Chapter 5

EFFECTS OF TEMPERATURE

Adequate protection of aircrews against the effects of temperature related to climate, the characteristics of the earth's atmosphere, and air friction of supersonic flight require a working knowledge of the meteorological, engineering, and aeromedical background of the problem.

The following are important considerations:

a. Temperature ranges of climate, atmosphere, and supersonic air friction.

b. Physiological accommodation to temperature variation within the range of tolerance.

c. Pathological reactions to temperature extremes.

d. Protection against the effects of temperature extremes.

e. Treatment of injuries resulting from temperature extremes.

AFP 160–4–1 provides Medical Service officers the information essential to the development of a preventive program to control the adverse effects of high temperature, and a guide to diagnosis and treatment.

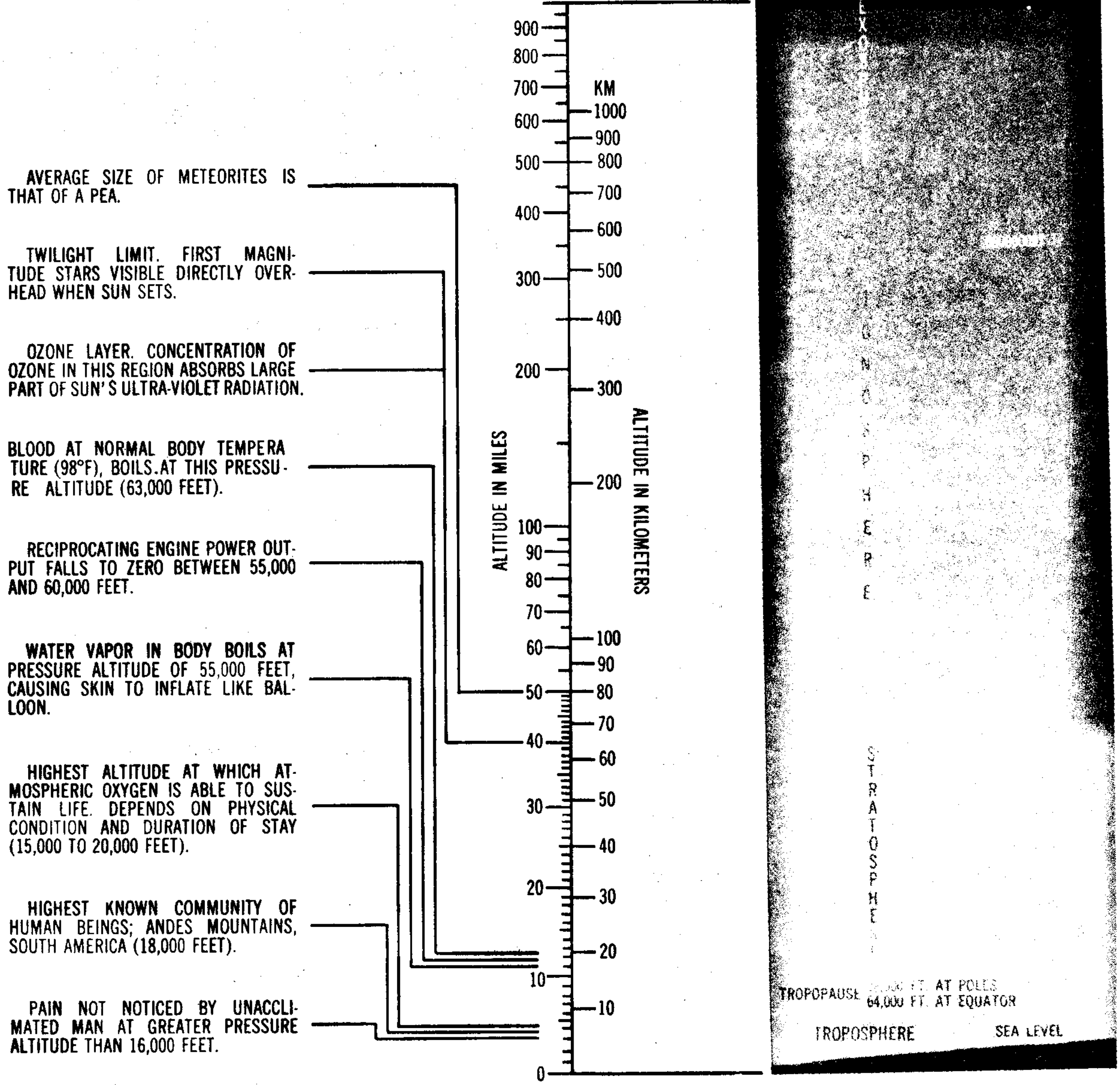
CLIMATE AND THE EARTH'S ATMOSPHERE

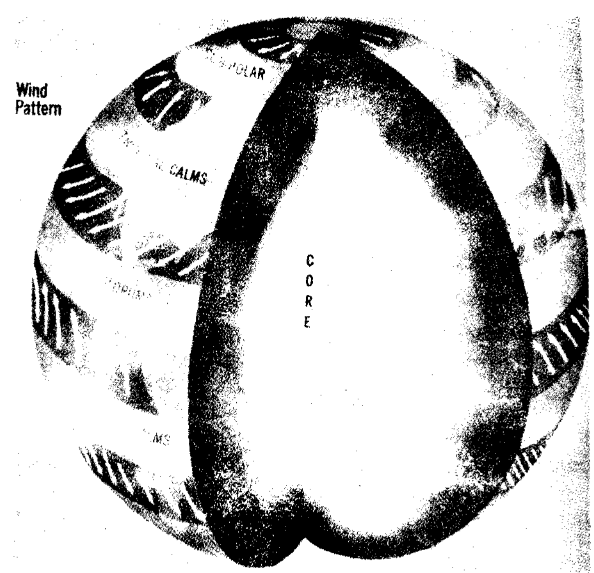
The extremes of geographic and seasonal temperatures encountered at the earth's surface range from $-90°$ F to $+140°$ F. This comprises a horizontal distribution of temperatures, subject to comparatively limited and gradual changes, with geographically distributed annual cycles. The extremes of this distribution are separated by the distance from the equator to the poles.

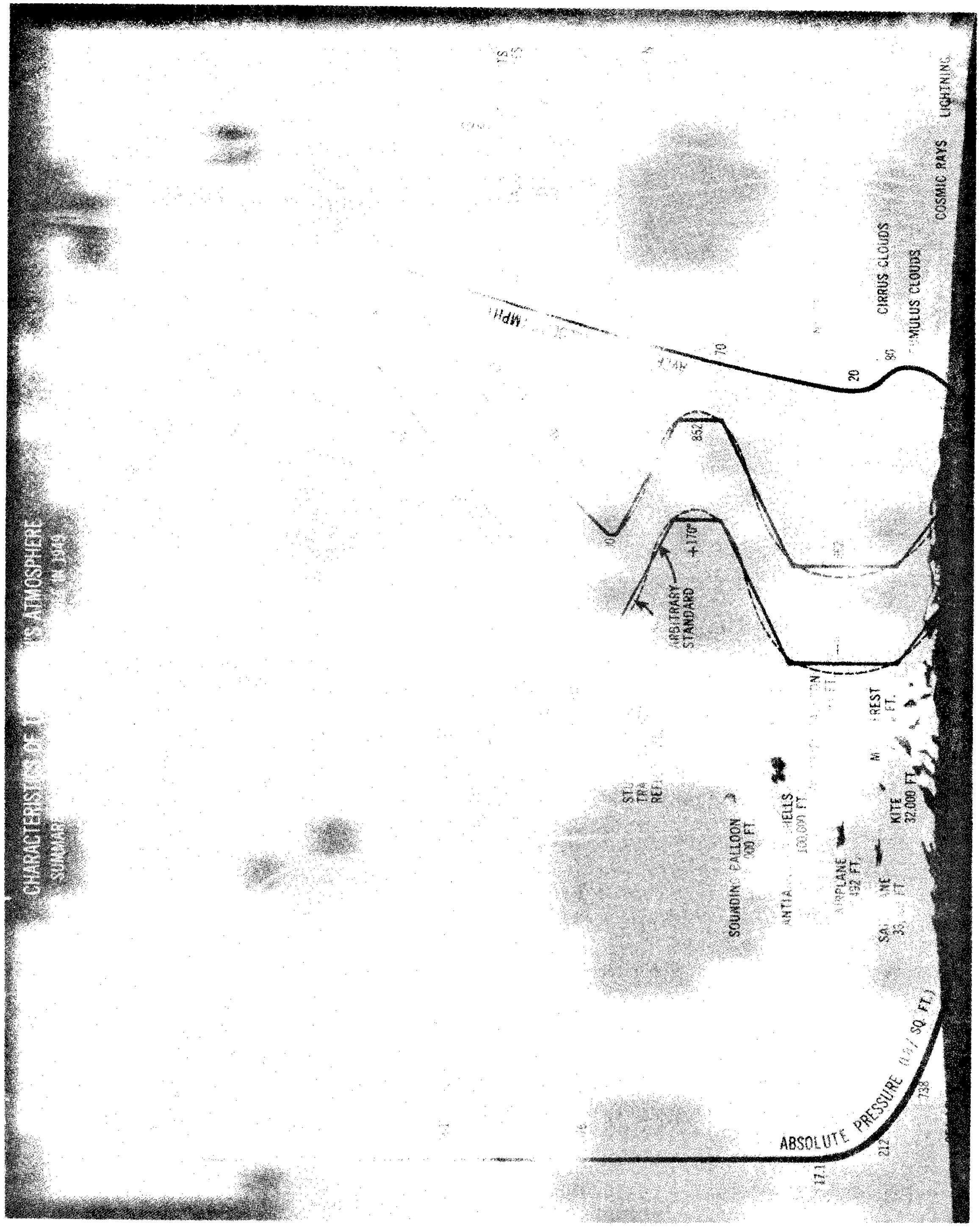
In contrast, the earth's atmosphere has a vertical distribution of temperatures in which the extremes are encountered within 50 miles above the earth's surface, and which are comparatively stable except in its lowest layer. The earth's atmosphere is divided into concentric shells. These are defined and described in the following paragraphs, beginning with the innermost shell.

