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PHYSIOLOGICAL REQUIREMENTS FOR DESIGN OF ENVIRONMENTAL CONTROL --ETC(U)

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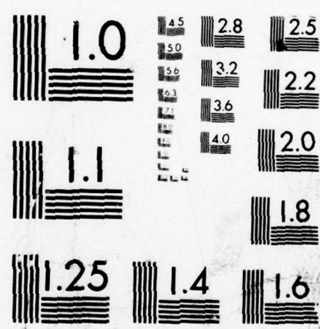

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Physiological Requirements for Design of Environmental Control Systems: Control of Heat Stress in High-Performance Aircraft

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Cooling of the cockpit in high-performance aircraft is usually based upon avionics requirements, with only secondary regard for the effect on aircrew. A shift in priority may now be needed because the new fighter aircraft demand maximal human performance which may be impaired by heat stress. This paper reviews current USAF specifications for the cockpit environmental control system (ECS) together with evidence that hot-weather flight operations involve significant aircrew heat exposure. A brief analysis is made of heat exchange between man and environment. Physiological and performance effects of heat stress are discussed. A new approach is suggested for writing ECS specifications in order to ensure adequate aircrew protection and optimal man-machine system performance.

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NOMENCLATURE

G = acceleration (g, multiples of earth gravity)
P_w = pressure, water vapor (torr)
P_{wa} = pressure, water vapor, ambient (torr)
Q_c = heat, conduction-convection (w)
Q_e = heat, evaporation (w)
Q_k = heat, convection (w)
Q_m = heat, metabolism (w)
Q_r = heat, radiation (w)
Q_s = heat, storage (w)
T_a = temperature, air (deg C)
T_{ac} = temperature, air, cockpit (deg C)
T_{ag} = temperature, air, ground (deg C)
T_b = temperature, black globe (deg C)
T_c = temperature, core of body (deg C)
T_d = temperature, dewpoint (deg C)
T_r = temperature, radiant (deg C)
T_s = temperature, skin (deg C)
T_w = temperature, wet bulb (deg C)
V = velocity (m/s)
$-$ = mean (e.g., $\bar{T}_s$, mean skin temperature)

INTRODUCTION

Design of the cooling functions of the environmental control system (ECS) for high-performance aircraft until now has reflected primarily the need to protect avionics, with only secondary consideration of aircrew requirements. This situation is now changing as new generation fighter aircraft demand maximal human acceleration tolerance combined with complex task performance, both functions which can be impaired by heat stress. Although cockpit cooling levies costly weight and power requirements, failure to meet minimum aircrew needs could adversely affect performance of the entire man-machine system.

Presumably due to their tropical origins, humans are well adapted to dealing with heat stress under natural conditions. Normal responses include dilation of blood vessels in the skin, sweating, and behavioral changes, such as removing heavy clothes and seeking rest in the shade. Unfortunately, the flight environment interferes with all of these responses. Aviators must work while fully exposed to sunlight, wear multilayer clothing, can evaporate little sweat, and suffer undesirable side effects from both vasodilation and sweating.

Excellent general discussions of human heat stress response and development of industrial heat exposure limits already exist in the literature (1-4).[1] This paper concentrates on the special problems of flight; it reviews current ECS specifications versus performance, summarizes the physical, physiological, and ergonomic problems of man in the cockpit, and suggests new approaches to optimal ECS design.

CURRENT ECS DESIGN AND PERFORMANCE

The current USAF specification for ECS is written in very general terms and applies to both high-performance and transport aircraft (5). It states that mean air temperature in the crew compartment should not exceed 21 C (70 F), but may rise to 27 C (80 F) for 30-min. periods. Radiant heat is mentioned only in terms of surface temperature and touch-burn. Humidity is covered by the statement that inlet air shall carry no entrained moisture. The document mandates a series of ECS performance tests during all phases of development from design through production sampling. Final ECS qualification involves assessment of the pre-production unit aboard aircraft in environmental chambers and during sojourns at bases selected to present extreme arctic, desert and tropic conditions. Ground operations and a varity of flight profiles are monitored for such variables as air temperature (T_a) for ECS inlet

[1] Underlined numbers in parentheses designate References at end of paper.

