TG-945

JANUARY 1968

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Technical Memorandum

AIRCREW COOLING STUDY

by F. JURGENS

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

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by F. JURGENS

PREPARED FOR NAVAL AIR SYSTEMS COMMAND,
CREW SYSTEMS DIVISION,
WASHINGTON, D.C. 20360, CODE AIR-531

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY
8621 Georgia Avenue, Silver Spring, Maryland 20910

Operating under Contract NOw 62-0604-c with the Department of the Navy

ABSTRACT

The naval aviator cannot wear separate garments for the wide variety of thermal environments in which he must work. The results of a study conducted to ascertain the thermal control requirements of these aircrewmen are presented. The study set out to define the heat and moisture removal requirements during ground and flight operations, to learn the effects of various clothing combinations, and to learn the effects of flight conditions on thermal moisture control.

The effects of both metabolic activity and environment on body temperature are considered, and various techniques of air and liquid cooling in a variety of garments are then reviewed in order to determine the most effective ways of keeping body temperatures at reasonable levels. Immediate use of forced-air cooling suits, more precise determination of the limits of "tolerable" working conditions, and further improvements in the design of liquid-cooled garments are recommended.

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AIRCREW COOLING STUDY

I. INTRODUCTION

A. Scope

A study, the findings of which are presented here, was conducted to ascertain the thermal control requirements of aircrewmen operating naval aircraft. The study defined the heat- and moisture-removal requirements for both ground and flight operations, and delineated the effects of various combinations of aircrew garments and flight conditions upon thermal and moisture control. The information gained was used as a basis for assessment of the effectiveness of air- and liquid-cooled aircrew undergarments in maintaining crew comfort by heat and moisture control. In addition, the study included an evaluation of the adequacy of existing liquid-cooled undergarments and established the requirements for heat exchangers other than ice.

B. Background

At present, most high performance aircraft provide comfort control of crew spaces by means of air ventilation from an air-cycle refrigeration system that conditions air bled from the turbine engine. When compared to a vapor-cycle mechanical refrigeration system, use of the air-cycle system for conditioning the crew space had the advantage of much less weight, smaller size, and less complexity. However, in certain aircraft the problem of aircrew cooling is complicated by the need of air- and/or water-impermeable outer garments to protect the aircrewmen against exposure and against explosive decompression. The problem that these garments create is that they prevent the normal cooling of the wearer both by evaporation of perspiration and by the outward flow of body heat. The problem has been partially relieved by integrating air ventilation ducts into the garment itself. This is satisfactory only while suitably cooled and dehumidified air is available for ventilation, a situation that does not exist when the aircrewman has just donned the garment or while he is out of the aircraft. Therefore, since conditioned air must be supplied to the garment as soon as it is donned and must be supplied continuously thereafter in order to maintain the thermal balance of the wearer, part of the problem still remains.

In an effort to improve the thermal management of aircrews in aircraft where air-cycle conditioning systems are either nonexistant or inadequate, the British Royal Air Force developed a liquid-cooled undergarment. This garment was designed to remove metabolic heat by circulating cold fluid through plastic tubes in contact with the skin and, thus, to transfer the heat from the skin to a heat exchanger (e.g., ice). The United States Navy became interested in that work and, accordingly, this current study, sponsored by the Navy, was initiated by the Crew Systems Divisions (AIR-531) of the Naval Air Systems Command.

The study undertook to discover the thermal requirements for aircrewmen operating naval aircraft and to evaluate the problems of using vent air thermal control. The problem areas had to be defined. Before this could be done, the heat and moisture removal requirements for aircrewmen in various pre-flight, flight, and post-flight operations had to be determined. Special consideration was given to the needs of crews during ground operations when no thermal control system is available. The analysis of the heat and moisture removal requirements led into a study of the effects of various combinations of aircrew garments and flight conditions on thermal and moisture control. Thus, there was laid a basis for a comparative evaluation of liquid- versus air-thermal control undergarments.

C. Physiological Considerations

Man is a homeothermic animal whose proper function demands a constant internal thermal environment. This thermal environment sees modest diurnal cycles as the basal metabolic rate rises with the increased activities of the working hours and falls with the decreasing physiological activity of sleep. Within this diurnal fluctuation, the acceptable internal temperature variation is fixed within very narrow limits.

To maintain the central body temperature within these very restrictive limits the body utilizes several mechanisms such as thermal energy being absorbed from a hot environment, and heat being produced internally by basal bodily activity and increased during periods of increased activity. The internal heat sources do not vary with the external environment: there may be inadequate heat generated in a cold environment and excess heat produced in a hot environment. The body cannot reduce the heat output associated with a given level of physiological activity, and heat generation can be increased only by the rather incapacitating and fatiguing process of shivering.

Since the body has very limited capabilities for regulating heat production, thermal management is largely dependent on the physiological mechanisms which regulate heat losses from the body. There are four such mechanisms: radiation, conduction, convection, and evaporation. Least important in most environments for the aircrewman is conductive heat loss, this may, however, be a significant factor in transporting heat from the aircrewman's body surface to the external surfaces of clothing in cold water exposure. While it is true that there may be damaging local heat exchanges with very hot or very cold cockpit surfaces and instruments, for thermal management considerations these can be ignored.

Radiant thermal exchange can be either positive or negative. In a hot environment, the body will absorb radiant energy from high temperature objects; in a cold environment, the body will radiate thermal energy. Under ordinary circumstances radiation is also a relatively ineffective avenue for heat loss from the body. The potential for heat exchange by this means is not encouraging, and little benefit is envisioned in attempting to exploit this mechanism for personnel thermal management purposes.

Because cockpit air currents are usually pronounced and because controllable air movement can be produced, convective heat exchange represents both a major mechanism of heat exchange by the aircrewman and a readily exploitable technique for thermal management control. At temperatures below approximately 86°F, convection represents the major source of heat loss from the body, and as long as environmental temperatures can be maintained below this level, convective heat exchangers are acceptable for heat removal. Because air has a very low specific heat (0.24 Btu/(lb-°F)), it is an inefficient medium for removing large amounts of heat. This is an especially serious limitation if high temperature gradients cannot be maintained between the body surface and the cooling air. As the thermal gradient decreases, very large quantities of air are required to effect the necessary heat removal.

In warm environments, the most effective means of heat removal is by the evaporation of body sweat, however, evaporation accounts for only about a quarter of the total heat loss from the body at environmental temperatures below 86°F. At these lower temperatures, if the environment is dry enough to permit it, evaporation is a very constant and uncontrollable source of heat loss. The minimal evaporative heat removal is provided by the vaporization of the insensible perspiration and by evaporation of water at the lung surfaces. There is an obligatory water loss through the skin which accounts for the insensible perspiration water loss. The expired breath is always nearly saturated at body temperature, a variable but uncontrollable heat loss results from this expiration of water vapor.

The mechanism of evaporative heat loss is used by the body for thermal regulation in warm environments and when the metabolic rate is increased by muscular activity. Because of the high heat of vaporization of water, large amounts of heat may be removed from the body by evaporation of sweat. Sweating rates can be very high: eight to ten pounds of water per hour can be lost through perspiration. This represents a staggering capability for heat removal.

Although the potential for heat removal by evaporation is high, excessive sweating is physiologically expensive for the aircrewman. Without adequate water intake, a water deficit will develop, and marked performance degradation is to be expected. However, for moderate heat removal requirements, it is a highly desirable technique. Under such circumstances, the responsibility for heat removal control remains with the aircrewman as his body regulates the rate of sweat production in response to heat removal requirements. It is also obvious that relatively warm air may be used if it is dry.

D. Heat Tolerance and Comfort Criteria

The human body has a rather remarkable ability to adapt itself to extremes of hot and cold, maintaining inner body (core) temperatures close to about 98½°F at the expense of allowing temperatures to change in the extremities when necessary. For very hot conditions, the body augments its heat dissipation through radiation, conduction, and convection by increasing blood flow near the surface of the skin, thereby increasing skin temperature. Also, sweat is produced and evaporated. Conversely, for cold conditions, the body reduces its heat losses by decreasing blood flow near the surface of the skin, thereby decreasing the skin temperature.

Within limits, the human body can operate even if its "core" temperature deviates from nominal. For limited periods of time, the body can operate despite thermal exchange imbalances. If metabolic heat production and heat loss can be balanced, the body can endure the thermal environment indefinitely. If the body cannot accomplish a balance, it will accumulate heat if too little heat is dissipated, and a thermal deficit will result if too much heat is lost. The capacity of the body mass to store heat is about 80 percent of the heat storage capacity of an equal mass of water. The body can tolerate deviations (from nominal) of several degrees Fahrenheit in core temperature (corresponds to storage or deficits of several hundred British thermal units) without drastic of permanent deterioration. To maintain thermal balance under the most severe transient conditions to which the aircrewman might be exposed may not be practicable. It is, therefore, important to determine what thermal imbalances are permissible.

Human performance is always degraded by abnormal body temperature conditions (see Fig. 7). The effects of short-term tolerable discomfort must be recognized. If one must perform dexterous manual operations, performance may deteriorate from even moderately cold fingers and hands. Also, one need only to recall his experiences with fever to realize that high body core temperatures severely decrease mental acuity.

"Comfort" must be defined for specific conditions that involve the three factors that influence thermal balance: metabolic activity (a heat source), thermal insulation characteristics of clothing, and characteristics of the heat transfer mechanism (air or water temperature, flow rate, and thermal radiation). Comfortable conditions are rather easily defined for a sedentary person who works in an air-conditioned office, and it is known that human performance is degraded by small degrees of discomfort. Most men feel comfortable at about 68°F with 50 to 60 percent relative humidity.

In the planning of aircraft design, the importance of aircrew comfort has been largely overlooked. In addition, there is reluctance to accept penalties (such as cost, space, weight, power consumption, maintenance, logistics, etc.) that must be borne if military aircrewmen are to be provided comforts that approach those in modern jet airliners. The aircrewman's immediate environment will obviously vary markedly at times from the ideal. If the temperature rises, the aircrewman can still regulate his body temperature by the evaporation of sweat, but at the expense of comfort.

Measurement of comfort is of necessity qualitative. The effects produced on it by temperature, humidity, solar radiation, and air velocity are well known. However, since there is wide variation between individuals in personal preference, it seems very desirable to provide the aircrewman with a controllable system which he can adjust to make himself comfortable. Not only that, but the ideal thermal management system is one which will permit him to control temperatures, humidity, and air movement independently. Temperature should be regionally controllable. Since such an ideal system is probably unattainable, one must acquire an acceptable comfort level with one or more of these parameters outside the desirable limits.

Empirical physiological tests are probably needed to define the effects of thermal discomfort on performance of aircrewmen for low levels of discomfort. There are, however, known limits of tolerance, and thermal comfort control should be designed and built so that aircrewmen do not approach such hazardous thresholds.

E. Current Use of Cooling/Thermal Comfort Garments

Some current aircrew garments are provided with ventilation components to assist in maintaining the crewman at a comfortable body temperature. The U.S. Navy, full-pressure suit, Mark IV, and the anti-exposure suit, Mark V, both incorporate ventilation components that can be connected to an aircraft air-conditioning system or blower (if available). Both the pressure suit and the anti-exposure suit possess high thermal insulation characteristics that limit the transfer of normal body metabolic heat to the temperature environment of the surrounding atmosphere. In normal air conditioned aircraft, the air-conditioning system supplies a flow of about 10 to 15 cubic feet per minute of cool, dry air through the ventilating garment to remove body heat. This air-conditioning is normally operated by compressed air diverted from the aircraft jet engines, and is available therefore, only when the engines are operating near normal power levels.

Similar air-cooled/ventilated pressure suits and survival garments are employed by both the USAF and the RAF. The Royal Aircraft Establishment and some aerospace industries in the United States have proposed water-cooled undergarments for personnel comfort in hot environments here the supply of suitable cooling gas is either lacking or inadequate. These liquid-cooled garments have been employed industrially and by the National Aeronautics and Space Administration.

Use of either air- or liquid-cooled undergarments introduces support requirements for supplies of cooling liquid in the ready room, in transit, and in the aircraft. Present-day high-performance jet-powered combat aircraft, such as the F4, F8, A5, A6, and A7, provide conditioned air for the aircrewman's air-ventilated garments. Surveillance type aircraft and helicopters generally do not provide such facilities. Survival suits are worn in surveillance and helicopter aircraft, but pressure suits are not worn in these craft since they do not attain high flight altitudes.

In most hot environments, the suited aircrewman dressed in summer flight jeans will experience thermal stress during pre- and post-flight operations. Stress placed upon the crewman on the ground is dependent upon the garments necessary for protection in the craft to be flown. The prolonged exposure to high heat and humidity will tend to acclimate the man to the environment. The thermal stress in hot environments appears to be a greater cause of fatigue than the long hours and emotional stress of military operations. Perhaps little can be done about flight duration and the stress of flying, but thermal management is possible with new and improved equipments.

Thermal control of the environment of the aircrewman is usually satisfactory during flight operations, but pilot performance may be degraded if he has reached a point of thermal fatigue prior to entering the plane. In military operations is Southeast Asia, aircrews are subjected to typical mean maximum temperatures in summer months above 90°F with relative humidity of 60 to 70% (P_{H_2O} = 22-25 mmHg). Temperatures and humidities of this magnitude promote perspiration, but impair the transfer of heat through evaporation. The problem is further aggravated by the protective clothing the aircrewmen are required to wear.

Succeeding sections of this report will discuss, in order, the following

(1) Heat loads upon the crewman from his own metabolic activity and the external environment that will have to be removed by his thermal control garment.

(2) Description and performance of currently available thermal comfort garments (air and liquid cooled).

(3) Logistical support needed for cooling garments.

(4) Applicability of available thermal comfort garments to specific applications.

(5) Conclusions and recommendations.

II. EFFECTS OF METABOLIC ACTIVITY AND ENVIRONMENT UPON BODY TEMPERATURE

A. Variations of Metabolic Heat with Bodily Activities

1. Metabolic Heat Production

The metabolic rate is a measure of the energy released in the body by the oxidative combustion of fats, carbohydrates, and proteins. All of this energy ultimately appears as heat and external work. That energy released by the internal bodily activities (e.g., heart activity, breathing movements, neural activity, muscle tone, kidney transport, liver function, etc.) during complete rest in the post absorption state (i.e., after ingested food has been digested) is called the basal metabolic rate. With increased activity, especially muscular, the metabolic rate markedly increases so that the energy released during strenuous exercise may be more than ten times the basal metabolic rate.

Since external work accounts for some of the energy expenditure, any determination of metabolic rate from heat measurement must allow for this factor. Mechanical conversion efficiencies for man vary between 5 and 35 percent.

The measurement of heat release as an indication of the metabolic rate is called direct calorimetry. Because of instrumental difficulties in making accurate measurements of the human heat release and the external mechanical work performed, this method is rarely used. Almost all metabolic rate assessment is accomplished by a technique called indirect calorimetry. In indirect calorimetry the metabolic rate is calculated from a measurement of the metabolic gas exchanges through the lungs. This is possible because of fixed relationships between metabolic gas exchange and total energy release. Since all of the energy released in the body results from the controlled oxidative combustion of fats, carbohydrates, and proteins, and since for each of these fuels there is a specific oxygen-carbon dioxide exchange, the total energy release may be determined from the amounts of fats, carbohydrates, and proteins consumed.

In normal metabolic states (i.e., with normal diet and no starvation symptoms) the amount of protein burned is fairly constant. Protein, contrary to common belief, is not utilized by the body primarily as an energy fuel. It is used to repair and build body tissue, which requirement is a fairly constant one. Therefore the protein metabolic rate is reasonably constant. For precise measurements it can be accurately calculated from a knowledge of the N-P-N (non-protein nitrogen) in the urine. In the body the protein molecule is not completely burned and the unburned nitrogen-containing fragments are excreted in the urine. For the indirect assessment of metabolic rate, the magnitude of protein breakdown is generally estimated.

The amounts of fats and carbohydrates burned within the body can be accurately determined from knowledge of the oxygen consumption rate and the respiratory quotient (RQ). The RQ is defined as the ratio of the volume of exhaled carbon dioxide to the volume of consumed oxygen. This ratio is approximately 0.85 for normal humans. Expressed in another way, the volume of oxygen absorbed from the atmosphere exceeds the volume of carbon dioxide exhaled by approximately 15%. All carbohydrates have a respiratory quotient (called respiratory exchange ratio

(R) when measured from the expired breath) of unity, and the RQ for a mixed fat is 0.707. Therefore, in steady state conditions the RQ (or R) will vary between 0.707 and 1.00, and will indicate the ratio of fat to carbohydrate combustion. When the gross RQ has been corrected for the protein burned, it is called the non-protein respiratory quotient, and defines the fat-to-carbohydrate combustion ratio. This is illustrated by Fig. 1.

It is necessary to know the amounts of O_2 consumed in fat, carbohydrate, and protein metabolism because different amounts of heat are released for each food relative to a given O_2 comsumption. This is called the caloric equivalent of oxygen. Equivalents for combustion within and without the body are listed in Table I. Although the metabolic rate can be calculated from the metabolic gas exchange, it is easier in routine work to use a nomogram. Such nomograms, with an explanation for their use, are included in Fig. 2.

There are wide variations in total energy requirement (amount of oxygen consumed) from man to man (because of training, day to day differences, acclimatation, and changes in operational conditions). Table II relates selected activities of aircrewmen to the cost of oxygen and the heat generated by the body.

2. Metabolic Heat Dissipation

The physiological regulation of body temperature is governed principally by the rate of blood circulation and the activity of the sweat glands. Heat is lost through convection (in the gas or liquid that moves around the body), conduction (heat transmission by direct contact of the body with conductive material), radiation (where the warmer of two bodies loses heat to the cooler, even without a surrounding atmosphere), and

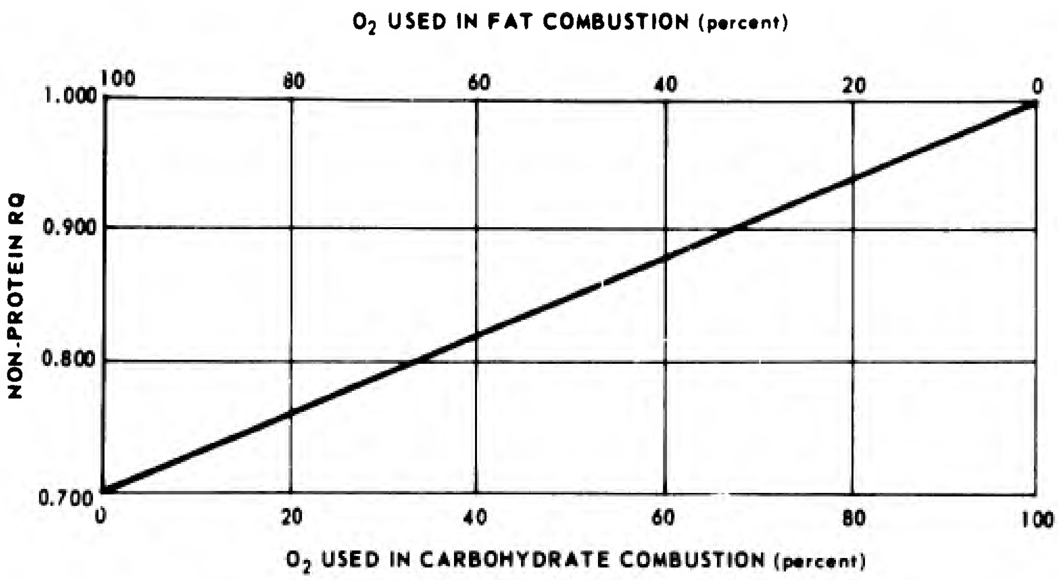

Fig. 1 NON-PROTEIN RQ vs. O_2 USED FOR CARBOHYDRATE AND FAT COMBUSTION

TABLE I

CALORIC EQUIVALENT OF OXYGEN

Substance	In vitro cal/gm O_2	In vivo cal/gm O_2	In vivo caloric value of 1 liter of CO_2
Fat	9.3	9.3	4.7
Carbohydrate	4.3	4.3	5.0
Protein	5.4	4.3	4.5

TABLE II

COST OF OXYGEN FOR SELECTED ACTIVITIES

Activity		lb O_2/hr	kcal/hr	Btu/hr
Asleep (men, aged 20-40)		0.04	72.0	280
Resting, sitting		0.06	78.0	400
Very light activity	- seated, writing	0.07	102.0	430
	- standing, relaxed	0.07	108.0	440
	- seated, assembling weapon	0.14	204.0	860
	- moving, walking slowly	0.15	228.0	900
Extreme activity	- marching, double time	0.52	800.0	3160
Piloting aircraft	- night flying, C47	0.06	780.0	480
	- C47 in level flight	0.07	102.0	400
	- instrument landing, C54	0.10	150.0	590
	- taxiing, C47	0.11	175.0	680
Piloting bomber	- aircraft in combat	0.12	175.0	700

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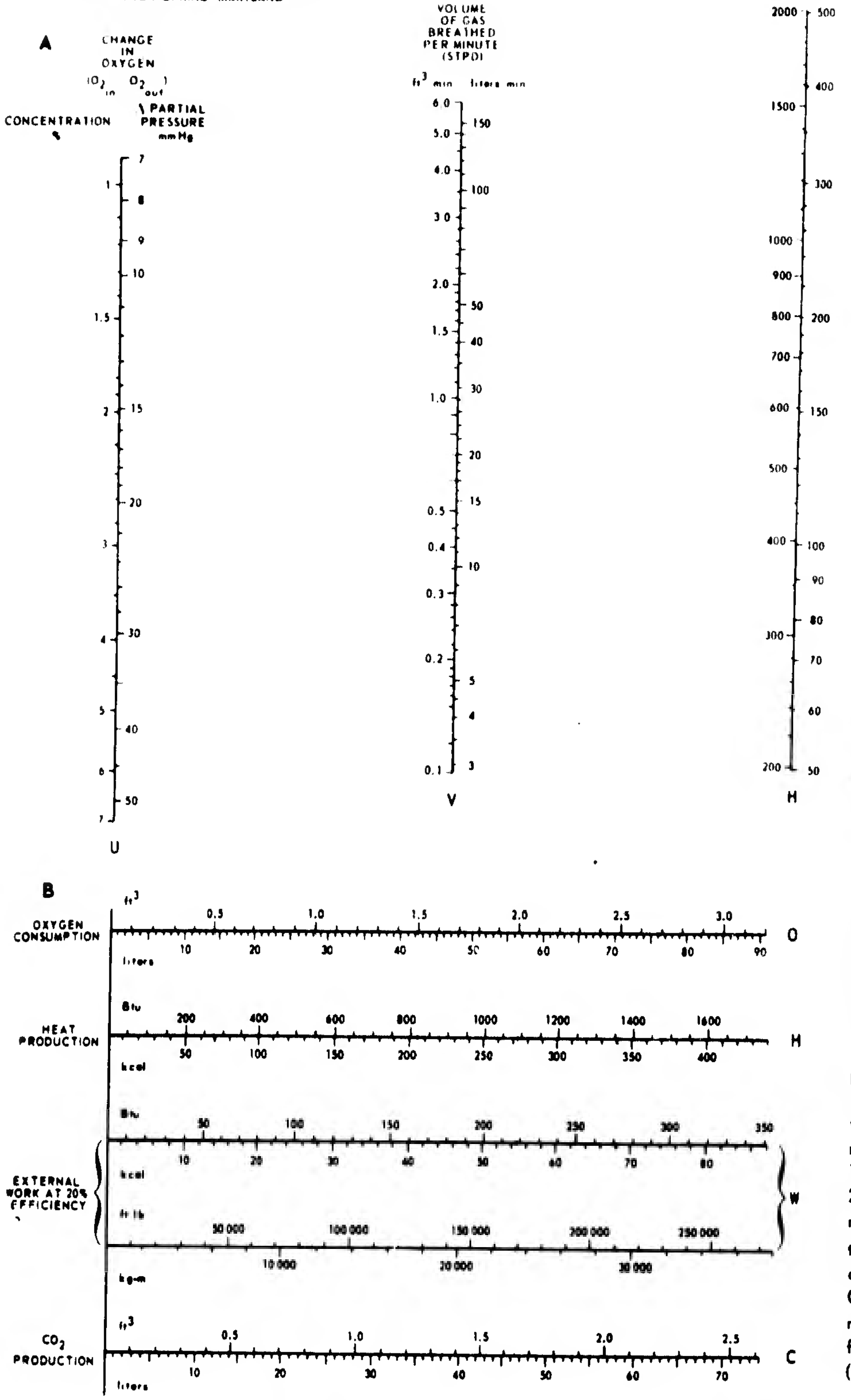


Nomogram A uses the standard values: RQ = 1.00 and 1 liter of oxygen is equivalent to 5.0 kcal. It permits direct calculation of heat output (H) in Btu/hr and kcal/hr from oxygen uptake (U) and ventilation rate (V). Alternatively, U can be calculated from H and V, or V from U and H.

Nomogram B uses the standard values: RQ = 0.82 and 1 liter of oxygen is equivalent to 4.825 kcal. This nomogram allows one to interrelate, by drawing straight vertical lines, the values for oxygen consumption (O), heat output (H), external work output (W), and carbon dioxide production (C), at typical conversion rates. Note that H may be as much as 3% lower or 5% higher than the quoted value at any specific oxygen consumption, depending on the RQ, which equals 0.7 for a pure fat diet and 1.00 for a pure carbohydrate diet. Values given in the third and fourth lines have to be modified if the efficiency changes. Typical ranges are 5 to 35%, average 20%, so that the listed work output may increase by three-quarters if the task is one that can be performed at high efficiency (e.g., bicycling). Conversely, the true value may be reduced by three-quarters if the function is inefficiently performed (e.g., high speed walking).

Heat output is determined for respiratory data in four stages. First, the oxygen cost is calculated from the respiratory ventilation rate of the subject and the change in oxygen concentration of the expired air. Second, the volume is corrected to 0°C, 760 mmHg, dry (STPD); this is particularly important at reduced atmospheric pressures. Third, the heat output corresponding to each unit volume of oxygen is selected, either by approximation or from a knowledge of the subject's diet or from his measured respiratory quotient.

Fig. 2 OXYGEN-COST NOMOGRAM (Ref. 33)

evaporation (where conversion of liquid into gas extracts heat from the remaining liquid).

The relative contributions of evaporation (E), convection (C) and radiation (R) for heat removal in several environments are shown in Fig. 3. (For the usual aviator environment, conductive losses are negligibly small.) These relationships indicate the relative amount of heat loss to the environment when a man from whom there is no conductive heat transfer is placed in various thermal environments. When the wall and air temperatures are high, the body relies increasingly on evaporation as a cooling mechanism. When the air and wall temperatures are equal to, or greater than, the mean skin temperature, the body must give up most of its heat through evaporation.

In hot environments the greatest portion of heat is liberated by the body through evaporation, but this process is influenced strongly by the relative humidity. As Fig. 3 indicates, evaporation becomes less effective as a mechanism for cooling as the humidity increases.

The effectiveness of sweating as a cooling mechanism is dependent upon the air temperature, the water vapor pressure (P_{H_2O}) of the gas in the ambient environment, air velocity, and clothing, while the thermoregulatory system attempts to maintain a balance at all times. With conditions as listed in Fig. 4, and with air and wall temperatures above skin temperature, heat can be lost only by evaporation, which can take place only if the air is not saturated. Each pound of water lost through evaporation removes 1050 Btu of heat.

The amount of heat loss through sweating (as a function of a number of parameters) is expressed by the equation (Ref. 13).

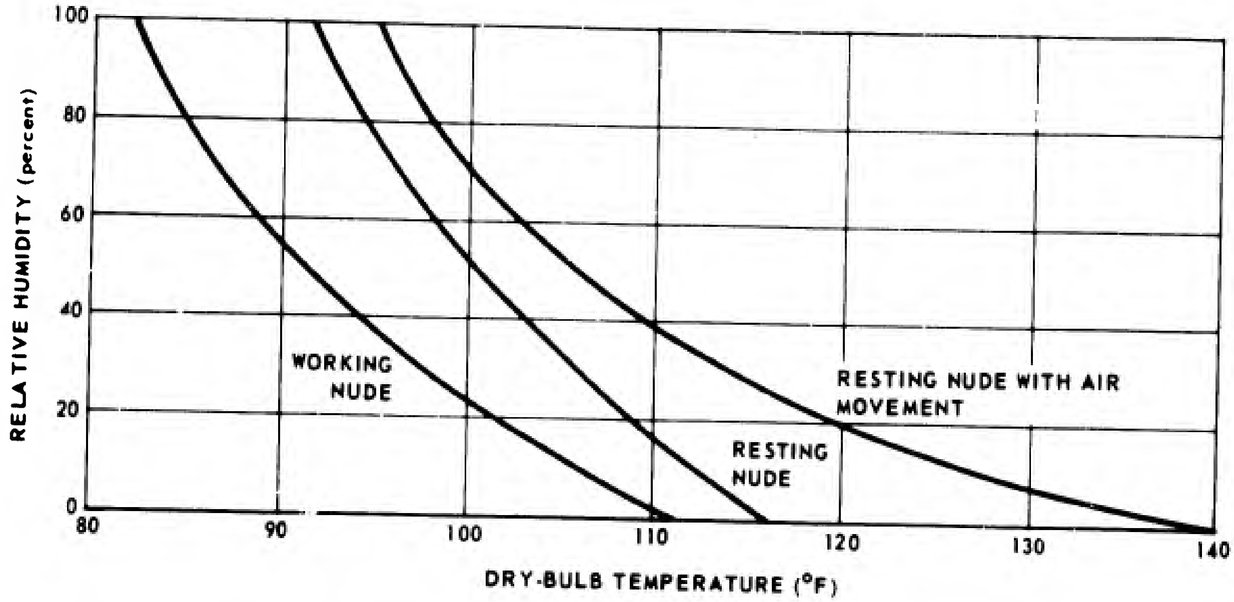


Fig. 3 APPROXIMATE UPPER LIMITS OF TOLERANCE FOR HEAT LOSS BY EVAPORATION (Ref. 14)

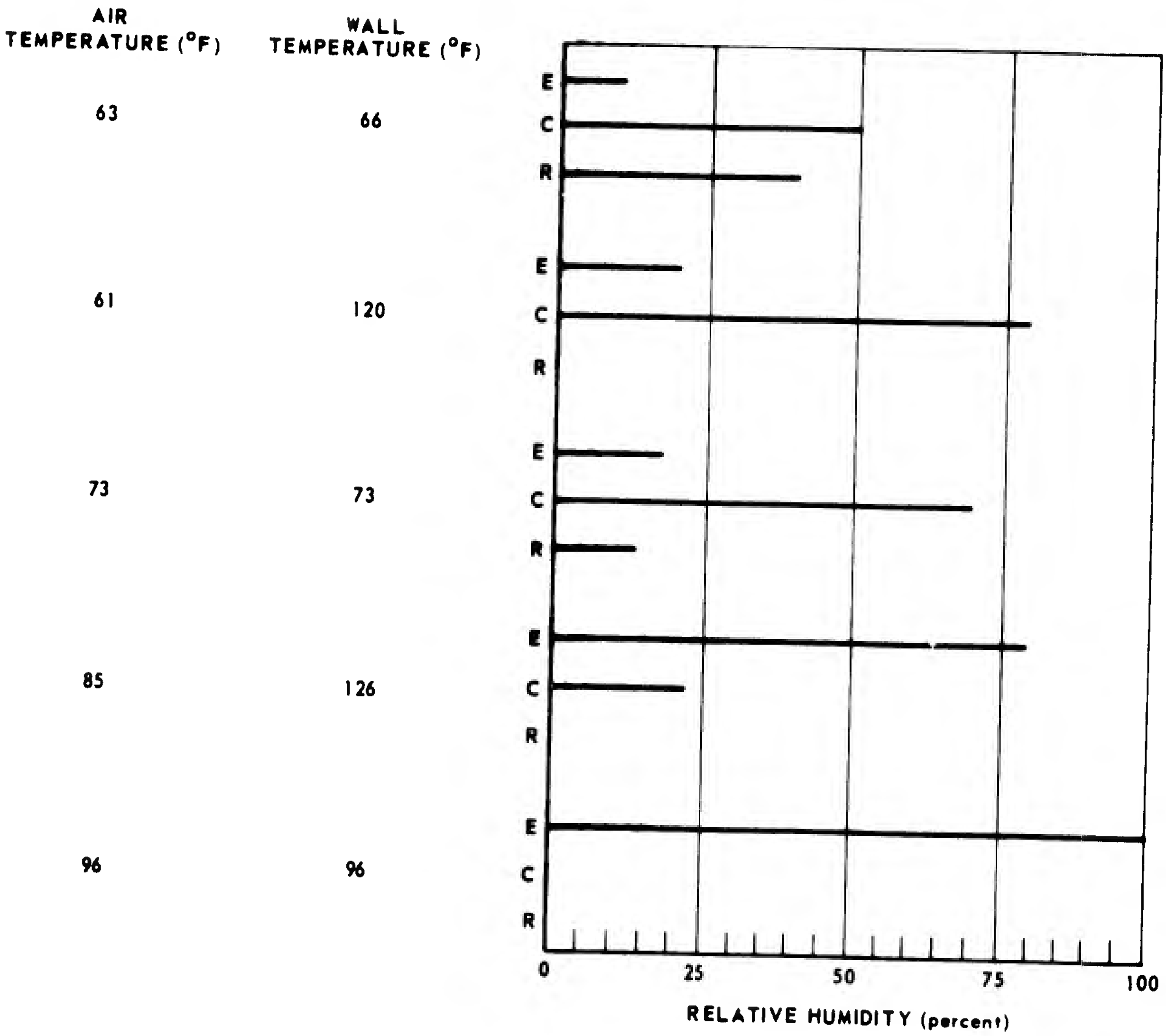


Fig. 4 RELATIVE CONTRIBUTIONS OF EVAPORATION, CONVECTION, AND RADIATION IN HEAT REMOVAL

$$Q_{evap} = KrB\mu \left(P_{s_{H_2O}} - P_{amb_{H_2O}}\right),$$

where

Q_{evap} = heat loss through evaporation [Btu/(ft^2- hr)],

K = coefficient of heat transfer,

r = latent heat of vaporization (Btu/lb),

B = $\frac{\text{velocity}}{(0.25)^{\frac{1}{2}}}$, wind velocity correction (ft/sec),

μ = fraction of total skin area moistened by perspiration,

$P_{s_{H_2O}}$ = saturated steam pressure at skin temperature (mmHg), and

$P_{amb_{H_2O}}$ = saturated steam pressure at ambient air temperature (mmHg).

As the $P_{amb_{H_2O}}$ increases, the factor μ will approach unity because more surface area of the body must be used to evaporate the same amount of sweat.

The sweat production of an acclimatized man during a four-hour exposure can be predicted by means of Fig. 5. These estimates are for a subject lightly dressed, in ambient air with velocity of 75 ft/min, and with air and wall temperatures equal. The curves shown are lines of equal predicted four-hour sweat rate (P4SR), i.e., loci of equivalent combinations of clothing, activity, and radiant surroundings in terms of sweat output. Also, since the rate of sweating is a function of the air-wall temperature, air movement, clothing, and radiation, changes of any of these variables will modify the curves.