The region of the atmosphere from 0 to 10 km (6.2 mi), where the temperature falls rapidly with increase of altitude, has long been called the *troposphere,* and the region from about 10 to 20 km (33,000 to 66,000 ft), where the temperature is approximately constant, is called the *stratosphere.* The *ionosphere* has its own well-accepted nomenclature, the terms D, E, F_1, and F_2 designating the four ionized regions with maxima of ionization at about 70, 100, 200, and 300 km (43.5, 62.1, 124.3, 186.4 mi), respectively. Aside from these, there is no generally accepted terminology of upper atmospheric regions.

The terms "upper" and "outer" atmosphere are used with different meanings depending on the context, and it is best to keep their meanings fairly elastic. The region from about 20 to 35 km (12.4 to 21.7 mi) which embraces most of the ozone has been called the *ozone layer* or *ozonosphere.* It has been proposed that the region from the top of the stratosphere, at about 20 km (12.4 mi), to the minimum of temperature, at about 70 km (43.5 mi), be called the *mesosphere*—and the region of increasing temperature, somewhere about 100 km (62.1 mi), the *thermosphere.* The *exosphere* has been used to refer to the outer fringe of the atmosphere, where the air particles execute long elliptical orbits bouncing outward from impacts with other particles and falling back under gravity. In general, the physical properties of the various regions are not yet well enough known to permit their fixation by an accepted terminology.


MI
KM
ALTITUDE IN MILES
ALTITUDE IN KILOMETERS
AVERAGE SIZE OF METEORITES IS THAT OF A PEA.
TWILIGHT LIMIT. FIRST MAGNITUDE STARS VISIBLE DIRECTLY OVERHEAD WHEN SUN SETS.
OZONE LAYER. CONCENTRATION OF OZONE IN THIS REGION ABSORBS LARGE PART OF SUN'S ULTRA-VIOLET RADIATION.
BLOOD AT NORMAL BODY TEMPERATURE (98°F), BOILS AT THIS PRESSURE ALTITUDE (63,000 FEET).
RECIPROCATING ENGINE POWER OUTPUT FALLS TO ZERO BETWEEN 55,000 AND 60,000 FEET.
WATER VAPOR IN BODY BOILS AT PRESSURE ALTITUDE OF 55,000 FEET, CAUSING SKIN TO INFLATE LIKE BALLOON.
HIGHEST ALTITUDE AT WHICH ATMOSPHERIC OXYGEN IS ABLE TO SUSTAIN LIFE. DEPENDS ON PHYSICAL CONDITION AND DURATION OF STAY (15,000 TO 20,000 FEET).
HIGHEST KNOWN COMMUNITY OF HUMAN BEINGS; ANDES MOUNTAINS, SOUTH AMERICA (18,000 FEET).
PAIN NOT NOTICED BY UNACCLIMATED MAN AT GREATER PRESSURE ALTITUDE THAN 16,000 FEET.
STRATOSPHE
TROPOPAUSE
FT. AT POLES
64,000 FT. AT EQUATOR
TROPOSPHERE
SEA LEVEL


Wind Pattern
POLAR
CALMS
CORE



EARTH'S STRUCTURE

The earth's interior, like its exterior environment, is presently defined as consisting of several concentric layers of material. The earth's crust is believed to have solidified between 2 and 3 billion years ago. The crust, which is called the continental layer, is approximately 30 miles thick, and is the only solid layer. The second layer is called the mantle, and extends to a distance of about 1200 miles below the earth's crust. The central core is estimated to be about 5500 miles in diameter. The temperatures and pressures which exist within the earth are many times those which exist in the atmosphere. It has been estimated that the temperature and pressure at the center of the earth's core are 3500 to 5500 degrees Fahrenheit and 3½ million times the pressure at the earth's surface, respectively. These extreme pressures cause the density of the earth's core to be increased to four or five times the average density of the crust.

The boundary between the troposphere and the stratosphere is called the *tropopause.* It is closest to the earth at the poles (approximately 6 miles) and farthest away at the equator (approximately 10 miles).

The troposphere is characterized by a constant rate of decrease in air temperature as the height above the earth increases, by turbulent air, and by the varying amounts of moisture content. All weather phenomena occur in the troposphere, for they are inherently associated with the physical properties of temperature gradient and moisture content.

Winds have been observed up to nearly 30 km (18.6 mi) altitude with sounding balloons. Average monthly data at sunset near Omaha, Nebraska, showed that the wind velocity increased with altitude from about 10 statute miles per hour at the surface to about 60 mph at 12 km (39,000 ft) where the stratosphere began. As the altitude increased to 20 km (65,000 ft), the wind velocity decreased to 20 mph and then increased to 35 mph at 28 km (92,000 ft). By means of smoke shells exploded at 30 km (18.6 mi) it was found that the average summer and winter velocities were 27 and 83 mph respectively. A maximum value of 147 mph was recorded in the winter.

The temperature ranges encountered in the various layers of the upper atmosphere are shown in the accompanying chart.

Radiant energy from the sun is absorbed at the earth's surface, except for that which is absorbed by clouds. The heating and cooling of the earth's surface is dependent on the duration and intensity of exposure to solar radiation.

All temperature phenomena in the atmosphere are caused by the presence of water vapor and by its absorption of long-wave radiation from the earth. Near the earth's surface, a body of air absorbs, by radiation from the earth, more heat than it can lose by reradiation to other bodies of air and the heavens. When the temperature of a body of air increases, the air rises. As it ascends, it expands because of decreasing atmospheric pressure. With expansion, the rising body of air cools, precipitating part of its moisture in the form of clouds. Hence, its absorption of heat by radiation from the earth decreases.

