

RECENT EXPERIMENTS WITH PERSONAL COOLING FOR AIRCREWS

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INTRODUCTION

Advanced aircrew clothing for fighter aircraft integrates items required for protection from fire, hypoxia, acceleration and perhaps chemical weapons. However, such multifunction clothing tends to store body heat (1,4), and there is a growing consensus that some form of personal cooling is required for hot-climate flight operations to prevent discomfort and hyperthermia that might otherwise affect crew performance (3). The goal here is not simply extension of tolerance time for work in an excessively hot environment, but assurance of continuing optimal human performance. Crewmembers are required to perform multiple complex tasks in a setting where a minor error can have a critical impact on mission accomplishment or even lead to loss of an aircraft.

Both air- and liquid-cooled garments have been shown to improve human tolerance for work under hot conditions, and new fighter aircraft use both. The F-22 is equipped to supply cool air to a vest worn next to the pilot's skin, while the Eurofighter 2000 uses a thermoelectric heat sink (capacity 150W) to provide cool liquid to a tubing-lined undershirt. Crews of older aircraft such as the F-15 and F-16 can also benefit from the advanced clothing designs. The United States Air Force has recently funded development of a prototype system named APECS, which uses a small radiator bolted to the existing air conditioning outlet to cool liquid for circulation through an undergarment. We report here on results from preliminary tests of F-22 air and APECS liquid systems under hot-weather flying conditions as simulated in a thermal chamber at Brooks Air Force Base (AFB).

METHODS

Experiments were performed according to protocols approved by the local Institutional Review Board. The subjects were all male volunteers (no females came forward) who gave informed consent and passed a basic physical examination. Eight subjects were studied wearing F-16 clothing with APECS cooling and without it (uncooled control); five of these subjects also wore the F-22 ensemble with air and APECS cooling to allow direct comparison of the two systems.

For each experiment, the subject dressed in shorts and was instrumented to measure heart rate, rectal temperature (T_{re}) and skin temperatures on the right lateral chest (T_{ch}) and anterior thigh (T_{th}). The subject donned the appropriate cooling garment and flight suit, followed by boots, anti-g leggings, counter-pres-

sure jerkin, survival vest, parachute harness and gloves. Preparation required 30 to 40 min and took place in a room maintained at 20°C.

The subject entered the thermal chamber set to preflight conditions (PRE) (Table 1). He stood on the static treadmill while his leads were connected to monitoring systems. He then walked at 2.5 mph on a level treadmill for 20 min to represent preflight activity (walking to and inspecting the aircraft). The subject next simulated cockpit entry by seating himself in an ejection seat located next to the treadmill and donning a helmet and oxygen mask. The cooling system (if any) was connected at this time. For air cooling, the vest was supplied with 425 L·min⁻¹ of air at 13°C; for APECS, the cooling shirt (covering torso and arms) was perfused with 0.6 L·min⁻¹ of water-antifreeze mix at 17°C. The flight phase (FLT) (Table 1) included an initial 30-min period of gradual decline in ambient temperature followed by 60 min of maintenance at the level representing cockpit conditions during cruise. Workloads for PRE and FLT were based on earlier studies in aircraft and centrifuges.

Table 1. Chamber conditions (dry bulb temperature, relative humidity).

	PRE	FLT
F-16 ¹	35°C, 40%	28°C, 20%
F-22 ²	43°C, 10%	21 °C, 10%

¹ F-16 conditions matched those measured during summer flying at Moody AFB, GA (4).

² F-22 preflight conditions simulated hot summer days at Edwards AFB, CA. Cockpit conditions (FLT) were set to design values since the aircraft had not yet flown.

RESULTS AND DISCUSSION

The T_{re} at chamber entry averaged 37.3°C (range 36.9 to 37.8°C). During PRE, skin temperatures quickly rose to plateau at about 37°C while T_{re} increased gradually, passing through a mean value of 37.6°C at the end of treadmill walking. These results were similar for all experiments despite the variation in ambient conditions (Table 1) and slight differences in the clothing assemblies for the two aircraft.