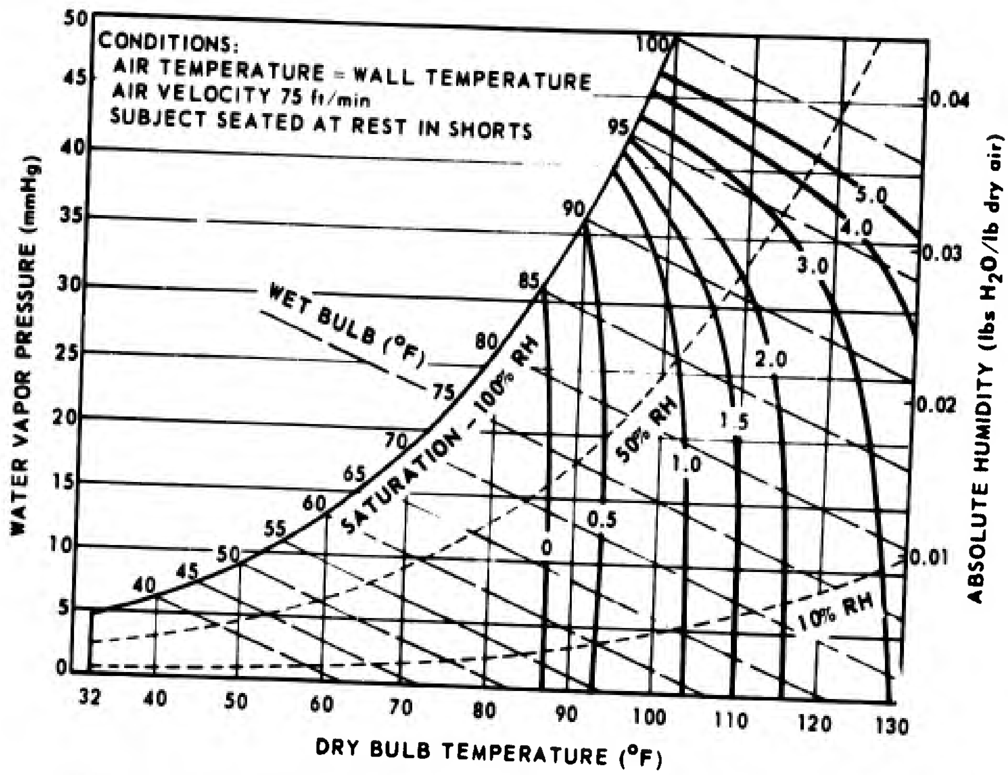


Fig. 5 PREDICTED FOUR-HOUR SWEAT RATE (P4SR) IS BASED ON THE SWEAT PRODUCTION OF ACCLIMATIZED MEN DURING 4-HOUR EXPOSURES TO HEAT. THE CURVES SHOWN ARE LINES OF EQUAL P4SR, THAT IS, LOCI OF THERMALLY EQUIVALENT COMBINATIONS IN TERMS OF SWEAT OUTPUT, FOR A SPECIFIC COMBINATION OF CLOTHING, ACTIVITY, AND RADIANT SURROUNDINGS; viz., SEATED AT REST, WEARING SHORTS, WITH AIR AND WALL TEMPERATURES EQUAL, AND AIR VELOCITY OF 75 ft/min. (Ref. 33)

It has been observed that an acclimatized man may have a steady-state sweat rate as high as 1.65 lb/hr without adverse effects so long as he maintains a favorable fluid balance. If water intake is started early enough before exposure and is maintained without interruption by frequent drinks, body weight can be maintained. If a deficit is permitted to accumulate, the ingestion of water causes unpleasant sensations and produces feelings of incipient nausea. If the gross deficit increases to one percent of the man's initial body weight, a compensatory upward shift in the rectal temperature, which is indicative of abnormal strain on the thermoregulatory system, is observed.

Figure 6 illustrates the manner in which comfort is related to water vapor pressures and air and wall temperatures. Beyond the limits of comfort, there exist imbalances that, if accentuated and maintained, could cause severe consequences ranging from heat stroke to death.

The desirable state of thermal balance is hard to achieve especially in military situations. Man does not have a constant metabolic rate; therefore, with a constant cooling rate, the balance will fluctuate between heat storage and loss. In most tropical environments, heat storage conditions predominate.

In a survey (Ref. 12) of personnel operating in tropical environments, 81 aircrewmen were questioned about their reaction to the heat they experienced during flight. The majority of the men (78%) thought that flying in a hot climate was more stressful than flying in temperate climates; of these, 57% considered that the heat in the cockpit was the cause of added stress. Of the 81 men who were questioned, 72 reported an increase in post-flight fatigue, and 58 of those men who experienced the increase, thought it was due to the heat. Seventy-one percent stated

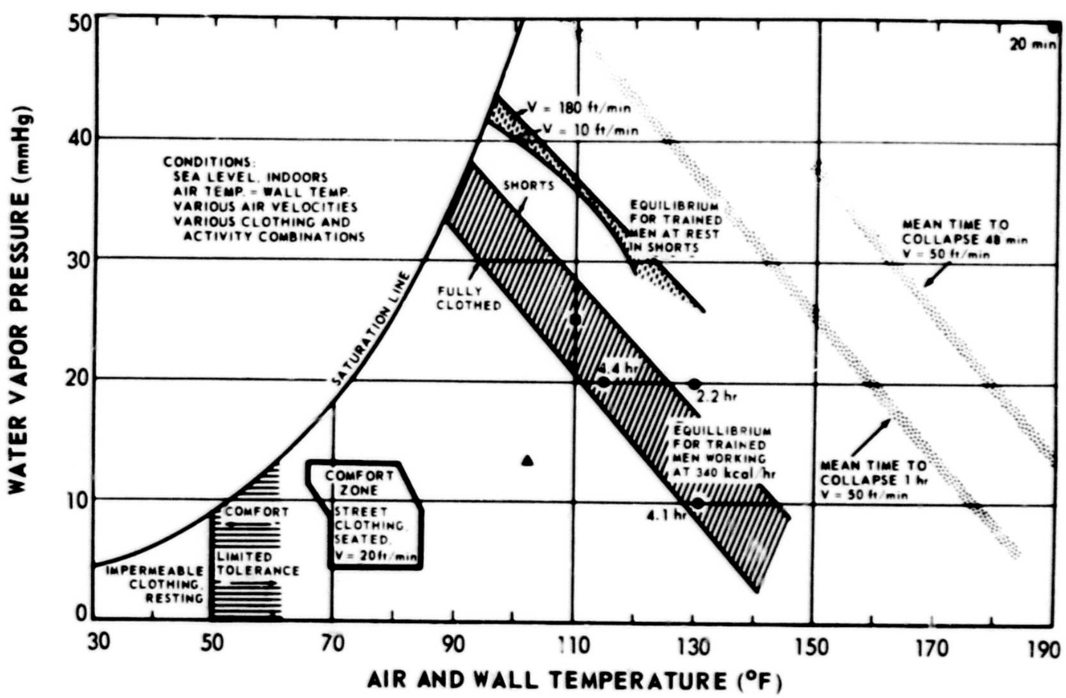


Fig. 6 HUMAN TOLERANCE TO HEAT LOSS (Ref. 33)

that more concentration was required when flying in the tropics. Sweat losses measured on a number of these aircrewmen were found to be consistent with exposure to moderate heat stress; all post-flight oral temperatures measured were below 100.4°F.

In field trials in another theater of operation, 54 percent of aircrewmen flying missions of two-hours duration in cockpit environments of 91.4°F and 100.4°F air temperature and 45 percent relative humidity were found to have oral temperatures between 99.5°F and 100.4°F (Ref. 12).

If an aircrewman experienced no rise in rectal temperature above 100.4°F (Ref. 12) during a short or medium duration flight, it is probable that the cockpit conditions were not severe enough to degrade his performance. Observations of the post-flight routine of aircrewmen subjected to a moderate degree of heat stress show that rehydration and sleep are mandatory. In most cases the former is possible (refer to the section on water loss), but during military operations such as those in progress in Southeast Asia, quick turn-arounds may preclude adequate sleep.

If thermal comfort is to be maintained for long periods of time, a man must be kept in or near a state of thermal balance. Balance can be achieved for a wide range of ambient conditions by physiological thermoregulatory mechanisms. For example, in cold environments, there may be increases in heat production to balance otherwise excessive heat loss, and in hot environments, there is the secretion of perspiration and adjustment of heat transfer from the deep tissue to the skin by alteration of the peripheral circulation patterns. Sweating begins in the resting man at a mean skin temperature of 94.1°F. Mild-activity aircrew duties probably reduce this to about 93.2°F. Metabolic heat production increases when mean skin temperature falls below 86°F. Between these two temperatures, i.e., 93.2°F and 86°F, the subject experiences no great thermal discomfort; however, mean skin temperature of about 91.4°F is preferred (Ref. 24). The aviator's alertness and initiative may suffer if his temperature is allowed to exceed this figure.

By itself, the mean skin temperature of a subject does not indicate adequately a condition of thermal comfort in steady state even though he may be in thermal balance. If the environment is uniform over the entire body, the skin will adjust to that temperature topography normally associated with comfort, if the other considerations are met. In the case of ventilated garments, liquid cooled suits, or clothing which does not completely cover the body or which varies in thickness and/or permeability, it is possible for a mean skin temperature of 91.4°F to be attained, while the temperature topography of the skin is grossly abnormal. Such a condition may represent thermal balance, and still not result in a sensation of comfort.

To obtain thermal equilibrium, the aviator must be able to make use of at least one of three parameters of thermal control (thermal conduction is ignored) as avenues for liberating heat. These parameters are related by the expression, $M = C + E + R \pm S$, where M is metabolism; C, convection; R, radiation; E, evaporation; and S, storage. If heat storage is to be zero, heat loss through convection, evaporation, and radiation must equal metabolic heat production. For an impermeable garment such as an anti-exposure suit, the radiative and convective components are small, and a high rate of evaporation of sweat is required to maintain thermal balance. If the moisture in the suit increases, heat removal by evaporation will decrease, becoming zero at 100 percent relative humidity. When this last means of heat dissipation becomes ineffective, the body begins to store up heat and there is a resulting increase in body temperature. Figure 7 shows the tolerance time as a function of change in body temperature.

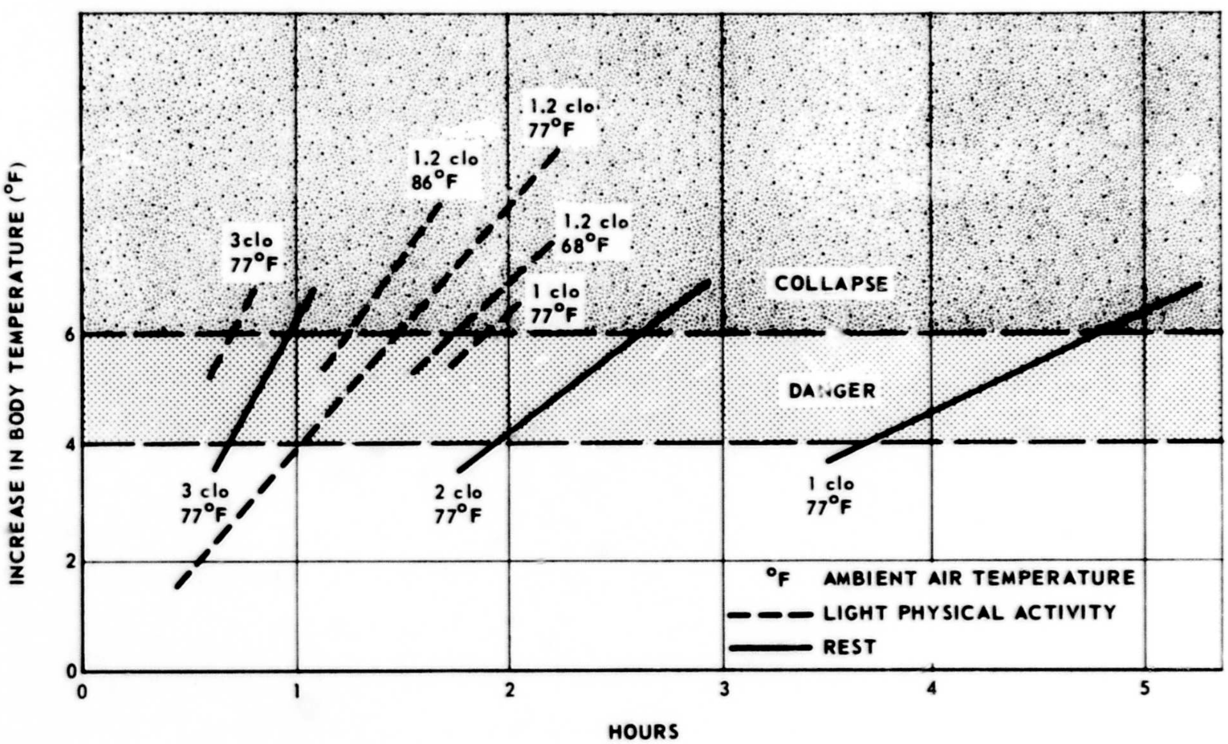


Fig. 7 TOLERANCE TIME vs. CHANGES IN BODY TEMPERATURE FOR VARIOUS CLOTHING ASSEMBLIES (Ref. 20)

The tolerance limit to heat exposure is defined as the maximum time a condition of thermal stress can be endured. It is indicated by the subject's report of faintness, nausea, tingling sensations in the extremities, mental confusion, compulsive restlessness, dyspnea, and/or heart rate in excess of 140 beats per minute.

It may be hypothesized that the human body can store a fixed quantity of heat before reaching a dangerous physiological condition. Experimental evidence may be summarized in the form of a hyperbolic limit equation. The average tolerance limits (Ref. 33) may be expressed as:

$$\Delta T = \frac{1700}{Q_s}$$

where ΔT is the time of exposure in hours, and Q_s is the body storage index, Btu/(ft^2-hr). Body storage index Q_s is expressed as:

$$Q_s = 0.83 \frac{W}{A} \frac{d}{dt} \left(\frac{1}{3} t_{skin} + \frac{2}{3} t_{rectal} \right) ,$$

where
- W = body weight (lb),
- A = body surface (ft^2),
- t = temperature (°F), and
- 0.83 Btu/(lb-°F) = a constant representing the average heat capacity (specific heat) of body tissue.

There can be no assurance that proficiency can be maintained for more than three hours for any condition outside the thermal comfort level. Minimum acceptable performance occurs at the limiting conditions (Ref. 33) defined approximately by $\Delta T = 1200/Q_s$. Metabolic rates are usually expressed relative to surface area because in most organisms the metabolic rate correlates more closely to surface area than to body mass. Heat storage relates to the warming of the entire body mass, and it may seem that temperature changes should correlate closely with total mass. The notation used here corresponds to the convention that has been established for studies of intermediary metabolism. Only small errors result when this less-precise expression is used for computations. If more precise calculations are required, the heat storage capacity can be expressed by the equation:

$$\Delta Q_s = 0.83\ W_s\ (t_{crit} - t_{skin}) + W_{core}\ (t_{crit} - t_{core}),$$

where

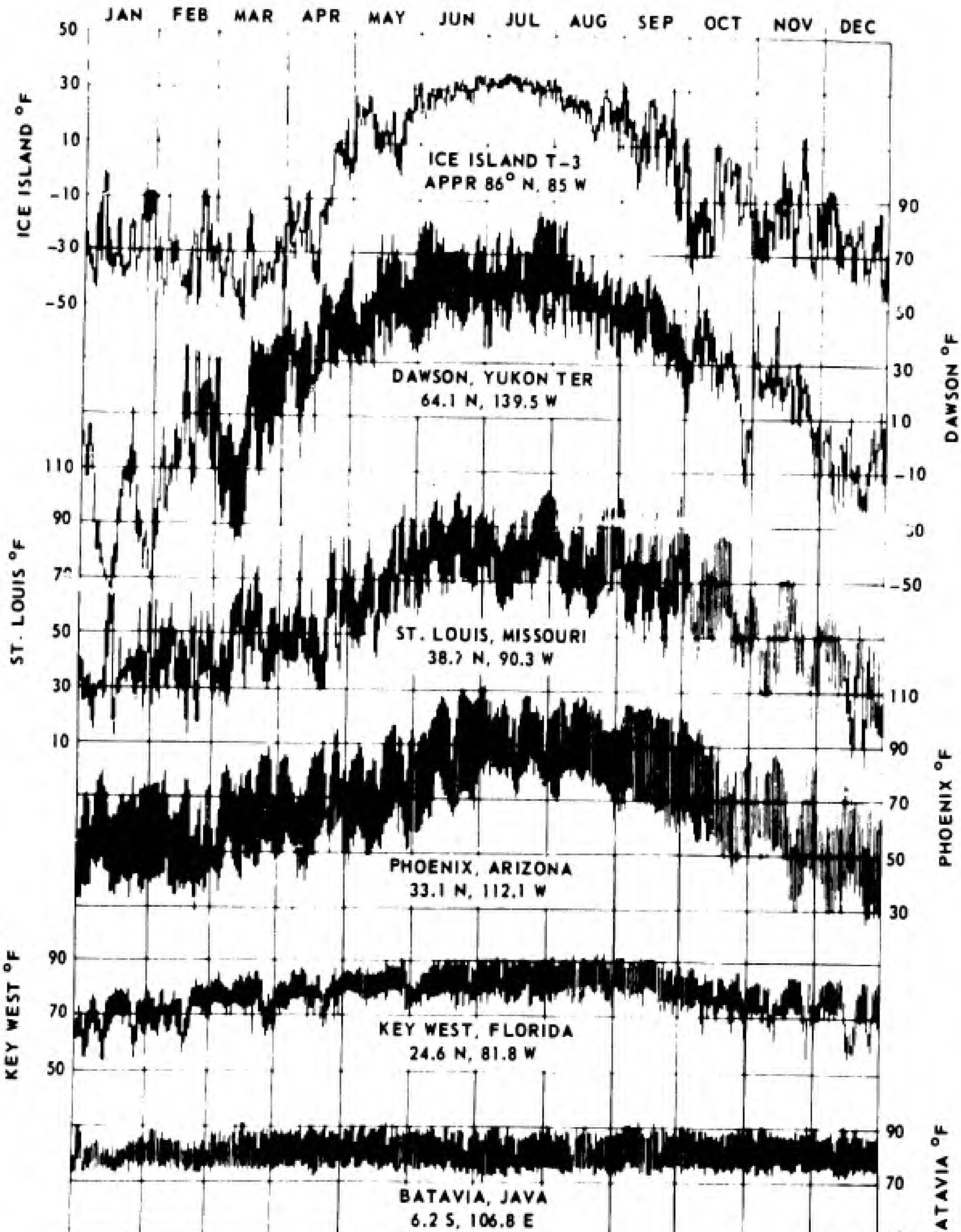
ΔQ_s	is the maximum amount of heat which can be stored before degradation of performance (due to body temperature rise) is to be expected,
t_{crit}	is the total body temperature (°F) for critical heat storage,
t_{skin}	is the normal skin temperature (93.5°F),
W_s	is fraction of body tissue weight in skin and exposed members (about 1/3 body weight),
W_{core}	is the fraction of body tissue normally maintained at 98.6°F (about 2/3 body weight), and
t_{core}	is the normal body core temperature (°F).

B. Geographical Factors Affecting Aircrew Cooling Requirements

Naval and Marine aviation operations throughout the world expose aircraft and aircrews to wide extremes of ambient temperature and humidity. Aircrew temperature control systems in combat naval aircraft must operate adequately in any portion of the world without requiring downtime for modification of either crew-heating or crew-cooling equipment. An aircrewman can largely maintain thermal comfort in a cold environment by wearing highly insulating clothes, but in hot climates some clothing must still be worn for physical protection, thereby imposing a need for special provisions for personnel cooling.

Since ground-level air temperature is influenced by chance factors such as cloud cover, rain, and wind, it is difficult to categorize in a meaningful way for design of crew comfort equipment. In many aspects, equipment can be designed for a "standard day," but only if the device's operation is judged by its average performance over a number of days. If an aviator must fly a grossly overheated aircraft on a very hot day, his performance will in no way be compensated or averaged out by a prior day's requirement to fly his aircraft in an over-cooled situation. Crew comfort equipment must be designed to produce tolerable (not necessarily ideal) crew environment under extreme weather conditions.

The United States Air Force has issued a reference, "Handbook of Geophysics for Air Force Designers" (Ref. 34). Figure 2-2 of the handbook is reproduced herein as Fig. 8; it shows actual recordings of daily diurnal temperature ranges for six widely spaced observation stations spanning latitudes from near the earth's North Pole to the Equator. Unfortunately, corresponding records of atmospheric humidity are not provided in this reference. Temperature records presented in Fig. 8 show that locations inland from the sea experience far greater daily and seasonal extremes in temperature. It is also noteworthy that summer temperatures in Key West, Florida, are substantially the same as the year-round temperature in Batavia, Java.



Climatic extremes of daily diurnal range of standard surface temperature at various stations for 1943 (Batavia); 1953 (Key West, Phoenix, St. Louis, Ice Island T-3); and Nov-Dec 1952, Jan-Oct 1953 (Dawson, Canada)

Fig. 8 CLIMATE EXTREMES OF DAILY DIURNAL RANGE OF STANDARD SURFACE TEMPERATURE (Ref. 34)

Worldwide temperature-extreme records can be compared on Figs. 9 and 10 (reproduced from Ref. 34), which show contours of highest and lowest recorded temperatures throughout the world. Figures 11 and 12 show contours of maximum temperature for the United States including, respectively, 99% and 90% of observations.

The current problem areas for thermal discomfort to Navy aircrewmen are reported to be in the Southeast Asian combat theater (South Viet Nam) and Florida. It is not suggested here that specific written reports have been received from these areas documenting discomfort; rather it represents orally expressed opinions of Naval and Marine aircrewmen who stated that under certain combinations of circumstances, they experienced severe thermal discomfort during aviation activities in these theaters when operating certain aircraft types. These thermal discomfort problems seemed related to the following factors.

(1) Aircrewmen must sometimes wear relatively heavy and moisture-impermeable flight garments in addition to, or in place of, the usual flight garment.

(2) Absence of, or off-design, operation of air conditioning equipment.

(3) Simultaneous occurrence of combinations of relatively high ambient humidity and temperature.

(4) Operation at relatively low flight altitudes.

Specific weather data were secured from the National Weather Records Center, United States Weather Bureau Navy Unit, Asheville, North Carolina, for three air-base locations in South Viet Nam. These bases are at Saigon, Qui Nhon, and Da Nang at locations shown in Fig. 13. Data on weather at these locations is summarized in the "Climatic

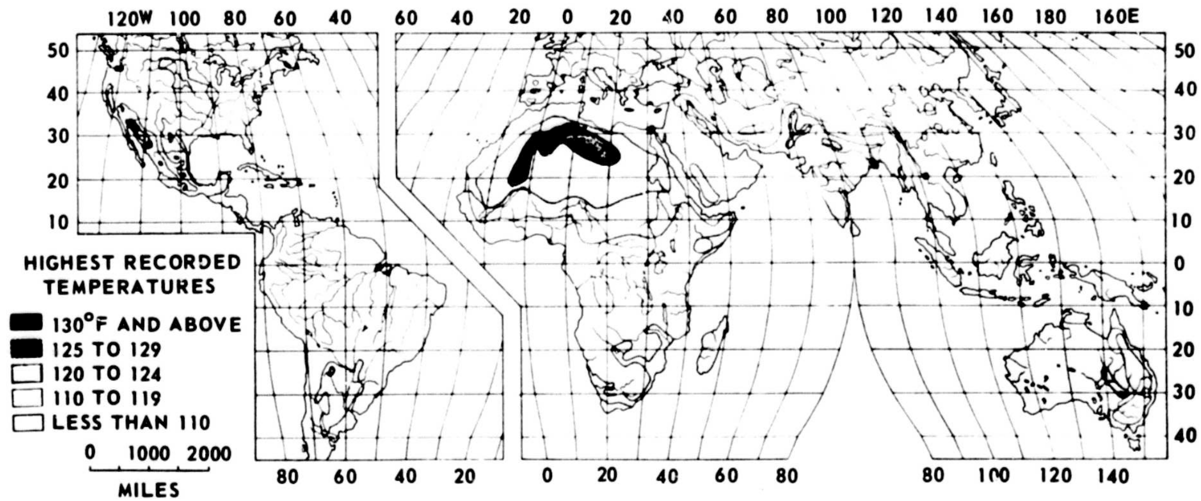


Fig. 9 **HIGHEST TEMPERATURES EVER OBSERVED** (Quartermaster Research and Development Command.) (Ref. 34)

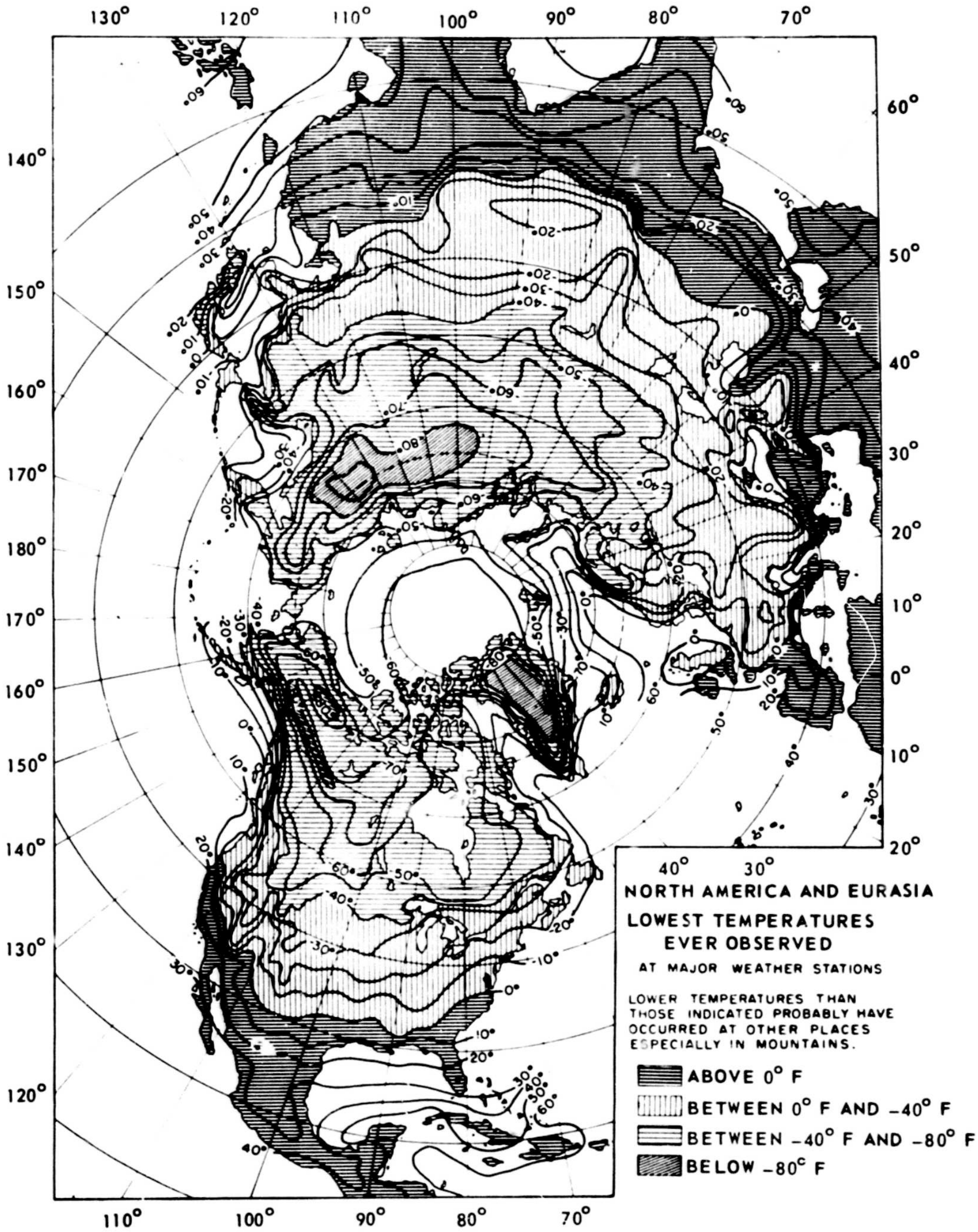


Fig. 10 LOWEST TEMPERATURES EVER OBSERVED (Ref. 34)

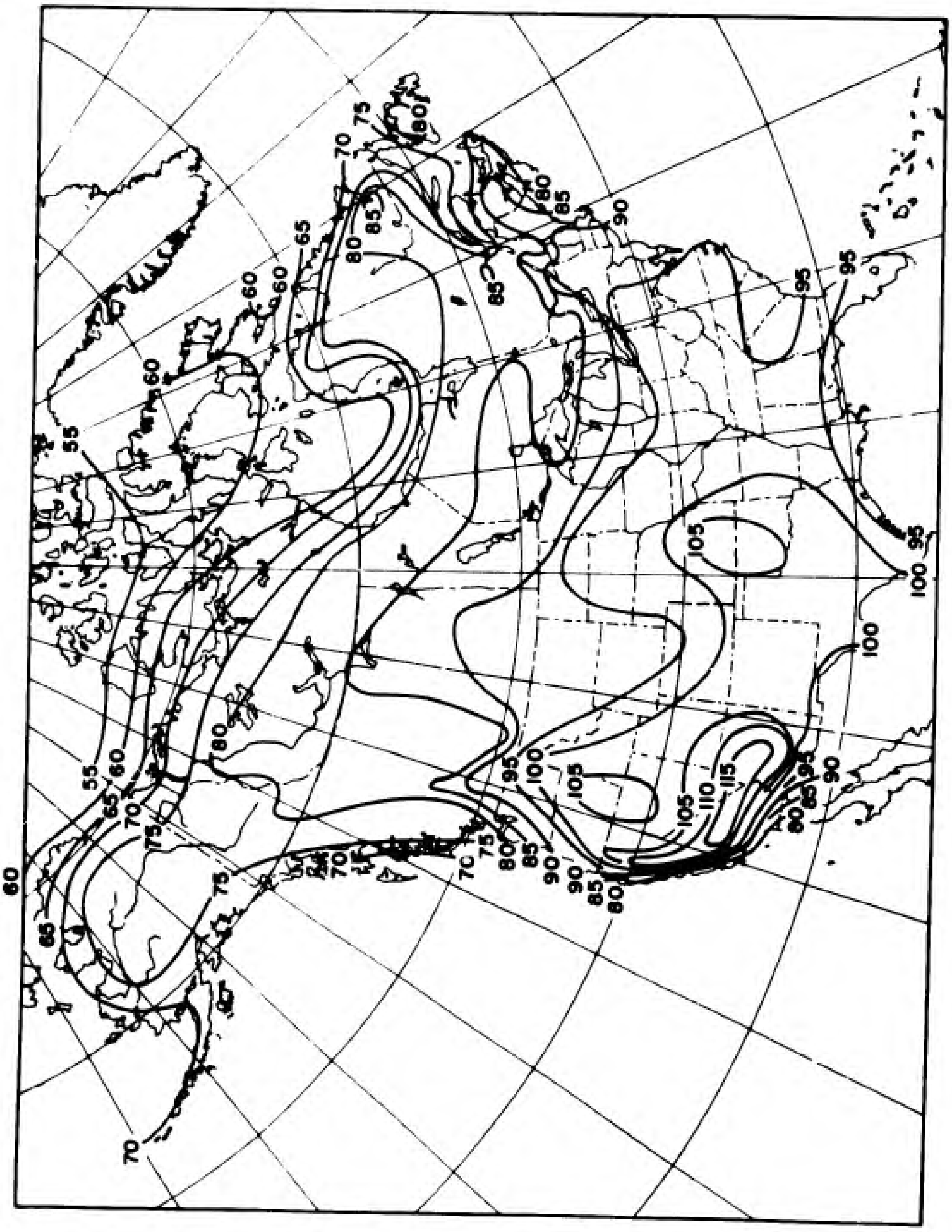


Fig. 11 NINETY-NINE PERCENT DESIGN TEMPERATURES, JULY ISOTHERMS (°F) (Ref. 34)

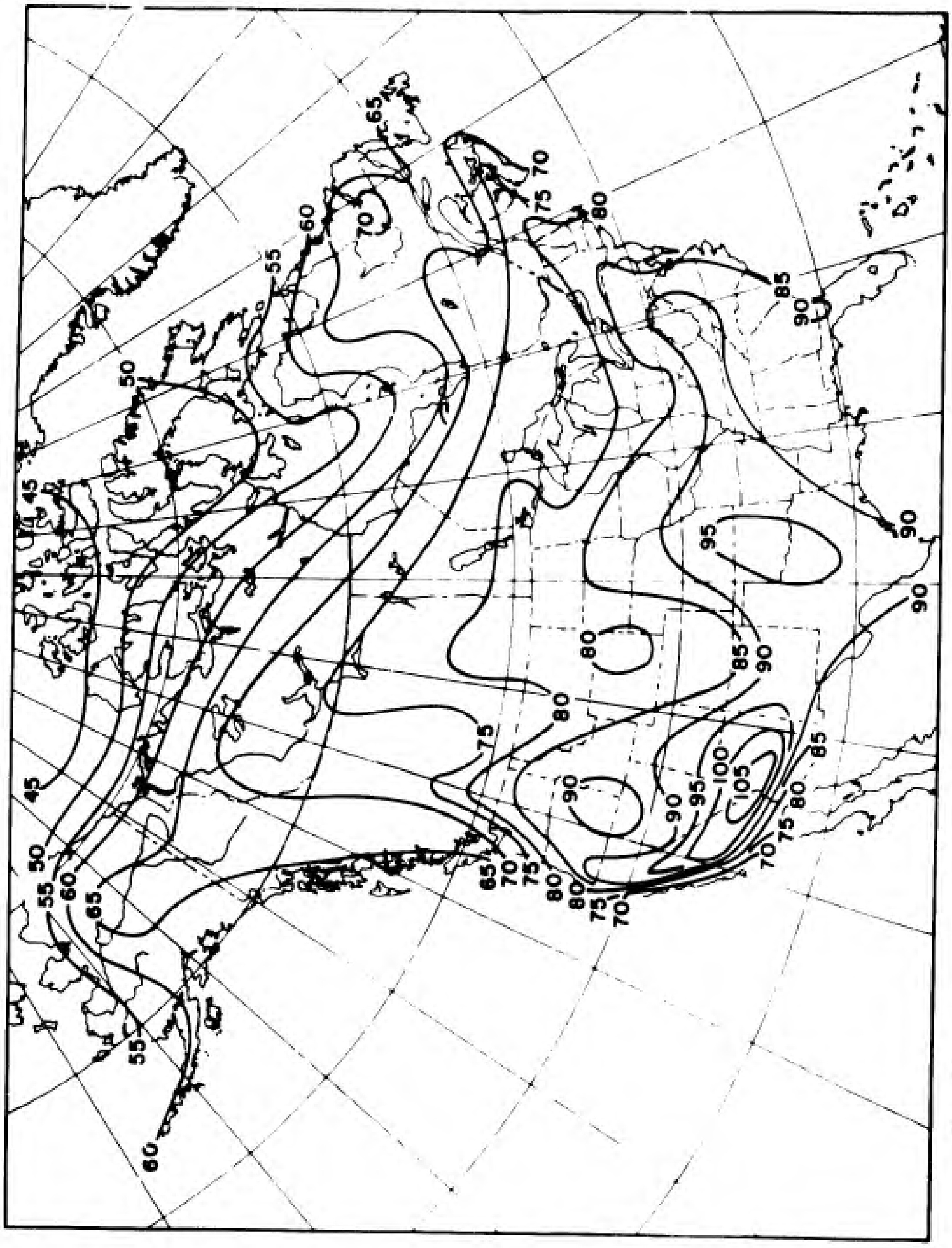


Fig. 12 NINETY PERCENT DESIGN TEMPERATURES, JULY ISOTHERMS (°F) (Ref. 34)

Fig. 13 **REPUBLIC OF VIETNAM STATION LOCATION MAP**

Briefs" (Tables III, IV, and V) for Saigon, Qui Nhon, and Da Nang. For purposes of comparison, similar weather data were secured from the same source for two locations in the United States, Eglin AFB, Florida, and Turner AFB, Georgia, and are shown in Tables VI and VII.

These data indicate a considerable similarity of temperature and humidity conditions between Viet Nam and Florida. The data do not correlate simultaneous combinations of extreme temperature and humidity, but merely give mean daily values and their extremes. Extreme humidity and temperature do not usually occur simultaneously, and it would be erroneous to analyze aircrew cooling requirements on the assumption that extreme values of temperature and humidity given in Tables III through VII do occur simultaneously. On the basis of these data, requests were made to the U.S. Weather Bureau (Navy Unit) for weather data from Saigon, Da Nang, and Qui Nhon for maximum humidity and temperature conditions occurring during July 1966. These data are presented in Table VIII.

The data in Table VIII indicate design conditions that must be considered if the aircrew cooling system is to maintain acceptable crew comfort on the worst day of the year. It is assumed that the aircrewman is exposed to the ambient air and that he experiences discomfort because of combinations of ambient temperature and humidity that will limit his normal cooling through the evaporation of sweat. The "cooling capacity" given indicates the amount of metabolic heat which an aircrewman could reject to ambient ventilating air flowing at a rate of 15 cubic feet per minute, with resultant 95% saturation by sweat evaporation.