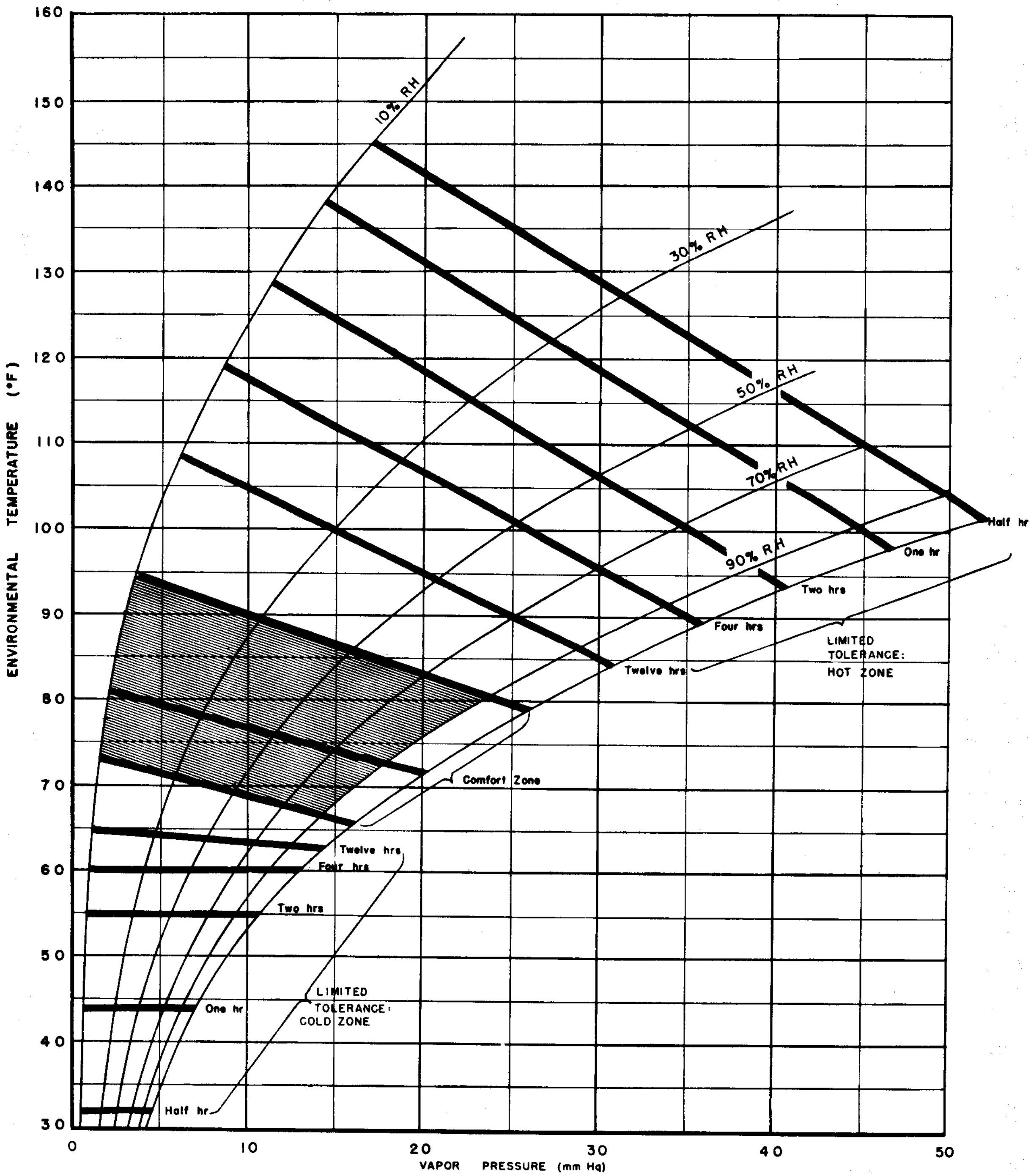
By repeated cycles of these physical phenomena, which are commonly known as "weather," relatively constant stratospheric temperatures of approximately —55° C are maintained. The water content of air in the stratosphere is so low that a balance exists between the absorption of radiation from the earth and reradiation to the heavens, resulting in a region of comparatively constant temperature.

Stratospheric temperature varies with latitude, being lowest over the equator at —80° C (—112° F), and highest over the poles at —40° C (—60° F). Temperature reversals may occur above the equator in the upper levels of the stratosphere. Reversal temperatures of +170° F are encounterd in the transition from stratosphere to ionosphere.

Inversions of temperature have been observed near the earth's surface. *For example,* at the polar regions this inversion is very pronounced. At Ladd AFB, Alaska, ground temperatures of —40° C or —45° C are not uncommon in the winter, while at the same time, at 8,000 feet, temperatures as high as —5° C may exist. Extreme cold (that is, less than —40° C) is usually encountered either on the ground or in the stratosphere, but practically never at 10,000 feet, regardless of latitude.

AIRCRAFT CLIMATES

Modern military aircraft have very efficient cabin and cockpit air-conditioning systems. Adequate ventilation, heating, and cooling are maintained as required by the aircrew members. Adjustment of automatic controls is usually the only requirement for the maintenance of a satisfactory climatic environment. This is true with such aircraft as the F-86, F-89, F-94, Century-Series Fighters, and the B-47, B-52, B-58, and other jet aircraft. Problems do arise, however, as a result of mechanical failure of accessory equipment—usually the air expansion turbines used for cabin refrigeration. Under



Sitting man dressed in conventional clothing (1 clo) doing light manual work.
Air motion equals 200 fpm.

(See MR No. TSEAL-3-695-56)

Figure 5–1. Thermal Requirements for Tolerance and Comfort in Aircraft Cabins.

these circumstances, very high cockpit temperatures may be produced which are quite intolerable for long periods of time. The thermal requirements for human tolerance and comfort in aircraft cabins for temperature range +30° F to 160° F are presented in figure 5-1.

Extreme heat due to solar radiation is encountered in aircraft standing on the ground and in fighter craft at low and moderate altitudes (up to 10,000 feet). In parked aircraft, internal air temperatures may reach 15° to 20° C higher than outside temperature because the hot metal of the fuselage heats the impounded cabin air. Plexiglas canopies create a "greenhouse" effect in planes parked or flying under solar radiation. This effect is due to inward transmission of visible and near-infrared radiation, thus heating the occupant and the walls of the cabin, which in turn reradiate far-infrared waves. However, since plexiglas has a low transmission for long infrared, radiant energy is "trapped" with a resulting increase in temperature.

The advent of high-performance aircraft, flying at speeds in and beyond the sonic range, has raised a further potential hazard in respect to heat loads on the cockpit enclosure. Heating of the cabin by compression of the atmosphere surrounding the aircraft and by skin friction can reach 800° F at 1,150 miles per hour near sea level. Protection from this heat is afforded by refrigeration cooling devices. The rapid rise of air and wall temperatures which would result in the event of failure of the refrigerated air-conditioning has been simulated in laboratory experiments. The results of these are summarized in figure 5-2. It shows the length of time healthy young men can tolerate the various levels of heat, the tolerance limit being the attainment of a physiological state close to fainting. In addition, preliminary results of experiments investigating the ability to perform flying tasks are shown, indicating the earliest point in heat exposure at which such performance was observed to start deteriorating, in a study of four experienced pilots at three temperatures.

REGULATION OF BODY TEMPERATURE

In common with other mammals, man possesses a delicate homeothermic mechanism that responds to the physical processes of heat transfer to maintain body temperature of 37° C.

Physical Processes

Conduction. This is the transfer of heat through a solid, liquid, or gas from one molecule to another at a rate depending upon the specific thermal conductivity of the material and the temperature gradient between the two points under consideration. The heat exchange between man and his environment by conduction is ordinarily small.

Convection. Natural or gravity convection is the process by which a liquid or gas, coming into contact with a source of heat, is heated, expands, and rises as it is displaced by the heavier, cooler liquid or gas that surrounds it. Prevailing winds or mechanical ventilation produce "forced" convection. Convection losses from the body are increased by low temperature, wind, and movement of the body.

Radiation. This is the transfer of heat by radiant energy through space in the direction of diminishing temperature gradient between two bodies. The human body receives heat by radiation from objects in the environment that are hotter than the body, notably the sun, and loses heat by radiation to the environment when the latter is cooler than the body. Radiation transfers are proportional to the size of the temperature gradient and body area exposed.

The sum of radiated and convected transfers, either from the body to the environment or vice versa, is related to the total temperature gradient (Newton's law of cooling). For a practical grasp of most cooling and heat-load problems, it is convenient to consider them together.

Evaporation. The body is enabled to lose heat by the process of vaporization of water from the surface and from the respiratory mucosa. Such transfer of heat derives from the fact that, in the transformation of water into vapor, heat is taken up from surrounding materials. At usual skin temperatures, the value of 0.58 kilocalories per gram of water vaporized is commonly accepted.

Stored Heat. Because of its large capacity, the body is further able to withstand cooling and heating stresses with a minimum shift in temperature. About 66 kilocalories of heat is transferred when the body cools or heats 1° C. Critical hypothermia or hyperthermia results when change in storage reaches approximately 180 kilocalories in the average man, but at lesser transfers, storage may be considered as an adaptive mechanism.