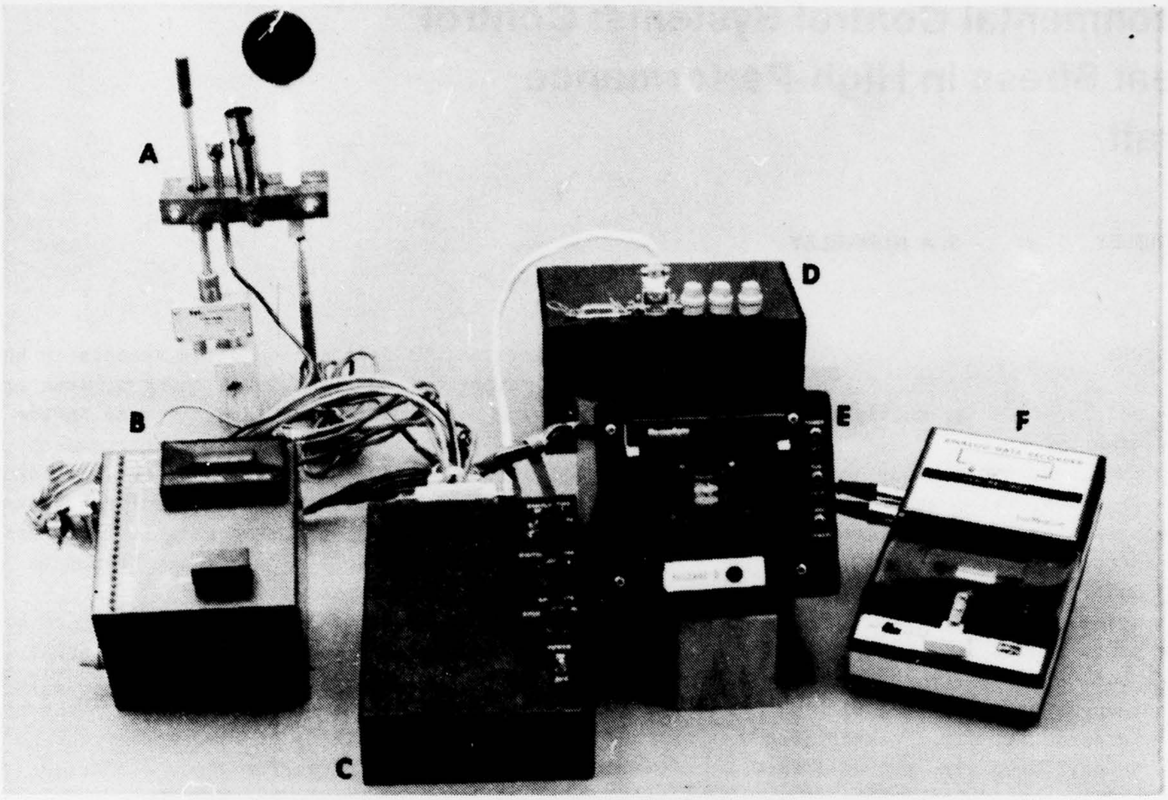

Fig. 1 Miniature Environmental Monitor, Version II (MEM II): A) sensor cluster with 5-cm globe, B) digital display unit, C) electronics, D) battery pack, E) digital recorder, F) analog recorder

and mean cockpit, dewpoint (T_d), air velocity (V), and surface temperatures. Detailed test methods are not given, leaving to the discretion of the contractor such items as selection of measurement techniques and placement of sensors in the cockpit. Failure of the ECS to meet original specifications may result in system modification and/or waiver of requirements. Once the system is in the inventory, modifications are extremely difficult.