The in-plane thermal environment is obviously quite severe when an aircraft in an already hot environment is also exposed to direct solar

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
SILVER SPRING MARYLAND

TABLE III
CLIMATIC BRIEF, SAIGON, VIET NAM

CLIMATIC BRIEF — 48900 SAIGON — 10 49 N 106 40 E 32 FT

ELEMENT	HR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	YR
TEMPERATURE <°F>															
EXTREME MAX.		98	102	103	104	102	99	94	95	96	94	95	97	104	45
MEAN MAX.		89	91	93	94	92	89	88	89	88	88	87	87	90	45
MEAN		78	80	82	84	82	81	80	81	80	80	79	73	80	31
MEAN MIN.		70	71	74	77	76	75	75	75	75	74	73	71	74	45
EXTREME MIN.		57	61	63	60	70	69	67	68	69	68	63	57	57	45
PRECIPITATION <IN.>															
MONTHLY MAX.		4.4	2.0	5.1	7.0	22.1	20.6	23.4	19.6	26.9	23.7	11.3	6.0	107.0	40
MONTHLY MEAN		.6	.2	.4	2.1	8.7	12.5	11.6	10.5	13.3	10.4	4.9	2.3	77.5	40
MONTHLY MIN.		0	0	0	*	1.9	5.9	3.9	4.6	5.5	3.2	.1	0	57.3	40
24HR MAX.		2.7	1.2	4.1	3.5	4.2	5.4	5.9	7.0	7.0	5.1	5.2	3.0	7.0	40
MEAN NUMBER OF DAYS WITH															
PRECIPITATION		2	1	2	6	17	22	23	22	23	21	12	7	158	40
THUNDERSTORM		1	1	2	7	17	15	11	9	11	11	5	*	90	12
FOG		9	7	8	3	5	3	3	3	3	4	3	4	55	10
TOTAL CLOUD	06	10.4	12.9	12.3	9.8	6.8	4.9	4.2	4.4	2.8	4.0	5.2	8.3	85.9	8
COVER ≤3/10	13	7.3	7.4	9.3	3.8	2.5	.7	.3	.6	.5	.3	1.7	3.9	38.8	8
TOTAL CLOUD	06	13.7	9.8	10.9	13.1	17.2	19.6	22.6	20.2	22.7	22.0	10.3	16.4	206.5	8
COVER ≥7/10	13	15.2	10.8	11.3	14.0	21.7	23.5	26.6	25.6	24.0	24.2	21.0	20.0	238.7	8
LOW CLOUD	06	21.8	21.4	24.4	20.8	23.2	21.2	20.9	21.0	16.7	18.9	20.7	20.4	251.4	8
COVER ≤3/10	13	15.8	16.3	15.9	10.4	10.3	7.4	5.8	8.0	9.3	9.3	11.4	13.6	133.5	8
RELATIVE HUMIDITY <%>															
MEAN		76	73	72	75	82	85	85	85	87	86	83	79	81	30
EXTREME MIN.		26	22	26	28	33	42	48	45	47	40	35	31	22	30
EXTREME MAX.		98	99	93	99	99	100	100	99	100	100	100	100	100	35
WIND <16PTS & KNOTS>															
PREVAILING DIRECTION		E	E	SE	SE	S	W	W	W	W	W	N	N		13
PREVAILING SPEED		5	6	7	7	6	7	7	8	7	6	4	4		13
MEAN SPEED		4	5	6	6	5	5	5	6	5	4	4	4	6	13
MAX. SPEED		22	18	21	32	25	28	25	25	25	20	16	18	32	13
LOW LEVEL MEAN RESULTANT WINDS <DDFFV>															
SURFACE		05025	12035	13045	13045	15025	24045	24045	24045	25045	29014	02014	03014		7
50 METERS		07037	12057	13077	13067	15047	23067	23067	24067	24057	17017	05026	06027		7
100 METERS		07048	11068	13087	13077	15048	23078	23078	24088	24077	18018	05027	06027		7
150 METERS		07049	11079	13099	14098	15059	23099	23099	24109	24088	19019	06039	06038		7
200 METERS		08059	1108A	13109	14109	1606A	23119	2410A	24119	24108	2001A	06039	07039		7
300 METERS		0805A	11098	1211A	1411A	1607B	2414B	2413B	2414B	24129	2001B	0704A	07039		7
400 METERS		0805A	1110B	1212B	1312B	1607C	2415B	2414B	2515C	2513A	2001C	0704A	06039		7
500 METERS		08059	1109B	1212C	1312B	1607D	2516C	2515C	2516C	2514A	2102C	0704A	05039		7
CEILING <% OF TIME>															
<20,000 FT.		33	29	33	39	48	48	52	53	49	46	45	50		6
<10,000 FT.		27	24	30	33	39	36	42	41	39	39	36	41		6
<5,000 FT.		20	18	23	28	37	33	38	37	36	35	30	31		6
<3,000 FT.		16	15	20	25	32	29	34	34	33	31	25	26		6
VISIBILITY <% OF TIME>															
<5 MI.	ALL HRS	6.1	5.5	5.6	6.2	8.3	10.0	9.2	9.3	10.9	10.9	5.6	5.8		6
<5 MI.	03-08	18.6	17.7	18.5	7.5	13.0	13.9	13.7	11.9	16.9	15.8	12.4	15.4		6
<5 MI.	09-14	3.0	2.1	3.1	1.5	5.4	3.9	6.2	7.1	8.5	7.2	1.6	2.6		6
<1 MI.	ALL HRS	1.6	1.2	.7	.9	2.3	1.9	1.6	1.5	1.4	1.8	1.4	1.3		6
<1 MI.	03-08	2.8	2.3	.8	1.6	2.7	2.3	2.0	1.6	1.8	2.6	3.3	2.1		6
<1 MI.	09-14	1.7	.8	1.5	.7	2.7	1.3	2.2	1.9	1.7	2.0	.6	1.3		6
TERMINAL WEATHER <% OF TIME>															
CIG<5000 FT.	ALL HRS	24.7	22.4	27.2	32.2	41.6	39.3	42.8	42.1	42.9	41.2	32.8	34.4		6
A/O VSBY<5MI.	06-11	25.9	32.9	45.2	48.2	31.5	52.5	53.5	57.6	63.6	51.5	33.7	34.6		6
	12-17	35.9	32.4	38.8	45.4	57.3	54.3	59.6	56.3	51.8	49.3	50.2	51.9		6
CIG<1500 FT.	ALL HRS	16.0	14.1	16.2	16.2	24.8	21.5	25.5	25.1	26.2	26.3	20.5	22.4		6
A/O VSBY<3MI.	06-11	20.9	19.4	27.9	20.1	29.1	29.9	34.5	37.9	37.5	33.3	25.8	22.2		6
	12-17	20.3	18.1	18.0	16.9	33.2	28.8	30.5	29.1	29.2	29.1	29.5	29.6		6
CIG <500 FT.	ALL HRS	13.8	11.6	12.6	14.0	22.3	15.6	20.5	19.2	19.3	20.4	17.3	20.2		6
A/O VSBY<1MI.	06-11	13.3	11.5	15.7	18.9	25.1	18.1	24.6	24.4	24.4	21.7	15.7	15.3		6
	12-17	20.0	17.6	17.2	15.5	30.6	21.7	25.1	23.9	24.8	23.4	27.4	20.5		6
MISCELLANEOUS															
MEAN PRESS.-MSL<MBS>		1013	1010	1011	1009	1007	1008	1007	1007	1008	1010	1011	1011	1009	31
MEAN CLOUDINESS<%>		53	46	49	58	72	70	82	79	82	74	68	63	67	34

TABLE IV
CLIMATIC BRIEF, QUI NHON, VIET NAM

CLIMATIC BRIEF   48870 QUI NHON

13 46 N   109 13 E   36 FT

ELEMENT	HR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	YR
TEMPERATURE <°F>															
EXTREME MAX.		91	96	101	97	103	106	108	106	102	99	91	87	108	32
MEAN MAX.		78	80	83	87	90	92	92	94	89	84	81	78	86	32
MEAN		73	75	77	81	83	85	85	85	82	79	77	74	80	36
MEAN MIN.		69	70	72	75	78	79	79	79	77	75	73	71	75	32
EXTREME MIN.		59	60	61	67	66	71	69	69	69	64	59	61	59	32
PRECIPITATION <IN.>															
MONTHLY MAX.		6.9	8.0	5.2	4.0	6.2	10.6	10.5	8.0	23.7	40.0	26.3	18.2	121.3	31
MONTHLY MEAN		2.0	1.4	1.0	.9	2.1	2.3	2.6	1.9	10.1	17.4	16.5	6.3	64.7	31
MONTHLY MIN.		.2	*	0	*	.1	*	*	*	1.[illegible]	3.3	4.1	.7	33.7	31
24HR MAX.		4.1	5.3	2.6	3.3	2.9	5.6	4.9	3.6	10.6	12.0	15.1	5.1	15.1	31
MEAN NUMBER OF DAYS WITH															
PRECIPITATION		10	5	3	3	5	5	6	6	15	18	18	16	110	31
THUNDERSTORM		0	*	*	2	7	4	5	4	7	2	*	0	31	9
FOG		4	3	2	0	0	0	0	0	0	*	*	*	9	7
TOTAL CLOUD	06	6.5	11.5	14.3	14.9	18.2	15.4	10.5	11.0	9.7	7.1	5.3	4.9	129.3	8
COVER ≤3/10	13	8.2	13.7	21.5	20.9	18.8	12.9	11.3	10.9	10.7	8.5	5.6	6.0	149.0	8
TOTAL CLOUD	06	6.5	11.5	14.3	14.9	18.2	15.4	10.5	11.0	9.7	7.1	5.3	4.9	129.3	8
COVER ≥7/10	13	19.4	11.2	6.8	4.9	5.4	10.5	12.8	13.2	13.1	15.4	19.7	21.2	153.6	8
LOW CLOUD	06	9.6	13.1	17.4	18.6	27.0	23.2	19.1	22.3	20.7	11.7	9.6	7.9	200.2	8
COVER ≤3/10	13	13.3	16.6	23.9	23.6	27.5	21.9	21.6	21.6	20.3	15.4	9.9	9.4	225.0	8
RELATIVE HUMIDITY <%>															
MEAN		84	85	83	83	81	77	70	73	81	85	86	85	81	11
EXTREME MIN.		47	37	42	45	35	30	30	31	37	46	45	48	30	11
EXTREME MAX.		100	100	100	99	100	99	98	98	100	100	100	100	100	18
WIND <16PTS & KNOTS>															
PREVAILING DIRECTION		N	N	N	SE	SE	SE	W	W	NW	N	N	N		6
PREVAILING SPEED		9	10	8	9	9	9	9	9	5	8	10	10	9	6
MEAN SPEED		9	8	7	7	6	7	7	7	6	7	8	9	7	6
MAX. SPEED		24	23	24	26	20	25	19	26	25	36	24	24	36	6
LOW LEVEL MEAN RESULTANT WINDS <DDFFV>															
SURFACE		35076	00057	00028	11027	13037	26037	27048	26036	29016	35046	35066	35096		7
50 METERS		35077	00068	07028	11038	14037	25037	26048	26037	29026	34057	35077	35097		7
100 METERS		35087	00078	07029	11038	14037	25047	25058	25047	29037	35067	35088	35107		7
150 METERS		00098	01089	07029	11039	14038	25048	25069	25047	28037	35068	00108	35118		7
200 METERS		00108	01089	0702A	11039	15038	25058	25069	25057	28047	35078	00108	00117		7
300 METERS		00118	0109A	0702A	12039	16048	25068	25079	25067	28058	00078	00118	00138		7
400 METERS		01129	0209A	0802A	12039	17049	25088	25099	25078	27058	00088	01128	01138		7
500 METERS		01129	0209B	0802A	1203A	18049	26098	25099	25098	27069	00089	01129	01148		7
CEILING <% OF TIME>															
<20,000 FT.		75	54	42	35	32	39	41	44	37	65	76	73		6
<10,000 FT.		74	53	39	30	26	26	29	30	27	57	73	70		6
<5,000 FT.		58	43	33	24	22	18	22	21	24	48	63	54		6
<3,000 FT.		32	25	23	19	19	16	19	16	20	43	53	37		6
VISIBILITY <% OF TIME>															
<5 MI.	ALL HRS	11.1	4.7	2.1	3.4	2.6	1.3	1.7	2.2	4.8	11.9	13.3	10.7		6
<5 MI.	03-08	13.8	7.4	4.6	7.0	.7	1.8	.6	1.5	5.1	12.0	14.5	14.7		6
<5 MI.	09-14	7.7	3.3	1.3	2.5	.8	.3	.6	.4	3.1	8.2	14.5	10.3		6
<1 MI.	ALL HRS	2.5	.9	.5	.7	1.1	.3	.3	.7	1.7	4.0	3.1	1.8		6
<1 MI.	03-08	2.3	2.5	.6	1.7	.2	.3	.3	.2	2.1	3.7	2.3	2.3		6
<1 MI.	09-14	2.9	.6	.4	.4	.0	.0	.0	.2	1.1	1.1	3.5	2.8		6
TERMINAL WEATHER <% OF TIME>															
CIG<5000 FT.	ALL HRS	59.1	43.4	33.1	25.4	22.4	18.3	22.2	22.1	26.3	50.4	64.1	55.1		6
A/O VSBY<5MI.	06-11	61.1	52.7	38.8	26.3	20.9	13.8	18.2	14.1	18.7	52.5	64.3	63.1		6
	12-17	52.9	34.6	20.3	14.7	17.2	23.2	25.0	26.4	31.5	44.9	64.0	55.6		6
CIG<1500 FT.	ALL HRS	19.5	14.6	11.3	12.6	16.2	14.4	17.4	15.7	17.0	29.8	26.9	19.1		6
A/O VSBY<3MI.	06-11	24.1	20.2	15.5	11.5	16.4	10.5	14.4	9.4	12.3	30.8	29.6	22.4		6
	12-17	20.2	12.3	8.6	9.0	14.8	19.3	20.7	20.8	22.2	26.2	27.9	19.3		6
CIG <500 FT.	ALL HRS	10.0	8.9	7.7	9.4	15.3	13.1	15.8	14.2	13.9	17.3	14.7	11.0		6
A/O VSBY<1MI.	06-11	12.3	12.0	9.9	8.5	15.0	9.7	13.7	8.9	10.2	16.7	14.1	11.8		6
	12-17	12.4	9.2	7.3	7.2	14.5	18.3	18.6	20.2	19.6	16.8	16.1	13.2		6
MISCELLANEOUS															
MEAN PRESS.-MSL<MBS>		1017	1014	1014	1010	1008	1006	1005	1005	1007	1011	1014	1014	1010	20
MEAN CLOUDINESS<%>		72	55	49	44	48	52	62	57	65	72	77	80	61	14

TABLE V
CLIMATIC BRIEF, DA NONG, VIET NAM

CLIMATIC BRIEF 4[illegible]85[illegible] DA NANG <TOURANE>

1[illegible] 02 N 108 11 E 23 FT

ELEMENT	HR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN	YR.
							TEMPERATURE <°F>								
EXTREME MAX.		94	98	99	105	102	105	105	102	99	96	90	87	105	23
MEAN MAX.		75	78	81	86	91	92	96	93	88	83	80	76	85	33
MEAN		69	72	77	80	83	83	86	84	82	79	76	75	79	28
MEAN MIN.		65	63	70	73	76	77	77	76	75	73	71	68	72	33
EXTREME MIN.		52	56	59	62	71	72	71	70	68	63	56	56	52	23
							PRECIPITATION <IN.>								
MONTHLY MAX.		12.4	10.4	5.7	7.6	16.6	20.9	9.9	13.2	46.3	49.5	38.0	21.3	120.6	27
MONTHLY MEAN		4.2	1.8	.9	1.3	2.6	2.8	2.8	4.7	15.7	23.3	15.1	8.7	83.9	27
MONTHLY MIN.		.6	*	*	*	0	.1	.1	.2	3.0	2.6	3.8	1.6	43.0	27
24HR MAX.		10.1	6.8	5.4	6.0	4.8	13.1	3.8	5.9	12.8	11.0	10.7	12.6	13.1	27
							MEAN NUMBER OF DAYS WITH								
PRECIPITATION		14	8	4	5	8	8	8	12	13	22	20	19	141	27
THUNDERSTORM		0	1	1	5	11	9	9	8	7	2	*	0	53	12
FOG		1	1	3	1	0	0	0	0	0	0	0	1	7	4
TOTAL CLOUD	06	4.3	5.7	4.9	5.9	6.0	6.3	4.4	3.3	4.8	6.2	2.2	2.0	56.0	8
COVER ≤3/10	13	7.2	10.3	12.0	11.8	10.2	5.6	5.2	4.5	6.3	7.7	3.9	4.0	88.7	8
TOTAL CLOUD	06	24.4	18.7	22.8	17.9	18.8	17.6	22.1	24.2	21.6	22.2	25.1	27.2	262.6	8
COVER ≥7/10	13	19.6	13.9	15.1	12.5	14.3	18.1	22.1	22.8	19.8	20.5	22.3	23.9	224.9	8
LOW CLOUD	06	8.1	10.5	12.4	19.8	27.0	26.7	25.0	26.7	21.2	14.7	8.1	6.7	206.9	8
COVER ≤3/10	13	15.8	17.4	20.4	25.6	27.0	25.0	26.7	25.7	23.1	16.7	10.8	10.1	244.3	8
							RELATIVE HUMIDITY <%>								
MEAN		86	86	85	84	81	77	75	77	84	86	86	86	83	23
EXTREME MIN.		36	36	30	26	31	27	31	32	26	40	35	35	26	23
EXTREME MAX.		100	100	100	100	100	100	100	100	100	100	100	100	100	28
							WIND <16PTS & KNOTS>								
PREVAILING DIRECTION		N	E	E	E	E	E	E	E	N	N	N	N	•	13
PREVAILING SPEED		9	7	7	7	8	7	8	7	9	9	9	9	8	13
MEAN SPEED		5	5	5	5	5	4	4	3	4	5	5	5	5	13
MAX. SPEED		26	28	30	24	20	33	25	28	28	40	30	36	40	13
							LOW LEVEL MEAN RESULTANT WINDS <DDFFV>								
SURFACE		01025	03026	06026	08026	08026	05015	13015	07014	01015	02025	03035	03025		7
50 METERS		00027	03027	08027	10027	12027	20016	20026	19016	32017	01037	03037	01027		7
100 METERS		01027	03028	09027	11037	13028	21017	20027	20017	31017	02038	04048	02038		7
150 METERS		01038	04028	10028	12038	14028	21027	21038	21017	31018	02049	04059	02039		7
200 METERS		02038	05029	11028	13038	15028	21027	21038	21027	30018	03049	04069	04049		7
300 METERS		03039	07029	13028	15038	16028	22038	21048	21027	28019	0405A	0506A	05049		7
400 METERS		05039	09029	14078	16048	18038	22048	22048	22038	26019	0405A	0507A	0505A		7
500 METERS		06049	09039	15038	16049	19038	22048	22059	22048	25029	0405B	0608A	0605A		7
							CEILING <% OF TIME>								
<20,000 FT.		76	70	57	43	34	34	36	38	42	67	65	72		6
<10,000 FT.		74	69	54	36	24	21	22	22	29	60	63	70		6
<5,000 FT.		46	45	38	24	17	14	15	13	23	40	38	44		6
<3,000 FT.		23	20	20	16	12	10	13	10	16	27	29	29		6
							VISIBILITY <% OF TIME>								
<5 MI.	ALL HRS	14.2	7.4	6.3	3.8	1.3	3.3	1.9	1.5	3.4	13.1	8.1	8.4		6
<5 MI.	03-08	16.4	12.6	12.7	8.4	1.4	1.8	1.6	.5	3.1	14.4	12.7	9.2		6
<5 MI.	09-14	14.4	6.7	5.2	2.0	.9	1.6	1.0	.5	2.2	10.3	7.5	7.1		6
<1 MI.	ALL HRS	1.7	1.2	1.9	1.6	.6	.4	.9	.3	.7	2.0	1.2	1.4		6
<1 MI.	03-08	2.3	2.3	3.5	2.4	.3	.6	.7	.3	.4	2.1	1.6	1.3		6
<1 MI.	09-14	1.5	.8	1.7	1.3	.2	.2	.9	.4	.6	1.6	1.4	2.3		6
							TERMINAL WEATHER <% OF TIME>								
CI[illegible] [illegible]00 FT.	ALL HRS	47.6	46.0	40.9	25.6	17.2	14.5	15.4	13.5	24.2	42.5	41.0	45.1		6
A/O [illegible]BY<5MI.	06-11	52.3	53.4	49.2	29.2	15.2	8.6	10.0	9.6	17.2	44.9	52.4	46.6		6
	12-17	39.7	33.8	27.4	16.8	15.2	16.2	17.3	12.8	21.5	39.6	33.9	41.4		6
CIG<1500 FT.	ALL HRS	14.5	11.4	13.6	11.6	10.4	8.8	11.3	9.9	13.7	20.8	22.0	16.5		6
A/O VSBY<3MI.	06-11	15.7	16.6	21.3	13.8	11.1	5.0	8.8	7.7	9.6	20.0	26.0	18.5		6
	12-17	12.5	10.6	11.4	9.6	10.7	11.1	14.1	10.7	13.8	20.4	25.8	20.7		6
CIG <500 FT.	ALL HRS	5.5	7.1	8.0	8.8	10.0	7.4	10.6	9.3	11.9	12.8	14.6	10.8		6
A/O VSBY<1MI.	06-11	5.9	7.7	10.6	10.0	10.7	4.4	8.7	7.7	8.7	12.4	17.5	12.1		6
	12-17	5.8	9.1	9.7	8.6	10.4	10.3	13.7	10.4	12.4	12.5	16.6	16.2		6
							MISCELLANEOUS								
MEAN PRESS.-MSL<MBS>		1018	1014	1013	1010	1007	1005	1004	1004	1005	1011	1015	1015	1010	26
MEAN CLOUDINESS<%>		77	64	60	53	61	59	73	68	75	76	81	82	69	10

TABLE VI
CLIMATIC DATA SUMMARY, EGLIN AFB, FLORIDA

CLIMATIC DATA SUMMARY — BASE: Eglin AFB, Florida

FIELD LOCATION: 30°29'N 86°31'W — FIELD ELEVATION: 5?' — PERIOD OF RECORD: Jan 1940 - Apr 1955 — DATE: Feb 61

ITEM	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TEMPERATURE												
EXTREME MAXIMUM	79	81	89	93	103	103	101	105	97	95	87	79
MEAN DAILY MAXIMUM	62	65	69	76	84	89	90	91	87	81	69	63
MEAN DAILY MINIMUM	43	45	50	57	64	72	73	73	69	59	47	43
EXTREME MINIMUM	10	12	18	28	40	56	60	64	48	32	16	18
MEAN NO OF DAYS												
MAXIMUM ≥ 90°F	0	0	0	#	3	14	15	19	10	1	0	0
MAXIMUM ≥ 80°F	0	#	1	10	25	30	31	30	27	21	2	0
MINIMUM ≤ 32°F	6	4	1	#	0	0	0	0	0	#	2	4
MINIMUM ≤ 0°F	0	0	0	0	0	0	0	0	0	0	0	0
PRECIPITATION												
MEAN MONTHLY												
PRECIPITATION (INCHES)	3.7	3.6	6.8	5.4	3.7	5.1	8.0	7.4	7.7	1.6	3.8	5.5
SNOWFALL (INCHES) (a)	0	0	0	0	0	0	0	0	0	0	0	0
MEAN NO OF DAYS												
PRECIPITATION	7	7	9	7	6	10	15	13	10	4	6	9
MEASURABLE SNOWFALL	0	0	0	0	0	0	0	0	0	0	0	0
SNOWFALL ≥ 1.5 INCHES	0	0	0	0	0	0	0	0	0	0	0	0
FLYING WEATHER (PERCENTAGE) (b)												
OBSERVATIONS WITH CEILINGS < 5,000 FT AND VISIBILITY < 5 MILES	40	37	34	31	21	17	15	13	19	15	25	37
OBSERVATIONS WITH CEILINGS < 1500 FT AND VISIBILITY < 3 MILES	24	20	22	21	11	4	3	2	8	5	12	21
OBSERVATIONS WITH CEILINGS < 1000 FT AND VISIBILITY < 3 MILES	20	17	19	17	7	3	2	2	5	4	10	17
OBSERVATIONS WITH CEILINGS BELOW 300'/1mi	10	7	7	5	2	1	1	1	1	1	4	7
TAKE OFF DATA												
MEAN VAPOR PRESS. (IN. HG)	.31	.34	.35	.45	.62	.76	.83	.83	.71	.48	.32	.30
TEMPERATURE OF DEWPT.	46	48	49	56	65	71	73	73	69	58	47	45
99.95% PRES. ALT (FEET)	500	500	450	450	400	450	200	200	250	450	450	350

REMARKS:

(a) Snow data Jan 1940 - Dec 1948
(b) Flying weather data May 1948 - Apr 1958

NOTE: # DATA NOT AVAILABLE. ⊕ LESS THAN 0.5 DAYS, 0.5%, OR 0.5 IN., AS APPLICABLE.

TABLE VII
CLIMATIC DATA SUMMARY, TURNER AFB, GEORGIA

CLIMATIC DATA SUMMARY — BASE: Turner AFB, Georgia

FIELD LOCATION: 31°35'N 84°07'W — FIELD ELEVATION: 217' — PERIOD OF RECORD: Oct 41 - Jun 46, Feb 48 - Sep 53 a — DATE: Nov 1961

ITEM	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TEMPERATURE												
EXTREME MAXIMUM	85	83	91	93	101	103	103	101	103	95	87	79
MEAN DAILY MAXIMUM	64	65	71	77	86	92	92	91	86	79	69	61
MEAN DAILY MINIMUM	44	45	51	56	65	72	73	72	68	58	46	42
EXTREME MINIMUM	20	16	20	34	46	60	66	62	50	33	16	20
MEAN NO OF DAYS												
MAXIMUM ≥ 90°F	0	0	#	1	10	21	21	20	10	#	0	0
MAXIMUM ≥ 80°F	#	1	6	14	30	30	30	31	26	17	3	0
MINIMUM ≤ 32°F	3	2	#	0	0	0	0	0	0	0	1	5
MINIMUM ≤ 0°F	0	0	0	0	0	0	0	0	0	0	0	0
PRECIPITATION												
MEAN MONTHLY												
PRECIPITATION (INCHES)	3.1	3.4	6.6	4.2	4.5	3.2	5.1	4.1	3.8	1.5	2.5	4.2
SNOWFALL (INCHES)	#	#	0	0	0	0	0	0	0	0	0	0
MEAN NO OF DAYS												
PRECIPITATION	8	8	10	8	8	10	13	10	9	5	5	8
MEASURABLE SNOWFALL	0	0	0	0	0	0	0	0	0	0	0	0
SNOWFALL ≥ 1.5 INCHES	0	0	0	0	0	0	0	0	0	0	0	0
FLYING WEATHER (PERCENTAGE)												
OBSERVATIONS WITH CEILINGS < 3,000 FT AND VISIBILITY < 3 MILES	34	36	30	23	18	17	23	20	26	22	26	38
OBSERVATIONS WITH CEILINGS < 1500 FT AND VISIBILITY < 3 MILES	15	18	15	8	6	4	7	7	11	10	11	20
OBSERVATIONS WITH CEILINGS < 1000 FT AND VISIBILITY < 3 MILES	12	14	11	5	4	2	4	5	7	7	9	17
OBSERVATIONS WITH CEILINGS BELOW 300/1 mi	4	3	2	1	1	#	1	1	1	1	3	6
TAKE OFF DATA												
MEAN VAPOR PRESS (IN. HG)	.28	.29	.31	.40	.56	.71	.76	.74	.64	.45	.30	.27
TEMPERATURE OF DEWPT.	43	44	46	53	62	69	78	70	66	56	45	42
99.95% PRES. ALT (FEET)	600	650	600	600	500	450	350	350	400	550	650	450

REMARKS:

a FLY WX - Nov 44 - Jun 46, Feb 48 - Jun 56.

NOTE: # DATA NOT AVAILABLE. ⊕ LESS THAN 0.6 DAYS, 0.6% OR 0.6 IN., AS APPLICABLE.

TABLE VIII
TEMPERATURE AND HUMIDITY CONDITIONS, SOUTH VIET NAM, JULY 1966

	TEMPERATURE (°F)		RELATIVE HUMIDITY	COOLING CAPACITY*	CLOUD COVER	
	Dry Bulb	Wet Bulb	(%)	(Btu/hr)	Date	Time
DA NANG (July, 1966)						
Maximum Temperature	99	70	22	950	July 3	1455
Maximum Relative Humidity	82	77	85	920	July 25	1355
Worst Cooling Condition	93	78	50	680	July 31	1255
SAIGON (July, 1966)						
Maximum Temperature	98.2	78	41	560	July 28	1300
Maximum Relative Humidity	82	77	80	910	July 23	0900
Worst Cooling Condition	98.2	78	41	560	-	-
QUI NHON (July, 1966)						
Maximum Temperature	101.8	79.8	39	368	July 3	1500
Maximum Relative Humidity	83	79.6	87	880	July 18	1700
Worst Cooling Condition	101.8	79.8	39	368	July 3	1500

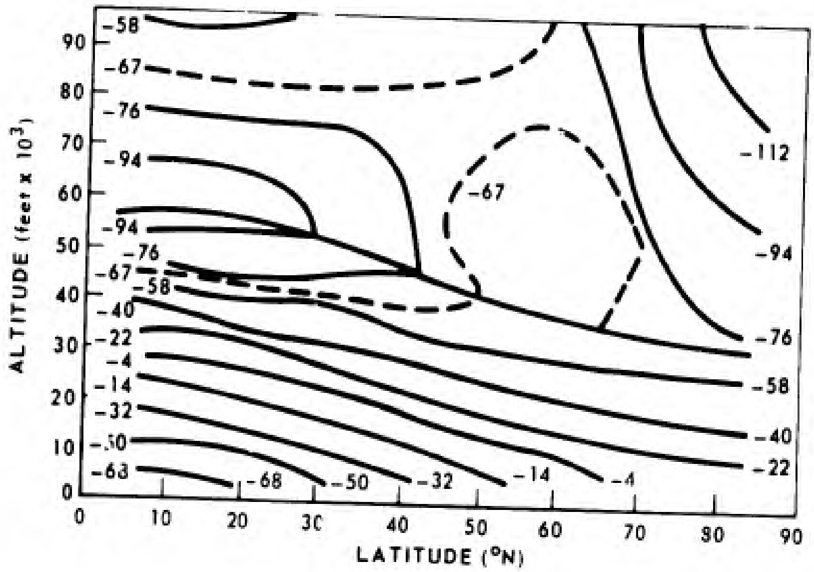
National Weather Records Center
U. S. Weather Bureau Section Navy Unit
Asheville, North Carolina

*Cooling capacity computed as per Appendix F.

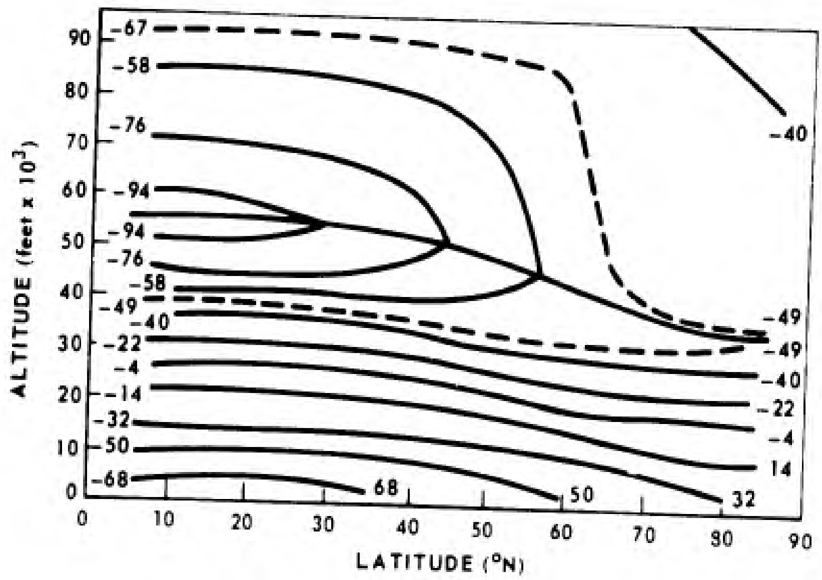
heating and parked with the air conditioning inoperative. When the aircraft engines are operative, ventilating air at lower than cockpit temperatures may be provided to cool the aircrewman. In some cases (reputedly the Navy A-5 attack bomber), the cabin conditioning air and the air supplied for electronics cooling are interconnected. Through a combination of circumstances, conditioning air introduced into the cockpit during idle has a higher-than-ambient temperature.

After take-off, the higher-power operation of aircraft engines generally provides more effective air conditioning. Ambient air temperature decreases with altitude during stable weather conditions as shown in Fig. 14. During abnormal weather conditions (e.g., storms) ground-level air temperatures may vary widely from nominal. Most such local activity is below 10,000 feet. When ground temperatures are high, the initial slope of the temperature-versus-altitude curve is steeper than usual.

Aircraft flight speeds approaching or exceeding sonic speeds produce intense air heating due to the compression effect. If the intake air to the aircraft is from the aircraft boundary layer (e.g., through a hole in the windscreen or canopy) the air will be heated as shown in Fig. 15. The first curve (M = 0.0) presents the maximum "hot day" air temperatures as a function of altitude; succeeding curves show the air temperatures produced for flight speeds from 0.25 to 1.5 times sonic speed. Air heating is negligible at sea level for speeds of 160 knots (M = 0.25), but increases rapidly with speed, and would produce temperatures intolerably high (160°F) at speeds of 500 knots (M = 0.75). Only jet or turbojet powered aircraft are capable of attaining speeds much in excess of M = 0.5, and these aircraft types can, and must, have both cabin insulation and air conditioning (by air bled from the jet engine compressor and cooled through an "air-cycle" refrigeration process).



(A) JANUARY



(B) JULY

Fig. 14 AVERAGE TEMPERATURES (°F) vs. ALTITUDE (Ref. 34)

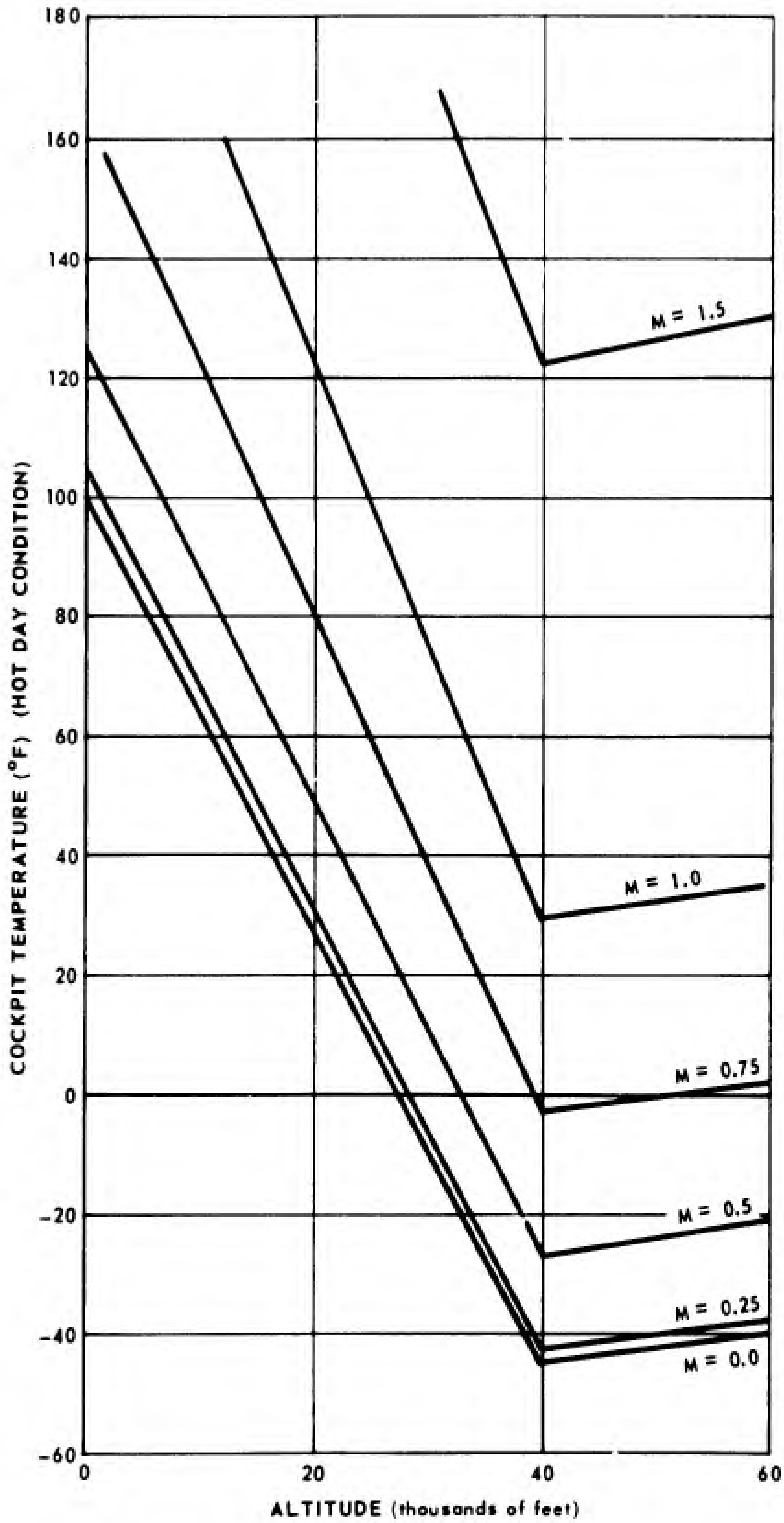


Fig. 15 EFFECT OF AIRCRAFT FLIGHT SPEED ON AIRCRAFT BOUNDARY LAYER TEMPERATURES

C. Analysis of the Thermal Environment of the Aircrewman

The thermal exposure of the aircrewman begins when he leaves the ready room and it continues until he returns to the ground. There are four principal phases of this exposure:

(1) Travel to aircraft from ready room.
(2) On-the-ground aircraft pre-flight inspection.
(3) In-the-aircraft pre-takeoff checkout.
(4) Post-takeoff flight.