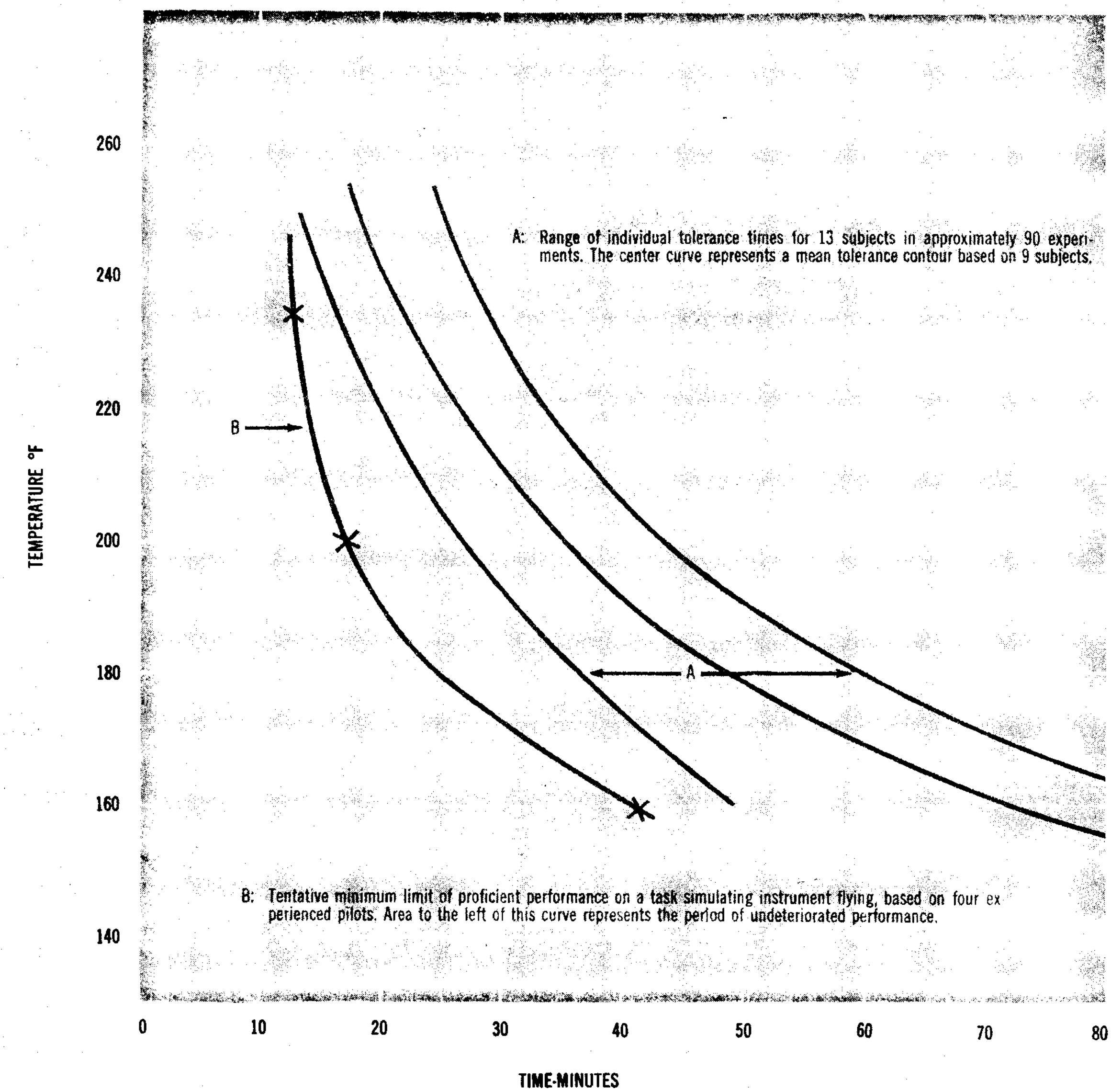


Figure 5-2. Limits of Tolerance and Performance Proficiency at Extreme Temperatures.

Ordinate values represent average air temperature, assuming wall temperatures approximately equal to that of the air and a constant humidity of 0.8 inches mercury vapor pressure (20mm Hg). This humidity level is equivalent to a relative humidity of 80% at 79° F or 41.5% at 100° F.

If the absolute humidity were lower than the above value, all contours would move to the right, and vice versa.

Physiological Processes

Vascular. Alteration in peripheral circulation constitutes one of the most important phases of regulation. Effective flushing of skin is accomplished not only by changes in tone of arterioles, venules, and capillaries, but also by the state of arteriolar-venular anastomoses (Sucquet-Hoyer canals), which are most numerous in the extremities. The primary importance of the sympathetic nervous system in this type of vasomotor activity is well established. Afferent impulses that alter vasomotor tone may arise from many sources, including reflexes from the skin (particularly of the extremities) and from brain centers. Vasodilatation, on the other hand, is caused by a local thermal stimulus, although the possibility of a specific vasodilator reflex mechanism is strongly suggested.

Metabolic. Under normal environmental conditions, the basal metabolism is 40 to 50 kilocalories per square meter of body surface per hour, and the processes of physical regulation are adapted to dissipate this amount of heat. At low temperatures, increased muscle tone (thermal tone), involuntary muscular activity (shivering), and voluntary muscular exertion all act to raise the heat production and thus, to restore body temperature. In addition, epinephrine, by virtue of its calorigenic effect, may be a significant factor in regulating body temperature. A small increase in metabolism during hyperthermia has been consistently found in man and experimental animals; it is attributed to acceleration of many of the chemical processes of metabolism.

Respiratory. Similar to metabolism, the respiration is augmented at temperatures both above and below the neutral temperature zone. At low temperature, ventilation increases, in part, as a result of heightened metabolism and reflex effects of the cold. At high temperatures, a deepening of the respiration, often associated with a sensation of air hunger, is a sign that the limit of tolerance is being approached. Usually the rate of breathing is not altered.

Secretory. Although insensible water losses occur at all temperatures, thermal sweating begins at a skin temperature of 33° C and increases in proportion to heat load. Sweat losses may amount to 2 to 3 liters per hour in strong subjects working in the heat. Temperature of the blood is considered to be the most important stimulus, but sweating may begin before a rise in body temperature occurs.

Zones of Thermal Regulation

Zone of Body Cooling (24° C and Lower). As the environmental temperature is reduced below the neutral range, and the cooling of wind is added, stored heat is lost, as shown by skin and rectal temperatures. Cutaneous vasoconstrictor activity is no longer adequate and, with cooling of the blood and skin surfaces, muscular hypertonus and shivering occur. At still lower temperatures, these trends reach their extremes, resulting in a pale and constricted skin ("goose flesh") and heavy shivering, which may elevate metabolism to three times the basal rate. Though final breakdown of thermal control depends upon the degree of physical activity, amount of clothing, and duration of exposure, three eventualities may occur:

a. If activity is restricted, the extremities, notably toes and fingers, approach freezing temperatures most rapidly, followed by depression of general body temperature. This type occurs most frequently in aircrew members.

b. If the individual is physically active, cooling develops with fatigue, and as exhaustion approaches, the vasoconstrictor mechanism is overpowered, sudden vasodilatation occurs with resultant rapid loss of heat, and critical cooling ensues. This is most frequent in arctic or cold-weather expeditions.

c. A third type is represented by "immersion foot" or "trench foot." Here, pathological effects are caused by continued exposure to cold without freezing. The prolonged vasoconstriction interferes with the nutrition of the skin and results in accumulation of catabolites. Subsequent warming results in extreme reactive hyperemia with edema.

Zone of Vasomotor Regulation (25° to 29°

C). In this temperature range, characterized by sensations of thermal comfort, the processes of heat production and loss are so poised that variations in cutaneous vasoconstrictor tone are adequate to maintain thermal balance. Essentially, the skin serves as a variable insulator. With cutaneous vasoconstriction, skin temperature is lowered and heat losses caused by convection and radiation diminish, but vasodilatation elevates skin temperature and increases these losses. Changes in stored heat and metabolism are small in this zone.

Zone of Evaporative Regulation (29° C and Higher). The primary defense against hyperthermia is provided by evaporation of water from the surfaces of the skin and from the mucosa of the respiratory tract. Secretion of sweat is the active physiological process, accounting for most of the water available for evaporation. When environmental temperatures are higher than skin temperatures, and especially on exposure to intense solar radiation, the evaporation may be inadequate to balance the gain by radiation and convection; hyperthermia, characterized by a rising body temperature and accelerated pulse, supervenes. A slight increase of metabolism is caused by the thermal stimulus—the greatest effect is flushed skin resulting from maximal vasodilatation. The consequences of failure of heat adaptation may take different forms depending on type and duration of exposure and on the state of acclimatization of the individual:

a. "Heat exhaustion" or "heat prostration" results from an inadequacy of the circulatory system to meet the demands for heat regulation imposed by high environmental temperature and humidity. Contributory causes in healthy individuals include disturbances of fluid balance such as result from salt depletion.

b. "Heat cramps" in the skeletal muscles are caused by excessive loss of sodium chloride in the sweat. This condition occurs typically in persons who undergo heavy exertion in the heat.

c. "Heat stroke" (sometimes called "sunstroke" when observed in open areas where solar radiation is excessive) occurs when the heat-dissipating mechanism fails, allowing the internal body temperature to rise to danger levels.

