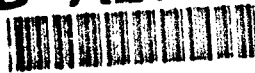


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VENTILATION LOSS IN THE NASA SPACE SHUTTLE CREW PROTECTIVE GARMENTS: POTENTIAL FOR HEAT STRESS

Gregory K. Askew and Jonathan W. Kaufman
Air Vehicle and Crew Systems Technology Department (Code 6023)
NAVAL AIR DEVELOPMENT CENTER
Warminster, PA 18974-5000

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INTRODUCTION

As part of the effort to improve Space Shuttle crew safety, the National Aeronautics and Space Administration (NASA) currently provides Shuttle crews with the S1032 Launch Entry Suit (LES) which provides both a counter pressure system, for protection against extreme hypobaria, and anti-exposure protection. Based on an expanded polytetrafluoroethylene (PTFE) membrane, the anti-exposure protection inherent in the S1032 is intended to provide thermal protection in 4.4°C (40°F) water for up to six hours.

The S1032 or S1035 is to be worn during launch and re-entry. Accordingly, it is conceivable that a person would be required to wear the S1032 or S1035 for up to eight hours due to a delayed launch. This could involve up to six hours awaiting launch followed by two hours of flight time until a stable orbit is reached, at which time the S1032 or S1035 could be removed. Two past studies (2,3) have demonstrated that heat stress due to a combination of ambient conditions and clothing was unlikely to be a serious problem for Shuttle crews.

The present study was intended to compare the S1035 to the S1032 to determine which suit poses the greatest threat of heat stress when used Ventilated (V) or Unventilated (UV) under conditions of temperature and time considered extreme for the Space Shuttle. The differences between the S1032 and S1035 consist primarily of the extent of anti-G protection inherent in the garments. The S1035 has greater pressure bladder coverage which results in an increase in the surface area through which water vapor can pass because the pressure bladder is comprised entirely of goretex.

MATERIALS AND METHODS

SUBJECTS:

Four healthy individuals (Table 1), 4 males, volunteered to participate as subjects after being fully informed of the details of the experimental protocol and associated risks.

Weight was recorded prior to each test run and the mean calculated. Body surface area (SA) was calculated (1) from the mean weight and height of each subject.

METHODS AND PROCEDURES:

All tests were begun in the morning, with the ventilated and unventilated trials scheduled to last up to eight hours. Subjects were exposed to the experimental conditions individually or in pairs. The minimum time interval between tests for a given subject was two days, so that acclimatization effects could be minimized.

The subjects reported to the laboratory on the morning of a test and were given a physical examination by the attending flight surgeon. Blood and urine samples were collected and analyzed as part of the flight surgeon's examination of the subject.

Changes in urine specific gravity (Δ SG) were determined with a clinical refractometer. Each subject's baseline weight was obtained on a scale accurate to $\pm 1/4$ lb (Continental Scale, Chicago, IL, model Health-O-Meter) and ECG electrodes (3M, Minneapolis, MN, Red Dct) were

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placed on the subject. ECG signals were amplified with isolated ECG amplifiers (Gould, Cleveland, Ohio, model 4600 series amplifiers). Heat flux/temperature transducers were attached to the following body sites: (A) forehead; (B) left upper chest; (C) left lower upper arm; (D) left hand, dorsal; (E) right anterior thigh; (F) left posterior thigh; (G) right shin; (H) right foot; (J) right upper upper arm; and (K) left lower back. These transducers consisted of a thermopile heat flux transducer with a thermistor located in the center (Hamburg Associates, Jupiter, FL). Analog signals from these transducers were amplified (Bioinstrumentation Assoc., San Diego, CA, model HF-12/Temp-14) and stored on the laboratory's data collection system (MDB Systems, Orange, CA, model MLSI-1123C-R-X computer, Data Translation, Marlboro, MA, DT2782 A/D boards). Two rectal thermocouples (Sensortek, Clifton, NJ, model RET-1) were inserted at least 8-10 cm anterior to the anal sphincter. Thermocouple outputs were measured with isolated signal conditioners (Opto, Huntington Beach, CA, model TC.4).