In the first two phases, the aircrewman experiences the same thermal environment as the ground personnel, but he is burdened by his flight garments. In the third phase the thermal problem is twofold: first, although the aircrewman is in the cockpit, the aircraft lacks the in-flight operation of climate conditioning; and secondly, the cockpit must be cooled down from previous solar exposure. During the post-takeoff flight phase, the crewman is in the controlled cabin environment provided by cabin ventilation or air conditioning.

1. Analysis of the Effects of Solar Radiation and Thermal Convection on a Man Standing on the Ground

a. Heat Transfer by Radiation Outside Cockpit. While on the ground outside the aircraft, the aircrewman is exposed to the direct radiation of the sun, heat reflection/re-radiation from the earth, and heating through contact with the ambient air. The following analysis of these thermal inputs uses the approach outlined in Ref. 33, which is a compendium of analytical methods and empirical data for use in the computation of thermal inputs to the aircrewman.

The intensity of incident radiation upon a man is a function of the percent cloud cover, geographic location, time of year and day, and clothing coverage.

On a clear day, the total radiation incident to Earth's surface is 69% of that outside of its atmosphere. Normal incident radiation in space is 428 Btu/(ft^2-hr); incident radiation at Earth's surface is equal to 296 Btu/(ft^2-hr). On an overcast day, this drops to 150 Btu/(ft^2-hr), which is approximately 35% of normal incident radiation in space. At night, this drops to zero. The rate ($\Delta Q/\Delta t$ = Btu/hr) at which a man will absorb this direct solar energy is expressed by the equation,

$$\frac{\Delta Q}{\Delta t} = S\, t\, \alpha\, A_s ,$$

where

S = incident radiation in space, 428 Btu/(ft^2-hr),

t = atmospheric transmission (0.35 - 0.69),

A_s = projected area (of man) exposed to solar radiation. This may be as much as 25% of his total body surface area. The total surface area for the average aircrew member is 19.35 ft^2, and the maximum value of A_s is 4.85 ft^2, and

α = $\dfrac{\text{solar energy absorbed by the clothing}}{\text{total incident solar energy}}$.

In addition to this absorption of direct solar radiation, the man absorbs re-radiated heat from the earth, which has also absorbed solar radiation. The energy that is absorbed by the man from this source may be expressed by the equation

$$\frac{\Delta Q}{\Delta t} = 0.5\, \alpha\, \epsilon\, \sigma\, A\, T^4 ,$$

where

$\frac{\Delta Q}{\Delta t}$ = heat exchange (Btu/hr), 0.5 = geometric factor for the man (an index of the effect of physical characteristics of the human upon absorption of energy from the earth's surface),

α = absorptivity of the man or his clothing (for infrared energy),

ϵ = emissivity of the surface of the ground (for infrared energy),

σ = Boltzmann's constant = 0.173×10^{-8} Btu/(ft^2 - hr-°R^4),

A = area of the man (ft^2), and

T = temperature of the surface of the earth (°R = 460 + °F).

These two equations can be combined to form a general expression for radiant heat absorption:

$$\frac{\Delta Q}{\Delta t} = S\,t\,\alpha A_s + 0.5\,\alpha\,\epsilon\,\sigma A\,T^4$$

Example: On a clear day, a pilot dressed in a flight coverall (with $\alpha = 0.6$), stands on a black-top runway (which has $\epsilon = 0.8$ and a surface temperature of 140°F, 600°R) with the sun directly overhead. The radiant heat absorption he will experience is:

$$\frac{\Delta Q}{\Delta t} = \left[(428)(0.69)(0.6)(0.645)\right] + \left[(0.5)(0.6)(0.8)(0.173 \times 10^{-8})\right.$$

$$\left.(19.35)(1.296 \times 10^{11})\right] = (114.28) + (1041.22) = 1155.50 \text{ Btu/hr.}$$

For an overcast day and with the same pilot dressed similarly and standing at the same place on the runway in an ambient temperature of 90°F (which would also be ground temperature), the t term would change to 0.35, and the radiant heat absorption becomes:

$$\frac{\Delta Q}{\Delta t} = \Big[(428)(0.35)(0.6)(0.645)\Big] + \Big[(0.5)(0.6)(0.8)(0.173 \times 10^{8})$$

$$\cdot (19.35)(9.15 \times 10^{10})\Big] = (57.97) + (735.12) = 793.1 \text{ Btu/hr.}$$

b. Heat Transfer by Convection. The Bioastronautics Handbook (Ref. 33) provides a summary of computational techniques for assessing convective thermal transfer to an aircrewman from his environment. A convenient nomogram, Fig. 7-18 in this reference, has been reproduced here as Fig. 16. The nomogram shows the convective heat transfer to a man clad in garments having an insulation value of 0 to 2 clo*.

2. Analysis of Thermal Radiation and Convection in Aircraft Cockpits.

Aircraft cabin environmental parameters that affect the thermal balance of a man within the cabin are:

(1) solar radiation,
(2) shade dry-bulb air temperature,
(3) mean cabin-wall temperature (which affects gray-body radiation),
(4) insulation properties of the cabin air as it affects heat transfer to crewman, and
(5) metabolic activity of crewman.

The crewman gains heat from body metabolic activity, incident solar radiation, reflection and radiation of thermal energy from the cockpit surfaces, and convection. If the temperature of the cabin environment is higher than the aircrewman's body temperature, he must eliminate heat either by convection or evaporation of sweat. Excess

*See Section II-D-2.

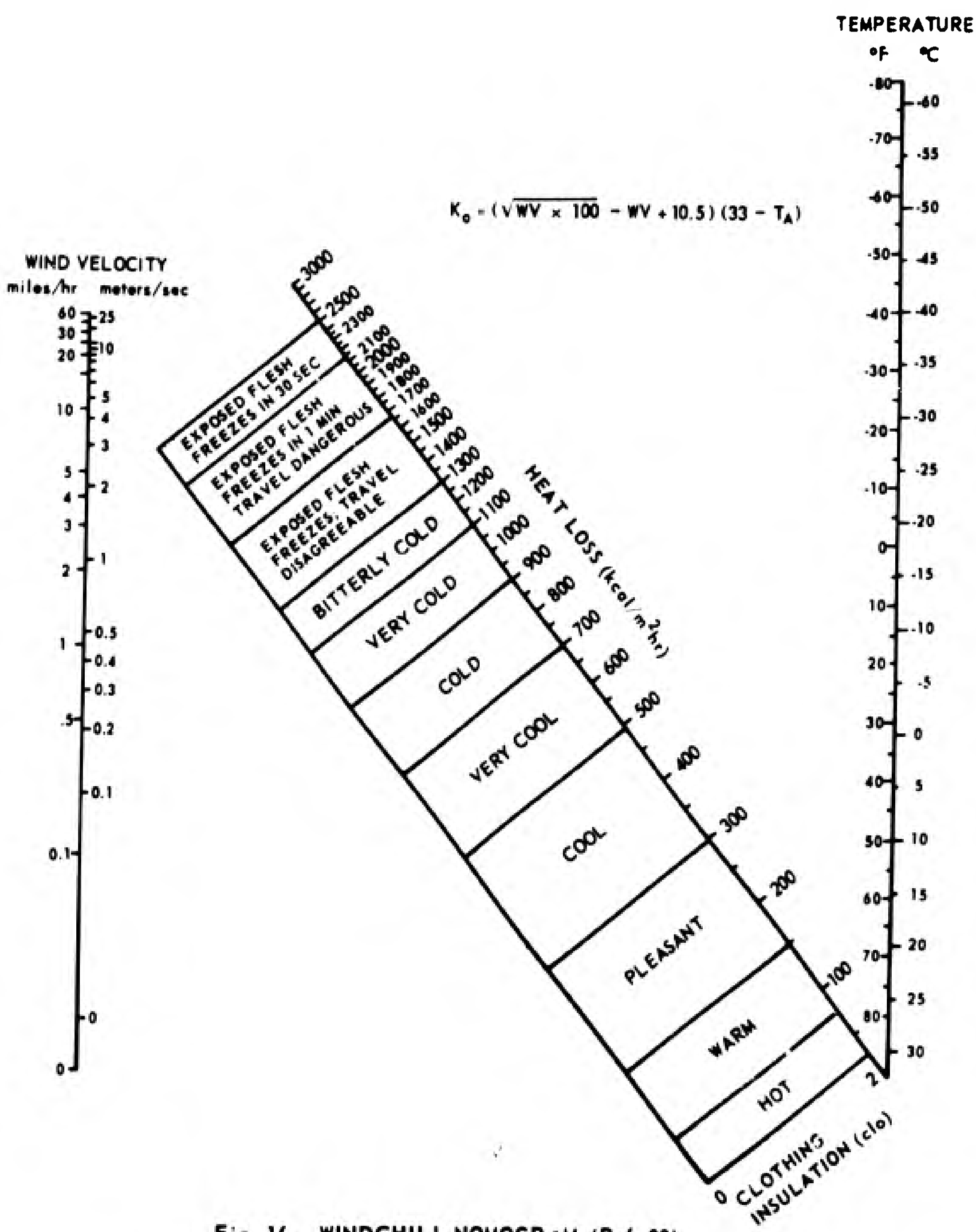


Fig. 16 WINDCHILL NOMOGRAM (Ref. 33)

of heat input over outflow will result in accumulation of heat within the body, and a rise in body core temperature will result. The heat balance (Blockley, Ref. 33, page 117) is:

$$Q = Q_s + Q_r + Q_c + Q_m ,$$

where

- Q = total rate of heat gain or loss by the crewman's body,
- Q_s = rate of heat flow, solar radiation,
- Q_r = rate of heat flow, thermal radiation from, or to, surrounding aircraft structure,
- Q_c = rate of heat transport from, or to, crewman from ambient cockpit air, and
- Q_m = rate of heat production resulting from body metabolic activity.

Rates Q_s and Q_m are always positive; rates Q_r and Q_c may be either negative or positive. These rates can be computed as outlined in Section II-A-2 of this report. Solar radiation impinging upon an aircrewman in the cockpit and upon a man outside of the aircraft will be about the same, except that for the former, the infrared radiation is absorbed by the plexiglass canopy.

The exposed metal surfaces of the aircraft cockpit become warm due to the "greenhouse" effect of the canopy, and for sunbaked aircraft they may attain temperatures of approximately 160°F. The heated structure will radiate to the crewman, and cockpit heating will also cause convective heating of the crewman by the hot air trapped in the cockpit. The total effect of cockpit wall temperature upon heat flow to the crewman can be seen in Fig. 17. A crewman dressed in one clo clothing will absorb 59.8 Btu/(ft^2-hr) from the environment. Solar radiation absorption

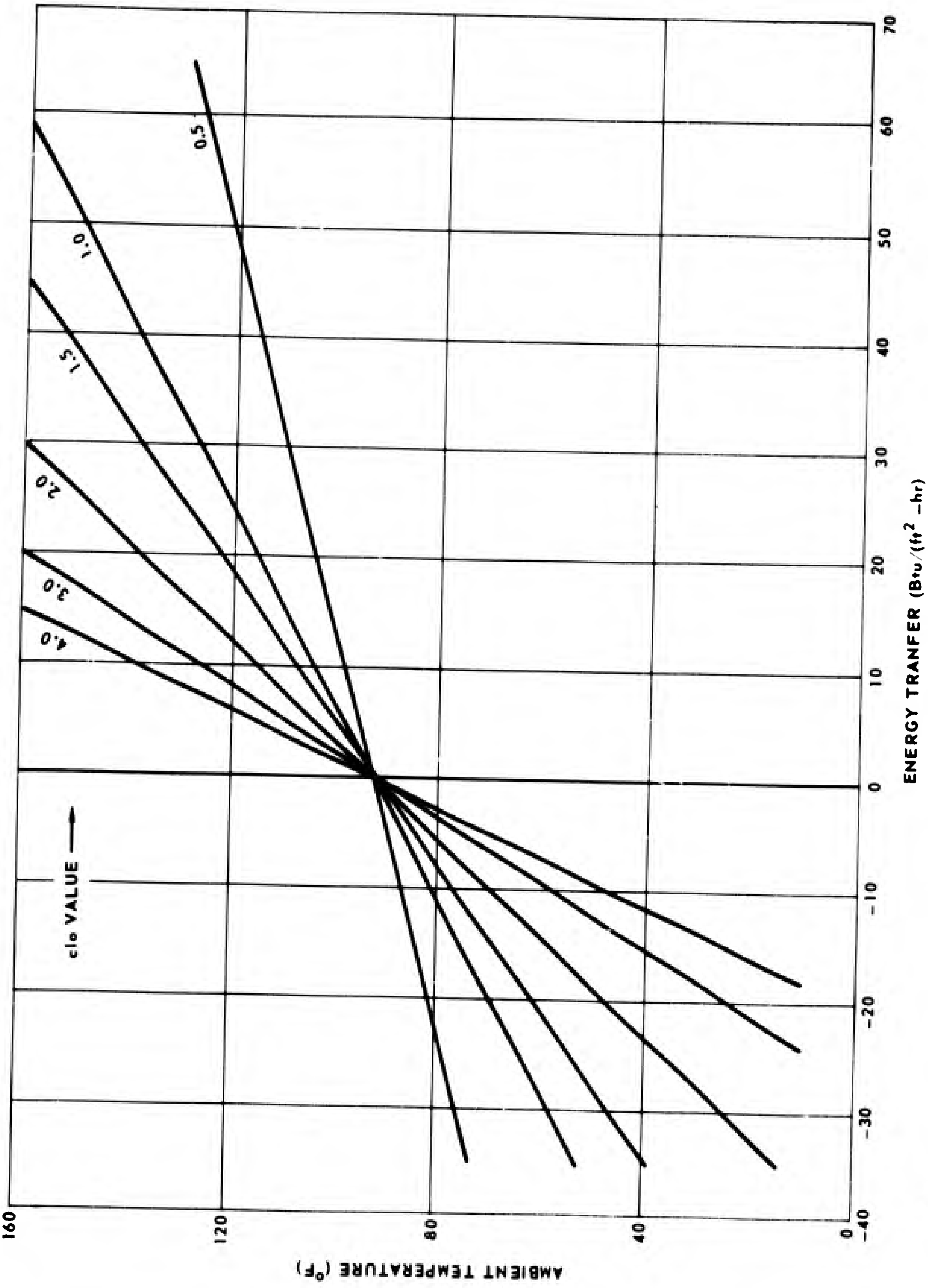


Fig. 17 THERMAL CONDUCTANCE OF CLOTHING LAYERS ENERGY TRANSFER vs. AMBIENT TEMPERATURE

and body metabolic heat must be added to this to determine the total heat input to the man. Any previous heat storage burden the crewman may have developed as a result of prior activity must be considered also.

3. Flight Thermal Stress

In flight, the thermal stress upon the crewman is reduced as a result of normal reduction in ambient air temperature at higher altitudes. At low aircraft velocity the effects of aerodynamic heating are very small; as the velocity increases this heating becomes significant. At high velocities this heating will raise the temperature of the metal in the cabin above 160°F. Such high temperatures are also reached when the aircraft is parked in the sun. The discussion of the gray-body radiation in Section II-C-1 illustrates the fact that cabin walls at high temperatures contribute significantly to the thermal load on the crewman.

High performance aircraft have environmental control systems that are capable of maintaining the crewman in thermal comfort under most conditions. This is accomplished by an air-cycle refrigeration system that can supply air as cold as -20°F to the inlet of the cabin. If this conditioning system fails in flight, the cabin temperature will approach that of the aircraft structure. The rate of temperature change will depend upon the velocity of air flow (supplied from alternate sources) within the cabin and the heat storage capacity and conductivity of the aircraft structure.

As a result of this aerodynamic heating of the aircraft, personnel will be exposed to the following dangers if there is inadequate cooling of the crew:

(1) . Burns result when the man's skin is exposed to temperatures over 113°F (Buethner, 1951). The severity of the burns will depend upon the <u>time</u> of exposure as well as upon the <u>temperature</u>. Examples given in Ref. 33 are:

	Seconds before pain
For the hand (bare) exposed to metal surface at 120°F	10-15
For the hand (leather gloves) exposed to metal surface at 150°F	25.2
For the hand (leather gloves) exposed to metal surface at 175°F	9.7
For the upper arm (flight coverall) exposed to metal surface at 150°F	7.5

If the crewman allows his hand to remain in contact with metal objects that are at temperatures listed above, he will receive a burn.

(2) Inefficient performance of mental tasks is the first dangerous consequence of general body heating where aircrews are concerned. A rise of 4°F in rectal temperature signals the onset of heat fatigue and its symptoms.

To avoid these dangers in the event of cooling system failure, the crewman must either remove the source of heat or reduce the aircraft speed enough so that the ram air ventilation system will provide enough cooling. In some military situations, neither of these alternatives can be exercised without changing the mission profile.

Aerodynamic heating will cause the cabin wall temperature to rise. In an effort to keep the cabin temperature within reasonable limits, the crewman may use any of the following corrective measures:

(1) Increase the rate of air flow through the cabin. This procedure is not desirable because the insulation value of air does not improve significantly with increase in air velocity; and increased velocity tends to produce local discomfort, particularly on thinly clothed or exposed skin such as hands and face, and it may cause irritation of the eyes. Military specifications restrict air velocity at head level to a maximum oı 200 ft/minute. Increases above this velocity do little to improve cooling.

(2) Lower cabin air temperature. This is a means by which the man's skin temperature may be lowered to near its normal level of 91.4°F. However, it implies a large temperature gradient between the cabin inlet and outlet air. With a cockpit wall temperature of 160°F, radiation to a man may be so intense that the temperature of the air surrounding the man must be as low as +20°F. To produce this condition, cabin inlet air temperature must be maintained at temperatures as low as -20°F, and outlet temperature will probably be on the order of +30°F. The result is that the man's feet may be frostbitten and his head quite hot, even though his mean skin temperature is an ideal 91.4°F. Military specifications allow a gradient

no greater than 10°F between the feet and head. A temperature gradient of even 10°F is undesirable; temperature differences within the cabin should be kept as small as possible. This can be satisfactorily achieved only by cooling the walls of the cabin.

(3) Interpose insulation to restrict heat flow. With high aircraft skin temperatures, there is increased dependence upon insulation between the skin of the aircraft and the cabin wall. The air flow through the cabin cannot readily be used as an insulator.

In aircraft with non-pressurized cabins, thermal regulation of crewmen during flight is presently accomplished by directing moving air through the cabin. The air flow is dependent upon the forward velocity of the aircraft and the size of the opening in the aircraft through which air is allowed to enter. There is little or no cooling capability while the aircraft is on the ground. While aboard the aircraft, the crewman is subjected to external heating from several sources such as solar radiation, gray body radiation from the aircraft structure, the greenhouse effect, and heat released by avionics. These heat loads, added to the crewman's metabolic heat, represent the total thermal load upon him.

An aircrewman working at a moderate level generates approximately 700 Btu/hr. Peaks of 1400 Btu/hr may be attained during high stress periods. In a cockpit with a plexiglass canopy, personnel will receive direct solar radiation at rates between 150 and 300 Btu/hr (depending upon the cloud cover). In the crew compartment, where avionics equipments are mounted, a substantial amount of heat is liberated. As an example, an oscilloscope which consumes 720 watts of electrical power dissipates 2450 Btu/hr, this is equivalent to the heat generated by three men. Different complements of these heat-liberating units are carried on each type of aircraft, and the avionic heat load will vary accordingly. The amount of air flowing through the aircraft is a function of the aircraft's forward speed and the number of openings (such as windows or hatches) by which air may enter and leave the aircraft. In the case of helicopters, the cockpit doors are removed and the aft doors are opened to permit the airflow desired. Opening these doors, however, results in an increase in noise level, reduced protection against ground fire, and produces excessive blast from the rotor blades during hover.

In non-pressurized aircraft, addition of cabin air conditioning by retrofit would not be feasible because of cost and weight limitations.

At the present time, many operational helicopters have been modified. After such modification, they are 20% heavier than they were when they were manufactured. This increase in weight has not been offset by an increase of engine power. Air conditioning systems which would be adequate to properly condition the cockpit area would be so large and heavy that they would severely aggravate the overweight condition. Such an increase in weight would decrease the cargo-carrying capacity of the helicopter.

D. Definition of Total Cooling Requirement

In order to define total cooling capabilities which are necessary to maintain a crewman in thermal balance and comfort, it is necessary to define heat loads which contribute to thermal imbalance and discomfort. Crewmen are subjected to two basic heat loads: internal heat generation (metabolic heat), and heating from energy sources external to the air-crewman's body (solar radiation, gray-body radiation, and ambient air).

The degree to which these heat loads affect the crewman is influenced by the clothing he wears. The effectiveness of clothing in impeding the flow of heat to or from the body is expressed in terms of the "clo" (defined in Section II-D-2). In cold environments the clothing impedes the flow of heat <u>from</u> the body; in hot environments the converse is true.

The total cooling requirement in any situation can be expressed by the equation:

$$Q = Q_m + AU_{(clo)} (T_{amb} - 91.4) + Q_{rad} ,$$

where

Q	=	total cooling capacity (Btu/hr)
Q_m	=	sensible heat loss component of metabolic heat (Btu/hr)
Q_{rad}	=	heat loss due to radiation
$AU_{(clo)}$	=	conductance of the clothing [Btu/(hr-°F)]
T_{amb}	=	effective temperature of the environment
91.4	=	assumed mean skin temperature (°F).

Effective air temperature (T_{amb}) is an index in which are represented the combined effects of ambient temperature, humidity, and air movement that produce sensations of warmth or cold. Figure 18 shows the relationship of effective temperature as a function of dry bulb and wet bulb temperature in a low air velocity environment. Correction must be applied to account for air flow velocities greater than the standard value of 20 ft/min. A correction must also be made for radiant heating. The correction of the effective temperature is approximately 0.5°F for each degree [illegible]n wall temperature when the wall and air temperature is equal. Solar radiation which impinges upon the crewman is not included in the equation; a correction for this heat input must be made to determine

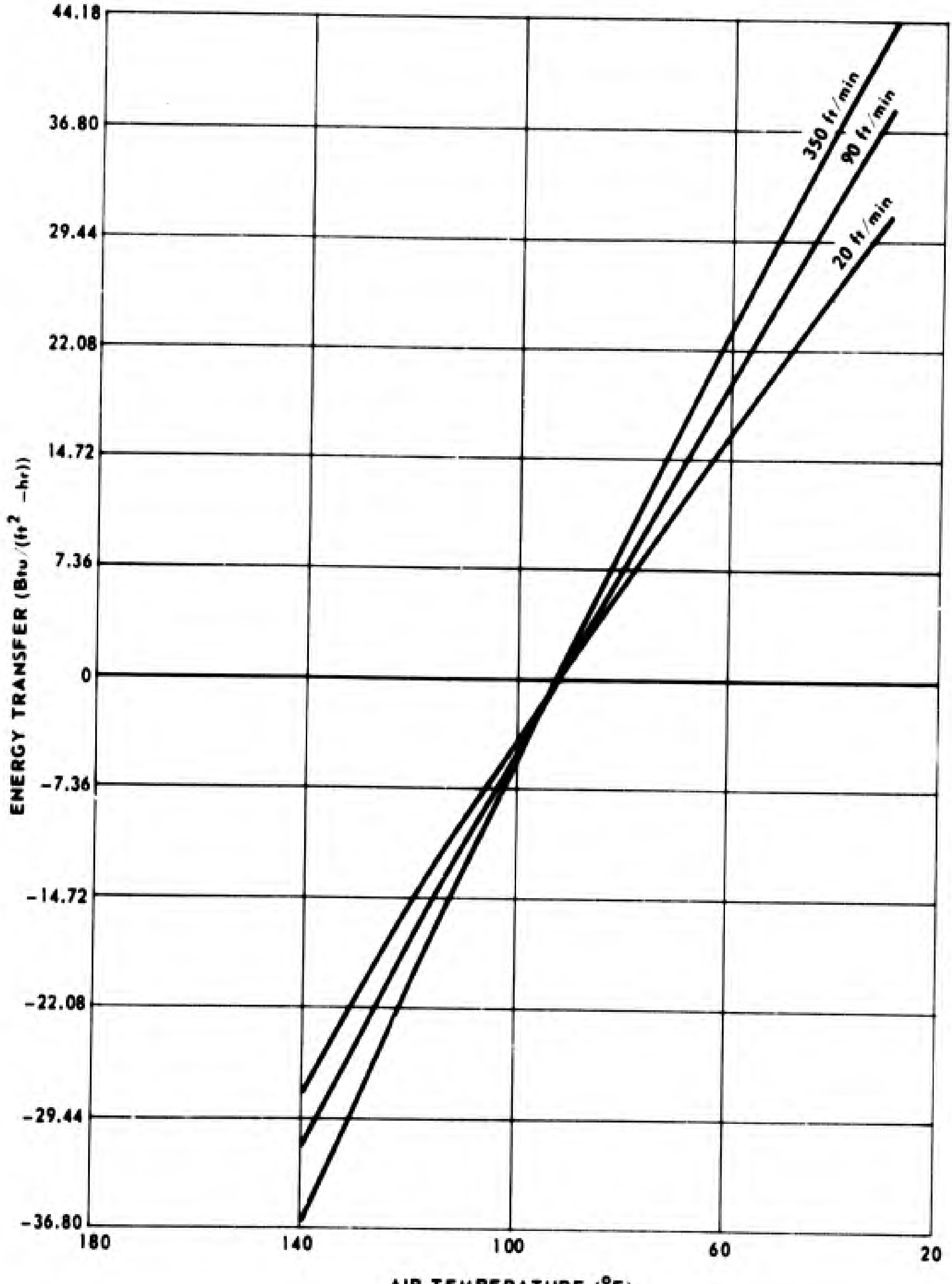


Fig. 18 EFFECT OF WIND SPEED AND TEMPERATURE ON HEAT REMOVAL (CREWMAN IN 2 clo GARMENT, WALL TEMPERATURE EQUAL TO AIR TEMPERATURE)

the total cooling requirement. It is not difficult to predict the effects of solar radiation which are dependent upon location, season, time of day, and weather conditions.

1. Thermal Balance and Comfort

Before requirements for personnel cooling can be defined, it is necessary to first review some facts related to the crewman's "private climate." The "private climate" is the environment inside the outer garment. The equation for a condition of thermal balance, i.e., that condition in which there is no heat storage in the aircrewman's body, is:

$$Q_s = Q_m - (Q_{evap} + Q_{conv} + Q_{rad}) = 0$$

It is desirable that thermal balance be maintained. In earlier sections of this report, heat storage (Q_s), thermal radiation (Q_{rad}), evaporation (Q_{evap}), convection (Q_{conv}), and metabolism (Q_m), have been discussed individually. Here, the effects of these factors and other factors related to the characteristics of clothing will be considered together in order to provide an understanding of how much heat must be removed to maintain thermal balance. Because of variations in cooling over the body surface and because of a static level of body heat storage below maximum tolerance, achievement of thermal balance does not assure thermal comfort.

Thermal balance can be achieved over a range of environmental conditions by the body's thermoregulatory mechanisms. The exchange of heat between the body and its environment must be accomplished at a rate which will permit the body to maintain a constant core temperature.

If the environment is too hot for the body to lose sufficient heat through convection and radiation alone, the thermoregulatory mechanism resorts to the secretion of sweat to achieve thermal balance. Sweating accomplishes little unless the water that is secreted is evaporated from the skin surface. With the secretion of sweat there is also an adjustment of heat transfer from the deep tissue to the skin by changes in blood circulation patterns. As the temperature outside the body increases, there is an increase in blood flow near the skin. These mechanisms enable the body to maintain thermal balance over a wide range of environments, but may cause discomfort when the subject is sweating and will cause dehydration if exposure is prolonged.

An unacclimatized crewman is usually considered to be in thermal comfort in an environment that promotes no thermoregulatory sweating. According to Kerslake (Ref. 24), thermoregulatory sweating begins in a resting man (Q_m = 400 Btu/hr) at a mean skin temperature of 94°F. If the mean skin temperature falls below 86°F, the body will increase metabolic heat production. Although a mean skin temperature of 91.3°F is desirable, a crewman will suffer no thermal discomfort if his mean skin temperature can be maintained within this 8°F span. An important aspect of thermal comfort is the nature of variations of temperature over the skin surface.

In Table IX are listed preferred skin temperatures for different parts of the body. As temperatures deviate from these ideal values, the crewman will become less comfortable.

In normal military operations, crewmen wear garments that have different clo values at different places on their bodies. For example, a crewman who flies in a jet aircraft wears a flight coverall, an integrated harness, flotation gear, and a survival vest. Most of the clothing covers the torso of the man and just lightly covers the arms and legs. In an air-conditioned cabin, the crewman will most likely adjust the temperature

TABLE IX
PROBABLE PREFERRED DISTRIBUTION OF SKIN TEMPERATURE

(Data from The Development of Water Conditioned Suits, by D. R. Burton and L. Collier (Ref. 7))

Region	Preferred Temperature (°F)	Preferred Temperature (°C)	Heat Loss (Btu/hr)	Heat Loss (kcal/hr)	Area (feet^2)	Area (meter^2)
Head	94.3	34.6	15.8	4.0	2.15	0.20
Chest	94.3	34.6	32.5	8.2	1.83	0.17
Abdomen	94.3	34.6	17.8	4.5	1.29	0.12
Back	94.3	34.6	49.1	12.4	2.47	0.23
Buttocks	94.3	34.6	32.9	8.3	1.94	0.18
Thighs	91.4	33.0	47.5	12.0	3.55	0.33
Calves	87.4	30.8	57.7	14.6	2.15	0.20
Feet	83.5	28.6	39.6	10.0	1.29	0.12
Arms	91.4	33.0	33.3	8.4	1.08	0.10
Forearms	87.4	30.8	34.0	8.6	0.86	0.08
Hands	83.5	28.6	63.4	16.0	0.75	0.07
Total body	Mean 91.4	Mean 33.0	423.8	107.0	19.46	1.80

so that his torso is at a comfortable temperature; as a result, the temperature of the air may be such that the legs and arms are cold. This condition will produce a condition that is uncomfortable but tolerable. Under such conditions, the crewman may have a mean skin temperature within the desirable range, but may not be in thermal comfort. If the same crewman were placed in an un-air conditioned environment, he would be in an uncomfortable and intolerable condition.

2. Thermal and Moisture Control Characteristics of Various Aircrew Garments

The suitability of any aircrew garment varies with relation to the environment in which it is used. Because the commitment of Navy and Marine aircraft is world-wide, aircrews must be protected from a wide variety of environments. Depending on the theater of operation, flight plans, etc., the crews choose from a variety of garments. These garments vary from lightweight summer flight suits to heavy, cumbersome, full-pressure suits for high altitude operations.

Thermal impedance of a clothing assembly is proportional to the sum of the insulation values of each of its components. Thermal resistance of clothing is measured in "clo" units. One clo is defined as the amount of insulation required to provide the same degree of comfort for a typical individual when he is clothed and at 70°F temperature as when he is in the nude, at rest, indoors, at 86°F, with low air movement of 20 feet per minute, and with 50% RH. More specifically, the clo unit equals 0.88°F/[(Btu/(ft^2-hr)]. For each 16°F drop in air temperature, a man will require 1 clo value of additional clothing. Some typical clo values for aircrew garments (Ref. 33) are:

Garment	Clo Value
Summer-weight coveralls	1
Summer-weight coveralls plus integrated harness	1.5
Summer-weight coveralls plus woolen jacket	2
Anti-exposure suit (dry suit)	2
Intermediate flying assembly	3
Heavy-weight pile flying assembly	4

The vapor resistance of clothing assemblies can be estimated if the vapor resistance of the individual fabrics is known. The vapor permeability of clothing is of minor importance in comfortable or cool environments; however, in warm or hot environments evaporation of moisture can be of major importance. Under such conditions, the insulation value of a clothing assembly becomes highly dependent upon the resistance it offers to the diffusion of water vapor. Wool actually absorbs moisture and does not feel as "wet" or clammy as cotton or nylon. However, nylon and other non-absorbent type fibers will be more or less vapor permeable depending on their construction. Moisture transfer is actually more efficient than non-absorbing type fabrics.

A crewman dressed in an impermeable garment is virtually in an oven when he is in a hot environment because his sweat will not evaporate and he will receive little or no convective cooling. A crewman dressed in a permeable garment in the same environment will be able to evaporate some sweat and have the additional advantage of convective cooling.

Figure 17 shows effective heat transfer through a garment as a function of ambient temperature and clo value at a low air flow (20 ft/min) rate.

Fighre 18 indicates the effect of air flow past a crewman dressed in a two clo garment. An example of the effect of clothing on the overall heat load on a crewman may be seen by referring to Figs. 19 and 20. If a crewman who is dressed in a two clo garment is standing in a hot environment (120°F) with variable air flow rates, the following heat gain through the suit will occur.

Air Velocity (ft/min)	Heat Transferred (Btu/(ft^2-hr))
20	15.5
90	17.6
350	20.4

Under the same two-clo condition, but at a low ambient temperature of 40°F, the crewman would be subjected to greater heat losses as follows.

Air Velocity (ft/min)	Heat Transferred (Btu/(ft^2-hr))
20	26
90	32
350	37

At 40°F, a four-fold increase in air velocity over 20 ft/min gives a heat transfer increase of 6 Btu/(ft^2-hr). To obtain an additional increase of heat transfer of 6 Btu/(ft^2-hr) above the original increase, the velocity must be increased 17-fold above the 20 ft/min. These data indicate that increasing air velocity to improve crewman comfort is efficient only to a limited degree. The amount of heat transferred from the crewman must be computed for the effective area of a seated man. This is approximately 0.7 of his total surface area.