Miniaturized instrumentation now makes it possible to monitor ECS performance aboard operational aircraft as well as during dedicated climatic tests. Flight-rated recording systems have been designed and built by both the RAF Institute of Aviation Medicine (6) and the USAF School of Aerospace Medicine (7); the latest version of the USAF instrument appears in Fig. 1. The two laboratories are now cooperating in evaluating ECS effects on aircrews. Four basic cockpit variables are recorded at a sensor cluster: T_a, T_d, V, and black globe temperature (T_b), a measure of radiant heat load widely used by physiologists. Aircrew responses can also be monitored, including skin temperature (T_s) at various sites, core temperature (T_c), electrocardiogram (ECG), and voice. Data collected to date include warm- and hot-weather missions by fighter aircraft with three different ECS types: single cycle (F-111), bootstrap (A-7, F-4, F-15), and an advanced design tested aboard an F-15 during 1977. Some of these data are discussed in the following.

Ground standby is the worst heat stress faced by aircrews. Some combat scenarios dictate that the canopy be sealed or at most cracked a few centimeters while the aircraft sits without active cooling. In the powered-down cockpit in full sun, air temperature (T_{ac}) exceeds ambient (T_{ag}) by about 20 C, while addition of avionics heating increases the difference to 30 C, producing physiologically intolerable conditions (8). Shading of the canopy and/or introduction of even a limited amount of cool air greatly improve the situation (9), but any pre-flight heat soak still significantly reduces the physiological reserves of aircrews (10).

The F-4 has long been a mainstay of USAF and RAF tactical forces but is known for an ECS which has only limited capacity to control air

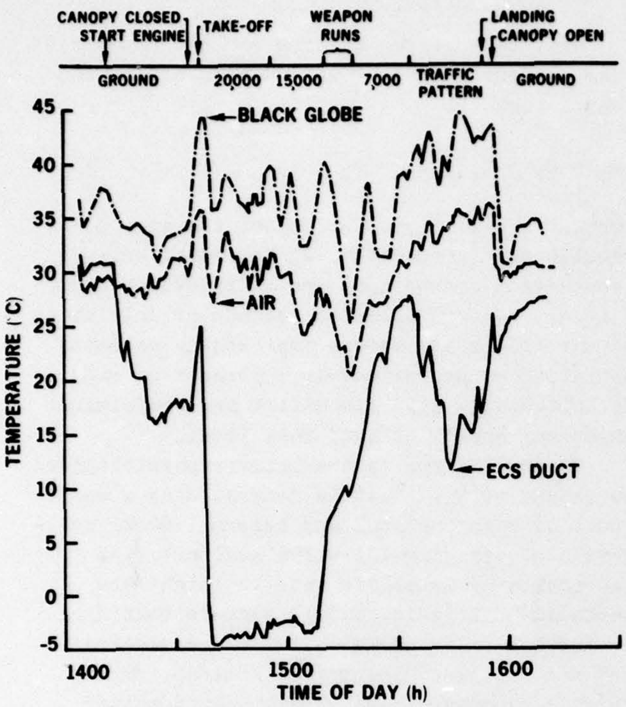

Fig. 2 Temperature data from F-4 flight at Edwards AFB on Sept. 27, 1977. Weather conditions: $\bar{T}_a$ = 28 C, $\bar{T}_w$ = 15 C, clear

temperature or humidity (11), as is confirmed by our data. Fig. 2 presents records from a warm-weather flight by an F-4. Note that cockpit temperature rose steeply with canopy closure. On take-off and climb, ECS inlet temperature dropped below zero, yet T_{ac} at head level remained about 30 C, with only a delayed trend downward. ECS temperature rose sharply on descent and T_{ac} reached 35 C before landing. The globe temperature was generally 7 to 8 C above T_{ac}.