Physiological Climate Stresses

Except in very special circumstances, which are seldom of practical importance, environmental temperature is properly represented by the air temperature. This obviously varies with season, climate, and weather, but its standard relationship to altitude is of most interest to the Flight Surgeon.

Cooling Stress—Low Temperature. In general, cooling stress is proportional to the total gradient between the skin and the environmental temperature. This determines the rate of heat loss from the body by radiation and convection.

Wind exerts a cooling effect upon an object warmer than its environment, as in the case of the human body exposed to cold. The magnitude of this cooling is represented in figure 5–3 which gives curves of relationship between the percentage increase in the calorie demand (the total gradient between the skin and air temperatures) and wind velocity for various amounts of clothing (expressed in *clo*). On bare skin, the cooling effect of wind acts in this instance to blow away the insulation afforded by layers of warm air at the skin surface, increasing markedly with velocity. With very heavy clothing (4 clo) the maximum cooling effect of wind is relatively small. Cooling stress is, therefore, proportional to the cooling gradient, and the added effect of wind is obtained by use of the appropriate curve in the figure, when wind velocity and the amount of clothing worn are known.

Heat Load—High Temperature. The heat load (heating stress) of the atmosphere is also proportional to the temperature gradient between the body surface and the environment, but the relationship here is the opposite of that which causes cooling, the body gaining heat by radiation and convection. There are two important additional factors: the effect of humidity on evaporative loss and the added heat gain from solar radiation.

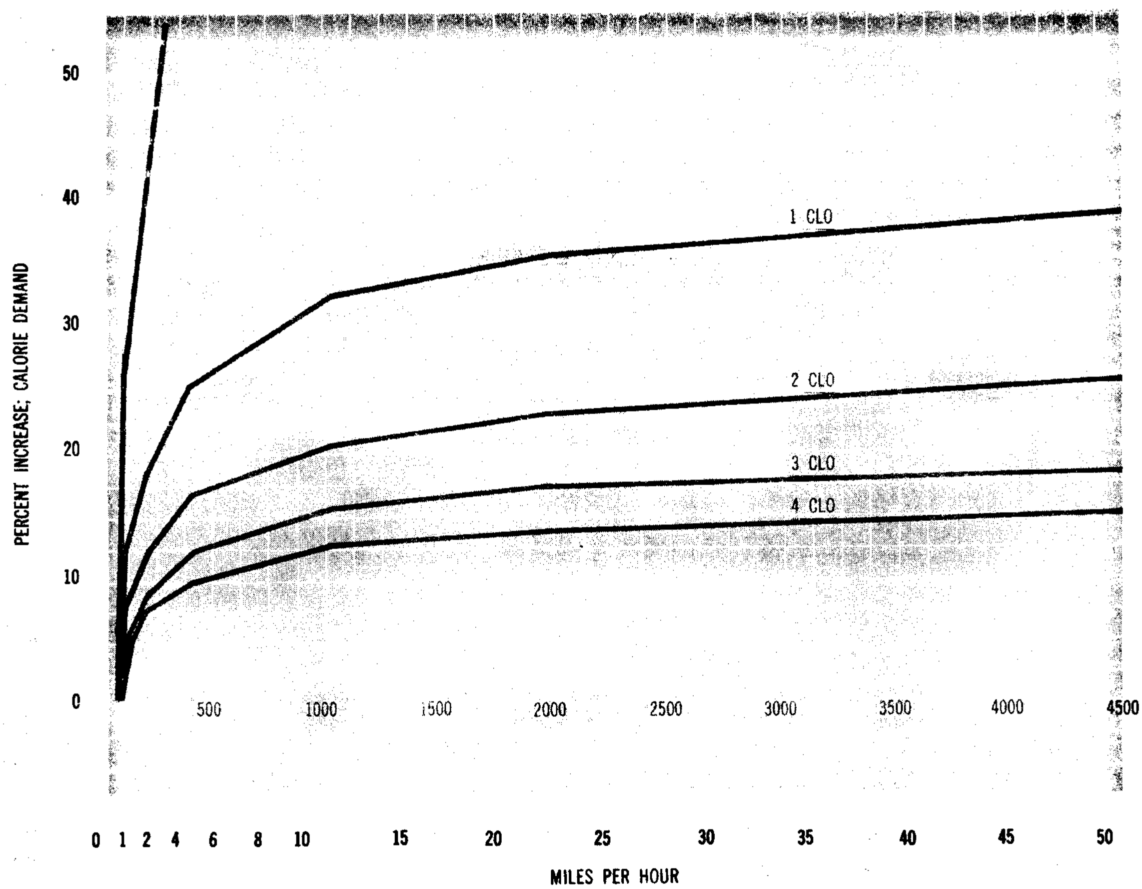


Figure 5–3. The Cooling Power of Air According to Velocity and Amount of Clothing Worn.

The temperature-humidity effect can best be assessed in terms of physiological tolerance. See figure 5–4 for tolerance limits for clothed, sitting subjects. It is noted that, in general, a much higher temperature can be tolerated when the humidity is low (desert conditions) and that the tolerable temperature is lowered as high humidity is approached (jungle conditions). Line AA gives comfort limits. Lines BB and CC show limits at two levels of physiological adjustment: BB gives the boundaries of evaporative cooling without hyperthermia, while CC assumes more stringent conditions in which approximately 50% of the total adaptive capacity of the acclimatized individual is utilized in a 2-hour exposure. With shorter exposures, of course, more extreme temperature-humidity conditions may be tolerated, as shown by lines DD and EE.

Outdoor exposures in hot climates usually involve additional heat load from incident solar radiation, which has been calculated to be 240 kilocalories per hour or two to three times the resting metabolism. Such a heat load can be tolerated when the humidity is low; however, it is of practical interest to note that high humidities, solar radiations, and air temperatures do not occur simultaneously in any known climate on the earth. Generally speaking, all hot climates are tolerable for the suitably acclimatized man, except for occasional very temporary occurrences of intolerable extremes of these conditions.

The Acclimatization Processes

Acclimatization to Cold. Changes in thermal sensation are an outstanding accompaniment of long-term exposure to cold. In the temperature zones, all persons experience

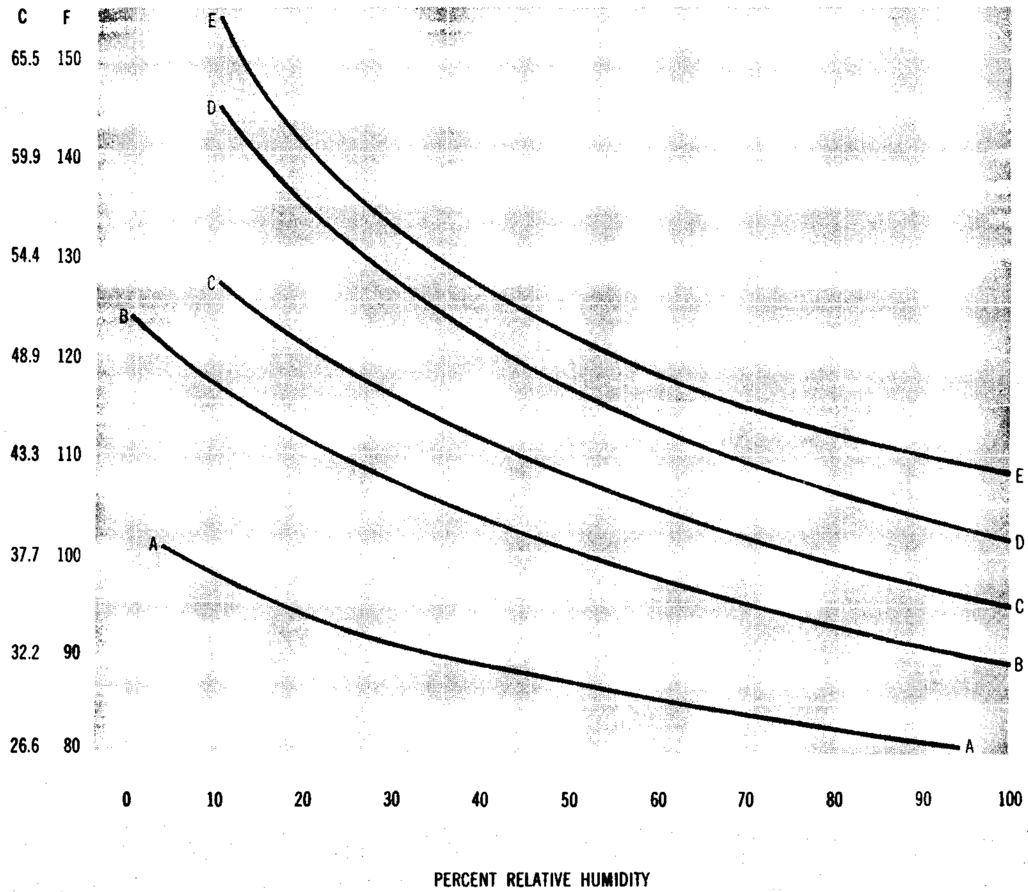


Figure 5–4. Relationship of Temperature—Humidity Effect.