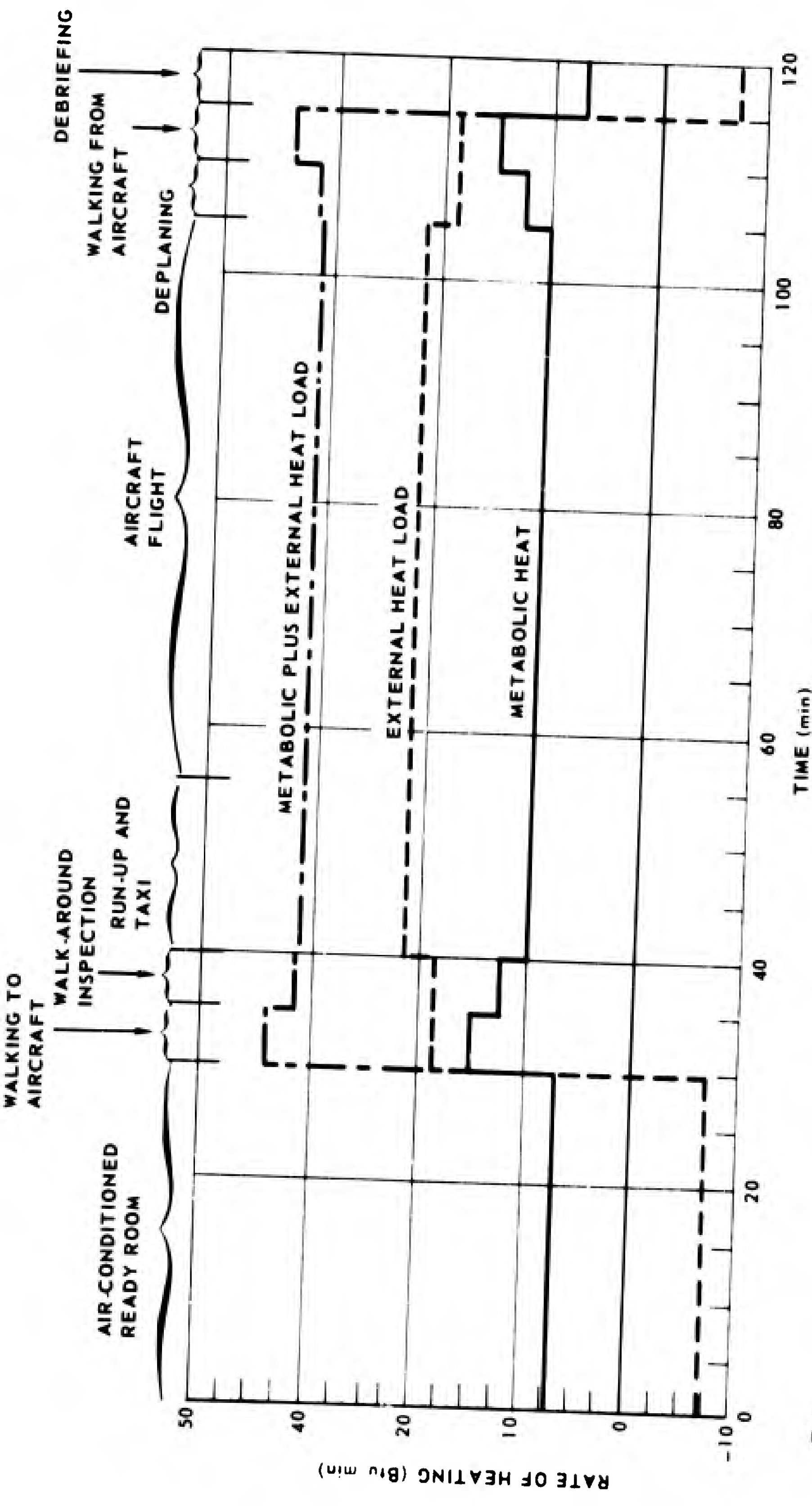


Fig. 19 THERMAL LOAD ON AIRCREWMAN DURING HYPOTHETICAL MISSION IN NON AIR-CONDITIONED AIRCRAFT

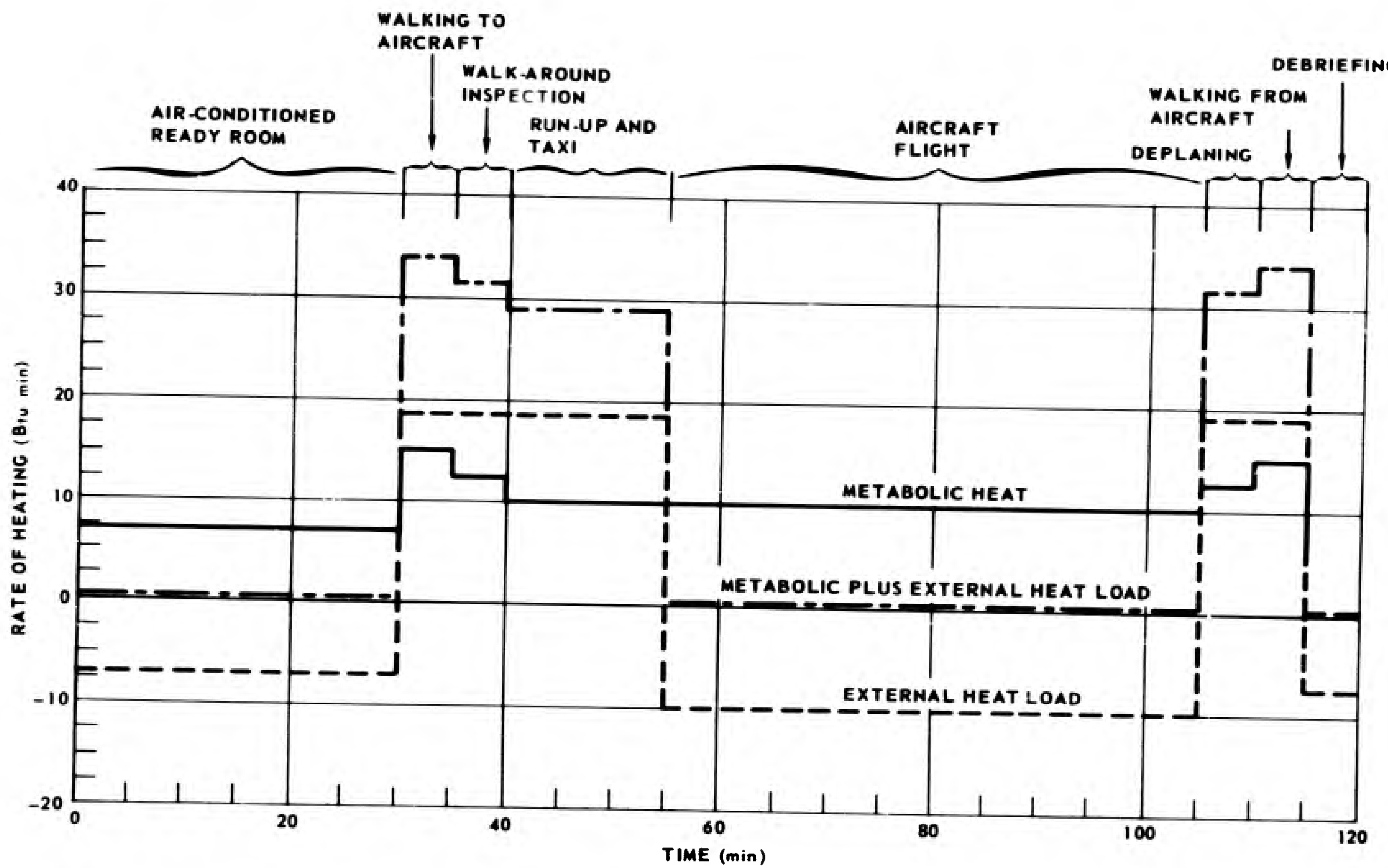


Fig. 20 THERMAL LOAD ON AIRCREWMAN DURING HYPOTHETICAL MISSION IN AIR-CONDITIONED AIRCRAFT

Observations made here relating to the two-clo garment are also valid for clothing with other clo values. In many cases, aircrew personnel will dress in uniforms that have different clo values over different parts of the body. An example of this is a helicopter pilot dressed in a lightweight flying suit and (ballistic) protective vest. The flying suit has a clo value of less than one whereas the vest has a clo value in excess of two. Under this condition, the crewman will transfer heat from areas not covered by his seat and vest. Heat flow from the covered areas will be impeded. This condition will cause thermal discomfort and perhaps imbalance.

3. Thermal Stress in Hypothetical Flights

Thermal stress experienced by a crewman during a hypothetical mission is plotted in Figs. 19 and 20. For these missions, the crewman was assumed to be dressed in an air- and moisture-impermeable, two-clo garment. The aircraft was assumed to be parked on an open airport apron, and exposed to solar radiation and ambient-air heating. Under these conditions, the metal portions of the aircraft may reach temperatures as high as 160°F. While walking to the aircraft, the crewman is exposed to solar radiation at an intensity of 18.5 Btu/min (see Section II-C-2). The length of the mission is taken as two hours from the time he enters the briefing room until he returns to the room after completing the flight. The crewman is assumed to be in thermal balance and comfort at the time he leaves the briefing room. Figure 19 represents his thermal inputs for flight in an un-air-conditioned aircraft, and Fig. 20 represents similar inputs for a flight in an air-conditioned aircraft. (The value of Q shown in Fig. 21 is the same as ΔQ evaluated in Section II-A-2.) To maintain thermal balance in the crewman, the value of ΔQ must equal Q_{evap} and

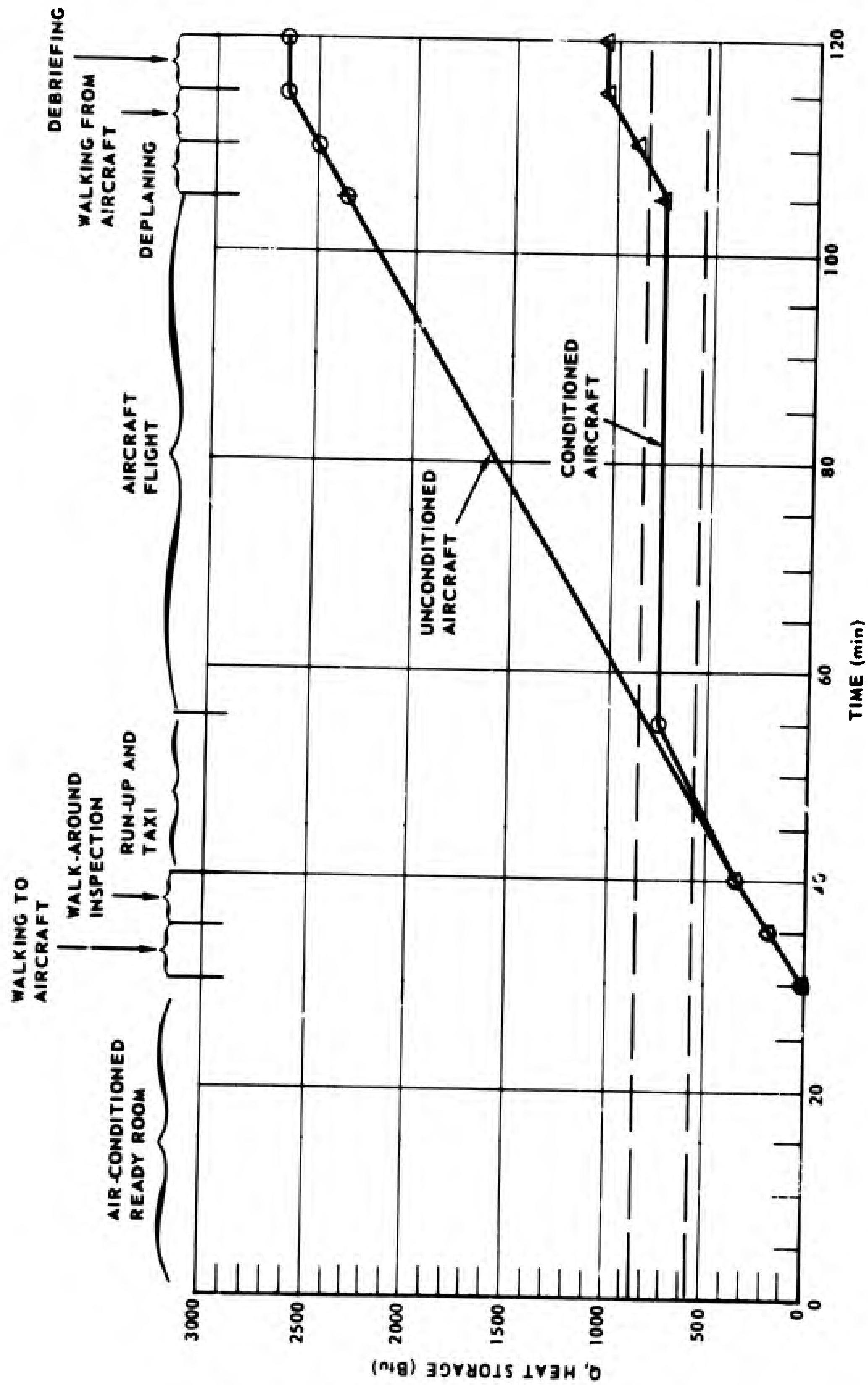


Fig. 21 HEAT STORAGE OF CREWMAN DURING HYPOTHETICAL MISSION

Q_{conv} as expressed in Section II-A-2. In the un-air-conditioned aircraft, Q = 2650 Btu for the flight. In the air-conditioned aircraft, this value was reduced to 1060 Btu. Figure 21 presents a plot of total heat stored by the man in his body as a function of time for both flight conditions. Superimposed on this plot are two levels of body core temperature which denotes, respectively, minimum predicted thermal storage tolerance levels (MPTSTL) (core temperature of 102.6°F) and a level at which collapse is predicted (core temperature of 104.6°F). These levels are computed from equations for heat storage and tolerance given in Section II-A-2 (from Ref. 33, p. 117). Between these heat storage levels there exists a danger zone within which symptoms of fatigue become progressively more severe. No allowance is made in these examples for heat loss from the crewman through evaporation of sweat; however, the evaporation of sweat will occur only to a negligible degree for a crewman wearing air and moisture impermeable garments. For aircrewmen clad in moisture- or air-permeable garments permitting sweat evaporation, thermal balance may be maintained by evaporative heat transfer. Required sweat evaporation rates for thermal balance is 2.5 lb/hr and 1 lb/hr respectively for un-air-conditioned or air-conditioned aircraft. These values are not unreasonable and would not cause severe dehydration for short flights. The secretion of sweat does not accomplish cooling in cases of poor body ventilation, because of the absence of evaporation.

The examples given illustrate the effects of inadequate thermal control for aircrewmen while on the ground. In both cases the crewman exceeded the MPTSTL before being airborne, and in the un-air-conditioned aircraft the collapse level was exceeded shortly after takeoff. In the air-conditioned aircraft, the crewman was kept at a steady level just below that for collapse, and exceeded it upon leaving the aircraft. These examples are realistic in that many crewmen operating in hot environments, while wearing anti-exposure suits, have experienced such stress (Ref. 20).

As indicated by Fig. 21 the thermal stress of the crewman on the ground will place him in an unfavorable thermal condition prior to takeoff. It is important that crewmen be under, at most, only a slight thermal stress immediately before a flight. If they are under significant thermal stress prior to takeoff, their flight performance will be compromised.

E. Thermal Comfort Problems Encountered by Aircrewmen

A number of visits were made to Navy installations during this study in order to obtain firsthand information from service personnel regarding their thermal comfort problems. Appendices A, B, C, and D are reports of trips to the following installations:

(1) Aeromedical Branch
Naval Air Test Center, Naval Air Station
Patuxent, Maryland

(2) Aviation Physiological Training Unit
Norfolk Naval Air Station
Norfolk, Virginia

(Squadrons HS-3, VS-37, VP-56)

(3) Landing Force Development Center
Quantico Marine Base
Quantico, Virginia

(Squadron HMX)

(4) Com Nav Air Pac Survival Office
North Island Naval Air Station
San Diego, California

(5) Ream Field
Imperial Beach, California

(Squadron HS-2)

(6) Miramar Naval Air Station
San Diego, California

(Squadron VF-21)

(7) Aviation Physiological Training Unit
Point Mugu Naval Air Station
Port Hueneme, California

(Air Development Squadron #4)

(8) Aviation Physiological Training Unit
El Toro Marine Air Station
El Toro, California

(3rd Marine Air Wing Equipment Office)
(Squadron VMCJ-3)

The major thermal problems described by flight personnel at these installations are:

(1) Overheating of aircrew personnel wearing unventilated anti-exposure garments in temperate cabin conditions.

(2) Extreme uncontrolled variations in cabin temperature and ventilation in un-air-conditioned aircraft.

(3) Thermal stress experienced by aircrewmen wearing heavy protective garments during ground operations.

(4) Problems resulting from abnormal operation in air-cycle conditioning systems during off-design or transient conditions.

(5) Thermal stress created by protective garments and equipment (such as ballistic protection) that impedes normal heat exchange through outer garments.

These problems were considered to be serious by many of the aircrewmen with whom these problems were discussed. Over one hundred flight officers were interviewed. Most of these men have flown Naval aircraft in many parts of the world, and have experienced wide variations in thermal problems.

III. DISCUSSION OF COOLING TECHNIQUES

A. Introduction

There are (in use or under development) two basic techniques for providing a private climate for personnel. These are the air-ventilated undergarments and the liquid-cooled heat exchanger.

1. Air-Ventilated Garments

Air-ventilated undergarment employ a number of different techniques to supply ventilating air to the airspace between the wearer's skin and the outer layer (or cover) of the garment. In this general class of garment are full-pressure suits, and anti-exposure suits with integral air ducts. Typically, air is supplied to the suit at a central location, is ducted (without coming into contact with the man's body) to each extremity (arm and leg), and is discharged from the ducts into the interior of the suit. The air cools the wearer as it flows over his body toward a centrally-located exit. One such air-ventilated garment is the tubular system, used by the Royal Air Force and the French Air Force, in which air is ducted to various areas of the aircrewman's body through small plastic ducts. Another is the double-walled suit, e.g., the MA-1 and MA-2 suits used by the United States Air Force, in which air enters between layers of the plastic garment and vents from between constricting layers, toward the skin, through small, uniformly distributed holes in the inner layer of the garment, passes over the skin, and exits through a centrally-located port. In addition to these two types there is the U. S. Army Natick Suit (Figs. 22 and 23), a garment interlined with Trilok, that covers about 12 square feet of the wearer's body. The ventilating air enters the garment at the back of the torso, flows (next to the skin) through the Trilok, and exits from the suit through ports at the extremities.

2. Liquid-Cooled Garments

a. Liquid-Loop Suit. Liquid-cooled garments of the liquid-loop variety have been developed by the Royal Aircraft Establishment in England and the Hamilton-Standard Company in the United States. The liquid-loop cooling garment removes heat by conduction from the private climate. This is accomplished by circulating a chilled liquid through plastic tubing that is in contact with the skin. The rate at which heat is removed is dependent upon the area of the tubing which is in contact with the skin and the temperature and flow rate of the cooling fluid through the tubing. A current full-body model is shown in Fig. 24, and a vest model (currently under test by the USAF) is shown in Fig. 25.

b. Cascade Cooling Suit. In an effort to improve thermal control of crewmen who wear air-ventilated full-pressure suits, AiResearch has incorporated several air-to-liquid heat exchangers within the suits (Fig. 26). These exchangers facilitate cyclic cooling of ventilating air as it passes over the wearer's body. As the cooling air passes over his skin, it cools the body and is then itself cooled by the heat exchangers. There is also radiant cooling, in varying degrees, in the neighborhood of the exchangers. Also, moisture is continually condensed and reevaporated. This contributes substantially to the ability of the system to remove heat.

A number of heat exchanger configurations have been developed for this system. These heat exchangers are a series of tubes which are

Fig. 22 NATICK AIR-COOLED SUIT, FRONT

Fig. 23 NATICK AIR-COOLED SUIT, BACK

Fig. 24 APOLLO LIQUID-COOLED SUIT

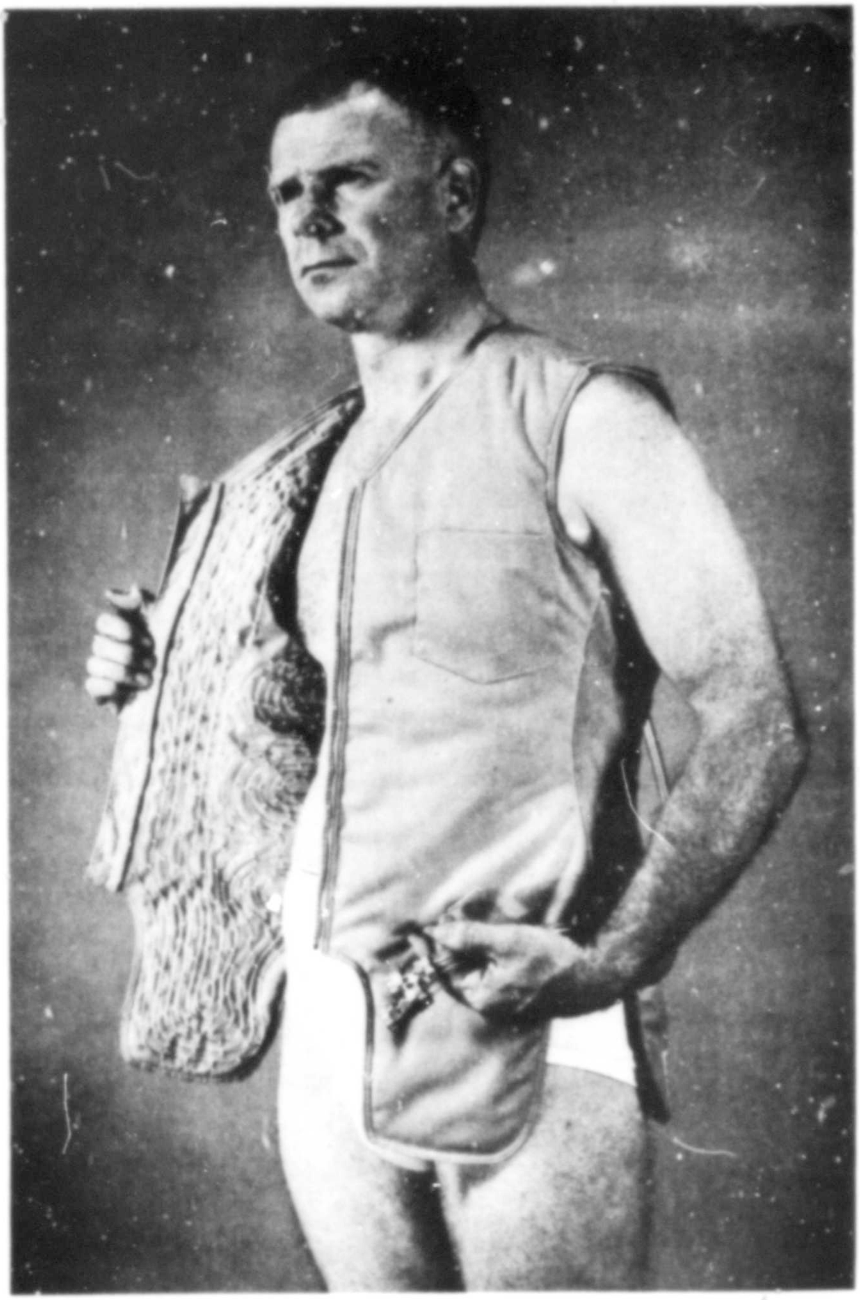


Fig. 25 USAF LIQUID-COOLED VEST BY HAMILTON-STANDARD
(This garment presently under test in Viet Nam)

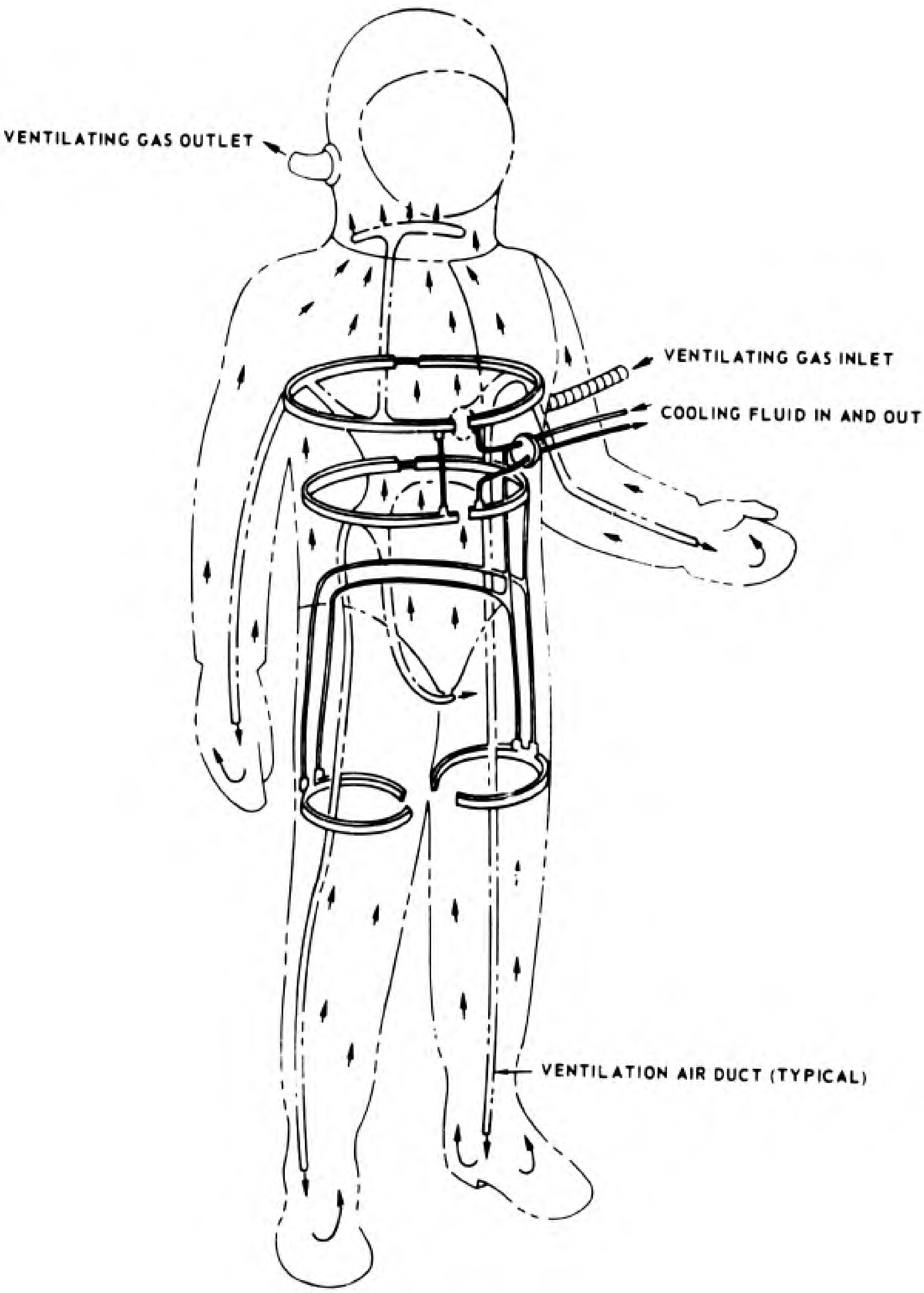


Fig. 26 AIRESEARCH CASCADE COOLING SUIT (Ref. 15)

placed around the chest and thighs. Glycol cooling fluid at a temperature above the dew point is circulated through the tubes. Liquid inlet temperature is usually between 32°F and 49°F, and flow rates are between 1 and 6 lb/min. Ventilating air is delivered to the suit at flow rates between 2 and 6 cfm, and the controlled temperature of the ventilating air is between 46°F and 60°F.

This system was developed for space application, and not for aircraft. In aircraft, the heat exchangers may present a problem because they are bulky and impair proper adjustment of harness.

c. Evaporative Cooling Garment System. A new concept for heat removal, by the Douglas Aircraft Corporation, is a thermal control system called the Evaporative Cooling Garment System (ECGS). It is still in the conceptual state. In the ECGS, water is evaporated to remove heat from the body. This is accomplished by the boiling of water within the private climate. The water boiler is a multi-layer assembly (Fig. 27) consisting of:

(1) An inner, water-permeable membrane (interface between the skin and garment).
(2) Noncompressible wicking material.
(3) An impermeable membrane.
(4) A pressurized area.
(5) An outer suit.
(6) Vent lines from wicking material to limiting valve orifice.

At reduced pressure, water boils at lower temperatures. In the ECGS, water is injected into the wicking material through which it diffuses. The permeable membrane also permits diffusion of sweat from

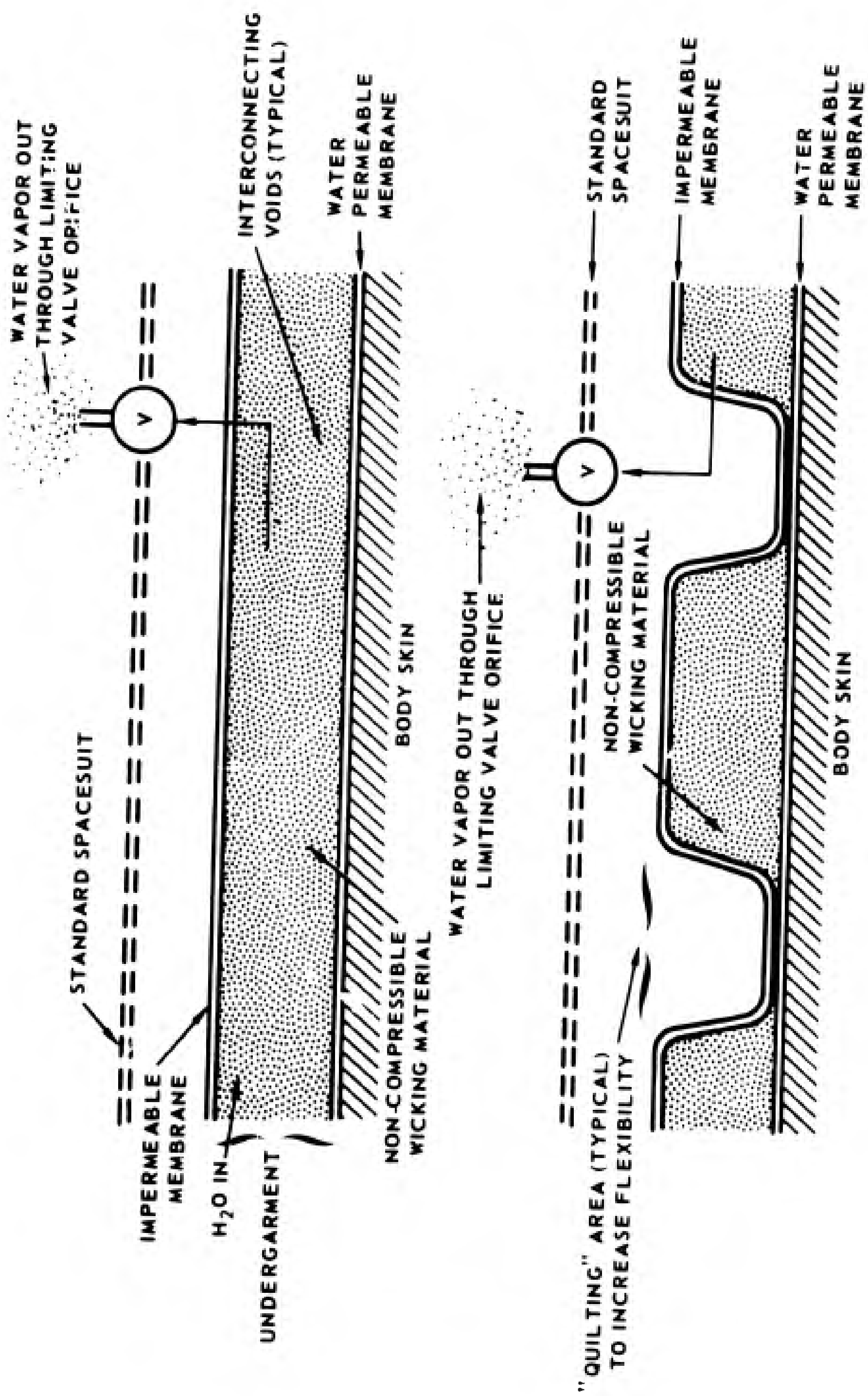


Fig. 27 UNDERGARMENT WATER-BOILER CONCEPT (Ref. 5)

the subject's skin into the wicking material. A vacuum transfer line that runs from the central orifice of the suit to the wick material exposes the wicking material to low ambient pressure. The heat removal rate can be adjusted as desired by adjusting (1) the thickness of the permeable membrane (between 0.005 and 0.040 inch), (2) the area of the membrane, and (3) the size of the opening in the limiting orifice. Douglas Aircraft Corporation personnel are of the opinion that this system has the capability of removing heat at ten times the rate at which liquid-loop cooling suits are capable.

The ECGS is basically designed for use in space applications in which a vacuum source is readily available. In aircraft it will be difficult to provide a vacuum source that is adequate for this system. The system has an advantage in that a minimum of electrical energy is required to pump the water that is fed to the boiler, then dumped overboard. With a water consumption rate of two pounds per hour, the cooling rate is 2000 Btu/hr.

B. Existing Air-Ventilated Cooling Garments

1. Ventilation Systems in Present Types of Impermeable Garment

a. U.S. Navy Full-Pressure Suit, Mark IV. The ventilation system for this garment is an integral part of the outer layer of the garment (Fig. 28). Air is supplied under pressure through a fitting on the left side of the suit to the air distribution ducts which are on the inner surface of the outer shell. The ducts are made of fabric-covered Trilok material, and emanate from the inlet manifold and extend to each of the extremities. The ducts terminate at the wrist of each arm and at boot-top height of each leg. One duct runs to the crotch area of the suit. In some models,

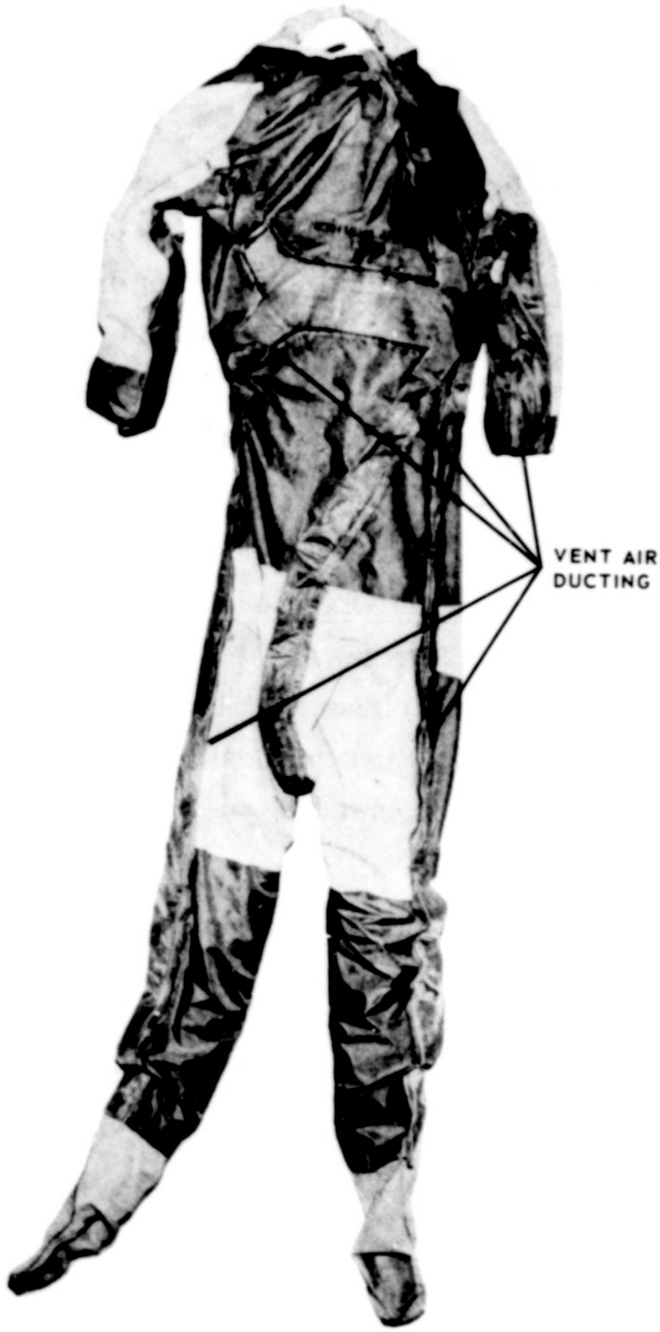


Fig. 28 U.S. NAVY FULL PRESSURE SUIT, MARK IV
(Ventilation Ducts) (From BuAer Bulletin 1-59)

there are extensions to the arm ducts so that ventilating air can be ducted into the gloves.