The A-10 presents a special problem because it flies a close-support role where climatic heating continues to be a significant factor with results such as those shown in Fig. 3. In this low-level desert flight, ambient temperature was 36 C, but T_{ac} averaged 45 C. Wet bulb temperature remained low throughout, reflecting the desert's dryness.

The interacting effects of speed and altitude were shown by a series of F-111A flights (Table 1). The aircraft flew selected speed/altitude combinations over desert where T_{ag} = 35 to 40 C and ECS was set on "full cold" throughout. Note that the duration of some low-level flights was fuel-limited, so that cockpit temperature was still rising when final $\bar{T}_{ac}$ was taken (12).

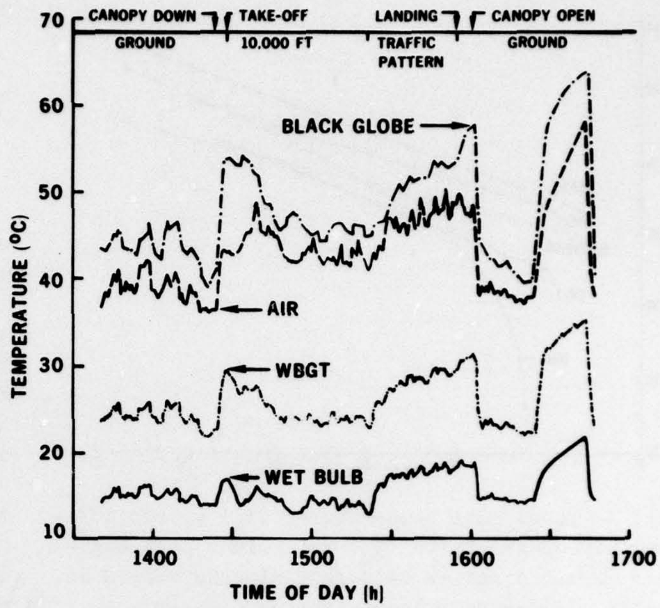

Fig. 3 Temperature data from A-10 flight at Edwards AFB on Aug. 9, 1977. Weather conditions: $\bar{T}_a$ = 36 C, $\bar{T}_w$ = 17 C, clear

Table 1 Final $\bar{T}_{ac}$ (deg C) for F-111A Flying Specified Speed (Mach Numbers) and Altitude (km) over Desert in Summer (12)

Speed (M#)	Altitude (km) 0.6	1.5	3.0
0.6	19.9	12.0	-
0.8	23.5	13.7	-
0.9	25.7	14.5	-
1.1	-	32.4*	16.9
1.2	-	33.4*	-
1.3	-	-	22.9*

* Test point flown for < 15 min.

A useful index combining the various heat-stress components is Wes Bulb Globe Temperature (WBGT), calculated as follows (13):

$$WBGT = .7\ T_w + .2\ T_b + .1\ T_a \qquad (1)$$

where T_w = wet bulb temperature, often derived from dewpoint. Thermal data collected aboard Buccaneer and Harrier aircraft show that during flights below 900 m (3000 ft), cockpit and ground conditions are directly related as follows (14):

$$WBGT\ gr = (WBGT\ co - .333)/1.183 \qquad (2)$$

where gr = ground and co = cockpit. Additional data from this laboratory (e.g., Fig. 3) indicate