The limiting environments of temperature and humidity for human tolerance, employing criteria which range from easy to difficult: AA, the upper limits of summer comfort zone; BB, the limits of evaporative cooling, with little or no rise in body temperature; CC, the limits of compensated hyperthemia; DD, 60-minute tolerance limit; and EE, 30-minute tolerance limit. (Winslow, Herrington and Gagge; Robinson, Turrell and Gerking.)

this type of adaptation to some degree during the winter season. Authorities disagree on the extent and duration of changes in metabolism with human acclimatization, but the metabolism of rats is increased by long exposure to cold if the adrenals are intact. Other studies emphasize the role of the thyroid gland in maintaining a higher metabolism under these conditions. Higher protein diets prevail in cold climates, and the specific dynamic action of this food element elevates metabolism. Whatever the nature of the psychological and physiological changes entailed and the extent of individual variation, acclimatization to cold is a matter of common observation.

Acclimatization to Heat. The major changes occur within a week and are chiefly cardiovascular in nature. During this period, the circulation adapts itself to the greatly increased cutaneous blood flow necessitated by the demands of heat dissipation. Heat stroke is prone to occur if exposure and activity are extreme, but its incidence is reduced as adaptation is achieved. Internal and skin temperatures, which increase abnormally in the heat, assume more normal values with acclimatization. The pulse rate also becomes stable with acclimatization.

Later adaptations include increased loss of sweat, more dilute sweat and, according to some authorities, increased plasma volume. Apathy, lack of desire to exert oneself, anorexia, and many other symptoms of maladaptation, which occur on initial exposure, become moderate or disappear entirely with acclimatization. In general, there are no qualitative differences between acclimatization to hot-dry and hot-humid conditions, and cross-acclimatization is effective. Gradations in exposure and activity in the heat are recommended to ease the transition from the unacclimatized to the acclimatized state.

PROTECTIVE CLOTHING

Thermal Insulation. The insulation of the body against cold may be measured in *clo* units. The *clo* is defined as that amount of insulation which will maintain normal skin temperatures when heat production is 50 kilocalories per sq.m. per hour, air temperature is 70° F, and air movement is 20 ft. per min. It corresponds roughly to the clothing worn by men in a temperate zone during the warm part of the year. It has the insulating value of a cloth approximately 0.42 cm thick.

The relationship between clothing (in *clo* units) required for various environmental temperatures is shown in figure 5–5. Two facts stand out:

a. The thermal insulation of the clothing determines the temperature that can be withstood in comparative comfort for a 6-hour period or longer, but for shorter exposures protection is afforded to much lower temperatures.

b. The limit of insulation with clothing is placed at 4 *clo* because such clothing is about 1-inch thick, which is the practical limit of permissible bulk and weight.

Windproofness. If wind penetrates the surface of clothing or enters openings at the neck, waist, sleeve, or trouser cuff, as much as 30% of the insulation intrinsic in the garment may be lost through forced convection of the entrapped air. Windproofness of the surface clothing depends upon tough, close-woven shell materials of long staple cotton. Adequate closures should be provided.

Thermally Adequate Footgear and Handgear. High surface-to-volume ratios and thermosensitive variations of blood flow to the extremities predispose them to rapid and extreme cooling. Practical coverings may seldom exceed 2 *clo* because of physical limitations. This maximum of protection is reached in footgear by the use of adequately large shoes or boots and several pairs of woolen socks. Suitable gloves must afford a compromise between the opposing requirements for insulation and dexterity. The practical solution lies in selecting the thickest glove that will permit necessary manipulative tasks to be performed and in supplementing this with warming mittens, donned when fine dexterity is not required.

Clothing Assemblies

The following lists various clothing assemblies and their temperature ranges:

(1) Extra heavy temp. range:
−22° F to −65° F

(2) Heavy temp. range:
+14° F to −22° F
Both covered by:
(a) Heavy aircrew assembly
(b) Heavy flying assembly

(3) Intermediate temp. range:
+14° F to +50° F
Intermediate flying suit

(4) Light temp. range:
+50° F to +86° F
(a) Light zone flying jacket
(b) Light flying suit

(5) Very light temp. range:
+86° F to +122° F
Very light flying suit
cotton (Byrd cloth)

(6) Ventilated antiexposure suit temperature ranges:
Bailout at −70° F
Cold Water Immersion
Arctic Exposure
Cabin Air/Wall Temperature
+165° F

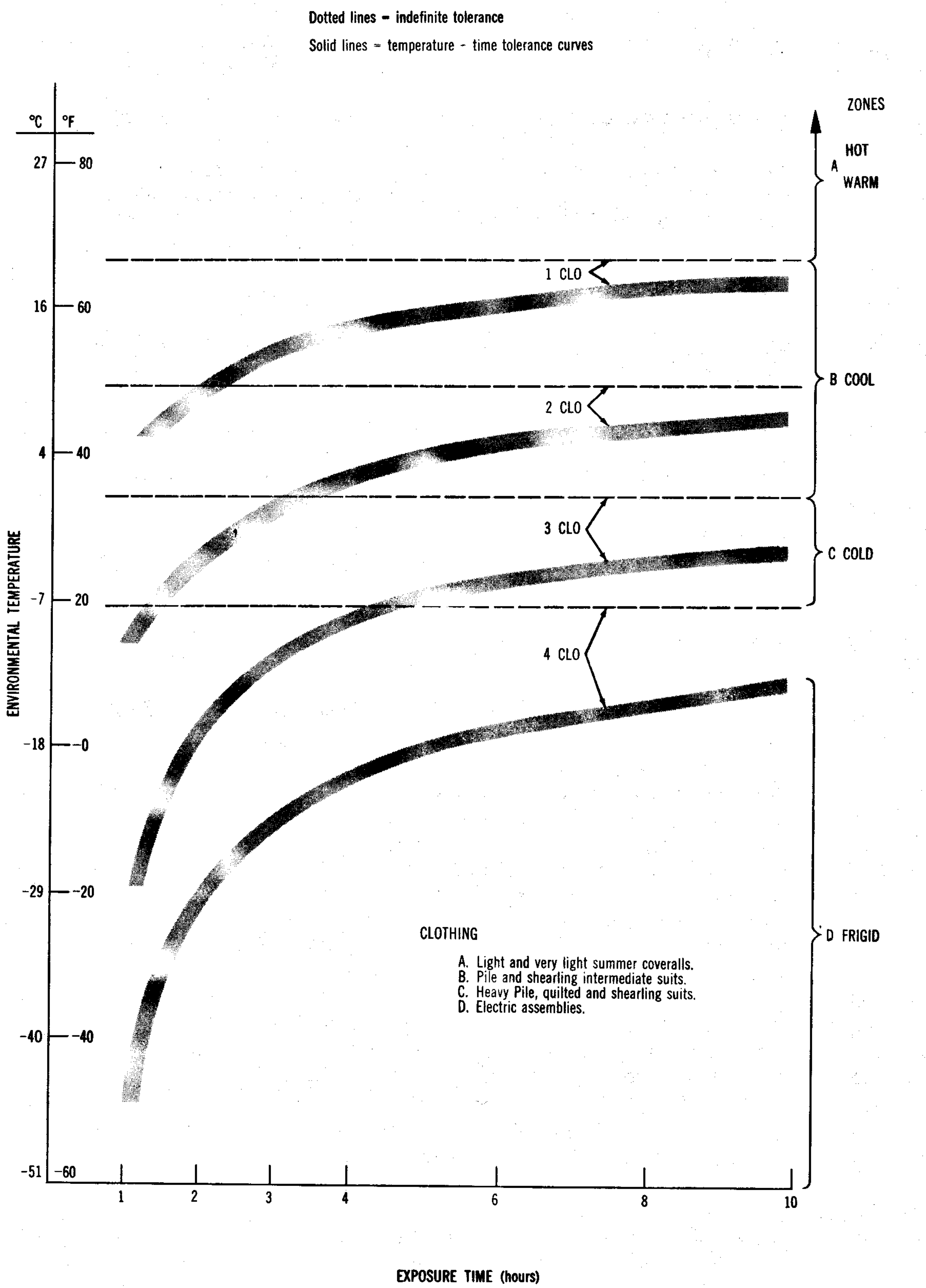


Figure 5–5. Cold Tolerance Curves With Clothing.

