Thermoregulatory and Orthostatic Responses to Wearing the Advanced Crew Escape Suit

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ABSTRACT

INTRODUCTION: Current NASA flight rules limit the maximum cabin temperature (23.9 °C) during re-entry and landing to protect crewmembers from heat stress while wearing the Advanced Crew Escape Suit (ACES) and Liquid Cooling Garment (LCG). The primary purpose of this ground-based project was to determine whether the LCG could provide adequate cooling if ambient temperature reached 26.7 °C. The secondary objective was to determine whether there would be a graded effect of ambient temperature profiles with maximum temperatures of 23.9 (LO), 26.7 (MID), and 29.4 °C (HI). **METHODS:** Eight subjects underwent a 5-h temperature profile (22.8-26.7 °C) in an environmental chamber while wearing the ACES and LCG. Subjects controlled the amount of cooling provided by the LCG. Core (T_{core}), skin temperatures (T_{sk}), and heart rate (HR) were measured every 15-min. A 10-minute stand test was administered pre- and post-chamber. Additionally, 4 subjects underwent the three 5-h temperature profiles (LO, MID, and HI) with the same measurements. **RESULTS:** In the 8 subjects completing the MID profile, T_{core} and T_{sk} decreased from the start to the end of the chamber stay. Subjects completed the stand test without signs of orthostatic intolerance. In the 4 subjects who underwent all 3 profiles, there was no discernible pattern in T_{core}, T_{sk}, and HR responses across the temperature profiles. **CONCLUSIONS:** In the range of temperatures tested, subjects were able to sufficiently utilize the self-selected cooling to avoid any potential deleterious effects of wearing the ACES. However, these subjects were not microgravity exposed, which has been suggested to impair thermoregulation.

Key Words: microgravity, space flight, protective garment, heat stress

INTRODUCTION

Since 1988, all crewmembers have been required to wear a protective garment during Space Shuttle launch and landing (Bishop et al., 1999). The primary purpose of this garment is to provide protection against rapid decompression at high altitude, against hypothermia in case of bailout over cold water, and against toxic gases that may be emitted from the Orbiter after landing. The current garment, the Advanced Crew Escape Suit (ACES), is comprised of an outer garment of a single layer of Nomex™, interlayer of Nylon reinforcement, and a gas container (i.e., bladder) consisting of a single layer of Goretex™. In addition, the ensemble includes a non-conformal (bubble-style) helmet, a lower body positive pressure garment (anti-gravity suit; g-suit), boots, and polypropylene undergarments **(Figure 1)**.

INSERT FIGURE 1 HERE

In the effort to provide the desired protection, an unintended side effect of wearing the ACES was body heat retention. Elevated core and skin temperatures would be expected to exacerbate the microgravity-induced reduction in exercise capacity (Levine, 1996; Moore, 2003) and orthostatic tolerance observed following short- and long duration space flight (Buckey et al., 1996; Fritsch-Yelle et al., 1996; Meck et al., 2001). An elevated core temperature has been suggested to be the cause of an increase in orthostatic intolerance following the adoption of this protective clothing during landing (Nicogossian et al., 1995). Additionally, increased core temperature may impair cognitive vigilance (Færevik, 2003).

To minimize heat retention, an attempt was made to ventilate the protective suit with cabin air, but was proven to be ineffective (Pandolf et al., 1995; Sawin et al., 1998). In 1994, plastic tubes were integrated into Capilene™ underwear such that cool water could be circulated near the skin surface so that body heat could be removed to the cabin air (Perez et al., 2003); this became known as the Liquid Cooling Garment (LCG). The water circulated from the suit was passed through a thermoelectric cooling unit external to the protective garment where the heat was transferred from the water lines to the ambient air. Originally, two crewmembers shared each cooling unit. At present, Individual Cooling Units (ICU) are used to remove heat from the LCG water lines.

NASA flight rules limit the maximum allowable cabin temperature prior to and during re-entry to protect crew health and comfort. Heat in the crew compartment is primarily the result of heat retained by the Shuttle itself during re-entry, but is further increased by hardware and avionics in operation as well as the metabolic heat produced by the crewmembers. The Shuttle payload doors are left open until just before de-orbiting to radiate as much heat as possible and decrease cabin temperature. At present, the upper limit of allowed temperature during descent and landing is 23.9 °C (75 °F). However, to meet the demands of mission objectives, flight controllers may consider waivers to allow higher cabin temperatures so that additional hardware can be in operation during descent.

The purpose of this project was to evaluate the cooling capabilities of the ACES ensemble, including the LCG, in normal subjects exposed to simulated cabin temperature profiles similar to that experienced by Space Shuttle crewmembers during re-entry and landing. The primary objective was to determine whether subjects wearing the ACES ensemble could tolerate a temperature profile with a higher maximum cabin temperature of 26.7 °C (80 °F). We hypothesized that subjects would be able to self-regulate their cooling with the LCG so as to prevent a rise in body temperature and heart rate. Further, we hypothesized that heart rate and blood pressure responses to standing would not be altered after this simulated landing temperature profile. Secondarily, we sought to characterize the body temperature and heart rate responses in a subgroup of subjects across a range of ambient temperature profiles while wearing the ACES ensemble. The temperature profiles examined include the currently allowed maximum temperature of 23.9 °C (75 °F) and two higher profiles with maximum temperatures of 26.7 °C (80 °F) and 29.4 °C (85 °F).

METHODS

Overall Protocol

Eight subjects, four men and four women, participated in this investigation (33.6±6.1 yr, 67.3±2.7 kg, 155.5±24.8 cm). All eight subjects participated in testing to meet the primary objective of this project in which subjects were exposed to a temperature profile with a peak temperature of 26.7 °C (80 °F). To meet the secondary objective of this project, four of the eight subjects (two men and two women) were exposed to three temperature profiles **(Table 1)**: one which simulates the currently allowed peak temperature of 23.9 °C (75 °F; LO), one in which the peak temperature was 26.7 °C (80 °F; MID) and one in which the peak temperature was 29.4 °C (85 °F; HI).

INSERT TABLE 1 HERE

All subjects passed a modified Air Force Class III physical, and were screened for illicit drug usage and for HIV and hepatitis antibodies. Testing procedures were fully explained to the test subjects, and written informed consent was obtained from each subject prior to participation in this study. The testing protocol and procedures were reviewed and approved by the NASA Johnson Space Center Institutional Review Board.

Subjects were dressed in the ACES ensemble and remained within an environmentally-controlled chamber for five hours. Temperature and humidity were controlled to simulate environmental conditions to which crewmembers are exposed during re-entry and landing. Temperature profiles were patterned from actual Shuttle re-entry and landing data provided by NASA Crew and Thermal Systems Division personnel. Prior to and immediately after chamber exposure, subjects performed a 10-minute stand test while wearing the ACES as a test of orthostatic tolerance. The overall subject timeline is described in **Figure 2.**

INSERT FIGURE 2 HERE (Test Timeline)

The schedule of the temperature profile was based upon several assumptions. First, the total amount of time spent wearing the ACES reflected that of the commander and pilot. The commander and pilot don their suits approximately two hours before de-orbit burn.