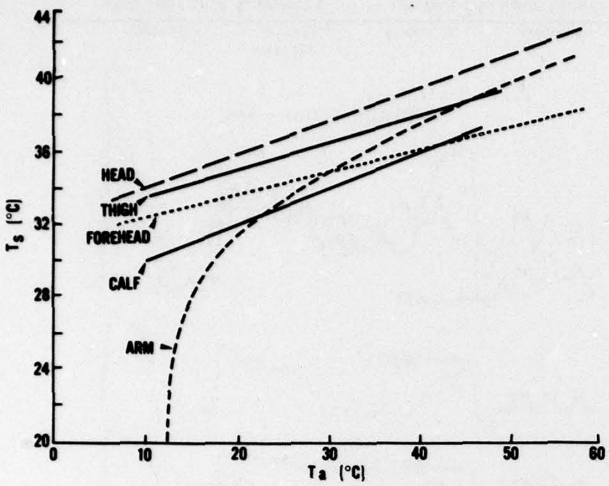

Fig. 4 Local skin temperatures (T_s) versus adjacent air temperatures (T_a) for flight test engineer during a series of desert flights aboard an F-111A. Lines show least-squares regressions except for arm, which was a visual estimation (modified from 12)

that this relationship holds for other aircraft and for both moderate and hot conditions.

In-flight measurements of T_s appear in Fig. 4 (12). Each line represents a regression of T_s on adjacent T_{ac}, reflecting both physiological factors and clothing. An unusual feature of the cockpit environment is the large longitudinal temperature difference; while the head and upper body are exposed to full solar heating, many aircraft route maximal cooling to the rudder well and lap area. As a result, pilots sometimes experience uncomfortably cold feet while sweating profusely.

The limitations of current fighter/trainer cockpit cooling are recognized at some USAF bases in the southern United States where procedures have been adopted to limit flights in extremely hot weather. Such rules have until now represented arbitrary application of industrial-type exposure limits. A recent development is the Fighter Index of Thermal Stress (FITS) (15). From a simplified FITS table, lay personnel can use T_{ag} and relative humidity to estimate heat stress in low-level flight and can determine appropriate protective procedures. FITS is the first known attempt to use the recently acquired inflight data to control aircrew heat stress, and refinement should be possible as the body of data increases. Although FITS is aimed primarily at training situations, similar estimates of stress effects may someday prove useful to commanders weighing combat options in hot climates.

HEAT EXCHANGE IN THE COCKPIT ENVIRONMENT

Heat balance for aircrew can be summarized by the following form of an equation often used by physiologists:

$$Q_s = Q_m \pm Q_r \pm Q_c - Q_e \qquad (3)$$

where Q_s is the rate of body heat storage, Q_m is metabolic heat production, Q_r is radiation, Q_c is conduction-convection, and Q_e is evaporation, all in w. Man can tolerate storage of only about 175 w•hr (150 kcal) before approaching collapse, a variation of approximately 7 percent in body heat content (1, 2). Discomfort and performance changes may appear at half that level.

Metabolic rate is the primary physiological determinant of T_c. Heat is generated as a waste product of both internal and external work, resting values averaging 105 w (90 kcal/hr) (1). Measurements of metabolic rate in flight are technically difficult, but it appears that aircrew metabolism is normally twice the resting level and may reach 350 w (300 kcal/hr) during aerobatic maneuvers (16). This heat together with any environmental contribution must be dissipated at the skin if heat storage is to be avoided.

Heat exchange between man and environment occurs through three mechanisms, the Q_r, Q_c, and Q_e of equation (1). Sources of heat in the cockpit are diagrammed in Fig. 5. Since conduction by direct contact with solids is negligible in most situations, physiologists conventionally reduce Q_c to its convective component, Q_k. For a clothed person in a warm environment, a reasonable value for $\bar{T}_{sk}$ is 35 C, while saturated water vapor pressure at 35 C is 42 torr. Heat exchange may then be estimated from the following equations (17):

$$Q_r = 6.6\ (\bar{T}_r - 35) \qquad (4)$$
$$Q_k = 0.6\ V^{.6}\ (T_a - 35) \qquad (5)$$
$$Q_e = 1.2\ V^{.6}\ (42 - P_{wa}) \qquad (6)$$

where $\bar{T}_r$ = mean radiant temperature of the surroundings and P_{wa} = ambient water vapor pressure.