This clothing assembly consists of the following items listed in the sequence of donning:

1. Heavy woolen underwear.

2. Anti-G-suit or K2B coverall.

3. One pair of medium weight wool socks.

4. The type MA–2 ventilating garment.

5. The type MD–3A coverall (insulation liner).

6. The type MD–1 antiexposure suit.

For the operation of this clothing assembly, an air source is necessary, capable of delivering up to 13.5 cfm of air against a back pressure of 7″ of water. The temperature range of this ventilating air must extend from 50° to 120° F depending on the thermal situation to be dealt with. The air source can either be the air-conditioning system of the aircraft or a specially developed, small, light-weight blower which is installed into the cockpit and utilizes cockpit air for ventilation.

Warm and Hot Zone Clothing. From 30° C up to the temperature-humidity limits of human tolerance, very lightweight clothing is used. Provided the clothing is permeable to vapor, its effect upon heat tolerance is small. In hot-humid conditions little or no effect of lightweight clothing is found, but in the hot-dry range, and with the additional load of solar radiation, clothing serves to increase heat tolerance, particularly in extremely hot environments where the tolerance duration is short. Here, insulation reduces the inward transfer of heat by radiation and convection, while evaporation loss is little impaired. This furnishes an explanation of the custom among desert peoples of wearing lightweight but flowing garments which keep the head and body well covered.

COLD-WATER IMMERSION

Protection of aircrews against emergency exposure to cold-water immersion has required the development of special survival or antiexposure suits. These suits have been developed chiefly along two lines: (a) Those designed to prevent entrance of water—*i.e.,* the "dry" suit principle; and (b) use of the "wet" suit principle in which no attempt is made to prevent water entry, but protection is provided by sealed insulation (unicellular foam rubber, *for example*) and by restricting circulation of the entering water.

Thermal protection with both types of antiexposure suits and consequent potential rescue time are much extended when the cold-immersed crewmember enters his life raft. Based on presently available experimental and operational data, figures 5–6 through 5–8 are predictive graphs showing human tolerance to cold-water exposure. Figure 5–6 illustrates the predicted tolerance time for the crewmember wearing wet clothing and remaining in the cold water. For convenience, short-time intervals are indicated. In figure 5–7, tolerance time in cold water with both the wet and dry suit is plotted. Figure 5–8 indicates tolerance time for the crewmember within the raft and exposed to various ambient air temperatures. These predictive data are based on the use of a canopy-type (MB-IV) raft. Predicted tolerance times are also based on average physiologic cold response rather than on that of the exceptional or cold-resistant type. Heat production of 75 calories per square meter per hour and a body surface area of 1.8 square meters are also assumed. If rescue is accomplished within the predicted tolerance time, serious injury or fatality should not occur. However, it should be emphasized that individual physiologic variation is extreme in this type of exposure, and this fact should always be kept in mind in rescue operations. The data are based on the assumption that adequate thermal protection of the hands and feet is provided. This, unfortunately, is technically difficult to provide under the more extreme exposure conditions (*i.e.,* air temperatures below 32° F and water temperatures below 40° F).

Local Cold Injury (Including Frostbite)

Exposure of limited body areas to local cold may produce abnormalities which vary from minor functional disturbances to actual gangrene. These various degrees of injury

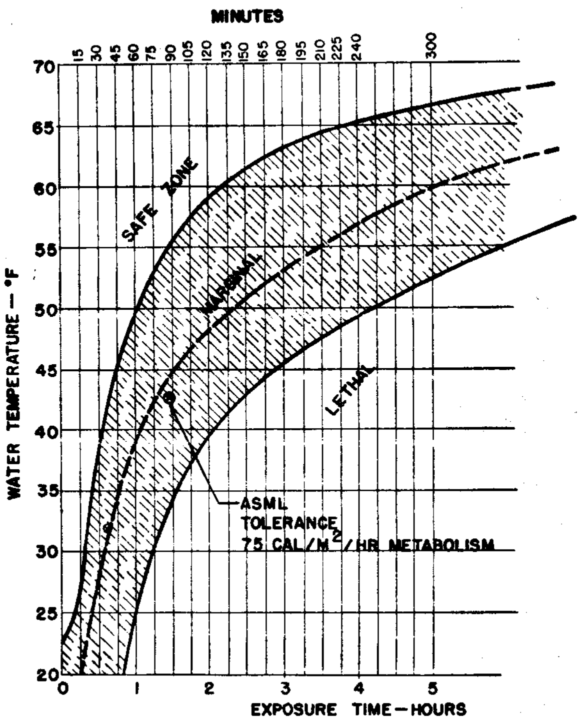


Figure 5–6. Tolerance Time in Cold Water With Wet Clothing.

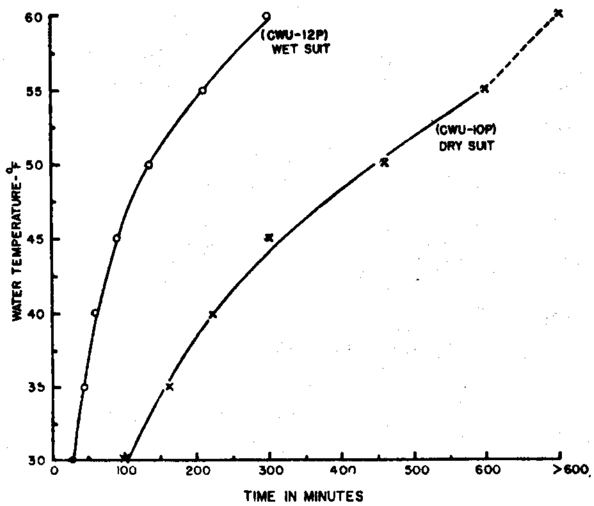


Figure 5–7. Tolerance in Cold-Water Immersion.

may result whether or not the tissues freeze. This emphasizes that the attained tissue temperature is not all-important, but rather the product of temperature and exposure time. This observation classifies the cold stimulus with other physical and chemical agents, the effects of which are represented by the intensity-time curve so well known in physiology and toxicology.

From a pathologic point of view, frostbite, trench foot, immersion foot, and shelter foot are the same. These specific terms merely describe the physical conditions under which the injuries are incurred. The term "local cold injury" should be used to include all such injuries. Even clinically it has been recognized that the symptoms and signs do not differ qualitatively in the so-called various types of local cold injury. Quantitatively, the signs and symptoms will depend on the severity of damage and the amount of tissue involved.

Incidence in the Air Force. From August 1942 to January 1944, 2,008 crew members of the Eighth Air Force were frostbitten on combat missions. During the same time 1,362 men received wounds from enemy gunfire. Ten and one-half days on the average were lost from flying duty by each thermal casualty, and 7% of the men affected were lost permanently. The average loss from frostbite for the entire period was 0.58% of all men dispatched on heavy-bomber missions.

After July 1943, improvement in design, supply, and care of the electrically heated flying equipment resulted in a decline in the frequency with which hands and feet were affected by the cold. During the same period, frostbite of the face, neck, and ears rose proportionately.

From January 1944, the rate of frostbite per thousand man missions steadily declined from 0.50% to reach a low of 0.03% by August. Many factors were contributory, but most important were: reduction in wind blast, particularly in the waist gunner's position in the B-24 and B-17; careful indoctrination of flying personnel by the flight surgeons; and particular care, supervision, and improvements in electrically heated equipment by the personal equipment officers.

