrupt exposure. A typical slow heat pulse starts with a chamber temperature of 20°C, then the walls are heated to produce a rise in wall temperature at the rate of 55°C/min. Figure 25 shows that in this kind of exposure the nude subject can tolerate a wall temperature of 210°C while light underwear allows him to reach 220°C. More layers of clothing allow him to reach higher temperatures, while heavy clothing with an aluminized layer, or the same clothing ventilated, allows the subject to go for many minutes at 260°C without undue distress. The slow heat pulse type of exposure was intended to simulate what would occur during failure of cooling equipment, either in high-speed aircraft flying supersonically in the atmosphere, or during reentry of a space vehicle. The report of Kaufman [33] has similar data for heating transients related to a theoretical curve for the Mercury vehicle during reentry.

Fortunately, there have been no major failures in cooling equipment to cause exposures of this sort to astronauts or pilots during flight. However, knowledge of means to protect men in these situations may be useful in future design studies.

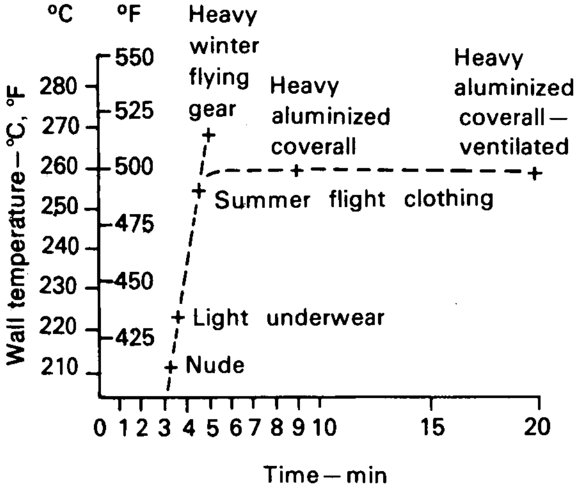

FIGURE 25.—Averaged values for pain-limited tolerances to slow heat pulses with subjects wearing different clothing assemblies. Dotted line traces hotter portion of slow heat pulses which began at 20°C with wall temperature rising at 55°C/min. (From Webb [54])

MODELS OF HUMAN TEMPERATURE REGULATION

It is possible to write equations describing heat exchange between the man's surface and the environment, heat flows within the body, and the temperature changes in the various parts of the body when the man works or is exposed to either heat or cold. Further mathematical descriptions can be made of the physiologic adjustments that help to dissipate excess heat or to conserve heat when necessary. Such systems of equations, or mathematical models, are useful to those who design life-support systems for space vehicles and cooling devices such as the water-cooled suit. Two such models will be described briefly, both having been of use in the US space program.

A general model of human temperature regulation has been described by Stolwijk and Hardy [48], and a revised and more complete version reported by Stolwijk [47]. The man is considered to be made up of a spherical head and single cylinders for the trunk, the two arms, the two hands, the two legs, and the two feet. Each of the six segments has four concentric layers of skin, fat, muscle, and core. All 24 compartments are connected by a central blood compartment, thus making 25 separate nodes. Each of the 25 compartments is represented by a heat-balance equation to account for conductive heat exchange with adjacent compartments, metabolic heat production, convective heat exchange with the central blood compartment, and evaporative heat loss and heat exchange with the environment where appropriate. Further, a controlling system or regulator receives temperature signals from all compartments and, after integration of this input, sends appropriate commands to appropriate compartments to produce changes in metabolic heat production, blood flow, or the rate of sweat secretion.

The model was presented in the form of a documented FORTRAN program. By putting the model on a digital computer, the authors were able to simulate man's response to exposures with abrupt changes in environmental temperature at rest, and able to simulate 30-min bouts of exercise at 25, 50, and 75% of maximum aerobic capacity at different ambient temperatures. The computer output provided predictions of rectal and skin temperatures, sweat rate, and metabolism, which gave reasonable approximations of experimental data gathered in the laboratory. Thus, the assumed characteristics of the physiologic controller produced regulatory responses and compartment temperatures that appeared similar to those actually measured in the laboratory. This complex and thorough model is quite powerful, and flexible enough to permit combining it with models of a space life-support system, so that reasonable predictions can be made about the interactions between the two systems. During the lunar extravehicular activities of the Apollo program, computer programs containing models of temperature regulation and of the portable life-support system were used effectively, in determining the physiologic state of the astronauts from the relatively small number of telemetered signals available.