Radiant heating is important in high-performance aircraft due to sunlight entering through their characteristic bubble canopies. Direct solar heating on a clothed man is on the order of 100 w (187 kcal/hr) (18, 19). Heating of the head is a special problem; temperatures under the white USAF helmet often exceed 40 C (9, 12).

Cockpit air temperature represents a balance between ECS cooling (mass flow and inlet temperature) and heat from various sources, including

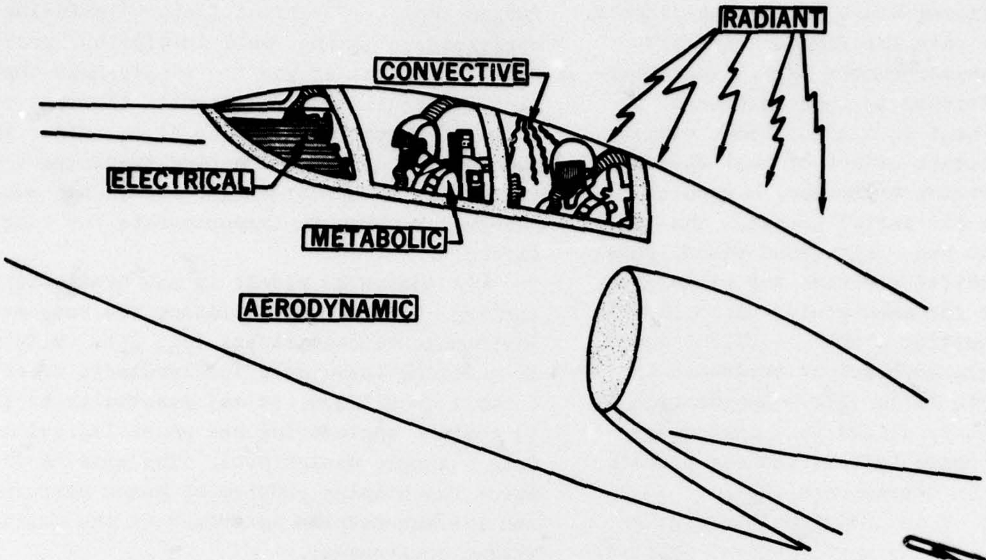

Fig. 5 Diagram summarizing heat sources in the cockpit of fighter/trainer aircraft

T_{ag}, aerodynamic heating, sunlight (greenhouse effect and surface heating), avionics and human metabolism (Fig. 5). Convective cooling of man occurs when $T_a < \bar{T}_s$. Raising V is relatively ineffective [see equation (3)], and V > 3 m/s (600 fpm) is disturbing to cockpit occupants. It is important to realize that physiologically meaningful heat exchange takes place only in the microclimate next to the skin; conditions which are normally adequate for light work may provide insufficient cooling in the cockpit due to multilayered flight clothing.

Evaporation of 1 g of water from the skin removes 67.5 w•hr (58 kcal) of heat. Evaporative cooling depends upon V and existence of a P_{wa} less than 42 torr in the microclimate. Man can secrete sweat at rates approaching 1 l/hr, but aircrew clothing severely limits evaporation. Profuse sweating has several undesirable side effects, including subjective discomfort, sweat dripping into the eyes, and gradual depletion of body fluid reserves. The adverse effects of dehydration will be discussed later.

Aircrew clothing is a major factor limiting heat dissipation by conduction and evaporation. The summer flight ensemble for pilots of high-performance aircraft includes cotton underwear, Nomex flight suit, anti-G suit, boots, gloves, helmet, oxygen mask, and restraint harness. The insulation provided is 1.5 to 2.0 Clo, where 1 Clo is the value for normal indoor clothing or 0.155 deg $C \cdot m^2/w$. Clothing also impedes air movement and forms a barrier against sweat evaporation, with complete impermeability under the helmet, mask, boots, and areas covered by anti-G bladders. In addition, about 25 percent of the body surface area is in contact with the ejection seat; once the temperature of the cushions has equilibrated with the clothing, there is no further heat exchange in that area.