Figure 1 shows mean data for the F-22 profile with either air or liquid cooling. Table 2 shows mean temperatures at the end of FLT for all four conditions. In control experiments (F-16 None), skin temperatures declined slightly as the chamber cooled in FLT, stabilizing at mean values of 35.7°C; T_{re} continued to rise during the first 30 min of FLT and occasionally reached or exceeded the 38°C level, which is regarded as the upper limit for unimpaired aircrew performance. Personal cooling of either type substantially lowered T_{ch} but produced no significant alteration in either the temperature of uncooled skin (T_{th}) or the core (T_{re}). Subjects reported that their torsos felt cold with both systems, but preferred the air

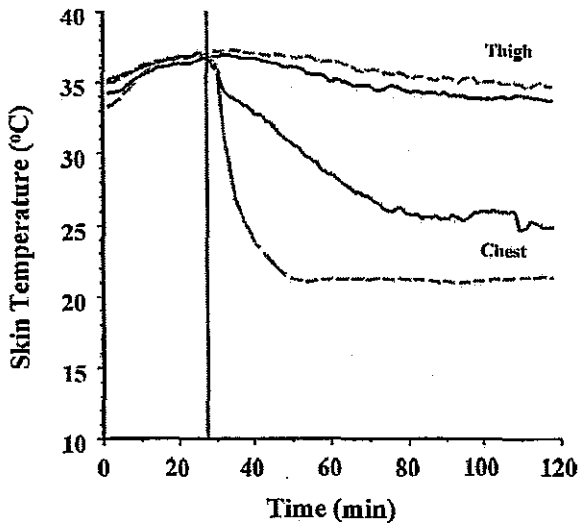


Figure 1. F-22 profile with either air or liquid cooling. Solid lines represent air cooling; dashed lines represent liquid cooling.

metabolic heat load. No significant difference was associated with the specific clothing ensemble (F-22 vs. F-16), "preflight" ambient conditions (F-22 very hot/dry vs. F-16 hot/humid) or the "inflight" cockpit environment (F-22 cool vs. F-16 moderate).

Comparison of air vs. liquid cooling requires that distinctions be made

vest because it dried the sweat, which had accumulated in their t-shirts during preflight activity. The liquid-cooled garment was said to feel clammy.

The validity of the simulated workload in PRE and FLT is confirmed by the fact that T_{re} in the control experiments matched values seen among pilots of fighter aircraft in actual hot-weather flying operations (3). As operated here, neither cooling system reduced peak core temperature, which may reflect primarily the

Table 2. Mean temperatures (°C) at the end of FLT. Data for five subjects who participated in all tests.

	F-16 None	F-16 Liq	F-22 Liq	F-22 Air
T_{th}	35.7	36.0	33.9	35.1
T_{ch}	35.7	27.8	25.0	21.4
T_{re}	37.8	37.9	37.8	37.7

among the theoretical capacity of each medium, practical cooling levels and the cooling produced by a specific system designed for a selected flow rate and temperature range. Liquid is clearly the more potent cooling medium as shown by immersion hypothermia, and liquid-perfused garments can produce intense cooling by combining low water temperature and extended body coverage; limitations reside in the size of the heat sink, garment coverage and the need for effective temperature control. Air has a much lower specific heat and presents real dif-

difficulties with distribution beyond the torso, but it has the advantage of local drying for skin and underclothing.

In terms of the specific systems tested here, the F-22 air cooling system was operating close to practical capacity with a very high airflow and low inlet temperature. Additional experiments (not reported here) demonstrated once again the impracticality of trying to distribute cool air over the entire body in personnel wearing multilayered aircrew clothing; among other problems, the high flow tends to inflate the limbs and thus reduce mobility.

In contrast, APECS can provide more cooling. APECS can be set to produce much lower water temperatures; a fixed setting of 17°C was used to minimize intersubject variability, and that in turn required selection of a water temperature that would remain tolerable for the entire 90-min period of operation. More sophisticated control of water inlet temperature can be expected to improve both comfort and cooling efficacy, and liquid-cooled garments can be extended to cover the entire body, as is the case for astronauts wearing space suits.

On reviewing the results of these experiments, it is clear that the best strategy for protecting aircrew would be to minimize preflight heat stress so that cooling in flight need only balance cockpit heat load without having to reverse pre-existing hyperthermia. In theory, it should be possible to accomplish this by transporting the crew directly from ready-room to cockpit while other personnel perform the required preflight aircraft inspection. Alternatively, a crewmember who is already dressed for inflight cooling could use a portable heat sink during preflight activity. Air cooling has proven impractical for this application, since air at ambient temperature offers little cooling, and air conditioners are not portable. Liquid cooling is possible, and the laboratory at Brooks AFB is currently rerunning the F-16 APECS protocol with the addition of preflight cooling by means of a small, ice-filled reservoir and battery-operated pump. Meanwhile, the APECS is also undergoing preliminary flight testing aboard F-15 and F-16 aircraft flying in hot weather at NASA's Dryden Flight Research Center.

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