Etiology. As stated above, the degree of local cold damage depends primarily on the actual temperature in the tissues and the duration of the exposure. Secondary factors

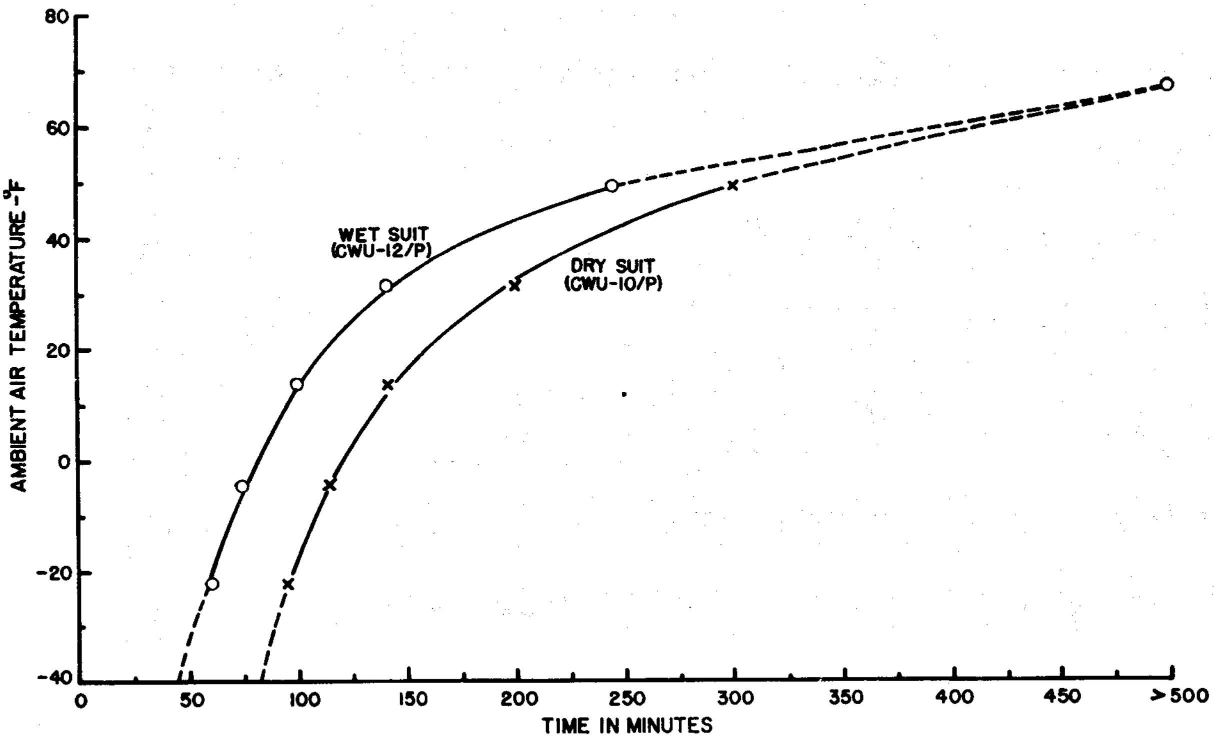


Figure 5-8. Tolerance in Raft Exposures (Following Water Immersion, at 32°F, Not Exceeding 5-Minutes Duration).

which play a part in the development of local cold injury are: wind velocity; contact with substances which alter heat conductivity (metal, moisture, etc.); changes in body temperature; degree of physical activity; and impairment of the circulation by body attitudes, clothing, or equipment.

Physiology and Pathology. When tissues are exposed to severe frostbite *in vivo*, vasoconstriction occurs followed by blanching and solidification. As long as the tissues are maintained in the frozen state, no other demonstrable changes occur, since at these temperatures no measurable metabolism occurs. With thawing, however, another series of events results: a. Hyperemia; b. edema (may produce skin blisters) with or without hemorrhage; c. necrosis; and d. healing.

The vasoconstriction during exposure to cold has a dual origin: direct action of the cold on the vessels and reflex nerve action. Lewis and Love theorized that the remarkable vascular events seen after thawing are set in motion by the action of a histamine-like substance from the tissue cells injured by freezing. Such a substance has not been demonstrated. The vasodilatation accompanying thawing may be due to paresis or paralysis of the cold-injured vessel walls.

Opinion is divided concerning the actual cause of tissue necrosis from cold. One group believes that the damage is due to direct action of cold on tissue cells. Another assumes that tissue damage is secondary to the vascular changes either stasis with sludging of the red cells in capillaries or actual thrombosis. Evidence presented up to the present indicates that cold injury is a true thermal injury just like a burn, but we cannot exclude with certainty the possibility that the abnormal vascular reactions caused by cold do contribute to the injury.

Not all tissues show the same degree of susceptibility to cold injury. This can be demonstrated experimentally by choosing a degree of cold injury that will cause gangrene of the muscles of an animal's extremity without resulting in necrosis of the overlying skin.

The sequence of increasing cold injury,

beginning with the mildest changes and progressing to complete gangrene, occurs in the following order:

(1) Loss of skin sensitivity, muscular paralysis, and atrophy.

(2) Muscle necrosis without skin necrosis.

(3) Combined muscle and skin necrosis.

(4) Complete loss of all exposed tissue from gangrene.

When necrosis is incomplete, connective tissue proliferates and replaces the gangrenous areas to a variable degree.

Gangrene of frostbitten tissue is of the dry type, provided secondary infection does not occur.

Symptoms and Signs. The symptoms are often mild and transient. This fact is unfortunate in that the afflicted individuals are not sufficiently warned of the impending danger. Often, relatively mild stinging or prickling is the only symptom noticed. The involved parts then tend to become anesthetic and turn white, waxy, and ultimately solid. During thawing of frozen parts, local pain is generally marked. Hyperemia and edema (often with skin blisters) become evident and tend to disappear in 3 to 4 days.

The skin becomes dull blue-gray in color, often with areas of hemorrhage. Depending on the degree of injury, the skin recovers or becomes gangrenous. In the former case, the skin appears thinner, shinier, and of finer texture than normal—a picture of atrophy. When necrosis of skin occurs, a demarcation line develops in 5 to 6 days between the viable and nonviable tissue and dry gangrene finally results. Sensation in recoverd parts is impaired for a variable period of time.

Prophylaxis. The prevention of local cold injury in Air Force personnel consists of adequate and proper use of clothing, indoctrination regarding the dangers of exposure to cold, and the construction of military aircraft to reduce the exposure of occupants to wind and cold.

TREATMENT

It must be borne in mind that there can be produced in tissues a degree of cold injury that precludes recovery. Therefore, when an extremity is exposed to very severe frostbite it is possible that three indistinct zones representing different degrees of injury are present: a. That which is injured beyond recovery as far as any known therapy is concerned, b. that which is severely injured but which may, in part at least, be saved from gangrene by adequate treatment, and c. that which is minimally injured and will recover with or without therapy. Treatment should be directed toward saving as much of the second zone as possible.

Our ideas concerning the rate of rewarming of frostbitten tissues have changed in the past few years. Several investigators have shown experimentally in animals and one in humans that, contrary to popular belief, rapid thawing of tissues frozen from relatively short exposures results in less loss of tissue from gangrene than does slow thawing. Rapid warming in 42° C water until the tissues become soft is especially beneficial with respect to skin. The good results with muscle are also definite but not as striking. Furthermore, function of limbs exposed to cold injury is much better maintained after rapid thawing.

It is not known how long the rapid warming can be delayed and still be beneficial, nor is it known whether rapid warming will be beneficial when the cold injury is incurred from long exposure. Since it is possible to demonstrate tissue damage within minutes after exposure to cold, it is probable that the beneficial results from rapid thawing will be less as the time of exposure to cold becomes longer.

The question as to the advisability of artifically causing vasodilatation or vasoconstriction as therapeutic measures has not been decided. Those who believe that the tissue damage is due to ischemia incident to vasoconstriction or stasis advocate vasodilatation by drugs, sympathectomy, or injection of sympathetic ganglia. Others believe that edema, which occurs after thawing, results in tissue hypoxia and death and, therefore, recommend constriction of the vessels.

The use of heparin in the treatment of experimental frostbite has been advocated by Lange and collaborators. Unfortunately, other investigators have not been able to reproduce their results. The rationale of heparin therapy is based on the hypothesis that cold-induced tissue necrosis is due to vascular thrombosis. There is much experimental evidence against this idea, and from the experimental results using heparin it is very doubtful that it is of value. In fact, it is questionable that any form of specific therapy will be beneficial once the cold-injured tissues have been returned to body temperature.

Avoidance of trauma to frostbitten parts must be emphasized. Massage or exercise of the parts while frozen is to be avoided. Cold injuries should be treated as other types of wounds resulting from physical causes—frostbitten upper extremities should be immobilized in slings and individuals with frozen lower extremities should be transported on litters.

The prevention of secondary infection is of paramount importance. Cold-injured parts should be treated aseptically by careful cleansing and covering with sterile dressings. The topical application of powdered sulfa drugs is not indicated. However, the local use of ointment in which 5% sulfa powder is incorporated reduces infection and also prevents the dressings from adhering to the parts. Antibiotics should be used as indicated. Prophylactic inoculation against tetanus is indicated in the more severe local cold injuries.

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