CONSEQUENCES OF HEAT STRESS

Man is a homeotherm whose internal temperature is regulated around an average value of 37 C (98.6 F). For men at rest or doing light work in heat, T_c = 38 C represents the average upper limit at which the body can establish true thermal equilibrium (3, 20). Above this level, regulatory mechanisms begin to lose their efficiency and heat storage accelerates; with such "environment-driven" conditions, it is only a matter of time until T_c reaches 39 to 40 C and collapse becomes likely.

Among the earliest measurable consequences of heat stress are changes in performance of complex tasks. The literature on this topic is large and often confusing, but it is clear that heat stress of the type seen in cockpits can be associated with altered learning curves, shortened time sense, impaired vigilance and increased error-rates on tracking (21). Although such changes are subtle, they are relevant to man in the cockpit. A study which compared F-4 photoreconnaissance scores in cold and hot weather demonstrated significantly lower values in heat (11). Zeller studied aircraft accident rates based on 7 X 10^7 flying hours and 3000 accidents, and found that the rate for fighter aircraft peaks during the summer months (22). While multiple factors contribute to these patterns, it seems likely that heat is a significant element.

Another important effect of heat stress is diminished acceleration tolerance, a problem of great significance for aerial combat. The body's normal responses to heat (cutaneous vasodilation and blood volume shift) decrease the circulatory reserves available for maintaining blood flow to the brain. Mild heating with T_c = 37.8 C and $\bar{T}_s$ = 35.0 C causes relaxed blackout threshold to decrease from 3.2 to 2.7 G (23). Dehydration by 2 to 3 percent of body weight is a common occurrence in men working in heat and may produce further reduction in G-tolerance (24).

The response of an individual to a given environment involves many physiological factors. Crews of high performance aircraft have several advantages: they are young (less than 35 years), physically fit, and heat acclimatized. On the other hand, combat introduces a number of detrimental factors, including unusual or prolonged duty hours, sleep loss, and repeated flights with inadequate recovery periods for body cooling and rehydration.

A number of basic measures can be used to maximize aircrew heat tolerance and thus diminish ECS cooling requirements. Procedures should insure adequate heat acclimatization for persons flying in hot climates: on initial exposure, men show far greater cardiovascular strain and heat storage than occurs after 7 to 10 days of conditioning (3). During ground intervals, aircrews should have ready access to palatable fluids, and they should also realize the importance of drinking large quantities, even beyond satiety; thirst is normally quenched before complete fluid replacement has occurred, producing a condition termed "voluntary dehydration" (18).

MAN-ORIENTED ECS SPECIFICATIONS

Ideally a military ECS specification should be written so that the aircraft designer can perform trade-off analyses, balancing the weight and power demands of cooling against other requirements to optimize overall weapons-system effectiveness. Unfortunately, such comprehensive analysis is now beyond our grasp, but reasonable models are available for some elements of the system.

An analysis of cockpit heat load has been published by Hughes (25), who developed a set of curves and computer programs to demonstrate the design impact of various factors including crew work load, clothing, wall insulation, and sunlight. The latter was the single most important factor, requiring a substantial lowering of T_{ac} to maintain estimated $\bar{T}_s$ at 33 C. Major improvement occurred upon decreasing transparent area or increasing canopy reflectivity, but such changes are seen as inappropriate for combat aircraft.

A choice of models is now available representing human thermoregulation and response to environmental heat stress (26, 27). With advances in modeling techniques and knowledge of actual cockpit conditions, it may eventually be possible to combine engineering and physiological models into a single design tool. The missing link remains the complex problem of human performance and the man-machine interface in the multistress flight environment.