Subjects were then dressed in the appropriate test ensemble. This clothing ensemble consisted of: 1) S1032 or S1035 garment; 2) parachute harness; 3) parachute pack; 4) flight helmet; 5) flight gloves; 6) ventilation system; 7) capilene underwear, expedition weight; 8) adult diaper; 9) socks; 10) boots; and a lumbar pad. The ventilation system was portable and had a 10 CFM output. This ventilator was used throughout the ventilated runs and during the cool-down period following dressing in the ventilated and unventilated runs.

Upon completion of dressing, the subject was weighed, followed by a 20 minute rest period which enabled the subject's temperature and heart rate to return to a resting condition before commencing that day's trial. The laboratory temperature was maintained at approximately 20°C (68°F) to minimize thermal stress during dressing.

Following the conclusion of the rest period, the subject entered the chamber and was placed in a supine position upon a Space Shuttle passenger seat (P/N 3172-13). Testing was performed in chamber conditions of dry bulb temperature (T_{db}) = $27.2 \pm 0.1^\circ\text{C}$, wet bulb temperature (T_{wb}) = $21.1 \pm 0.3^\circ\text{C}$, and globe temperature (T_{gl}) = $27.3 \pm 0.1^\circ\text{C}$. For the ventilated (V) and unventilated (UV) trials, subjects were to remain supine until 6 hours had elapsed, at which time they could move to a seated position. Subjects were permitted to read, listen to music, or sleep during testing; no gross movements were allowed save for the effort to sit up. Eating and drinking were ad libitum throughout the trial (Table 2). Individuals were requested to remain in the chamber for eight hours, unless their run was terminated early due to a rectal temperature (T_{re}) exceeding 39°C , a rate of T_{re} increase of $0.6^\circ\text{C}/5$ minute period, heart rates exceeding 90% of the maximum predicted for age, or the subject, flight surgeon, or principal investigator requested termination.

Subjective sensations were evaluated every 30 minutes throughout the exposure period by means of scales for comfort, sweating, temperature, and fatigue. Subjects were instructed to indicate their subjective sensation for each criterion except temperature on a 1 - 7 scale, and on a scale of -7 to 7 for temperature. Comfort (Cm), sweating (Sw) and fatigue (Ft) used a 1 to indicate the most pleasant situation and 7 to indicate the greatest unpleasantness. Temperature

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(Temp) used -7 to indicate extreme cold, 0 indicated thermal neutrality, and 7 indicated extremely hot.

Total sweat rate (SRT) was determined by the difference between the post-test nude weight, corrected for fluid and food intake, and the pre-test weight. The change in garment weight (ΔGW) due to the uptake of sweat was determined by:

$$(1) \quad \Delta GW = (CW2 - NW2) - (CW1 - NW1)$$

where CW is clothed weight, NW is nude weight, and 1 & 2 signify pre- and post-test values respectively. The percentage of sweat evaporated (%E) (4) was calculated from:

$$(2) \quad \%E = (SRT - \Delta GW) / SRT$$

STATISTICAL ANALYSIS:

Differences between experimental conditions were evaluated with a repeated measures ANOVA. This test was used to compare the effect of subjects and suits versus time. Differences were considered significant at the level of $p < 0.05$.

RESULTS

The results of this study indicate that no physiological strain was imposed by either the S1032 or S1035 under any of the experimental conditions. No statistical differences were observed between subjects over time or suits over time. No statistical differences were observed between initial and final T_{re} ($p < 0.05$) (figure 1). No statistical differences were observed between initial and final HR ($p < 0.05$) (figure 2).

Final values of T_{re} , and heart rate (Table 3) exhibited no indication of physiological stress. While discomfort was reported due to prolonged immobilization and lying in essentially one position, none of the trials were terminated early.

Water intake had a range of 0 - 1578 g of water in this study (Table 2), with no significant difference in consumption during the V versus UV runs ($p < 0.05$). Subjects reported feeling better when they consumed greater amounts of water. It was unclear, however, whether their greater comfort was due to the increased water intake or whether they consumed more water when they were in better spirits.

%E was not observed to be significantly different between experimental conditions (Table 3) ($p < 0.05$). Mean SRT for the V and UV runs were not statistically different among experimental conditions (Table 3).