A Self-Regulating Model

The complete biothermal model described by Stolwijk is too complex to reproduce here, but a simplified 2-node self-regulatory model from the same laboratory can be presented.[4] The model generates for any exposure time, t, values for: mean skin temperature, core temperature, volumetric flow rate of blood in the skin, evaporative heat loss from the skin and thermoregulatory sweating, body heat storage; and it predicts the important variable skin wettedness for a given set of conditions.

The model begins with a definition of a standard man:

Body mass = 70 kg
Surface area = 1.8 m^2
Skin mass = α70 kg
Core mass = $(1-\alpha)$70 kg

Latent heat of evaporation of sweat = 0.58 W-h/g
Minimal skin conductance = 5.28 W/m^2-°C
Thermal capacity of the body = 0.97 W-h/kg-°C
Thermal capacity of blood = 1.163 W-h/l-°C

Initial conditions at time 0 for physiologic thermal neutrality are:

Metabolic heat production $(M) = 58.2$ W/m^2-h
Mean skin temperature $(\bar{T}_{sk}) = 34.0$°C
Core temperature measured in the rectum $(T_{cr}) = 37.0$°C
Skin blood flow $(\dot{V}_{skbf}) = 6.3$ l/m^2-h
Skin/core mass ratio $(\alpha) = 0.1$
Evaporative heat loss from skin $(E_{sk}) = 5$ W/m^2
Thermoregulatory sweating $(E_{rsw}) = 0$

Heat balance equations for skin and core at any time t are expressed in terms of heat flow from the skin (H_{sk}) and heat flow from the core (H_{cr}) *in W/m^2*:

$$H_{sk} = (5.28 + 1.163\dot{V}_{skbf})(T_{cr} - \bar{T}_{sk}) - E_{sk} - hF_{cl}(\bar{T}_{sk} - T_0) \qquad (8)$$

where h is the combined transfer coefficient for convective and radiant heat exchange; F_{cl} is the thermal efficiency factor for clothing when clothing insulation (I_{clo}) is known $(F_{cl} = 1/1 + 1.55hI_{clo})$; and T_0 is the operative temperature, which is the average of mean radiant temperature and air temperature.

$$H_{cr} = M_{\text{net}} - (5.28 + 1.163\dot{V}_{skbf})(T_{cr} - \bar{T}_{sk}) \qquad (9)$$

where M_{net} is M minus respiratory heat loss and positive work accomplished.

Body storage of heat (S) in W/m^2 is:

$$S = H_{sk} + H_{cr} \qquad (10)$$

$$S = M_{\text{net}} - E_{sk} - hF_{cl}(\bar{T}_{sk} - T_o) \qquad (11)$$

The thermal capacities for skin and core are:

$$J_{sk} = \alpha\ (0.97)\ (70) \qquad (12)$$

$$J_{cr} = (1 - \alpha)\ (0.97)\ (70) \qquad (13)$$

Changes in skin and core temperature $(\Delta t = 1$ min) are:

$$\Delta\bar{T}_{sk}/\Delta t = 1.8H_{sk}/J_{sk} \qquad (14)$$

$$\Delta T_{cr}/\Delta t = 1.8H_{cr}/J_{cr} \qquad (15)$$

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[4] This model is adapted from the appendix to the article: Gagge, A. Rational temperature indices of man's thermal environment and their use with a 2-node model of his temperature regulation. *Fed. Proc.* 32:1572–1582, 1973.

At the end of each succeeding minute of exposure to given conditions:

$$t = t + \Delta t \qquad (16)$$

$$\bar{T}_{sk} = \bar{T}_{sk} + \Delta\bar{T}_{sk} \qquad (17)$$

$$T_{cr} = T_{cr} + \Delta T_{cr} \qquad (18)$$

The above definitions and equations describe man in a passive state. The model continues now to describe the control system with its various regulations, at any time $t + \Delta t$.

A control signal from the skin is:

$$(\mathrm{Sig})_{sk} = \bar{T}_{sk} - 34 \qquad (19)$$

and a warm signal is positive $(\mathrm{Sig})_{sk}+$, while a cold signal is negative $(\mathrm{Sig})_{sk}-$.

Similarly a control signal from the core is:

$$(\mathrm{Sig})_{cr} = T_{cr} - 37 \qquad (20)$$

and warm and cold signals have appropriate signs.