Underneath the outer suit, the crewman wears a lightweight, knitted-cotton undergarment that has Trilok panels under the right arm and along the front of the upper thighs. Air exiting from the ducts at the extremities is routed between the undergarment and the outer shell. The undergarment acts as a wick that aids in the removal of moisture from the skin. Air moving over and through the undergarment fabric, removes the moisture, and convectively cools the man. Expended air exits through a vent in the right rear of the suit, into the aircraft cabin.

b. U. S. Navy Anti-Exposure Suit, Mark V. The ventilation-insulation liner in the U. S. Navy Anti-Exposure Suit, Mark V (Fig. 29) consists of a sandwich of materials. The outer face is a lightweight, closely-woven, nylon material; the innermost layer is a flame-resistant cotton fabric. Sandwiched between these two layers is a Dacron fiber-fill batting material.

The air distribution system is integrated with the liner and lies between the outer face material and the Dacron batting. It consists of a bladder and arm and leg ducts. The ventilating air first enters the inlet port under the left arm, and is then directed into the rectangular bladder that extends the full width of the back. Four ducts, which are fabric-wrapped coil springs, lead from the four corners of the bladder. These ducts distribute air to points near the sleeve and leg endings of the liner. The air emerges from the coil-spring ducts through small openings, and passes over the body. It finally exits from the suit through the exhaust valves in the outer shell.

Fig. 29 DONNING MARK V INSULATION-VENTILATION LINER
(Passing Anti-G Air Inlet Through Liner)
(From BuWeps Bulletin 60–61)

c. U.S. Air Force Ventilating Garment, MA-1 and MA-2. This garment is one of the first wholly-separate ventilation garments to be used. It covers most of the wearer's body, and is worn next to the skin. It consists of two sheets of vinyl plastic which are separated by a loose spacer material. This material offers little resistance to air movement. Ventilating air escapes from between the vinyl sheets through very small holes in the inner sheet. Supply air reaches the skin at many points, and causes evaporation of sweat from much of the body surface. When the suit is inflated, "domes" are formed above the skin. Air which escapes from the small holes in the dome is released in high-velocity jets. Turbulent airflow and effective evaporation results. This ventilation garment also has large holes through both sheets of plastic.

The MA-2 garment is basically an MA-1 suit which extends the ventilation capability to below the knee (Figs. 30 and 31).

d. French Air Force Ventilated Garment. This is a one-piece undergarment made of silk and cotton jersey. It weighs 1.099 kg. Ventilation air, which is piped into the suit through a one-inch I.D. flexible tube, enters a circular ventral distribution pocket, ten inches in diameter. The distribution pocket is on the right side of the undergarment, and is made of an impermeable fabric. Between the internal and external faces of the distribution pocket, there is permeable padding of "thistle" fabric which resists warpage and crushing. Radiating from the pocket, like spokes of a wheel, are 18, 1.4-inch-wide flat tubes. The outside surfaces of the tubes are made of impermeable material; their inside surfaces have many tiny orifices from which come jets of turbulent air directed toward the skin. The small openings are arranged so as to provide uniform cooling. Along the trunk there are very few ventilation openings. In this region most of the skin cooling is accomplished by conduction.

Fig. 30 USAF MA-2 DUCTING GARMENT, FRONT

Fig. 31 USAF MA-2 DUCTING GARMENT BACK

Internal padding similar to that in the air distribution pocket prevents any warping or crushing of tubes in heavily constricted zones, e.g., under the buckles of the harness. Clogging and warping of the openings is also reduced through use of a layer of permeable fabric between the tubes and the skin of the subject.

One of the eighteen tubes, which is along the center line, runs to the head assembly and does not contribute to ventilation of the rest of the body. The other tubes are distributed over the trunk. Approximately one-quarter of the total surface of the body (not counting the head) is covered by these tubes. Tubes also ventilate the gloves, and footstraps facilitate ventilation of the boots.

Operation of this garment is summarized as follows: Air emerges from the inside faces of the distribution tubes along their entire length. Because the air flow is turbulent, the air effectively transfers heat from the skin. If perspiration is present, this air also removes the water vapor. The air flows over the skin through paths of least resistance, and finally escapes at the extremities or at the neck of the suit. As it flows toward the exits, this air is continually mixed with other cooler and drier air coming out of the tubes. This partially reduces the temperature gradients between the skin zones which are situated near the distribution pocket in the abdominal region and those which are further removed from it. The air distribution tubes are sufficiently flexible and flat that they do not cause any discomfort when the outer suit is pressurized.

e. <u>U.S. Army Natick Garment.</u> The U.S. Army Quartermaster Corps, Natick Laboratory, has developed a personal undergarment which is cooled by ram air. This garment consists of three layers of synthetic fabrics: lycra, polypropylene, and nylon. The lycra layer is the innermost layer, which is worn against the skin. This fabric has two-way stretchability and is quite comfortable. The second layer, Trilok, which is used as a spacer layer, is made of nylon and polypropylene filament. The outer layer is made of tight-woven nylon which prevents gas flow through the walls of the suit. The three layers of fabric are sewed together to form a one-piece, long-underwear-type garment. A panel of lycra replaces the three-layer material at the areas adjacent to body joints where a high degree of flexibility is necessary. The air is fed through the flight suit into the cooling undergarment, and is distributed via the spacer material to all parts of the suit. The flow of air is not affected radically by restrictions caused by parachute harness or a ballistic vest. The present suit is quite flexible, and does not seriously restrict movement of the crewman as he performs his normal tasks. This suit is lightweight, and is easily donned and doffed. Velcro tape, used instead of zippers, simplifies opening and closing, and eliminates snagging of the suit. Because of the nature of the new types of materials used in the construction of this garment, cleaning and mildew problems are non-existant.

This suit provides a flow of air over the body. The airflow conducts away the heat and evaporates the perspiration from the skin. The lycra layer is of 40x40 mesh which absorbs perspiration. The gas enters the ventilated garment near the kidney, which is the only convenient place at which a hose may be attached when a crewman is equipped with survival gear, ballistic protection, and a parachute. From this point of entry, the air flows toward vents at the ankles, wrists, and neck.

f. <u>U. S. Navy Pensacola Ventilated Flight Suit</u>. In prototype, this garment consisted of the regulation summer flight coverall together with the air ventilation system of the Arrowhead full-pressure suit. The latter was made up of five Trilok panels to which air channels routed ventilating air from the air inlet. The panels were fastened to the coverall and were arranged with one panel positioned across the back and two on each front side of the chest and abdominal area.

Ventilating air entering the suit at the manifold is distributed through the air channels to each of the Trilok panels from which it enters the private climate. The air is then vented from the suit through the cuff, ankle, and neck openings.

This garment is designed in such a way that the ventilation system can be removed from the coverall fo laundering, and the ventilation system is interchangeable with other coveralls.

2. Support Requirements for Ventilated Garments

a. Full-Pressure Suit and Anti-Exposure Suit. Conditioned air from the cabin supply system is used for ventilation and pressurization of full-pressure suits. Ventilation air for anti-exposure suits is supplied by conditioned air from either the cabin supply system or a separate seat-mounted blower.

(1) Air Flow Control. Ventilating air must be supplied to anti-exposure and pressure suits at a flow rate of 14.0 cfm. A manually-operated flow control valve is installed in the cabin to permit each suit wearer either to shut off air supplied to his suit, or to restrict air flow to rates below the design flow rate. The valve is configured so that it can also control air delivered to the aircraft by ground cooling units.

(2) Air Temperature Control. Inlet air temperature, measured at the suit, can be adjusted to any temperature between 50° and 100°F under normal operating conditions, and between 70° and 100°F

under retarded throttle conditions. The controller regulates the air temperature. During transient conditions of airplane or system operation, it is intended that ventilating air temperature at the suit inlet be maintained within ±5°F of the control point setting. The temperature selector panel is graduated in degrees Fahrenheit for the full control range. During pressure suit operation, the temperature should remain within the range shown in Fig. 32. During anti-exposure suit operation, temperature should remain within the range specified by Fig. 33.

(3) Air Pressure Control. The pressure drop through the anti-exposure suit and the inlet tubing does not exceed 3.0 psig at the design flow rate of 14.0 cfm. Pressure drop through the pressure suit and its inlet tubing is nominally the same as that for the anti-exposure suit. During normal use of the pressure suit (when the cabin is pressurized) and when the cabin is unpressurized and the cabin pressure is below that corresponding to an altitude below 35,000 feet, the control system regulates the inlet pressure to 3.0±0.2 psi above cabin pressure. During emergencies above 35,000 feet, a suit air pressure of 6.5±0.2 psia is required at the suit inlet in order to maintain a pressure of 3.5 psia within the pressure suit.

Aircraft that are not equipped with such conditioning systems are generally equipped with a blower assembly. This blower is specified in MS-17269 and MIL-M-8609. It delivers air at ambient cabin temperature, 16 cfm at pressures of 13 inH_2O, and consumes 300 watts of power at 28 volts DC. The amount of cooling that can be provided by ambient air is a function of the dry- and wet-bulb temperatures and flow rate. A complete discussion of this type of cooling is included in Appendix E.

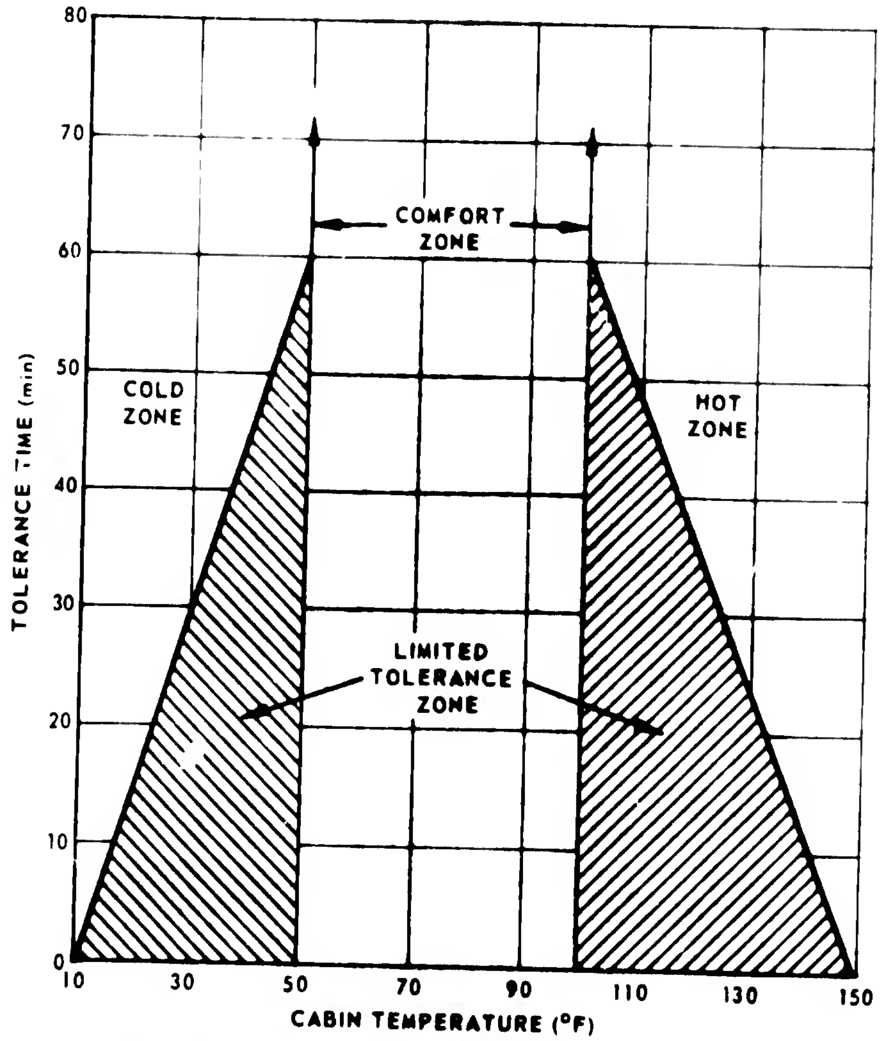


Fig. 32 CABIN THERMAL REQUIREMENTS DURING NORMAL USE OF PRESSURE SUIT (Data from Mil-E-18927 D, 14 Aug 1959)

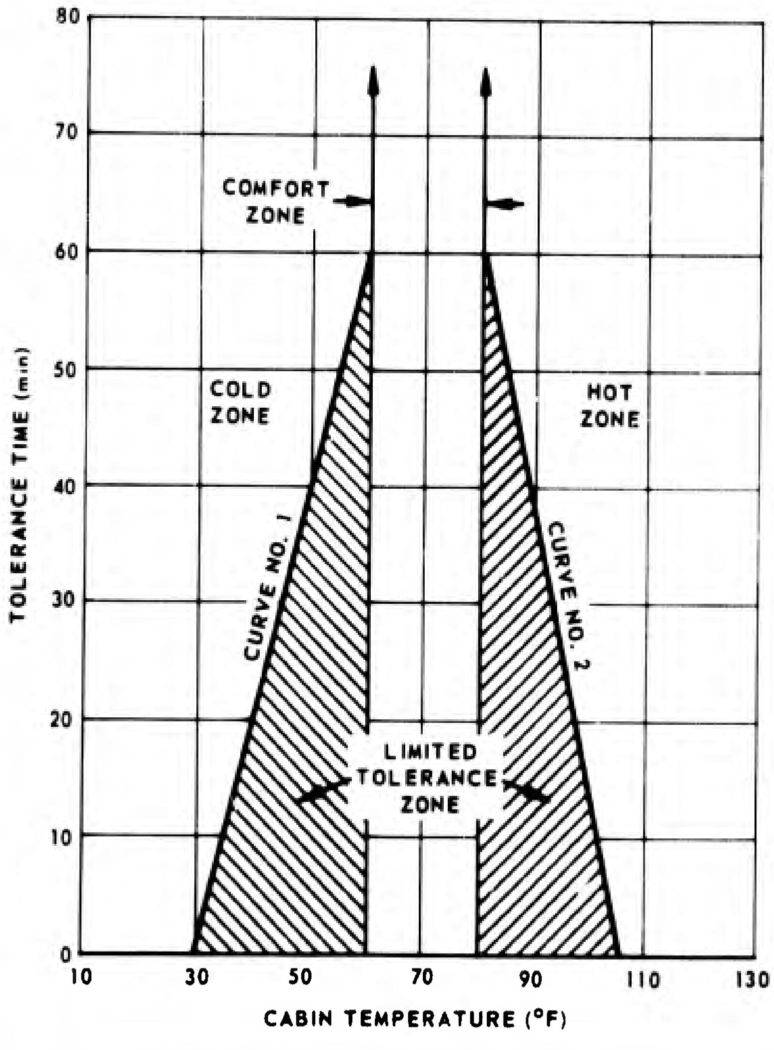


Fig. 33 THERMAL REQUIREMENTS FOR PRESSURIZED CABIN AIRCRAFT (Data from Mil-E-18927 D, 14 Aug 1959)

In some older aircraft, there is no provision for supplying ventilating air to anti-exposure suits. When flying these aircraft, aircrewmen generally leave the garment zippers open, or else do not wear the garment at all. This is obviously not good safety procedure.

(4) Ground Support. Ground support equipment for these garments is not widely available in the fleet. The portable cooler that is used to ventilate the pressure suit is a liquid oxygen converter. This converter has a storage capacity of 0.1 cubic foot of liquid oxygen. When filled, it weighs 28 pounds. This quantity of LOX is sufficient to cool the aircrewman for one hour, following a one hour standby. The aircrewman can control the cooling rate by adjusting the rate of LOX evaporation. These converters are not widely used because they are heavy and bulky; also they restrict the aircrewman s activity because of the fire hazard created when oxygen enriched air is vented.

b. Air Force MA-1 and MA-2 Garments. To adequately cool an aircrewman wearing either the MA-1 or MA-2 cooling garment, an air supply capable of delivering conditioned air at a rate of 15 cfm and a pressure of 8 inH_2O is required. When the cotton underwear that is worn between the conditioning garment and the skin becomes wet due to perspiration, there is an increase in back pressure accompanied by a corresponding decrease in air throughput. The ratio of back pressures between dry and wet undergarments is greater than 3: when undergarments are dry, a flow of 9 cfm produces a pressure drop of 4 inH_2O, whereas when they are wet, a flow of only 4.5 cfm creates a back pressure of 7 inH_2O. To maintain adequate heat removal rates, input air temperature must be low enough to minimize sweating. This requires supporting equipment to provide air at temperatures below 86°F in aircraft that are not equipped with air-cycle refrigeration systems. Aircraft that have such systems have a refrigeration capability in excess of that required for crew cooling.

c. U. S. Army Natick Garment. This garment is designed so that a large volume of air can be moved over the man's body, with a low pressure drop. The U. S. Army Natick Laboratory is using a dual impeller blower assembly with the suit in the Mohawk aircraft. This blower supplies 25 cfm of air at a 4 inH_2O head, to the inlet of the suit. The electrical requirement for this blower is 208V, 400 cps, 1.3 amp.

While he is on the ground, a battery-powered blower can be used to cool the aircrewman. A blower pack containing rechargeable batteries, blower assembly, and controls would weigh less than five pounds.

A hand-carried blower pack containing a fan-motor assembly weighs 2.2 pounds, provides 10 cfm at 5 inH_2O, and consumes 36 watts of power. A battery pack with a storage capacity of 120 watt-hours weighs three pounds. With a little additional effort in packaging, the total weight of the entire unit could be approximately six pounds. It could support a man for a two-hour period.

d. U. S. Navy Pensacola Ventilated Coverall. In the aircraft this garment is designed to be supported by the standard anti-exposure suit blower rated at 16 cfm at 13 inH_2O. Because of the high ambient cockpit temperatures on the ground and at low altitudes, the inlet of the blower is connected to a supply of ram air. The high pressure side of the blower line is equipped with a quick disconnect to permit emergency egress from the aircraft. The motor control consists of an on-off switch. Future plans call for the replacement of the individual Mark V blower by a dual headed blower capable of supplying 25 cfm per man.

C. Liquid-Cooled Garments

1. Description of Garment

a. British Royal Air Force Developments (Refs. 7, 8, 9, 10). The basic development of the liquid-conditioned suit was initiated at the Royal Aircraft Establishment, Farnborough, Hants, England, where the work is still continuing. Similar suits are being manufactured in the United States by the Hamilton-Standard Co., a division of United Aircraft Corp., Windsor Locks, Connecticut (Ref. 19).

The liquid-conditioned suit nominally acts as a heat exchanger between the aircrewman's body and the circulating fluid. Heat is removed or provided to maintain his body in a condition of comfortable thermal balance. Since these garments generally provide no mechanisms for removal of sweat, flow and/or temperature of the circulating fluid must be controlled closely to maintain body temperatures in the narrow range between chill and onset of sweating.

Figure 24 shows one of a number of different models of the liquid-loop garment. These models vary from full-length suits, which cover the entire body except for the head, neck, hands, and feet to vests that cover the upper torso, buttocks, and hips (Fig. 25).

The area of contact between the aircrewman's skin and the heat transfer area of the liquid cooling suit is small. Heat flow from the outside environment through his outer garments will be absorbed by the wearer's body. Heat flow through a garment is dependent on the clo value of the garment, the wind velocity, and external temperature. This heat input from external sources must be added to the wearer's metabolic heat production in any determination of the amount that must be removed by the circulating fluid.

To determine the amount of tubing needed to cover a given area of body, it was assumed by Kerslake (Ref. 7) that regional heat generated during work is proportional to the regional mass of muscle tissue. Table X indicates the percentage of tubing length and heat transfer for various regions of the body. As indicated by this table the major coverage area of the liquid-cooled garment is thighs, calves, arms, and back. The data shown in Table X were developed as a guide for the distribution of tubing. Minor modifications of 1.5% were made.

TABLE X
PERCENTAGE OF TUBING LENGTH AND HEAT TRANSFER FOR VARIOUS REGIONS OF THE BODY

(Data from The Development of Water Conditioned Suits, by D. R. Burton and L. Collier (Ref. 7))

REGION OF BODY	LENGTH OF TUBING (% of total)	HEAT TRANSFER (% of total)
Head	0	4.15
Hand	0	5.51
Forearm	10.82	8.93
Arm	18.57	8.72
Back	11.00	12.89
Chest	9.67	8.52
Foot	0	10.39
Calf	16.47	15.15
Thigh	23.22	12.44
Buttock	4.05	8.62
Abdomen	6.20	4.68
Entire body	100.00	100.00

The heat transfer network within the suit consists of a number of polyvinyl chloride tubes through which the cooling fluid is circulated. The number of these tubes that are required and their inside diameter are functions of the coolant flow rate that can be provided and of the pressure drop that can be tolerated between the inlet and outlet of the cooling loop.

The inlet coolant connection is at the rear of the suit. The fluid enters a manifold from which four main distribution tubes (0.13 inches I.D.) emanate. Each of these tubes serves as a secondary manifold for one limb. Heat transfer networks are fed from these manifolds. The heat transfer tubes are smaller in diameter than the feed lines. The diameter of the lines is determined by the number of parallel circuits they must supply. These networks are sewed into a support garment such as long underwear or elastic netting; this is done to insure intimate contact with the skin surface. The fluid flowing through the tubing returns to a central exit manifold in the front of the suit. Here it leaves the suit and is returned to the external refrigeration system.

Reference 7 gives a complete discussion of the design of the RAE liquid-cooled undergarment: it goes into specifics such as the diameters and lengths, flow rates, construction, and other pertinent data. Reference 18 presents a discussion of the Hamilton-Standard Corporation approach to this garment.

b. Hamilton-Standard Development. At the present time, Hamilton-Standard is incorporating liquid-loop cooling into an Apollo Portable Life Support System (PLSS) suit. The thermal control system in this suit utilizes a combination of gas and liquid-loop conditioning. The major mechanism for heat removal is incorporated in the liquid-loop cooling garment worn by the astronaut. Cooling liquid is circulated through tubes that are in contact with portions of his body. At the same time, ventilating gas is passed over the skin to remove body moisture and odor, and to pressurize the Apollo suit. The system is designed to remove heat from a man who has an average metabolic rate of 1200-1600 Btu/hr and short-term peaks of 2000 Btu/hr.

Circulating coolants are refrigerated in a sublimator assembly in which water sublimates, thereby removing heat at a rate of 160 Btu/(hr-°F-ft^2). Both the gas- and liquid-cooling circuits utilize the sublimator to cool the fluids. The gas circuit uses a brushless DC motor centrifugal pump unit that provides a constant gas flow of 6 scfm at a pressure of four inches of water. The liquid coolant is also circulated by a brushless DC motor centrifugal pump that produces constant water flow of 4 lb/min. Inlet water temperature can be set at 45, 65, or 77°F by adjustment of the diverter valve assembly.

The liquid-loop suit presently employed in this system uses a 40-parallel-flow-path suit with 300 feet of tubing. For the 2000 Btu/hr heat removal rate, the liquid-coolant inlet temperature is 47°F, and coolant flow rate is 4 lb/min. The temperature difference between inlet and outlet is 9°F. The air cooling loop, while circulating only 6 scfm, is capable of absorbing approximately 850 Btu/hr through convective and evaporative perspiration cooling. Use of the two cooling systems in combination also provides a backup capability in the event that one of the two systems fails.

Listed here are component parts of the liquid/air conditioning system (less the external heat exchanger):

Component	Power Requirement/Capacity		Weight (lb)
Water pump assembly	16.5V DC	/ 10 W	1.4
Diverter valve	Manual		0.33
Fan and motor assembly	16.5V DC	/ 30 W	1.85
Power supply (battery)	16.8V DC	/ 240 watt-hr	5.4

A system similar to that developed for the PLSS would appear to have future potential for use in aircraft. It could provide a comfortable environment for an aircrewman when it is operated in either of its modes. The system could be used with a portable liquid-loop refrigeration unit with a brine-solution heat sink. When on the ground, a portable heat exchanger weighing less than ten pounds could adequately cool an aircrewman by using the liquid-loop capability. In the ready room, the portable refrigerator could be powered from electrical power outlets. After the crewman boards the aircraft, the air-cycle air conditioner would cool him. The portable cooler would then be connected to the aircraft's electrical power system, and the brine solution would be refrozen. In the event of failure of the air-cooling system, the crewman could switch to the liquid-loop system, which could probably keep him near thermal balance for the rest of the flight. The capacity of the system would be dependent upon the amount of frozen brine solution used.

An additional advantage of the PLSS thermal management system is realized through use of ventilating air to control moisture and odor within the suit. At times, cooling by the liquid-loop system may be inadequate to prevent sweating. This moisture is not normally removed in other liquid-cooled suits. Circulation of air – even at low flow rates – will help control this moisture accumulation.

There are two basic types of liquid-loop garments: the full suit, which covers 16 square feet of the body surface area, and the vest, which covers 7.5 square feet. The full suit has been constructed in various arrangements in which there are differences in both the number of parallel tubes and the total length of tubing. The number of the tubes varies from 40 to 48, and the total length of tubing used varies between 232 and 300 feet.

2. Support Requirements for Liquid-Cooled Suits

The power required to pump cooling fluid through the liquid-cooled suit is quite small. It is less than one watt for the Royal Air Force unit and ten watts for the Hamilton-Standard Apollo PLSS unit. Variations in these reported power consumptions may result from differences in fluid-mass flow rate. The RAF suit circulates 1.105 lb/min at approximately 0.3 psi ΔP, and the Hamilton-Standard suit circulates 4 lb/min at a pressure of 5.65 psi ΔP. This difference in reported pressure drops appears to be reasonable because pressure drop is proportional to the square of the mass flow rate ($P \propto \dot{m}^2$) for the same suit design; thus, a 4:1 mass flow rate change produces a 16:1 change in pressure drop. The flow rate is maintained constant in the RAF and Hamilton-Standard garments, and the coolant temperature is adjusted so that the desired rate of heat transfer is achieved. As a result of the Hamilton-Standard procedure of pumping 4 lb/min, only a small temperature differential (Δt) exists in the circulating water between inlet and outlet. The lower flow rate in the RAF system causes a larger Δt, and coolant at a lower initial temperature must be supplied to the suit.

a. <u>RAF Portable Coolers</u>. The Royal Air Force has developed a portable cooling system for the liquid-loop suit. This system connects to the liquid-loop suit by means of a pair of quick-connect leak-proof fittings. The portable unit is an insulated ice chest that will hold eight pounds of ice. The circulating water is pumped by a miniature gear pump (Watson-Marlow Air Pump Co.). The pump, complete with rechargeable battery, weighs 12 ounces. The batteries, from which the pump consumes approximately one watt of power, are capable of operating it for three hours without their needing to be recharged.

b. USAF Portable Coolers. A portable cooler is being developed by the USAF at Wright-Patterson Air Force Base for use with the Air Force's liquid-cooled vest. This portable cooler uses a 12V DC electric diaphragm pump that pumps 1.5 lb/hr, a diverter valve, and an insulated ice chest. The cooling fluid is circulated through the chest in a manner similar to the way it is circulated in the RAF system. Chests with different capacities (from 8 to 50 pounds of ice) are used to accommodate either a number of men for short missions, or fewer men on missions that are longer in duration. The consumption rate (i.e., melting rate for ice) (given in Ref. 21) varies from 4.4 to 8.25 lb/hr. The rate of ice usage varies with environment and efficiency of the vest. The rate of heat absorption by the vest varies from 850 to 1200 Btu/hr.

3. Limitations of Liquid-Cooled Garments

Liquid-loop cooling systems are designed to remove both the metabolic heat produced by the aircrewman and the heat that passes through his garment by conduction. Extensive tests have been made by Hamilton-Standard Co. and by the USAF Biomedical Branch, Wright-Patterson Air Force Base. Test results indicate that liquid cooling systems reduce overall sweat rates, but do not eliminate sweating. In Table XI is a listing of tests performed with the liquid-loop system. In most of these tests,

TABLE XI
TEST DATA FOR CONTROL AND AIR-COOLED CREWMEN

Test Number	Testing Organization	Type of Suit	Ambient Environmental Conditions		Ventilation-Air Conditions			Metabolic Rate	Evaporative Losses		Heat Storage	Rectal ΔT
			(°F)	(% RH)	(°F)	(cfm)	(% RH)	$(\frac{Btu}{ft^2\text{-}hr})$	$(\frac{Btu}{ft^2\text{-}hr})$	(lb/hr)	$(\frac{Btu}{ft^2\text{-}hr})$	(°F)
A- 1	Bio-Med Branch W-P	Control	110	--	--	--	--	20	--	0.34	21.6	2.52
A- 2	Bio-Med Branch W-P	USAF MA-1	110	--	70	5	<5	20	--	0.27	2.2	0.18
A- 3	US Army Natick Lab	Control	125	25	--	--	--	20	--	Un-avail.	39.8	2.6
A- 4	US Army Natick Lab	Natick Garment	125	25	75	15	34	20	--	0.7	0 to -7.7	0.5
A- 5	Bio-Med Branch W-P	Control	115	20	--	--	--	20	--	1.0	24.6	1.08
A- 6	Bio-Med Branch W-P	USAF MA-1	115	20	115	11.5	20	20	--	0.5	27.2	1.42
A- 7	Univ. of Calif.	USAF MA-2	120	11	90	10	--	18.7	28.3	0.56	1.2	--
A- 8	Univ. of Calif.	USAF MA-2	120	11	70	2	--	19.9	15.2	0.30	3.4	--
A- 9	Univ. of Calif.	USAF MA-2	120	11	50	6	--	18.7	7.1	0.14	-1.0	--
A-10	Univ. of Calif.	USAF MA-2	120	<5	50	10	--	18.5	38.9	0.75	-1.5	--
A-11	Univ. of Calif.	USAF MA-2	120	<5	70	6	--	19.1	34.6	0.67	2.5	--
A-12	Univ. of Calif.	USAF MA-2	120	<5	90	2	--	22.4	34.3	0.66	21.7	3.0

the subjects sweated between 0.1 lb/hr and 0.7 lb/hr; these rates are quite acceptable under most flight conditions. In these garments, however, the accumulation of sweat presents problems. Wet undergarments are uncomfortable and reduce conductive-heat-transfer efficiency between the cooling tubes and the skin.

At the present time, emphasis is being placed upon development of the vest configuration. This garment removes heat in the torso, which is not the major source of heat; therefore, it is not a fully adequate system in terms of overall thermal comfort.

At the present time, the portable ice chest is the only operational unit available for support of these garments outside of the laboratory. For short missions, the ice chest is adequate, but it is not practical for long-duration missions or large crews. In the course of this study by the Applied Physics Laboratory, discussions were held with manufacturers of liquid-loop avionic cooling units to explore the feasibility of adapting these units to suit cooling applications. These suppliers expressed the opinion that their systems could be modified to support suits, but that additional engineering effort would be required. Avionic cooling units now in use supply fluid at higher temperatures than are permissible if the suits are to be adequately supported.

D. Tests of Thermal Control Garments

The USAF flight tested the Hamilton-Standard liquid cooled vest (Table XII) in the fall of 1966. Tests were performed in Florida and Panama. A total of forty flights were made using this vest with a crushed-ice heat exchanger. In Florida the temperatures were 85-90°F, and the relative humidity was 50-70%. In Panama, the ground temperature varied from 95-100°F and relative humidity was 60%.

TABLE XII
TEST DATA FOR WATER-COOLED CREWMEN

Test Number	Testing Organization	Type of Suit	Ambient Environmental Conditions		Circulating-Fluid Conditions		Metabolic Rate	Evaporative Losses	Heat Storage	Rectal ΔT	Average Skin Temperature
			(°F)	(% RH)	(°F)	(lb/min)	$\left(\frac{Btu}{ft^2\text{-}hr}\right)$	(lb/hr)	$\left(\frac{Btu}{ft^2\text{-}hr}\right)$	(°F)	(°F)
W-1	Bio-Med Branch W-P	RAF Full Garment	110	<5	70	2.2	20	0.07	-0.1	-0.11	--
W-2	US Army Natick Lab	H-S Full Garment	125	25	73.8	0.28	20	0.13	23.9	0.8	--
W-3	US Army Natick Lab	H-S Vest	125	25	73.8	0.28	20	0.15	23.9	1.7	--
W-4	Bio-Med Branch W-P	H-S Half Suit	115	20	35	1.55	20	0.3	--	-0.18	--
W-5	Bio-Med Branch W-P	H-S Vest	115	20	35	1.55	20	0.5	--	0.54	
W-6	Bio-Med Branch W-P	H-S Vest	115	20	35	1.55	20	0.4	--	0.90	--
W-7	Bio-Med Branch W-P	H-S Vest	135	15	35	1.55	20	0.7	--	0.54	--
W-8	Hamilton-Standard	H-S Vest	72	--	49.6	4.0	60	--	--	1.3	76.4
W-9	Hamilton-Standard	H-S Vest	72	--	54.9	4.0	80	--	--	1.4	82.4
W-10	Hamilton-Standard	H-S Vest	72	--	79.6	4.0	20	--	--	0.1	91.4
W-11	Hamilton-Standard	H-S Vest	72	--	45	4.0	80	0.31	--	1.8	--
W-12	Hamilton-Standard	H-S Vest	72	--	45	4.0	100	0.18	--	3.2	81.5

The flight tests were performed by crew members of C-123, B-26, and A1-E aircraft. Use of the liquid-loop cooling vest was not restricted to pilots of the aircraft. In some cases, the most active aircrewmen wore the vests. In others, some of the least active members wore them. A full discussion of these flight tests will be prepared when a detailed report is obtained.

During these flight tests, aircrewmen who wore the vest had sweat rates lower than those who did not wear them. The vest reduced the sweat rate, but did not eliminate sweating.

Following are discussions of tests of thermal control garments. These tests were performed by the activities indicated. For each test, subjects were dressed in impermeable, military-type garments made of material that had thermal insulating capability in excess of 1.5 clo. In some tests there were also control subjects. These subjects were dressed in clothing similar to that worn by the other subjects, but they did not wear thermal control garments.

The tests are identified by "A" and "W" prefixes. Those designated "A" relate to air-cooled garments and those identified by "W" relate to water-cooled garments. See Tables XI and XII for data.

Tests	Experimenter	Reference
A-1 and 2, W-1	Veghte	27
A-3 and 4, W-2 and 3	Spano	26
A-5 and 6, W-4 thru 7	Kaufman and Pittman	21
A-7 thru 12	McCutchan	24
W-8 thru 12	Jennings	18

1. Tests A-1,A-2, and W-1

These tests were performed on subjects wearing the Full Pressure Suit (FPS) AP/225-2 in the unpressurized condition. Three subjects participated in this test: one wore just the full pressure suit, the second was equipped with the Farnborough air-cooled system under his full pressure suit, and the remaining subject wore a Farnborough liquid-cooled garment.

As indicated in Tables XI and XII, the subject equipped with the liquid-cooled garment had a negative heat storage, the air-cooled subject had a small positive heat storage well within acceptable limits, and the control subject experienced excessive build-up of heat. During these tests, rectal temperatures indicated that the subjects who wore cooling garments were in near thermal balance and in thermal comfort. The control subject experienced thermal discomfort and a 3°F increase in rectal temperature indicating thermal imbalance. The data from this experiment indicates that the cooling garments improve the aircrewman's resistance to thermal stress and that the liquid-cooled garment is somewhat more effective.

2. Tests A-3, A-4, W-2, and W-3

These tests were conducted in the course of evaluation of equipment for the Mohawk aircraft. Four subjects were dressed in similar fashion in regulation Army flight gear (including flak vest). One subject was a control, the second was equipped with an air-ventilated garment (Section III-B-2-c), the third wore a full-length liquid-cooled garment, and the fourth subject wore a liquid-cooled vest. The liquid-cooled garments were manufactured by the Hamilton-Standard Division of United Aircraft Corporation.

In the test chamber an environment of 125°F, 25% RH, and low-velocity air movement was maintained. The conditioned air and fluid were controlled in such a manner that the two cooling fluids had the same enthalpy change between inlet and outlet of the suit. This condition is achieved by providing mass rates of flow (of the fluids) equal to the reciprocal of their specific heats. The cooling water had a mass flow rate of 0.27 lb/min at a temperature of 73.8°F; cooling air had a mass flow rate of 1.14 lb/min (15 cfm) at 75°F and a relative humidity of 34%.

The subjects sat at rest in the environmental chamber. Their metabolism rates were approximately 400 Btu/hr. The test ran for two hours. Before the tests were completed, the control subject was removed from the environmental chamber when he became ill as a result of being exposed to the hot environment, and complete data were not obtained on him. The remaining subjects completed the experiment, and were not affected adversely. The results indicate that if adequately conditioned air is supplied to the Natick garment, its wearer can maintain a reasonable thermal balance. Even when the cooling water temperature in the water-cooled suit rises above the desirable level, the subject does not appear to experience adverse physiological effects.