DISCUSSION

It is clear from the results that neither the S1032 or S1035 posses an increased heat stress risk to users of this equipment under the test conditions. While T_{re} did increase during runs, their levels were never indicative of a physiological hazard. It appears that the inactivity of subjects, coupled with relatively mild ambient conditions, permitted adequate physiological adjustments to prevent thermal strain.

This lack of physiological stress is demonstrated by the relatively small changes in T_{re} . At no point during any of the runs were T_{re} values observed which would indicate any physiological hazard. While the final T_{re} 's for the V and UV runs suggest some degree of heat stress, the relatively high initial T_{re} 's indicates that much of the stress was incurred in the dressing process. An elevated initial temperature might also explain the cooling which was observed, since subjects may not have fully adjusted to the initial garment microenvironment prior to the start of runs. The heart rates observed during runs also suggest a negligible physiological heat stress imposed on subjects, since they were only slightly elevated over initial values. Though the sweat losses indicated exposure to elevated temperatures, evaporation was sufficient to minimize increases in T_{re} . The small increases in T_{re} indicated that evaporative heat loss was sufficient to dissipate heat without accumulation within body tissues.

Much of the physiological adjustment can be attributed to the near basal state of activity in the study. This is reflected in the heart rates exhibited by the subjects. The relatively low heart rates observed in this study would be expected for the minimal exertion required of subjects (subjects often slept a considerable percentage of their time in the chamber). It is significant that the subjects used in this study were not athletes; individuals with greater fitness levels could be expected to have much lower heart rates under the same conditions.

Discomfort experienced in the UV and V runs was believed to be primarily due to lying on one's back without appreciable movement for 6 hours. Water intake was in some way related to subjective comfort. It was observed that during periods of obvious discomfort drinking was minimal. Subjects would drink only minimal amounts during these periods despite encouragement. This was especially true during UV runs. It appeared that subjects generally consumed food and water during periods of relative comfort. This did not impact the quantitative physiological results but clearly impacted the ability of subjects to be alert and functional. While this type of response might be lessened with more highly fit individuals, it should be considered if circumstances require extended periods in a motionless supine position. It is worth noting that even highly fit subjects had difficulty with subjective tolerance of experimental conditions quite similar to those experienced in this study (2).

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Changes in the design of the S1032 garment led to the lack of significant difference between the S1032 and S1035. In these test, this suggests that the design modifications had no effect on thermal stress in the simulated pre-launch environment.

This study indicates that the conditions encountered in the Space Shuttle cabin during pre-launch should not act to produce heat stress, even if ventilation is not provided to users of the S1032 or S1035. Changes in the design of the S1032 garment led to the development of the S1035. The lack of significant differences between the S1032 and S1035 in this study suggests the design modifications had no effect on thermal stress. Finally, the discomfort of lying motionless for 6 hours may be a cause of concern, since decreased alertness and distraction are apparent. Allowing personnel the opportunity to periodically sit up would greatly improve comfort.

CONCLUSIONS

1. Ambient temperatures of 81°F were insufficient to produce significant levels of heat stress in individuals wearing either a ventilated or unventilated S1032 or S1035 ensemble.
2. Loss of ventilation in either the S1032 or S1035 does not significantly increase the physiological hazard for individuals wearing either ensemble over an 8 hour period in 81°F temperatures.

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TABLE 1: Physical characteristics of subjects.

Subject	Gender	Age (yrs)	Height (m)	Weight (kg)	Surface Area (m2)
A	M	28	1.78	66.0	1.82
B	M	31	1.70	67.0	1.78
C	M	29	1.73	64.8	1.77
D	M	48	1.67	64.0	1.73

Table 2. Water and Food Intake

Garment	Subject	Water Intake (g)	Food Intake (g)
1032V	A	0	500
1032V	B	911	260
1032V	C	773	40
1032V	D	---	---
1032UV	A	433	110
1032UV	B	490	130
1032UV	C	1064	40
1032UV	D	363	0
1035V	A	0	220
1035V	B	732	190
1035V	C	654	80
1035V	D	281	0
1035UV	A	0	200
1035UV	B	1578	160
1035UV	C	828	40
1035UV	D	267	0