The control of blood flow through the skin is by vasoconstriction (Stric) or vasodilation (Dilat).

$$(\mathrm{Stric}) = 0.5\ (\mathrm{Sig})_{sk}- \qquad (21)$$

$$(\mathrm{Dilat}) = 150\ (\mathrm{Sig})_{cr}+ \qquad (22)$$

$$\dot{V}_{skbf} = [6.3 + (\mathrm{Dilat})]/[1 + (\mathrm{Stric})] \qquad (23)$$

Sweat production ($\dot{Q}_{sw}$) in g/m²-h is based on the difference between mean body temperature ($\bar{T}_b$) and a threshold mean body temperature of 36.7°C.

$$\bar{T}_b = \alpha\ (T_{sk}) + (1 - \alpha)\ T_{cr} \qquad (24)$$

$$\dot{Q}_{sw} = 285\ (\bar{T}_b - 36.7) \qquad (25)$$

Evaporative heat loss by thermoregulatory sweating (E_{rsw}), in W/m²-h is:

$$E_{rsw} = 0.68\ \dot{Q}_{sw}^{(\mathrm{Sig})_{sk}/10} \qquad (26)$$

For a given environment, the maximum rate of evaporative heat loss ($E_{\max}$) is:

$$E_{\max} = 4.22\ h_c(\bar{T}_{sk} - T_{\mathrm{dew}})\ F_{pcl} \qquad (27)$$

where h_c is the convective transfer coefficient; T_{dew} is the dewpoint temperature; and F_{pcl} is the permeation efficiency factor for clothing (defined by $F_{pcl} = 1/1 + 0.143\ h_c I_{clo}$).

The wettedness of the skin from regulatory sweating (W_{rsw}) is:

$$W_{rsw} = E_{rsw}/E_{\max} \qquad (28)$$

and total skin wettedness (W) is:

$$W = 0.06 + 0.94\ W_{rsw} \qquad (29)$$

Evaporative heat loss from the skin (E_{sk}) is defined by:

$$E_{sk} = W\ E_{\max} \qquad (30)$$

The skin/core mass ratio (α) is modified by vasoconstriction, and $\dot{V}_{skbf}$ becomes less than 6.3 l/m²-h.

$$\alpha = 0.1 + 0.25\ (6.3 - \dot{V}_{skbf})/6.3 \qquad (31)$$

Shivering is seen in the model as a regulatory response to cold signals, the effect being to increase metabolic heat production.

$$M = 58.2 + 19.4\ (\mathrm{Sig})_{sk}-\ (\mathrm{Sig})_{cr}- \qquad (32)$$

Using the model equations, one may simulate the regulation of body temperature by iterative calculation. From the heat balance Equations (8) and (9), at any time t the $\Delta\bar{T}_{sk}$ and ΔT_{cr} are determined from Equations (12) through (15) for each successive interval of 1 min. These new values for $\bar{T}_{sk}$ and T_{cr} are used to calculate new values for $\dot{V}_{skbf}$, $\dot{Q}_{sw}$, E_{rsw}, W_{rsw}, W, E_{sk}, α (if there is vasoconstriction), and a new M if there is shivering, using Equations (16) through (32). These new values are reinserted into Equations (8) and (9) for new heat balances at time $t + \Delta t$. The entire cycle is repeated to derive new values for the other variables.

Successful regulation of body temperature occurs when:

$$S = O = H_{sk} + H_{cr}$$

Model of Man in a Water-Cooled Suit

A different and simpler model [56] has been used to develop automatic controllers for the cooling required from a water-cooled garment worn by a man exercising in the thermally isolated state. The problem involved here was simpler because it was assumed that with proper control, the man would need minimal regulatory responses internally in order to dissipate the varying levels of metabolic heat produced during various levels of work. In this model there were only three anatomical compartments: the skin, the core, and the skeletal muscle. Equations were written for heat production in each compartment and heat flows between compartments and to the water-cooled garment. Predictions could be made for temperatures in the various compartments and for the course of heat removal required from the water-cooled garment. One useful equation described the transfer function between heat production and the cooling required to maintain the man in comfort—that is, a man who was virtually sweat-free and who could dissipate metabolic heat at minimal physiologic cost.

At equilibrium during rest, compartment temperatures do not change, and heat production equals heat loss:

$$M = M_{re} + M_m + M_s = H + L \qquad (33)$$

where M_{re}, M_m, and M_s are heat productions in the core, muscle, and skin compartments respectively; H is heat removed by the water-cooling garment; and L represents the small losses of heat elsewhere than to the suit.

In about an hour, after the man starts to work, a new equilibrium between heat production and heat loss is reached, with new steady-state values for compartment temperatures:

$$M = \Delta M + M_{re} + M_m + M_s = H + L + W \qquad (34)$$

where ΔM is the added heat production from working and W is external work done.