3. Tests A-5, A-6, and W-4 through W-7

These tests were conducted on a large number of subjects who wore different conditioning undergarments, and on control subjects. Each of the subjects was dressed in the K2B summer flying suit.

The data indicate that by circulating cold water through a water-cooled vest, sufficient body heat can be removed to prevent the core temperature from rising. With air-ventilated garments, circulation (through the garment) of air that is at a temperature above the mean skin temperature caused the subject's core temperature to rise higher than that of a subject who was not ventilated. When air that is at a temperature above mean skin temperature is blown over a subject's skin, the man absorbs heat from the air. For these tests, no attempt was made to develop system components that were compatible with flight operation conditions.

In the tests of liquid-cooled suits, the average ice consumption per man is 13.3 lb/hr. For long flights, such a high consumption rate would present a weight and logistics problem. Even though the vest neither maintained thermal balance within the subject nor kept him comfortable, it is capable of reducing some of the strain associated with operations in hot climates.

4. Tests A-7 through A-12

These tests were performed by the University of California under contract to the USAF Wright-Patterson Air Development Center. Subjects for these tests were dressed in the Mark IV anti-exposure suit and the MA-2 ventilating undergarment.

In tests A-7, A-8, and A-9 the temperature in the test chamber was held constant and the temperature and flow rate of the conditioning air was changed. The data indicate that ventilating air supplied at medium rates and at low temperatures minimizes sweating and removes body heat by warming the ventilating air. High flow rates of air that is at temperatures near the mean skin temperature tend to induce sweating, and the basic mode of heat transfer is by evaporation of the sweat. At low flow rates and comfortable cooling air temperatures, the subject tends to lose heat through evaporative and convective heat transfer.

Tests A-10, A-11, and A-12 indicate that in an environment as hot as 100°F, a subject must be supplied with cold air if he is to be kept reasonably comfortable. In test A-10, the subject was ventilated with 50°F air at 10 cfm. Even in the hot environment, this produced a negative heat storage. In the other two tests at this temperature, the subjects absorbed heat and experienced high sweat rates. Under such conditions, a crewman would experience thermal fatigue in a short time. A cabin temperature of 160°F is probably the maximum to which a crewman will be exposed in aircraft on the ground.

5. Tests W-8 through W-12

These data were obtained from subjects who worked on a treadmill while they were dressed in the Apollo space suit in a room at 72°F (still air). Each subject was dressed in a model of the Hamilton-Standard liquid-cooled suit.

The data indicate that the subjects were uncomfortable under most conditions, as was indicated by the low mean skin temperature. Discomfort results when low cooling-fluid temperatures cause a drop in skin temperature, but low fluid temperature must be maintained if necessary heat transfer from the subjects skin to the fluid is to take place. For each of these tests, both sweat rate and change of core temperature were kept to a minimum.

In test W-11, the subject exercised to raise his metabolic rate to 1600 Btu/hr. This rate of heat production can be expected during a "space walk," but is above the normal exertion level of aircrewmen. With this thermal load, the liquid-cooled garment was capable of keeping the subject's temperature below the thermal danger zone, and of maintaining a low sweat rate. These data indicate that an aircrewman being subjected to a thermal load (metabolic + external heat entering the suit) equal to 1600 Btu/hr could be maintained in an acceptable, although undesirable, thermal condition.

6. Assessment

The results of the liquid private climate garment testing shown in Table XII were obtained almost exclusively with Hamilton-Standard manufactured garments. These garments included the full length underwear and the vest model. The data indicate that with adequately chilled fluid and a fluid flow rate in excess of 1.55 lb/min, an aircrewman can be maintained in a thermally favorable condition. The fluid temperature should be substantially lower than that used in the air private climate garment because of the thermal impedance of the plastic tubing in the garment.

In tests W-2 and W-3, the fluid temperature (73.8°F) was above the normal value used in most liquid cooled garments; also, the flow rate was extremely low. If the thermal impedance of the plastic tubing within the garment were zero, the 20°F rise in the cooling fluid temperature could take place. This 20°F rise, at a flow rate of 0.28 lb/min would give a heat-removal capability of 5.6 Btu/min or 336 Btu/hr (which is less than the subject's metabolic rate), but the thermal impedance of the tubing may well cause a 10 to 15°F temperature gradient across the tubing wall. This temperature gradient would reduce the heat removal capabilities to a very low value.

Tests W-8, W-11, and W-12, conducted by Hamilton-Standard indicate that a fluid temperature of 45 to 50°F and a flow rate of 4 lb/min is desirable. Under these conditions the circulating fluid would have a small temperature rise (3 to 6°F) and have a large heat removal capability (1000 Btu/hr). A circulating-fluid temperature of 50°F would be best in terms of personal comfort and would be sufficient for the necessary heat removal capability, even with the temperature gradient across the tubing.

The data presented in Table XI are based on laboratory tests conducted by the indicated organizations. These tests were conducted on two types of air-cooled garments, the U. S. Air Force MA garments and the U. S. Army Natick garment. Tests A-2, A-4, A-8, and A-11 were all conducted under similar suit-inlet air temperatures, but with different ventilating-air flow rates. The results obtained from these tests indicate that crewmen would be in a thermally favorable condition when the evaporative water loss is 0.27 lb/hr to 0.7 lb/hr and the heat storage rate is -7.7 to 3.4 Btu/(ft^2-hr). With these rates, the crewmen could be expected to perform their assigned mission with little or no thermal stress problems.

In the cases where the inlet air temperature approached that of the skin temperature, there was an increased dependence on evaporative heat transfer to maintain thermal balance. In tests A-7 and A-12, the inlet air temperatures were 90°F and flow rates were 10 and 2 cfm, respectively. It is interesting to note that heat storage is reduced by increased air throughput, and thereby improves the crewman's thermal condition. This would indicate that a crewman can possibly be ventilated by ambient air flowing at a rate of 10 to 15 cfm and still be maintained in a zone of near thermal balance.

The values presented in this discussion are those obtained during individual testing and most likely will vary substantially from one individual to another under similar environmental test conditions.

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IV. APPLICATION OF COOLING TECHNIQUES IN SOLVING CURRENT PROBLEMS

When, in an effort to improve aircrew comfort, the desirability of making alterations to existing aircraft and aircraft support equipment is considered, the extent to which the present deficiency decreases proficiency of performance of the crewman must also be determined. If the thermal stress is such that it drastically affects the aircrewman's ability to complete his mission, or endangers the crew, a retrofit cabin air conditioning system may be justified. However, in many aircraft such an approach is not feasible because of the limitations placed on weight, volume, and electrical or mechanical power.

Among the considerations that arise there are those such as aircraft rework, short potential service life of aircraft, and amount of lead time before implementation of modifications. A typical example of this is the CH46 Marine helicopter that has sufficient electrical power and space for the installation of an air conditioner, but the additional weight cannot be carried. Furthermore, from an operational standpoint, these aircraft cannot be spared from present assignments for installation of the system. In general, aircraft of this type having a large canopy area and large volumes of open space, would require a very large air conditioner (about 10-ton capacity) for adequate thermal control. Accordingly, to solve the thermal stress problem in this type craft, a different approach must be used.

An alternate approach to the cabin conditioning system is to provide a private climate conditioning system for the crewman within their garments. The private climate system (PCS) consists of either a liquid- or air-cooled undergarment and its necessary support equipment. The use of the PCS would impose a much smaller weight, volume, and power penalty to the aircraft and provide an equal or more effective thermal control for the crew. In the aircraft, the installation of the PCS could be more readily accomplished than installation of a cabin conditioning system.

To support the use of the private climate garments, the following equipment is necessary:

1. Air-cooled
   - (a) Blower to supply air at desired flow rate and pressure, or
   - (b) Air conditioner
     - (1) Air-cycle system (integrates part of aircraft structure)
     - (2) Vapor-cycle system (modular plug-in type)
   - (c) Air ducts to garments from blower outlet or air conditioner
   - (d) Air ducts to blower inlet from ram air inlet
2. Liquid-cooled
   - (a) Chilled fluid
     - (1) Supplied by ice chest, or
     - (2) Supplied by mechanical refrigerator
   - (b) Piping for circulating fluid

Most current Naval aircraft could support the air-cooled garment in that they are equipped either with an anti-exposure suit blower or with an air-cycle air conditioner having suitable interconnecting air ducts to the garment from the air source, or they could be equipped with a retrofit system consisting of an air- or vapor-cycle air conditioner system having the necessary interconnecting air ducting to the garment. The retrofit of a blower assembly and the air duct from ram-air inlet-to-blower and blower-to-garment could be accomplished by squadron level maintenance personnel, whereas the more extensive retrofits would require rework by higher echelon maintenance personnel. It is felt that by use of the items listed here, a crew comfort system could be implemented in a short period of time at minimum cost and aircraft rework, once the requirement for such a system is defined. At present the thermal stress problem exists, but has not been well defined or officially specified as requiring correction.

The U.S. Navy Pensacola Ventilating Garment (Section III-B-1-f) is an example of the implementation of existing techniques for aircrew cooling in a thermal stress problem area. The aviation physiologist assigned to the Pensacola Naval Air Station recognized the thermal stress problem experienced by both student and instructor pilots flying T-28 aircraft. The flight profile of this type aircraft required extensive flight time at low altitude and low speeds, therefore, most flights were not subjected to the natural air cooling which occurs at increased altitude. This aircraft has a large canopy that produces an extensive greenhouse effect. In an effort to reduce the thermal stress, the physiologist at this station procured obsolete Arrowhead full-pressure suits that were equipped with an air ventilation system. This ventilation system was removed from the suit and installed in the regulation summer flight cover-all. (The discussion of this garment can be found in Section III-B-1-f and support requirements in Section III-B-2-d.)

A flight-test program was initiated using the air ventilated summer coverall in the T-28 with good results. The initial testing consisted of twenty-two flights by two pilots. One of the test pilots who conducted twenty flights had formerly experienced substantial sweating during similar flights, but returned with dry garments when wearing the air-cooled garments. The air-cooled summer flight suit received enthusiastic endorsement from pilots in the squadron. Additional improvements are planned by the Pensacola personnel.

The U.S. Army Natick garment (Section III-B-1-e) uses the same basic principles as the Navy Pensacola Ventilating Garment, but it should be more effective than the reworked air ventilation system used in that garment. The Natick garment covers approximately 65% of the body surface, whereas the Pensacola air ventilation system covers 25% of the body area. The Natick garment will also have a lesser pressure drop across the suit because of the elimination of the internal interconnecting air ducts.

In order to implement the use of liquid PCG, it is necessary to supply chilled fluid from sources described previously in this section. At the present time the liquid PCG is used primarily with an ice-chest coolant supply because of the unavailability of suitable mechanical refrigeration units. The U.S. Air Force is presently testing liquid PCG vests using an ice chest (Refs. 18, 23), with good physiological results and aircrew acceptance, but this system presents logistical, weight, and mission-duration problems that are still to be solved.

The present Air Force tests using the ice chest approach reduce the sweat rate somewhat, but do not eliminate sweating. This system must supply an equivalent cooling capacity (melting ice up to 50°F) that is many times the metabolic rate. The actual requirement on a heat exchanger will depend upon the insulation of the storage tank, the transfer lines, and on the man himself. Under actual conditions (Ref. 18) in Panama and Florida, flight tests were performed using the liquid PCG and ice heat exchanger. During eight flights totaling 15 hours, 143 pounds of ice were used, averaging 9.5 pounds per hour. The final water temperature inside the ice chest was not indicated, therefore, the total amount of heat transferred is not known exactly. The melting of 9.5 pounds per hour of ice will have an equivalent cooling capacity of 1400 Btu per hour.

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V. CONCLUSIONS AND RECOMMENDATIONS

Studies abstracted in Section II of this report, have demonstrated that some garments normally worn by aircrewmen have enough thermal impedance to cause dangerous heat accumulation in the wearer even in moderately hot environments. Thermal stress caused by hot weather can be aggravated by heat accumulation in unventilated aircraft. Under these conditions, acceptable degrees of thermal balance can be maintained through heat removal by either a liquid- or gas-cooled heat exchange garment. Both types of cooling garment require support equipment to provide a flow of coolant. The maximum heat removal rate of either type of garment is determined by the effectiveness of the thermal contact of the coolant fluid with the body of the aircrewman, and by the temperature and flow rate of the cooling fluid. The degree of comfort that is afforded by any system is related to the ability of the wearer to match the cooling effect of the garment to his needs; excessive cooling can produce discomfort that is as objectionable as that caused by deficient cooling.

In large measure, an aircrewman may be kept in a condition of acceptable thermal comfort through use of the convective and evaporative cooling techniques discussed in Section II-C. Thermal discomfort is minimal when air cooling garments are employed in aircra[illegible] in which there is an adequate supply of refrigerated air. Aircrewmen suffer thermal discomfort in existing aircraft principally because of the lack of an adequate supply of ventilation air. In low performance aircraft, which fly at speeds of Mach 0.5 or less, acceptable aircrew cooling can be provided by ventilating garments using ram air. The cockpits of high performance jet aircraft are, in general, satisfactorily air conditioned except for certain off-design operating conditions in A-5 aircraft. Even under these conditions, cooled air that is available in the A-5 could be used satisfactorily with air ventilated garments if it was supplied to the suits.

It is essential that air-flow resistance interposed by air-ventilated garments be low so as to permit adequate flow of ventilation air without use of excessive pressure, which causes suit "ballooning" and requires excessive blower power.

Liquid-cooled crew garment systems exist but they are not yet perfected, especially with respect to operational coolant-liquid supplies. Present-day aircraft are not equipped to provide cool (45°F or less) liquid. Small refrigerative devices still need to be developed. Until practical coolers are developed, ice chests and ice supplies must be used with liquid-cooled suits. Currently available liquid-cooled garments have insufficient thermal contact area with the wearer's body and have excessive thermal impedance requiring inordinately cold coolant liquid for effective cooling.

A. Immediate Problem Alleviation

The following recommendations are made with a view to immediate problem alleviation.

(1) Wider use should be made of air-ventilated garments whenever Naval aircraft must fly in hot climates or when aircrew members are required to wear insulating or impermeable garments. The ventilation garment should be one that has low airflow impedance and that will facilitate aircrew cooling in un-air-conditioned aircraft through the use of ram air.

The U.S. Army Natick Laboratory has developed a suitable garment of this sort for the Mohawk aircraft, and this should be considered for Navy usage.

(2) Aircraft that are not air-conditioned should be equipped with ventilation blowers connected to ram intakes for ventilation of cooling garments. These air supplies could also have small electric heaters to warm the crewman if it were to become necessary to operate the aircraft with the cabin unheated.

B. Future Improvements

Additional studies need be made to define suitable criteria for tolerable (as contrasted to comfortable) thermal conditions in which the aircrewman will not be seriously impaired in the performance of his duties.

(1) It is recommended that studies be made to determine quantitative limits of tolerable body heat storage by aircrewmen. This study is needed to determine the duration and extent to which the aircrew thermal environment can be allowed to deviate from optimum conditions. Tests could be performed best by having test subjects who are experiencing various degrees of thermal comfort or discomfort to operate a flight simulator and by assessing variation of proficiency as it relates to thermal discomfort. A statistically significant number of subjects should be tested. Both transient and steady-state thermal comfort should be investigated. Liquid-cooled garments appear to offer great promise of providing a solution to many of the crew-cooling problems that are encountered in contaminated or very hot environments. Improvements and additional developments are needed.

(2) If possible, the following improvements need to be made in liquid-cooled garments:

a. Increase body area coverage and provide better distribution of cooling surfaces. Cooling surfaces of present liquid-cooled garments cover only 5 to 10% of the body surface. Correspondence needs to be improved between cooling surface location and heat generation distribution in the body.

b. Thermal impedance of the garment should be reduced so that it is not necessary to use extremely cold coolant. Use of a lower thermal-impedance cooling garment in conjunction with warmer coolant would permit more thermal regulation by the wearer's body through its control of skin thermal impedance.

c. Some ventilating airflow between the liquid-cooled garment and the wearer's skin should be provided for removal of perspiration and to provide a means of emergency cooling in the event of failure of the main liquid-cooling loop. The Hamilton-Standard PLSS spacesuit cooling system developed for NASA employs such a system.

(3) It is recommended that development of a laboratory model of a dual-purpose (portable and in-plane) coolant-refrigeration system for use with liquid-cooled garments be started. This system should probably be an electro-mechanical refrigeration system having ice-storage capability.

(4) It is recommended that consideration be given to the development of a liquid-cooled survival suit based upon the skin diver's "wet suit" concept. The use of liquid for cooling will permit the use of a

closely-fitted, moisture impermeable, insulated, liquid-cooled garment. Sealed thermal insulation in the garment will permit it to remain a thermal insulator and to provide buoyancy indefinitely while immersed. The use of a close-fitting survival suit will minimize the inflow of water between the aircrewman and his garments upon submersion, and will greatly reduce chilling of the aircrewman that results when cold water enters the space between his clothing and his body.

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Appendix A

The Johns Hopkins University
APPLIED PHYSICS LABORATORY
Silver Spring, Maryland

SLS-163-66
March 11, 1966

MEMORANDUM

TO: R. G. Bartlett

FROM: F. C. Jurgens

SUBJECT: Trip Report on Visit to Naval Aviation Test Station at Patuxent River on 3 March 1966.

The writer accompanied by Dr. Frank Bader and Mr. R. G. Heidelbach spent the day at the Patuxent NAS, Lexington Park, Md., to talk with Dr. Robert Kelly (Lt.), Messers. Roger Seltz and Lee Fields on air crew cooling and oxygen system.

In the discussion of crew cooling systems Dr. Robert Kelly stated that this problem varied with the types of aircraft. In the area of rotary-wing aircraft, there is no cooling system other than fans or ram air from ducts. In multi-engine transports the problem is of inadequate heating since the plane spends very little time at low altitudes. In the jet aircraft the problem areas vary with the aircraft. In the F-8 and F-4 the air cooling system appears to be satisfactory, but cooling systems in some of the other aircraft are not fully satisfactory.

During the visit M/Sgt. Petroff discussed and displayed the Pressure Suits including the Goodrich Model Mark IV and the Arrowhead Models. In addition, he demonstrated the exposure suits which consist of a rubber suit worn over an insulated coverall. The exposure suit can be cooled from the aircraft air conditioning system if one exists. Dr. Kelly wore an exposure suit in preparation for a flight over the Chesapeake Bay. He stated that even with the air temperature around 65°F he felt more comfortable with both layers of the suit unzipped while on the ground. In addition he said that many pilots do not wear the exposure suits when they should because of the discomfort on the ground and at low altitude. The time from suit-up to climbing into the aircraft and startup is approx. 30 minutes under normal condition; under some conditions, such as ready aircraft for aircraft carrier defense, the pilot might sit in the airplane at the catapult for a number of hours without the engine running. If an exposure suit was worn by this pilot he would become quite uncomfortable. At present there are some methods of ground cooling for the pressure suit and anti-exposure suits, but the units are heavy and dangerous since they utilize a LOX converter. The unit is approx. 1 cu. ft. in vol. and 25-28 lbs. when full of LOX. This unit would be sufficient for one hour standby and one hour operation before fully expending the LOX.

<u>Background on Air Conditioning Systems on Jets</u>

Present air conditioning systems on jet aircraft consist of a hot bleed air intake at the inside diameter of 17th stage of the engine compressor section and is directed thru the air conditioning unit. This unit cools the air by means of a heat exchanger and an expansion turbine refrigeration unit. The heat exchanger reduces the temperature of the engine bleed air by transferring heat thru coils to ram air from the engine intake duct. The refrigeration unit further cools some of the warm air from the heat exchanger by expansion thru the turbine. The air conditioning system provides the following services:

a) cockpit temperature control and pressurization

b) pressure suit ventilation and pressurization

c) windshield defogging and rain removal

d) pressurization and cooling of integrated electronic package

e) automatic cooling of the electronics compartment

f) automatic pressurization and cooling of radar set

g) automatic pressurization of fuselage fuel coils and tanks

h) air for the anti "g" suit

In the F-4 and F-8 aircraft, provision has been made to maintain the pressurization and ventilation to the pressure suit. In the F-4-H1 the ventilation system can deliver up to 10 cfm of air per suit at any temperature selected by the pilot. The A-4 aircraft is equipped with a pressurized cabin but not for pressure suit ventilation.

Impression Gained from this Visit on Cooling Systems:

1. Most jet aircraft have a inplane cooling system for the cabin and to some extent for pressure suit ventilation.

2. Rotary wing aircraft have no ventilation cooling system other than fans.

3. Ice for liquid cooled suits would be a logistic problem in many theaters of operation.

4. LOX and liquid N_2 would be a logistic problem in many theaters of operation of marine units. LOX for cooling would be a fire hazard aboard most aircraft.

5. Ground support equipment must be developed to maintain the ventilation cycle thru the suits from suit-up in the ready room, thru briefing and transit to the aircraft.

6. Liquid or air cooled suits should be designed for the sitting position rather than the standing position.

7. When a cooled suit is ready for operational use by the fleet, all ground and logistic problems should be solved to assume maximum usage and comfort for the aircrewmen.

8. On a long flight it has been found that the most common areas of discomfort when wearing the pressure suit are the hands, feet, and the crotch. In some cases the hands have discolored from the lack of proper cooling.

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The visit to Patuxent NAS was helpful and points up some of the needs of the Navy for adequate crew cooling system. In an effort to obtain more information, visits to additional Naval, Marine, Air Force, and Army installations should be made. The writer plans to meet with the Marine Development Center, Quantico, Virginia; San Diego, California; Norfolk, Virginia; and Mayport, Florida.

F.C. Jurgens

F.C. Jurgens

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Appendix B

The Johns Hopkins University
APPLIED PHYSICS LABORATORY
Silver Spring, Maryland

SLS-205-66
27 May 1966

To: R. G. Bartlett, Jr.

From: F. C. Jurgens

Subject: Trip Report - Marine Landing Force Development Center, Quantico, Virginia, March 31, 1966

The writer visited the Marine Landing Force Development Center, Quantico, Virginia on 31 March 1966 to ascertain the status of aircrew cooling in the Marine fixed wing and rotar wing aircraft. The main areas of discussion were:

1. Performance of present cooling systems in jets and rotary wing aircraft, and

2. Cooling problems associated with the ballistic protective vest for aircrew.

The day was spent talking with Lt. Col. Brigham and Capt. Anderson of HMX squadron; Major Corham and Capt. Pycion, jet pilots recently returned from Da Nang, Viet Nam, who are attached to LFDC; and Capt. Reno, a helicopter pilot from a squadron at the base.

In the discussion with Major Corham and Capt. Pycion who have recently returned from the Da Nang MCAS in Viet Nam, we found that these pilots flew the F-4 or F-8 aircraft and they explained that the following problems exist in the crew's comfort equipment. The air temperature at the Da Nang base ranges between 86°F and 105°F and humidity ranges from 83% to 100%.

Most aircraft are stored out in the open with no covering over them. This exposure permits the cockpit to reach a temperature of 130°F.

1. With all the gear the pilots are required to wear (over 50 pounds) during a tactical flight, they are sweating just going from the ready room to their aircraft.

2. With the canopy open and the engine running, the airconditioner supplies sufficient air to cool the torso of the pilot to a comfortable level, but the lower portion of the cockpit, which does not receive sunlight, is uncomfortably cold. The outlets of the airconditioner are so directed that the cold air flows directly into their faces.

3. The procedure for bleeding the airconditioning system is such that there is always some water left in the system. The unit is turned on for maximum cooling while the pilot is still on the ground. Often water and/or snow is expelled from the air-conditioning outlet.

4. At high altitudes the airconditioning system is switched over to heating. In some cases the system could not supply sufficient heat to the lower portion of the body thereby causing the pilot to suffer cold feet.

5. After the aircraft is maintained at high altitude for a period of time, the canopy temperature approaches the outside air temperature and altitude must be rapidly reduced. As a result of this descent, water vapor condenses on the canopy, requiring the pilot to fly by instruments until the defogger has a chance to clear the windshield. This transient from visual flying to instrument flying can cause a dangerous situation during a combat strike or during landing. With the defogger blower on full, the pilot experiences severe turbulence from the air blast; this too can produce a safety hazard.

6. Any modification of personal equipment must be designed so as to be compatible while walking through the jungle or other terrain after a bail-out or crash landing. In addition, it would be desirable if cooling could be provided while on the ground between the ready room and the aircraft prior to engine start.

The Marine helicopters now in use in Viet Nam are the UH1E, CH46A, and the CH53A. These helicopters are turbine powered and have crews in excess of four men. These units have no provision to supply ventilating air by any means other than picking up ram air by external scoops or by opening windows and hatches. The noise level is quite high even with the craft closed up. In Viet Nam these craft fly with all doors open; this presents communication problems between personnel and other aircraft. In some cases the combination of aircraft noise and weird noises from air blowing through the cockpit have caused communication loss. Work is being done to improve the crew helmets and communication equipment in an attempt to eliminate the communication problem, but without closing the cockpit, this will be difficult. This closing of the cockpit can only be accomplished if an adequate ventilation system for the crew is supplied.

The method used in airconditioning jet aircraft is an air cycle refrigerator using turbine air. In the discussion with LFDC personnel this method was proposed to aid in crew cooling. The Marines stated that these aircraft could not afford the loss of any turbine air because there is a requirement for every ounce of power in normal operation. From the time these helicopters were designed until the present, many of the units have increased their empty weight by 20% with no increase in engine power.

The engine deicer system uses bleed turbine air as would an air cycle refrigeration unit. When the icer is turned on during flight, there is a 5% loss in engine power. The pilot usually does not use his deicer, and when he does use it, it is only for a short period of time. It would not be feasible to use the air cycle refrigeration for cabin cooling because the power required to cool this area cannot be spared. Therefore, any process used to cool the crew must be independent of the engine air supply but could obtain electrical power from existing generators or alternators. The addition of mechanical or thermoelectric units to produce cooling must not present a large weight penalty to the craft. The use of ice as a cooling exchange medium is not desirable because of logistic consideration in areas such as Viet Nam.

The LFDC is charged with the development of ballistic protection for Marine helicopter pilots and co-pilots. This protection consists of an armored seat and ballistic vest. These items are designed to stop a 30 cal. bullet at 100 yards. The present helicopter seat is constructed of aluminum alloy and does not offer any ballistic protection. The armor seat is constructed of steel and will protect the crewman's side and back areas. The ballistic vest will offer protection to the man's chest area. In addition, the crew have crotch and lower torso protection from a "diaper" type garment.

The vest and diaper units are constructed of heavy military type fabric which are gas impermeable, quite uncomfortable, and heavy to wear. With all this ballistic protection worn over the nylon flight suit there is little or no ventilation reaching the man to cool him. The Army has similar problems with their helicopter pilots and are developing a gas cooled undergarment which is to be worn under all of the above mentioned equipment. This garment is to supply the cooling directly to the skin and use the flight suit and vest as insulation from the outside environment.

At the present time the helicopter crews have shrapnel vests and diapers to wear; but because of the extreme heat and humidity in Viet Nam, many of the men do not wear it unless directly ordered. This, coupled with the removal of windows and hatches to increase the rate of cooling in the cockpit, reduces the crew's protection from ground fire.

F. C. Jurgens

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Appendix C

The Johns Hopkins University
APPLIED PHYSICS LABORATORY
Silver Spring, Maryland

SLS-185-66
16 May 1966

To: Dr. R. G. Bartlett

From: F. C. Jurgens

Subject: Trip Report on Visit to Norfolk Naval Air Station at Norfolk, Virginia on 3-4 April 1966.

The writer, accompanied by Dr. Frank Bader, made a two-day visit to the Naval Physiological Training Unit, Naval Air Station at Norfolk, Virginia. The Unit is under the command of Lieut. Cdr. Schrimshaw who is also on the Survival Staff, Com Nav Air Lant. Our visit was conducted by Lt. J.G. Frank Martirano who is an Aviation Physiologist. In addition to the above officers, Ensign N. Bird is on the staff. This Unit is charged with the training of personnel in the use of oxygen equipment, high altitude breathing, ejection seats procedure, and the use of pressure suits for high altitude flying. They are also responsible to evaluate the performance of aircrew in different flight profiles and to assist in the improvement of the aircrewman's wellbeing during flight.

In hopes of making this visit a productive one, Lt. Cmdr. Schrimshaw assigned Lt. J. G. F. Martirano as our guide while at the air station. He made a number of appointments with the air squadron at the station. The major role of the air groups at the Norfolk NAS are anti-submarine type squadrons. These squadrons fly the P2V and S2E (multi-engine aircraft) and the HS3A helicopter. Interviews were held with each of these squadrons in an effort to obtain information that may be common and/or special to each type of aircraft.

The writer attended a training class on the use of breathing apparatus in the high altitude chamber up to 35,000 feet. He was also instructed in the use of the Martin-Baker aircraft ejection seat and was ejected by same. This course is required for any personnel who may fly in military jet aircraft.

The air groups visited were:

HS-3	flying HS3A helicopters
VS-37	flying S2E 2-engine aircraft
VP-56	flying P2V 2-engine aircraft

The hS-3A helicopter is powered by two turbine engines and has enough fuel for approximately four hours without air-to-air refueling. At the present time, a method is being tested whereby the HS3 units will stay up for a longer time relieving the S2E aircraft from the short range search missions which they presently fly. The S2E aircraft can, and do, fly missions upward of six hours at a time. The P2V aircraft is the long range member of the search team flying 10-14 hours, and has an average mission of 12.2 hours. All three of these aircraft spend almost all their time below 5000 feet and usually below 2,500 feet. The use of these patrol and search aircraft is not limited to any special area of the world. They fly over the arctic as well as the tropics.

One of the standard items of each crewman's clothing on these planes, when the ocean water temperature is below 60°F, is the so-called "Poopy Suit" or anti-exposure suit. Every crewman is required to wear one under the above temperature requirement, but in many cases, this is not adhered to by the crewmen due to their discomfort.

The following is a summary of the crew comfort problems expressed by the squadrons visited. The problems in most cases are general to all the aircraft of the P2V, S2F, and HS-3 classes.

EXPOSURE SUIT

The poopy suit consists of two coveralls: one is a water impermeable rubber suit which is worn over an insulated cloth garment which has sewn in a series of ventilation ducts. The cloth garment has knitted cuffs for the wrists and ankles. The ventilation intake port is on the left front just above the waist and the air ducts run from this point to each leg and arm. The air is then vented into the area between the body and the cloth garment finding its way to the torso where it then passes into the space between the rubber and cloth suits. The air from this area is vented through a poppet valve in the rubber suit which permits the air to leave the suit. This valve closes off when there is no air flow. This is also necessary to prevent water from entering the suit in the event the crewman is submerged.

Some of the problems aircrewmen have found with these suits are:

1. The crewmen must wear a rubber suit up to two sizes larger than the insulated inner garment. The donning time for some of the men is as much as one hour if they are alone.

2. When wearing the poopy suit and heavy socks, the crewmen must have a large size boot which is not always available. The rubber suit extends down to the tip of the toes in the form of a sock. In many cases the feet of the men sweat at such a rate as to have water accumulate in their socks.

3. Except for some aircraft carriers which have ready rooms equipped with a ventilation system, there are no provisions to ventilate this suit while outside the aircraft.

4. In aircraft which are equipped with seat-mounted blowers there is a need for warming of the air. The air for these blowers is taken from the cockpit which may be quite cold in some cases. A small electrical heater, placed in series with the blower and the suit to maintain a comfortable level, would give the crewman a temperature regulation of his environment inside the suit.

5. The zipper configuration presents some problems in the area of the crotch and the collar. The zipper running to the top of the suit zips to the adams apple and presents an annoyance to many men. The flap at the neck of the suit tends to chafe the neck unless the man wraps a towel around the collar. In the crotch area, the pilots find it quite difficult to use the flight deck relief tube. The use of an alternate relief station is not possible due to cramped quarters.

6. The present rubber exposure suit is constructed of sheet rubber which cannot be stretched without exerting a large, strong force. In some cases, the pilots have found it quite difficult to reach the throttle control. The pilots have expressed a desire to have more flexible joints at the knee, arm pit, and elbow. This could be accomplished by the addition of a bellows section at the elbow and arm pit and a pre-stretched knee cap section.

The present suit has been designed for the men in a standing position and should be modified as stated above to relieve the strain areas when the crewman is seated.

7. The rubber portion of the exposure suit is equipped with a relief valve designed to vent the suit when it is pressurized and to seal the suit when immersed in water. During normal flying conditions, with the suit fully zipped up, there is a tendency for the suit to blow up like a balloon. In this condition the crewman has difficulty performing his tasks. In most flying conditions the crewman leaves the collar zipper open and hopes he remembers to close it if he becomes immersed in water.

The use of the regular poopy suit on the P2V is usually limited to the pilot and co-pilot who do not have time in an emergency to don the quick-don-suit as could the rest of the crew. Since the poopy suit is quite uncomfortable to wear for 10-14 hours, the quick-don-suit is supplied as an alternate safety measure.

SEATS

The aircraft viewed have standard aluminum alloy bucket seats with provisions for a cushion for the crewman to sit on. The seats are adjustable in that they can be moved front to rear and can be adjusted for different heights. Some of the deficiencies of the seats are as follows:

1. In many cases the seat cushions are not the proper size. In the aircraft inspected, some of the seat cushions were as much as three inches too short for the bucket seat. Many crewmen complained when these undersized cushions were pulled forward to prevent the front edge of the seat from cutting off the circulation in the legs. A flange in the back of the seat, uncovered by moving the cushion forward, rubs the spine bone.

2. In some cases the supply of cushions is short, leaving some crewmen to sit in the metal seat without one.

3. Since there is no ventilation provided by the seat cushion for cooling, a number of pilots have used a steel wire seat cushion, sold for automobiles, with good results. The A-6 aircraft has a ventilated seat cushion covering the seat completely and receives its air from the poopy suit ventilator blower. This seat cushion would be a welcome addition to these patrol aircraft.

4. Some of the seat cushions supplied to these squadrons have horsehair fill; the crewmen have found that these cushionslose their support in a short period of time.

5. Some of the pilots complained that the angle of the seat back, especially in the SH3A helicopter, was such that they must lean forward to operate the controls. This causes the back to lose the support of the seat. The lack of support has caused an increase in the fatigue rate of pilots.

6. The pilot's seat in the HS-3A is designed for a 20g force, but the seat's mounting fixture has yielded at a 5g force.

FLIGHT SUITS

The present summer suit is made of a flame retarding nylon which is not water permeable. The pilots are responsible for cleaning of the coveralls. After two washings, the coveralls are required to be turned in because they are no longer flame retarding. Some of the problem areas are:

1. The zippers on some models of the flight suits do not operate very well. The front zipper is a dual operating one, that is, it can be opened from the neck to permit donning and from the crotch for relief. In many cases the zipper does not operate properly, requiring some time to correct.

2. Many of the aircrew will launder these new coveralls when first received to soften them so they are more comfortable to wear even though this procedure removes the flame retarding characteristic of the material.

3. The summer weight suit is not conducive to ventilation through the material; therefore, it would t desirable to ventilate the area between the suit and the body.

AIRCRAFT HEATER

The heating and ventilating systems in the above mentioned aircraft consist of a combustion heater, electrically driven blower, ducts, and defroster tubes. The heating system is designed to maintain a +40°F cabin temperature at an outside air temperature of -25°F. The mounting of these heaters varies with the aircraft; the HS3 helicopter has it mounted above the main cabin in the engine area, and the S2E aircraft has it mounted right in front of the pilot's compartment. The P2V aircraft has two heaters - one mounted in the tail assembly and one in the forward section of the fuselage. The heaters are used to maintain the cabin at a comfortable level and to deice the windshield of the cockpit. In the P2V, the heater system supplies hot air to either the personnel area or the wing empennage deicer boats, but not both at the same time.

In most cases these heaters are not sufficient to maintain a comfortable level throughout the complete aircraft because the different heat loads at the various crew stations may vary. The control of the heater system is in the cockpit so that when the flight deck personnel are comfortable they may turn off the heater, but the electronic monitoring personnel may still be cold.

AIRCRAFT VENTILATION

The ventilation of these aircraft is accomplished by the use of ram air which is drawn in by external air scoops. This air is used to cool the avionics compartment and personnel areas, but most air is directed to the avionics compartment. In many cases the avionics compartment is vented to the cabin of the aircraft thereby increasing the heat loads on the crew. In cold weather, this is quite helpful in that it adds heat to the cabin, but during hot weather this heating is undesirable. Many pilots feel that they are parasites on the avionics cooling system; they prefer a separate ventilation system for personnel and avionics. The venting of the avionics compartment should be overboard and not into the cabin; this would reduce the thermal load on the aircrew.