The desire to provide only the minimum necessary cooling poses an important question. Should the ECS insure thermal comfort for aviators, or is some lesser amount of cooling acceptable? Comfort is not a luxury; it is the subjective correlate of physiological thermoneutrality, where heat balance is maintained through vasomotor control with minimal sweating. When body temperatures exceed comfort levels (T_c > 38 C and $\bar{T}_s$ > 34 C), thermoregulatory processes lose efficiency and thermal tolerance becomes time-limited due to gradual depletion of physiological reserves, with duration depending upon the severity of stress and characteristics of the individual. Transient heating (15 min. or less) is readily tolerated if conditions return to comfort immediately thereafter, but in flight operations, the 15-min. period is often exceeded and subsequent cooling is usually less than adequate so that stored heat remains trapped in the body throughout the flight. Furthermore, even mild heat stress is probably associated with decreased tolerance for the other stresses of flight, including not only acceleration, but hypoxia and motion sickness as well.

New ECS specifications should be written for application to fighter/trainer aircraft, as distinguished from transports, and should utilize state-of-the-art techniques for data acquisition and analysis. A physiologically rational specification should require cooling capacity sufficient to maintain $\bar{T}_s \leq$ 35 C with the cockpit in full sunlight, with avionics on, and allowing for aircrew clothing appropriate to the aircraft's intended mission. The P_w should be $\leq$ 20 torr and

V surrounding occupants should not exceed 3 m/s. Aircrew members should have sufficient individual control of ECS inlet temperature, flow, and direction so that upper body temperature can be kept $\leq$ 36 C while foot and leg temperatures remain $\geq$ 29 C.

Qualification tests of ECS performance should include the following measurements under representative ground and flight conditions:

1 Determination of T_a, T_d, T_b, and V at an instrument cluster located near the pilot's head but away from air inlets or hot surfaces. A small black globe (5 cm) is substituted for the standard industrial size (15 cm).

2 Mandatory measurement of T_a at: (a) ECS inlet, (b) rudder well, (c) lap, and (d) chest level. ECS distribution duct temperatures, cockpit surface temperatures, and ECS mass flow are also relevant.

3 Measurement of T_s at calf, thigh, upper arm, chest, and head. Other physiological variables should be measured if possible, including heart rate, core temperature (auditory canal or rectum), and weight loss across the flight.

4 The foregoing data must be correlated with sortie details including ground weather, time of day, speed, altitude, ECS setting, and exact time of events, such as canopy closure. Aircrew comments should be formally elicited regarding thermal comfort, air distribution, noise, the presence of water, fog, or ice, and effectiveness of defog air.

Description of the cockpit thermal environment must go beyond simple air temperature and relative humidity. Various indices exist which take into account the three major variables, T_a, T_d, and T_b. The WBGT is probably the most suitable for current use, since it is easily calculated, widely accepted, and allows comparison to a large body of physiological literature. Nevertheless, environmental data should never be reported as an index alone, but actual constituent values should also be given. A WBGT line has been added to the raw data on Fig. 3 and reflects the heavy weighting of wet bulb temperature.

Where cooling of the entire cockpit proves too costly in trade-off analysis, or long ground standby is required, conditioning of the microclimate can be used. One answer is the air-ventilated suit (AVS); however, air is a relatively inefficient cooling medium due to its low specific heat, and such suits actually cool through sweat evaporation (28). An attractive alternative is the liquid-conditioned garment (LCG) (29); a full-length LCG was used by Apollo astronauts in space, but abbreviated versions may suffice in aircraft. The LCG requires less power and provides more efficient cooling than does the AVS, and is independent from engine power.

Adequate design and testing of ECS and/or personal cooling presuppose knowledge of aircraft mission, including flight profile, required clothing, and crew workload. Design must allow for "worst case" conditions, i.e., ground operations and low-level flight in hot, humid climates. Where cooling capacity is inadequate, heat can become one of the factors determining training limitations and/or combat casualties. For this reason, it has become imperative to develop and strictly enforce physiologically sound ECS and personal cooling specifications.

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