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Table 3. Initial and Final Rectal temperatures, Heart Rate and Percent sweat Evaporated (%E)

Garmet	Subject	Init Tre	Final Tre	Init HR	Final HR	%E
1032V	A	37.2	37.4	69	86	.42
1032V	B	37.3	37.3	73	82	.79
1032V	C	37.4	37.2	81	73	.70
1032V	D	---	---	---	---	---
1032UV	A	37.2	37.3	65	80	.42
1032UV	B	38.0	37.8	87	101	.52
1032UV	C	37.3	37.1	71	61	.39
1032UV	D	37.5	37.7	67	77	.44
1035V	A	37.7	37.5	67	88	4.33
1035V	B	37.4	37.1	76	93	.82
1035V	C	37.3	37.7	77	41	1.0
1035V	D	36.7	37.5	72	59	.95
1035UV	A	37.4	37.3	61	82	.44
1035UV	B	37.8	37.1	85	83	.86
1035UV	C	37.5	36.7	53	49	1.45
1035UV	D	37.0	37.5	56	76	.54

Figure 1. Average rectal Temperatures, Vented and Unvented trials for S1032 and S1035

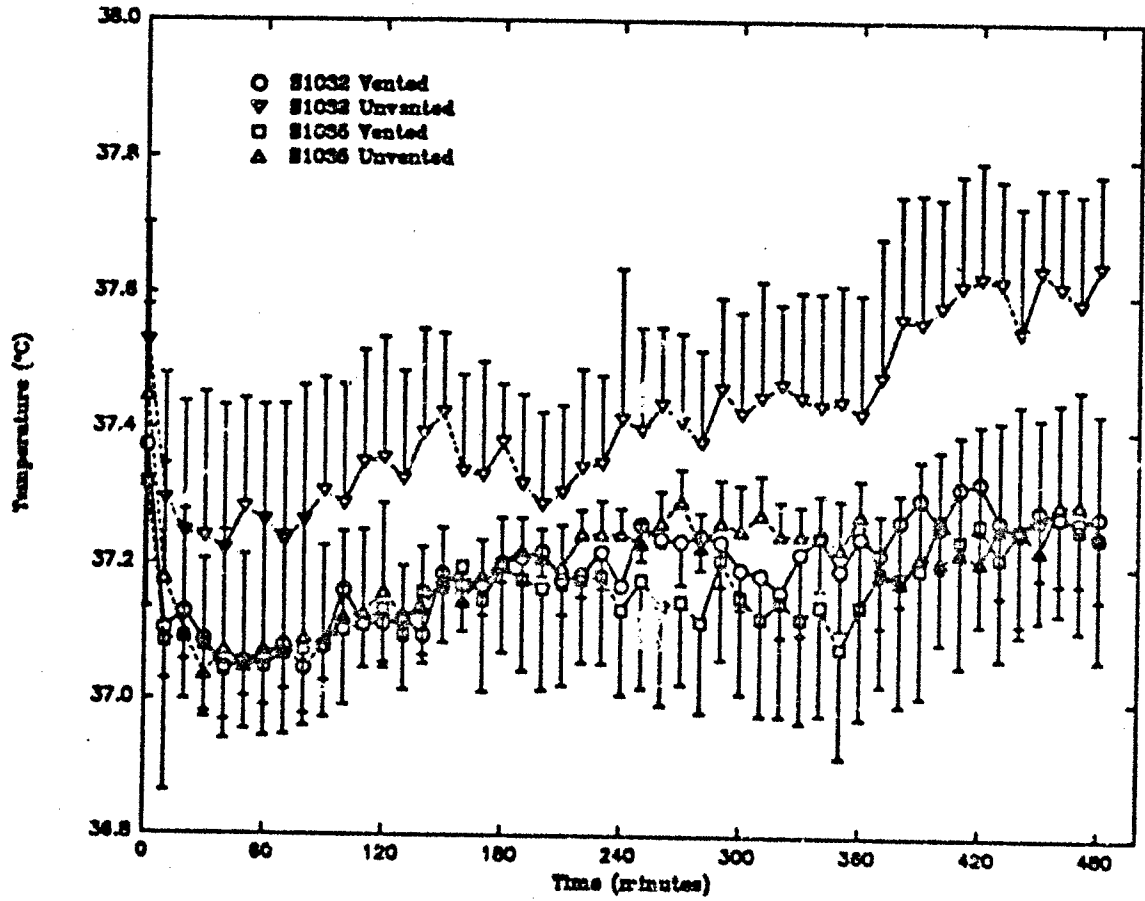
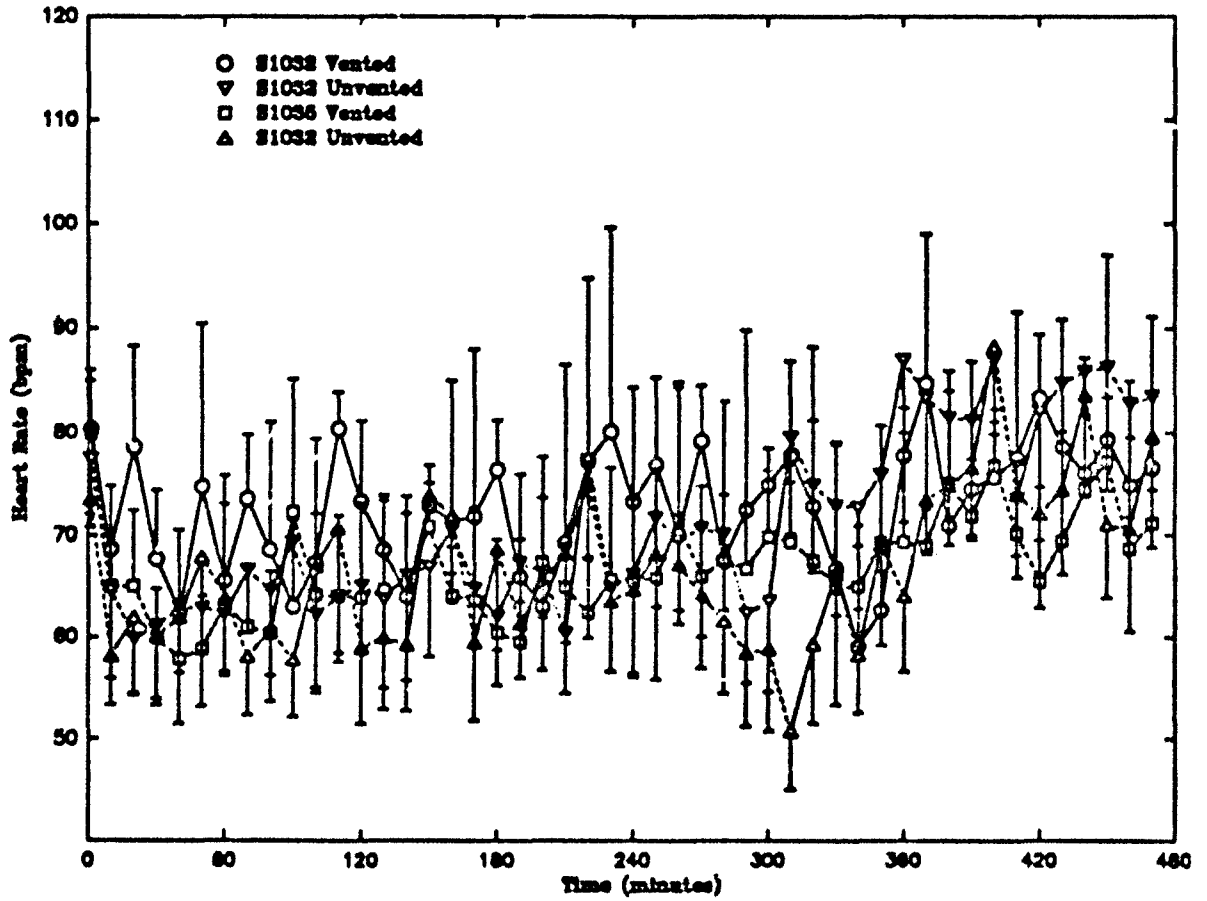


Figure 2. Average heart rate, Vented and Unvented trials for S1032 and S1035. Error Bar at the 99% confidence level.



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