In the S2E aircraft and HS3 helicopter the cabin ventilation is accomplished by a number of small rectangular outlets in the lower portion of the cockpit. These outlets do not blow the air at the personnel, but just into the area of the feet. The S2E was originally designed with an air outlet near the base of the control column, but due to maintenance problems of keeping these outlets clean and operating, they were closed off and are no longer usable. The P2V uses eye ball socket ventilators similar to that used in commercial aircraft to supply passengers with fresh air. In hot environments the air from these socket outlets is not sufficient to adequately cool a man.

The flight profiles of these aircraft are such that the crews have opened windows and hatches to improve the flow of air through the cabins. This procedure does improve the thermal conditions in the cabin, but presents new problems with increased noise level and the blowing around of papers and other material. In addition to this, most of these aircraft have blackout curtains at the radar or sonar observer station to permit the observer to view the scopes without using the hood attachment. The use of these hoods for the long missions presents a fatigue problem. These blackout curtains prevent the flow of air through the cabin area, thereby reducing the cooling effects of the open windows and hatches.

PROBLEM AREAS

1. Maintenance of the heater presents some problem in that the glow plug which ignites the gasoline has a tendency to function improperly, which turns the heater off.

2. The heater control for the plane is in the cockpit, and the pilot controls the heat to his liking. In some planes there are curtains to shield the light from the radar observer's area which also has a tendency to restrict the proper heating of this area. When flying on a sunny day when the outside temperature is around freezing,

the pilots (flying in poopy suits) are comfortable but the personnel just behind the cockpit (who do not have poopy suits on) are quite cold with the heater turned off. This situation creates constant requests from the observer for the pilot to turn on some heat.

3. During aircraft carrier landing practice by the S2F, the heater is required to be turned off to reduce the fire hazard in case of a hard landing. In some cases, these practice missions last a few hours in sub-zero weather. In these operations, many pilots have found it quite difficult to maintain their physical coordination while trying to keep themselves warm.

DISCUSSION

The major area of crew comfort problems is the anti-exposure suit being worn both in the aircraft and on the ground when the air temperature is above 70°F, and while flying where the air temperature is above 80°F, and no anti-exposure suit is required. The modification of present aircraft to improve the heating and cooling characteristics would not be feasible at the present time because of the cost, weight penalty, and aircraft down time required. A system which could permit control of the crewmens' environment would be possible in a cooled undergarment. Such a garment should reduce the crew discomfort a great deal by enabling a man to keep himself at a comfortable level no matter what changes occur in the cabin's temperature. In many cases the aircrew open the windows and hatches in hot environments to cool the cabin, but this increases the noise, wind blast, and carbon monoxide. By following this procedure, the increase in cabin cooling does not equal the increase in the discomfort levels stated above. The gas cooled undergarment would permit the crew to fly with the hatches and windows closed, which is the preferable mode.

An improvement of the present anti-exposure suit, Mark V, is an important item in the eyes of aircrewmen. The present suit is quite unsatisfactory in any environment other than in cold water, where it means the difference between life and death. In many instances aircrew personnel have flown without the poopy suit so they can be comfortable during these long flights. A new anti-exposure suit should have more adequate cooling, increase freedom of movement, should not balloon when being ventilated, and should be easy to don and remove in a short period of time.

CONCLUSION

Crews of patrol aircraft, flying in all types of climate conditions, must perform their assigned task even though the environment presents personal physical discomfort and some loss of safety. It appears that modification of present ventilation equipment must be limited due to cost, weight, and time requirements. The addition of personal thermal control clothing would be more desirable and could be implemented with a minimum of aircraft modification and cost. The personal control environment extremes, minimize fatigue due to heat and increase both efficiency and safety.

F. C. Jurgens

F. C. Jurgens

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Appendix D

The Johns Hopkins University
APPLIED PHYSICS LABORATORY
Silver Spring, Maryland

SLS-232-66
28 June 1966

To: Dr. R. G. Bartlett

From: F. C. Jurgens

Subject: Trip Report - U. S. Army Natick Laboratory, Natick, Massachusetts, 18 April 1966.

The writer visited the U. S. Army Natick Laboratory, Advanced Projects Branch, Clothing and Organic Material Division, on 18 April 1966. This branch is under the direction of Mr. Leo Spano. Most of the day was spent talking to Mr. Vincent Iacono, who has been working on the Mohawk cooling problem and cooling garments for NASA, Manned Spacecraft Center, and Marshall Space Flight Center.

The Advanced Projects Branch was directed by the Army's Limited Warfare Command, Fort Bragg, North Carolina to develop a crew cooling system for the Mohawk aircraft. The Natick Laboratory developed (and shipped within 60 days after being so directed) a personal undergarment which is cooled by ram air. This garment consists of three layers of synthetic fabrics - lycra, nylon, and polypropylene. The garment is so constructed that the lycra layer is the innermost layer which is worn against the skin. This fabric has two-way stretchability and is quite comfortable. The second layer, used as a spacer layer, consists of nylon and polypropylene filament. The outer layer is of tight-woven nylon used to prevent gas flow through the material. The three layers of fabric are sewn together to form a one-piece long-underwear-type garment. A panel of lycra replaces the three layer material at the areas adjacent to body joints where a high degree of flexibility is necessary. The air is fed through the flight suit into the cooling undergarment where it is distributed via the spacer material to all areas of the suit. The flow of air to any given portion of the body will not be affected radically by the restrictions caused by parachute harness or ballistic vest. The present suit is quite flexible and does not restrict the movement of the crewman performing his normal tasks. This suit is both lightweight and easily donned and removed. Velcro tape is used to replace zippers thereby improving opening and closing and eliminating snagging of the suit by the zippers. Due to the new materials being used, cleaning and mildew problems are eliminated. Samples of this material have been obtained from Natick and are in the writer's possession.

In operation, this suit provides a flow of air over the body. This airflow conducts away the heat and perspiration from the skin. The lycra layer is of 40 x 40 mesh which wicks the perspiration. The airflow is confined by the man's body on one side and the tight-woven nylon layer on the other side. The gas enters the ventilated garment in the area of the kidney, which is the only convenient place left when the crewman is equipped with survival gear, ballistic protection, and parachute. From this point the air is free to flow to the vents at the ankles, wrists. and neck.

To control the airflow in the suit, which in turn controls the rate of cooling, the pilot opens and closes the air scoop in front of the plane. In the present Mohawk setup, this control effects the flow of air to both men simultaneously. This control is to be modified to permit each crewman to regulate his own cooling rate. By controlling the flow rate through the suit the crewman can adjust his cooling or heating rate.

Currently, the Army is testing their gas cooled suit in the Mohawk aircraft in Viet Nam. The gas for this sytem is supplied with the aid of a blower mounted in the nose of the airplane. Air is picked up by an airscoop which can be adjusted to control the air intake. The air is then ducted to a dual centrifugal blower which has a thruput of 25 cfm at 4 in. of water pressure. From the output side of the blower the air is routed along the side of the cockpit in a 1" diameter duct to a quick disconnect fitting mount alongside the ejection seat. A flexible line runs from the quick disconnect to the fitting on the flight suit. Photographs and drawings of the Mohawk installation are on file in the writer's office and are available at any time.

CONCLUSION

This garment may be used as part of a first generation of crew cooling systems. It requires a minimum of modification to aircraft and personnel gear. Most aircraft have sufficient electrical power to operate a blower to feed air to the suit at a suitable rate of flow and pressure. The use of a personal cooling garment will not impair the man's movement on the ground or in the aircraft and will surely aid him in performing his required task by maintaining him at a more suitable comfort level.

In the near future, it would be advisable if one of these garments were obtained from the Army for testing in Naval aircraft such as the P2V or S2F. The Advanced Project Branch expressed the desire to show these garments to the Navy and APL.

SUMMARY

At the present time, the Army's gas cooled garment is under test in Viet Nam and at the Natick Laboratory. The results of these tests are not available at the present time. The basic gas cooled garment is a simply and functionally designed unit and should prove effective in most hot environments.

F. C. Jurgens

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Appendix E

The Johns Hopkins University
APPLIED PHYSICS LABORATORY
Silver Spring, Maryland

SLS-247-66
7 July 1966

To: Dr. R. G. Bartlett

From: F. C. Jurgens

Subject: Trip Report on Visits to Naval Installations at North Island, Reem Field, Miramar, and Point Mugu; El Toro Marine Air Station; and AiResearch Division of Garrett Corporation; April 25, 26, 27, and 28, 1966.

References:

(A) Evaluation of Wet Suit Anti-Exposure Suit, Final Report, Commanding Officer, Air Anti-Sub Squadron 41.

(B) Internal Thermal Environment Program, December 6, 1962, SS 847R prepared by AiResearch Manufacturing Corporation, Los Angeles, California.

(C) Internal Thermal Environment Management Program, September 1963, LS 108 prepared by AiResearch.

(D) Internal Thermal Environment Management Program, September 1964.

(E) Extravehicular Suit Thermal and Atmospheric Control, February 1964, SS 3056.

(F) Metabolic Research Methods and Results, MS-AP-1125-1, prepared by AiResearch Manufacturing Corporation, 1966.

(G) Portable Environmental Control System Program Review, MS-AP-1138-1, prepared by AiResearch Manufacturing Corporation, 1966.

(H) Sensitivity to Water Deficit of the Thermo Regulatory System, prepared by W. V. Blockley, Webb Associates, Malibu, California.

SUMMARY

The writer visited the above air stations to ascertain the thermal comfort problems in Naval aircraft. Items of special interest were: (1) the cooling requirements of helicopters and fixed-wing aircraft, and (2) information and performance data on a modified wet suit for in-flight use. The visit to AiResearch Manufacturing Corporation was to observe the work being done in internal thermal environmental control and their facilities for physiological testing.

The morning of April 25 was spent at the ConNavAirPac Survival Office in discussions with Captain Walter Goldenrath and Mr. W. Oppenhauser. The topics of discussion (reference A) were the anti-exposure wet suit and general aircrew cooling problems. The afternoon was spent, accompanied by Mr. William Oppenhauser, at Reem Field Helicopter Station and Miramar Jet Air

Station. At these stations discussions were held concerning overheating in the aircraft and on the ground due to lack of adequate ventilation.

On April 26 the writer visited the AiResearch Manufacturing Division of the Garrett Corporation where they are working on a composite gas-ventilated, water-cooled garment for the Mark IV full pressure suit and the Apollo space suit (references B, C, D, and E). In addition, they have an environmental-physiological test facility for complete equipment check-out (reference F). A discussion was held on an oxygen generation system for extravehicular operation (reference G).

On the evening of April 26 a discussion was held with Mr. W. V. Blockley of Webb Associates who has been working on the physiological effects of dehydration on the human body in a hot environment.

On April 27 a visit was made to the Aviation Physiological Training Unit at Point Mugu Missile Test Center. The day was spent in discussions with Lt. Cdr. F. Formuller on problems with anti-exposure survival suits.

April 28 was spent in discussions with the Aviation Physiological Training Unit and Marine Aviation Equipment Officers at El Toro Marine Air Station on problems in the Marine helicopters and jet aircraft.

With lack of pilot and aircrew acceptability of the present anti-exposure suit, Capt. Goldenrath initiated a feasibility study to investigate a possible replacement. The diver's wet suit was selected for modification. The results obtained from this feasibility study of the wet suit as a possible aviator's anti-exposure suit conducted by Air Anti-Submarine Squadron Forty-One indicated that the modified ventilated/custom fit wet suit was superior in all respects to the present Mark 5A "Dry Suit". To complete the wet suit evaluation, Cmdr. Naval Air Force, U. S. Pacific (CNAP) authorized US-41 to procure fifty-two wet suits in order to more extensively evaluate pilot/aircrew acceptability of these suits in actual flight conditions. This current evaluation was conducted utilizing personnel assigned to US-41.

A second anti-exposure suit which Capt. Goldenrath is working with is one sold commercially for use on pleasure boats. It is a pair of coveralls consisting of three layers of material; the outer layer of nylon, the middle layer of unicellular foam, and an inner liner of cloth. The use of the anti-exposure suit is stated in Naval requirements, and the present Mark 5A suit is designed to fulfill these requirements. With improvements in rescue techniques, the requirement for four-hour protection at 32°F may be modified to a shorter period of time. The present suit places many physiological restraints on the user such as thermal stress, fatigue, restraint of motion, and general discomfort. In many cases, aircrew have flown without the suit but have taken a quick-don suit along.

The anti-exposure suit under study at North Island by Capt. Goldenrath uses the principle of design of the skin divers' wet suit. The skin divers' wet suit is constructed of an outer layer of sheet rubber with an inner layer of unicellular foam rubber. The insulation of the man wearing the wet suit is obtained by having a layer of water trapped between the man's body and the unicellular foam. The water for this insulation is obtained by leakage at the waist of the suit. The flight type wet suit is constructed of three layers of material. The outer layer is a fabric such as nylon, the center layer of unicellular foam, and an inner layer of soft fabric. The suit does not fit as snugly as does the skin divers' suit because there is a need for air or liquid cooling between the man and the suit. The use of a wet suit as an anti-exposure suit is ruled out because the man's body could not stand the prolonged direct contact with water even if the water was circulated to aid in maintaining a good thermal level. The suit under study permits the crewman to wear a dry, comfortable fitting suit in normal operation and, if immersed it will protect him for some time. The suit is designed to limit the flow of water inside the suit but if water does find its way into the suit, it will not be permitted to circulate, thereby preserving to some degree the insulation from the cold water. The fit of the Mark 5A inner garment is fairly good, but the outer rubber suit is not good.

The aviators' wet suit does not use water as an insulating medium but uses the principle of the skin divers' suit in that there is a foam rubber barrier between the body and water. This suit is semi-form-fitting. The design of this suit can be adjusted by a parachute rigger with a pair of scissors and a sewing machine. The construction of the suit is such that it will permit the sewing of new seams without losing the water-tight integrity of the suit. With a few basic sizes, the suit can be modified to fit most men with a minimum of effort. In a confined volume between the suit and the man the temperature is first cold to the body, but is gradually warmed by the body heat and then offers an insulating layer against the outside water temperature. This wet suit has many advantages over the present Mark 5A anti-exposure suit such as:

1. It can be form fitted to the individual with a minimum of effort and cost.

2. It offers increased mobility in and out of the aircraft.

3. It can be donned with a minimum of effort.

4. It can maintain its protection even if the suit has water in it.

5. It is of one-piece construction.

6. The material does not dry rot as does the outer rubber liner of the Mark 5A.

<u>Disadvantages of the wet suits over the Mark 5A</u>.

The length of time the wet suit will protect the man at 32°F is not as long as the Mark 5A.

After the crewman reaches dry land, or a raft, and the air temperature is below 60°F, the man will not have air exposure protection.

<u>Similar disadvantages of the wet suit and Mark 5A</u>.

No adequate ventilating systems are available to cool the suit in in-plane and ground environments.

This wet suit has been flight tested aboard the HS-3 helicopter and S2F aircraft with a high degree of acceptance by the aircrew. At the present time most of the testing has been limited to the North Island area.

On the afternoon of Monday, April 25, the writer was accompanied by Mr. Oppenhauser of the Aircraft Survival Branch to Reem Naval Auxiliary Air Station. The HS-3 helicopter squadron visited at this station had just returned from Southeast Asia where they flew surface surveillance and search missions. These missions were flown off aircraft carriers with durations up to eleven hours. To accomplish these long missions, the helicopters refueled from destroyers to eliminate the need to return to the aircraft carriers. These extended missions have magnified the problems in the area of fatigue and crew comfort.

Some of the problem areas the aircrew find as high discomfort factors are such that the cockpit enclosure of this type helicopter is effectively a greenhouse, and the flight deck crew receive a large amount of solar heating. The observers sitting behind the flight deck are heated as though they were in an oven due to the lack of air flow through the craft when it is closed up. If the crew opened up the hatches and windows to obtain cooling, there would be an increase in noise and wind blast levels; this increased noise level presents problems in communications. The wind blast presents problems in that the observers try to keep their blackout curtains closed in order to monitor their gear, but the wind blows the curtains open.

The design of the crew seat and cushions is such that after a number of hours of flight, fatigue sets in. In many cases the blood circulation in the legs is cut off by the front edge of the seat pressing against the back of the leg where the cushions do not protect. Most of the crew of the HS-3A helos have placed a boiler plate between the seat pan and the seat cushion for flak protection. With the addition of these plates, some of the cushioning effect of the aluminum seat is lost; therefore, there is an increased reliance on the seat cushion for vibration isolation and support for hard landings.

The present seat is adjustable in the fore-aft, up-down directions to permit the pilots to obtain a fairly comfortable position when at the controls. The seat adjustment, however, does not permit the pilot to assume a more relaxed position when he is not flying. A seat in which the pilot could relax would somewhat reduce the fatigue experienced during long flights.

The present seat positioning is not satisfactory since in some cases such as landing, the seat position changes abruptly; this produces an unsafe condition.

The design of the seat mounting fixture to the aircraft is not sufficiently strong to hold the seat in a sudden high "g" force in excess of 5 "g's". The seat itself is designed for a higher force.

FLIGHT CLOTHING

The HS-2 squadron were issued two types of flight suits upon their deployment to Southeast Asia. These suits are the Army heavy canvas suit and the Air Force lightweight nylon suit. Many pilots preferred the heavier weight Army suits because they could obtain the proper fit; the Air Force suits had very poor fit. Both suits are not conducive to keeping the airmen cooled with the limited ventilation in the cockpit.

Aircrews on the HS-3 helos do not usually wear parachutes or flak vests except on long flights such as surface surveillance and search missions. The use of this extra gear increases the crew cooling problem considerably in that it prevents ventilating air from reaching the skin and prevents any flow of air under the flight suit.

This type of helo is equipped with a seat mounted blower which could be used to ventilate the A-6 type seat cushion or the Army gas cooling suit. Since this blower presently supplies cabin air, it may be desirable to change this supply to ram air.

The visit to Reem Field was followed on the same day by a visit to VF-21 squadron flying F4C aircraft out of Miramar NAS. This squadron had just returned from duty in Southeast Asia where they flew mostly over North Viet Nam. The flight profile for this type aircraft in tactical operation is to fly most missions at altitudes upwards of 40,000 feet; when nearing the target the planes drop to lower altitudes then return again to high altitudes. This profile is employed to conserve fuel and to evade anti-aircraft missiles and guns. At this altitude there is no cooling problem, but there is some lack of heat in the lower portion of the cockpit. During flight the plane is pressurized but pilots do not wear full pressure suits except for the boots. The pilots wore a cotton camouflage flight suit. This suit is constructed of heavyweight cottom and is extremely warm to be worn on the ground; however, most pilots preferred them for their camouflage protection. The pilots stated that the full pressure suit was much more comfortable to wear and also provided ventilation for comfort while in the plane, but the suit would have to be disconnected if forced down in the jungle. The lack of ventilation while disconnected would make this suit prohibitive to be worn on the ground. Many of the pilots wear the pressure suit flight boots because they are comfortable and easy to put on.

On most flights the aircrew wear the regular flight suit, integrated harness, radio, knives, side arms, flotation gear, and survival vest. The weight of this personal equipment is between 40 and 50 pounds. Sporting all this equipment, crewmen walking from the suit-up room to ready room then to the aircraft find their clothing becomes wet with perspiration. After boarding the aircraft, the crew may have as much as a thirty minute wait before they are airborne. During this period of time they receive little or no cooling from the aircraft cooling system even though the engine is at 75% power setting. The plane's cooling system doesn't perform adequately until the plane reaches an altitude of 5,000 feet.

Many of the flights from this Naval Air Station are over the ocean where the water temperature is less than 60°F for at least eight months of the year and air temperature is usually in excess of 60°F. Under Naval regulations, the aircrew is required to wear the anti-exposure suit due to the low water temperature. The pilots prefer not to wear the suit if they feel they could glide back to land.

Discomfort also results with use of the integrated harness. It is felt that the regular parachute harness, without the nylon panels, would be more comfortable. It has been suggested that the nylon panels be used to hold the survival gear and flotation equipment. The later method would reduce the number of separate pieces of gear the aircrew would have to don and doff.

On F4C aircraft most flight missions require the use of oxygen masks; therefore, it is important that the pilot have a proper mask which should be fitted to his facial contour. In many cases the masks do not fit properly thereby permitting oxygen to escape into the man's eyes which produces drying of the eye.

Many pilots have found the dynamic mike an improvement in terms of communication, but it causes some discomfort in that it rubs on the lips and cannot be adjusted when the oxygen mask is on. It was suggested by Mr. Oppenhauser that the mike be placed by the O_2 inlet. This modification relieves some of the discomfort which the pilots have expressed.

On the morning of April 26, a visit was made to the Life Sciences Department, AiResearch Manufacturing Division of the Garrett Corporation, Los Angeles International Airport, California. The Department is under the direction of J. N. Waggoner, M. D., and Mr. E. G. Worte is the Project Director of the Internal Thermal Environment Section.

This department is working on a company sponsored program to investigate methods of reducing the latent heat load of personnel wearing pressure and space suits. This includes the development of a physiological testing facility for metabolic research and thermal and atmospheric control for extravehicular and full pressure suits. In addition to the above department, the writer visited the Space System and Cryogenics Department where they are working on portable environmental control systems (PECS). This system supports extravehicular activity, oxygen, and cooling backpack using an oxygen generating candle. The engineer assigned to the project is Mr. Donald Myers. At the present time this work is still in the development stage but AiResearch feels it will solve most of the engineering problems prior to manufacture. Reports (references B, C, D, E, and F) prepared by AiResearch on this system were obtained by the writer and are available at any time.

The work done on internal thermal management of the Apollo EVA spacesuit and the Mark IV full pressure suit has been documented by AiResearch; a copy of this report (reference G) is also available from the writer.

On April 27 the writer visited Point Mugu NAS, Oxnard, California, where he talked with Lt. Cdr. Frank Formuller and Mr. Tinklepaugh. Lt. Cdr. Formuller is in charge of the Aviation Physiology Training Unit and is also working in the Aircrew Equipment Branch. The Aircrew Equipment Branch is responsible for studies of physical stress in cold water and evaluation of flight clothing both on the ground and in the air.

At the present time Lt. Cdr. Formuller is setting up additional testing facilities for water survival testing. For a good part of the year the water off Pt. Mugu is below 60°F; this is an ideal location for testing of the anti-exposure suits with cooled undergarments. A laboratory is being set up to measure partial pressures of oxygen and carbon dioxide during physiological experiments to determine metabolic rates.

Mr. Tinklepaugh is assisting Lt. Cdr. Formuller in his work and has a number of his own experiments in progress. One of these experiments is exothermal salve which releases heat at a controlled rate when exposed to water. This salve has a base material of calcium chloride combined with an agent to control the rate of heat release. This salve could be useful in survival in both water and ground conditions to prevent frostbite or to warm the body in desired areas.

The visit to El Toro Marine Air Station was made on 27 April where the writer visited with Cmdr. Bowers of the Aviation Physiology Training Unit and Lt. Williams who is the Flight Equipment Officer, Third Marine Airwing.

At the present time the Marines are flying UH1, CH34 and CH46 helicopters. The UH1E helo flying gun platforms are flying from two different air stations in Viet Nam. On some flights the helos will stop for refueling and armament at different bases, then continue their missions. With these movements the craft might not return to their home station for two or three days. Many of these intermediate bases are jet bases and may not have the equipment to maintain the aircraft other than fuel and armament. Therefore, any cooling system should be self supporting, and must require a minimum of ground support.

Many of the CH46 helos are equipped with anti-exposure suit blowers mounted under the crew seat which supplies cabin air to the suit. The UH1E and CH46 craft have sufficient electrical power to supply a personnel blower to each of the flight crewmen, the CH34 electrical system may or may not have sufficient power. The CH34 helo has a reciprocating engine craft and is being phased out at the present time.

The Marines do not have any extensive maintenance facilities above the squadron level in South Viet Nam. The squadron maintenance facilities consist mostly of tents since there is a lack of building supplies. The Marines stated that aircraft modification which would require rework or a long ground time would not be possible in Viet Nam. Extensive modification would have to wait until the plane is normally scheduled for overhaul which may be as long as 15 months.

The weight of most Marine helos is such that the craft is substantially above its originally designed weight. In some cases the CH46 helo is as much as 20% above this designed weight with no increase in engine power. The newly developed boron carbide ballistic vest which will be worn by the four crewmen will increase the basic weight by 100 pounds. This craft is also equipped with an armored seat which weighs much more than the standard aluminum seat. This increased weight will therefore reduce the payload which the helos will be capable of carrying. The weight problem is a factor which must be considered in the design of a crew cooling system for the helo.

Over the combat zone in Viet Nam most helicopter flight personnel wear some flak or ballistic protection. This protection consists of a vest front and a crotch protecting "diaper". The pilot's back is protected by an armored seat which has a gas ventilated cushion. The gas supply for the cushion is supplied by a seat mounted blower. This blower supplies cabin ambient air at approximately 10 cfm at 4 inches of water. Most CH46 helos have this blower mounted in the craft, and modification kits are in the supply system for those craft not equipped. The UH1E and the CH46 helos have sufficient electric power to operate these blowers, but the CH34 craft have only a marginal amount of power available for this purpose.

In most cases the aircrews do not don the ballistic protection until boarding the craft. Prior to this time the crew wears the regular flight suits, side arms, and helmets. Even with this minimum amount of clothing most pilots and crew are much too warm by the time they reach their aircraft. In some cases the crew takes as long as one hour, going from preflight briefings to take off. The jet aircraft have approximately the same problems on the ground as do the helos. During time of heavy ground traffic the jet pilots may spend as much as 15 minutes extra waiting for clearance to take off. During this period of time they have the canopy open and the air-conditioner on. Once airborne the F4 and some A4C and E models have sufficient cooling, but none of the EF10B and a few A4Cs are sufficiently cooled. While airborne, the helos are not cooled at all. After landing the jet aircraft taxi to the refueling area then to the parking ramp before the pilot can leave the plane. During this period of time there is insufficient crew cooling.

The service personnel at this meeting felt that a crew cooling system which could be 50 - 75% effective would be quite acceptable at the present time as a stop-gap solution to present problems in Viet Nam. A more effective system would require time for development and aircraft modification. Since present helos have no cooling facilities, any cooling system would be both beneficial and desirable.

The design of a cooling garment should be such that it requires the minimum of maintenance and should be capable of being repaired by squadron parachute riggers. The material used in this garment should be such that it can be washed and dried in a humid environment such as in Viet Nam. At the present time the only garment driers in Viet Nam are assigned to the F4 squadrons.

CONCLUSION

At the present time there is a definite requirement for personnel cooling in all helicopter and fixed wing aircraft while airborne and for all flight personnel while on the ground in the Southeast Asia combat zone. The lack of adequate ventilation of the aircrewmen in many cases have caused fatigue, and physical injury due to the removal of body protecting armor because of the high heat and humidity.

Most pilots/aircrewmen expressed the opinion that a system which would supply some cooling under their flight suit will substantially aid in providing comfort. Any increase in aircraft weight due to the addition of cooling equipment must be kept to a minimum.

The results obtained by the evaluation of the modified wet suit are quite encouraging and may well be one of the answers to the survival suit problem.

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Appendix F

The Johns Hopkins University
APPLIED PHYSICS LABORATORY
Silver Spring, Maryland

SLS-315-66
11 October 1966

To: Dr. R. G. Bartlett

From: Frank Bader

Subject: Aircrew Cooling Capability of Hot Air Unsaturated (by moisture).

It is well known from experience that hot atmospheric temperatures are within human tolerance if the ambient air is not highly moisture-saturated and personal garments permit cooling of the wearer through evaporation of perspiration.

Aircrewmen generally wear rather moisture-impermeable coveralls and thus because of thermal insulation and deprivation of sweat evaporation, experience overheating when operating non-airconditioned aircraft at low altitudes in hot climates. Equipping the crewman with an efficient air ventilated undergarment could restore to him an ability to evaporate his perspiration and thereby accomplish removal of his body metabolic heat through the latent heat of evaporation of the perspired moisture. The notes below indicate the amount of metabolic heat which might be removed in this way by circulating air over the crewman's body.

1. Water vapor obeys substantially the general ideal gas law.

$$PV = \frac{W}{M} RT,$$ where V is the total gas volume

P is the water vapor partial pressure

W is weight of water present

M is molecular weight of water

R is universal gas constant

T is gas temperature, absolute

2. If water be evaporated, the weight of water vapor and its pressure will increase in a linear relationship to one another.

$$\Delta P \cdot V = \frac{\Delta W}{M} RT$$

We are now in position to compute the weight of water which might be evaporated to increase the ambient water vapor pressure in the air (humidity) to near saturation values.

$$\Delta W = \frac{M}{RT} \Delta P \cdot V$$

In commonly used units $M = 18$ (water is H_2O)

$R = 1554$ ft. lbs./ pound mole/ degree R

$T = 93^oF.$

p_{H_2O} sat @ $93^oF. = 0.77$ psia

$= 110$ psf

P 95% sat $= 103$ psf

Then if we evaporate moisture into the ventilating air to produce 95% saturation, we have increased the water vapor pressure ($\Delta \rho$) by $(103 - P_{H_2O \text{ ambient air}})$ and the amount of water evaporated will be

$$\Delta W = \frac{M}{RT} V \cdot (103 - P_{H_2O \text{ ambient air}})$$

$$\Delta W = 0.000021 \, V \, (103 - P_{H_2O \text{ ambient air}})$$

Evaporation of each pound of air will require 1040 BTU (at $93^oF.$),

$$\Delta Q = 1040 \, \Delta W = 0.0218V \, (103 \; P_{H_2O \text{ ambient}})$$

and this will serve to either reduce the air temperature to $93^oF.$ if initially above this value or to cool the crewman, thus ΔQ_V, the cooling of the crewman, will be their difference.

To cool air initially above $93^oF.$ will require absorption of heat

$Q_A = V_\rho C_p \, (T_i - 93)$ if T_i is incoming air temperature $^oF.$

ρ is air density

C_p is air heat capacity

$$\rho C_p = (0.072)(.24) = 0.017$$

$$\Delta Q_V = \Delta Q - \Delta Q_A$$

3. $$\Delta Q_V = V \left[0.0218 \; (103 - P_{H_2O \; ambient}) - 0.017 \; (T_i - 93) \right]$$

One can secure the ambient water vapor pressure from knowledge of the "wet bulb" ambient air temperature and reference to a table of water vapor pressure (pounds per square foot) versus saturation temperature; T_i, of course, is the ambient "dry bulb" temperature.

This equation can be put into a slightly more convenient form to accommodate conventions of measuring airflow (V) in cubic feet per minute and heat removal in BTU/hour.

4. $$\Delta Q_H = 1.31 \; V \left[(103 - P_{H_2O \; ambient}) - 0.78 \; (T_i - 93) \right]$$

A graph, figure (1) has been prepared showing the evaporative heat removal capacity in BTU per hour of an airflow of 60 cubic feet per hour (one cubic foot per minute). As aircrew ventilation airflows are around 10 to 15 cubic feet per minute, one can multiply the graphical ordinates by such an airflow value to get the available cooling or conversely, divide required hourly heat removal rates by the graphical ordinates to compute required ventilation airflows needed to remove the defined heat loads.

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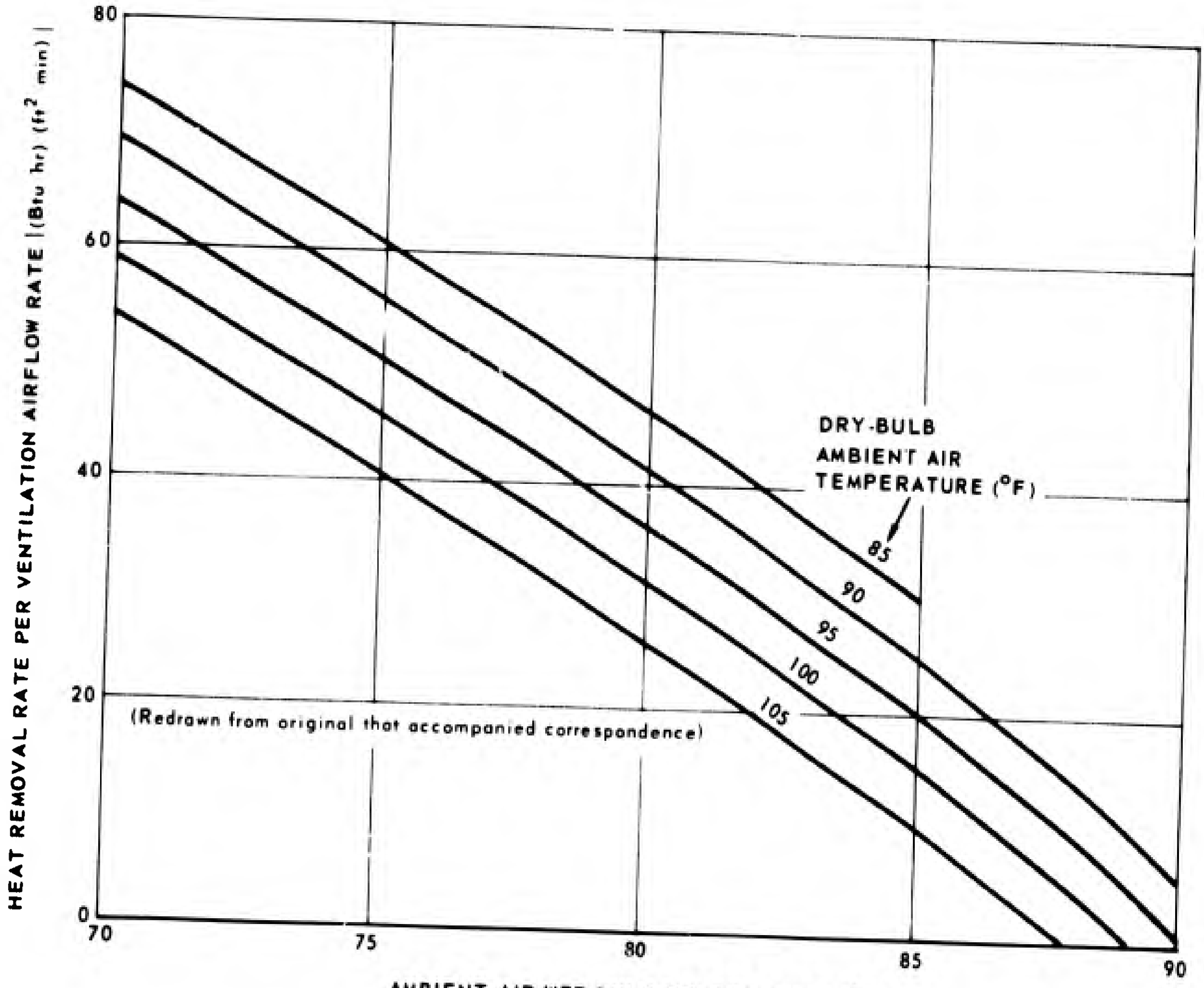

VENTILATION-AIR EVAPORATIVE COOLING CAPABILITY

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The Johns Hopkins Univ., Applied Physics Lab. 8621 Georgia Avenue Silver Spring, Maryland 20910	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP n. a.

3. REPORT TITLE

Aircrew Cooling Study (U)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Memorandum

5. AUTHOR(S) (First name, middle initial, last name)

Frederick Jurgens

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1968	171	34

8a. CONTRACT OR GRANT NO. NOw 62-0604-c b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) TG-945 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) n. a.

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale: its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
n. a.	Naval Air Systems Command

13. ABSTRACT

The naval aviator cannot wear separate garments for the wide variety of thermal environments in which he must work. The results of a study conducted to ascertain the thermal control requirements of these aircrewmen are presented. The study set out to define the heat and moisture removal requirements during ground and flight operations, to learn the effects of various clothing combinations, and to learn the effects of flight conditions on thermal moisture control.

The effects of both metabolic activity and environment on body temperature are considered, and various techniques of air and liquid cooling in a variety of garments are then reviewed in order to determine the most effective ways of keeping body temperatures at reasonable levels. Immediate use of forced-air cooling suits, more precise determination of the limits of "tolerable" working conditions, and further improvements in the design of liquid-cooled garments are recommended.

DD FORM 1 NOV 65 1473

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14. KEY WORDS

Thermal Stress

Thermal Control of Aircrews

Personnel Protective Garments