The instantaneous heat content, Q, of each body compartment may be written as:

$$Q_m = m_m c_m T_m \qquad (35)$$

$$Q_{re} = m_{re} c_{re} T_{re} \qquad (36)$$

$$Q_s = m_s c_s T_s \qquad (37)$$

where m is mass, c is specific heat, and T is absolute temperature.

During the transition from rest to work, and from work to rest, compartment temperatures change according to the general equation for change in heat content:

$$\Delta Q(t) = H(t) = mc \int_{t_1}^{t_2} T(t)dt \qquad (38)$$

Heat flow between any two compartments is defined by:

$$H = h(T_2 - T_1) \qquad (39)$$

where h is a heat transfer coefficient.

An expression may now be written for temperature changes in the muscle compartment:

$$C_m\dot{T}_m = \Delta M + M_m - W - h_{m-re}(T_m - T_{re}) - h_{m-s}(T_m - \bar{T}_s) - L_m \qquad (40)$$

where

$$C_m\dot{T}_m = m_m c_m \int_{T_1}^{T_2} dT,$$

and $\bar{T}_s$ is mean skin temperature.

Similarly, in the rectal compartment:

$$C_{re}\dot{T}_{re} = M_{re} + h_{m-re}(T_m - T_{re}) - h_{re-s}(T_{re} - \bar{T}_s) - L_{re} \qquad (41)$$

And in the skin compartment:

$$C_s\dot{T}_s = M_s + h_{m-s}(T_m - \bar{T}_s) + h_{re-s}(T_{re} - \bar{T}_s) - h_{s-w}(\bar{T}_s - T_{wi}) \qquad (42)$$

where T_{wi} is the temperature of the water entering the water-cooled garment.

No loss term is shown for the skin, since it was assumed that all heat from the skin went into the water-cooled garment. Respiratory heat loss was assigned to L_{re}.

Heat flow from the skin to the water in the cooling garment is determined by a transfer coefficient, h_{s-w}, and the temperature gradient:

$$H_{s-w} = h_{s-w}(\bar{T}_s - T_{wi}) \qquad (43)$$

The water-cooled garment was treated as having no mass and no losses, hence $H_{s-w} = H$, which can be measured experimentally from change in water temperature across the cooling garment multiplied by the mass flow rate and specific heat of the water.

Finally, the model included an equation for generating T_{wi} from M. Inspection of the data had shown that for step increases in M the manually controlled T_{wi} had changed exponentially, with a new level being achieved in about 50 min. Since T_{wi} appeared to be proportional to M, one can write:

$$\Delta T_{wi} = T_{wi}(0) - T_{wi}(t) \qquad (44)$$

where $T_{wi}(0)$ is an initial inlet temperature, and $T_{wi}(t)$ is the inlet temperature at time t.

Using the empirically observed proportionality between M and T_{wi}:

$$(M_0 - M) \approx T_{wi} \qquad (45)$$

or, adding a proportionality constant, B,

$$B(M_0 - M) = T_{wi} \qquad (46)$$

The exponential change in T_{wi} can be written as:

$$T_{wi}(t) = T_{wi}(0)e^{\frac{-t}{\tau}} + B(M_0 - M) \qquad (47)$$

or, rearranging terms:

$$\tau\dot{T}_{wi} = -T_{wi} + B(M_0 - M) \qquad (48)$$

Equation (48) is the equation defining the function of an automatic controller; it was given earlier as Equation (5).

The terms used in the model Equations (40), (41), (42), and (48) were given the numerical values shown in Table 5.

These biothermal models help to summarize what has been useful in the area of human thermal response in the space environment. As more information about human heat production and thermal tolerance is gathered, such models can be further refined and expanded. As new thermal problems arise or as new protective equipment and life-support systems are developed, models of this sort will continue to be helpful both in design of equipment and in monitoring the use of equipment and the state of the astronaut during flight.

TABLE 5.—*Values for Terms in the Model Equations*

B	1.95	°C-min/kcal
C_m	18	kcal/°C
C_{re}	40	kcal/°C
C_s	3.2	kcal/°C
h_{m-re}	5.0	kcal/min-°C
h_{m-s}	0.3	kcal/min-°C
h_{re-s}	0.3–0.6 (generated)	kcal/min-°C
h_{s-w}	0.5	kcal/min-°C
L_m	0.07	kcal/min
L_{re} (at $M=5$)	0.15	kcal/min
(at $M=10$)	0.22	kcal/min
M_0	20	kcal/min
τ (for T_{wi})	10	min

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